Crystal G. Foley (SBN 224627)
SIMMONS BROWDER GIANARIS
ANGELIDES & BARNERD LLC
100 N. Sepulveda Blvd., Suite 1350
El Segundo, California 90245
Telephone: 310-322-3555
Facsimile: 310-322-3655
cfoley@simmonsfirm.com

Attorneys for Plaintiff
Labyrinth Optical Technologies LLC
[Additional Counsel Listed on Signature Page]

SACV12-759 AG (MLGx)

UNITED STATES DISTRICT COURT
CENTRAL DISTRICT OF CALIFORNIA

| | |
|---|---|
| LABYRINTH OPTICAL TECHNOLOGIES LLC<br>*Plaintiff,*<br><br>vs.<br><br>ALCATEL-LUCENT USA, INC.,<br><br>*Defendants.* | CASE NUMBER:<br><br>To be Supplied by the Clerk of The United States District Court<br><br>**COMPLAINT FOR PATENT INFRINGEMENT; DEMAND FOR JURY TRIAL**<br><br>DATE: May 10, 2012 |

Plaintiff Labyrinth Optical Technologies LLC ("Labyrinth") files this action for infringement of United States Patents No. 8,103,173 ("the '173 patent") and 7,599,627 ("the '627 patent") against Defendant Alcatel-Lucent USA, Inc. ("Alcatel"), seeking damages and injunctive relief. Labyrinth alleges as follows:

**JURISDICTION AND VENUE**

1. This is an action for patent infringement arising under the Patent Laws of the United States, 35 U.S.C. § 1 et seq., alleging infringement of United States Patent Nos. 8,103,173 ("the '173 patent") and 7,599,627 ("the '627 patent"). Copies of the patents are attached hereto as Exhibits A-B respectively, and are incorporated herein by reference in their entirety.

2. This Court has exclusive subject matter jurisdiction over this action under 28 U.S.C. §§ 1331 and 1338(a).

3. This Court has personal jurisdiction over Alcatel because Alcatel has conducted business in this district and has infringed, contributed to the infringement, and/or actively induced others to infringe Labyrinth's patents in this district as alleged in this Complaint (at a minimum by using, offering for sale and/or selling products which fall within the scope of the claims of the '173 and '627 patents).

4. Moreover, upon information and belief, Alcatel continues to conduct business in this district and infringe, contribute to the infringement of, and/or actively induce others to infringe the '173 and '627 patents in this district.

5. Venue is proper in this Court pursuant to 28 U.S.C. §§1391(b), 1391(c) and/or 1400(b), in that a substantial part of the events giving rise to Labyrinth's claims occurred in the Central District of California and Alcatel is subject to personal jurisdiction in the Central District of California (and thus for purposes of venue Defendant resides in the Central District of California).

## THE PARTIES

6. Plaintiff Labyrinth is a limited liability company organized and existing under the laws of California, and having a principal place of business at 500 Newport Center Drive, 7th Floor, Newport Beach, California 92660.

7. Upon information and belief and after a reasonable opportunity for further discovery, Alcatel is a corporation organized and existing under the laws of the state of Delaware, having a principal place of business at 800 North Point Parkway, Alpharetta, GA 30005. Alcatel's registered agent for service of process in the State of California is The Prentice-Hall Corporation System, Inc., 2710 Gateway Oaks Dr., STE 100, Sacramento, CA 95833.

## THE PATENTS IN SUIT

8. In optical data communications, systems were upgraded from a 10 Gb/s data transmission rates to a 40 Gb/s transmission rates. Data transmission rates at the much faster 40 Gb/s (or higher) presented extensive design challenges because the effects of polarization mode dispersion (PMD), chromatic dispersion and fiber non-linear effects such as cross-phase modulation become more dominant at the higher transmission rates.

9. The inventors of the patents-at-issue were driven to find a cost-effective method and system that compensates for PMD, optimizes signal to noise ratio performance and minimizes phase noise and nonlinearities (chromatic dispersion) associated with transmission over fiber at high data transmission rates.

10. The '173 patent entitled "Method and System For A Polarization Mode Dispersion Tolerant Optical Homodyne Detection System With Optimized Transmission Modulation" was duly and legally issued on January 24, 2012.

11. The assignee of the '173 patent is Labyrinth.

12. The '173 patent is valid and enforceable and has been at all times relevant to the instant action.

13. The '173 patent claims a system and method for coherent optical detection for an optimized transmission modulation.

14. For example, claim 1 of the '173 patent provides:

(1) A method of compensating a quadrature modulated optical data signal for effects of chromatic dispersion occurring during transmission over optical fiber, the method comprising the steps of:

(a) separating in-phase and quadrature components of the optical data signal;

(b) optoelectrically converting the in-phase and quadrature components of the optical data signal into in-phase and quadrature data signals;

(c) applying a corrective function to the in-phase and quadrature data signals, the corrective function modifying the in-phase and quadrature data signals in a manner that precisely counteracts effects of chromatic dispersion on the in-phase and quadrature components of the optical data signal.

'173 patent, Col. 12, lns. 42-56.

15. The '627 patent entitled "Method and System For A Polarization Mode Dispersion Tolerant Optical Homodyne Detection System With Optimized Transmission Modulation" was duly and legally issued on October 6, 2009.

16. The assignee of the '627 patent is Labyrinth Optical Technologies LLC.

17. The '627 patent is valid and enforceable and has been at all times relevant to the instant action.

18. The '627 patent claims a system and method for coherent optical detection for an optimized transmission modulation.

19. For example, claim 22 of the '627 patent provides:

(22) A method of reducing the transmitted power of a quadrature modulated optical data signal, comprising the steps:

(a) providing a quadrature modulated optical data signal by a transmitter;

(b) during all transitional states of the quadrature modulated optical data signal in which data symbols can change in value, reducing, by the transmitter, the power to zero such that transmitted power decreases to zero at approximately a mid point of each of the

> transitional states, where data signals are in effect spread out by approximately fifty percent in the frequency domain equivalent to a multiplication by a sine wave at half the data rate, and results in each symbol returning to zero at approximately a mid-point of the transitional states.

'627 patent, Col. 16, lns. 30-44.

## THE INFRINGING PRODUCT

20. Defendant Alcatel, within the United States, manufactures, uses, offers for sale, or sells at least Alcatel-Lucent's 1830 Photonic Service Switch, Metro/regional/long-haul WDM Platform that falls within the claims of the '173 patent.

21. For purposes of an example only, Alcatel's 1830 Photonic Service Switch, Metro/regional/long-haul WDM Platform falls within the scope of at least claim 1 of the '173 patent as it meets each limitation recited therein. Alcatel's 1830 Photonic Service Switch, Metro/regional/long-haul WDM Platform separates the in-phase and the quadrature components of the optical data signal upon reception, opto-electrically converts the in-phase and quadrature components of the optical data signal into in-phase and quadrature data signals, and it applies a corrective function to the in-phase and quadrature data signals, which modifies the in-phase and quadrature data signals that precisely counteracts effects of chromatic dispersion on the optical data signal.

22. On belief and information only, Alcatel's 1830 Photonic Service Switch, Metro/regional/long-haul WDM Platform falls within the scope of at least claim 22 of the '627 patent as it meets each limitation recited therein. Alcatel's has performed published experimental results where it uses a Carrier Suppression, Return to Zero, Quadrature modulated optical data signal, which during all transitional states of the quadrature modulated optical data signals, the transmitter

reduces the power to zero such that transmitted power decreases to zero at approximately a mid-point of each of the transitional states. Exhibit C, Chongjin Xie *et al.*, Transmission of Mixed 224-Gb/s and 112-Gb/s PDM-QPSK at 50-GHz Channel Spacing Over 1200-km Dispersion-Managed LEAF® Spans and Three ROADMs, Journal of Lightwave Technology, Vol. 30, No. 4, Pg. 547, February 15, 2012. On belief, Alcatel's 1830 Photonic Service Switch, Metro/regional/long-haul WDM Platform may have the limitations of claim 22 also.

23. Defendant Alcatel does not have a license or other authorization to practice the claims set forth in the '627 patent.

**COUNT I**

**Alcatel's Patent Infringement Under 35 U.S.C. §271 of the '173 Patent**

24. Labyrinth incorporates by reference the allegations of paragraphs 1-23.

25. Alcatel has directly or indirectly infringed the '173 patent at a minimum by making, using, selling and offering for sale a product that falls within the scope of the '173 patent, including, but not limited to, the Alcatel's 1830 Photonic Service Switch, Metro/regional/long-haul WDM Platform.

26. Alcatel has caused and will continue to cause Labyrinth substantial damage and irreparable injury by virtue of its continuing infringement.

27. Labyrinth is entitled to recover from Alcatel the damages sustained by Labyrinth as a result of Alcatel's wrongful acts in an amount subject to proof at trial and an injunction preventing Alcatel from continuing its wrongful acts.

28. Upon information and belief and after an opportunity for further discovery, Alcatel's infringement of the '173 patent is willful and deliberate.

**COUNT II**

**Alcatel's Patent Infringement Under 35 U.S.C. §271 of the '627 Patent**

29. Labyrinth incorporates by reference the allegations of paragraphs 1-28.

30. Alcatel has directly or indirectly infringed the '627 patent at a minimum by making, using, selling and offering for sale a product that falls within the scope of the '627 patent, including, but not limited to, the Alcatel's 1830 Photonic Service Switch, Metro/regional/long-haul WDM Platform and publishing the results of their research. Ex. C.

31. Alcatel has caused and will continue to cause Labyrinth substantial damage and irreparable injury by virtue of its continuing infringement.

32. Labyrinth is entitled to recover from Alcatel the damages sustained by Labyrinth as a result of Alcatel's wrongful acts in an amount subject to proof at trial and an injunction preventing Alcatel from continuing its wrongful acts.

33. Upon information and belief and after an opportunity for further discovery, Alcatel's infringement of the '627 patent is willful and deliberate.

**WHEREFORE**, Labyrinth respectfully requests that the Court enter a judgment as follows:

A. That Alcatel has infringed the '173 and '627 patents under 35 U.S.C. §271;

B. Permanently enjoining and restraining Alcatel, their officers, directors, agents, servants, employees, licensees, successors, assigns, those in concert and participation with them, and all persons acting on their behalf or within their control under 35 U.S.C. §283 from further acts that infringe the '173 and '627 patents, including but not limited to, making, using, selling, offering to sell, importing, exporting, advertising, or otherwise using, contributing to the use of, or inducing the use of all infringing products produced by Alcatel;

C. Requiring Alcatel to:

1. Send a copy of any decision in this case in favor of Labyrinth to each person or entity to whom Alcatel has sold or otherwise distributed any products found to infringe the '173 and '627 patents, or induced to infringe the '173 and '627 patents, and informing such persons or entities of the judgment and that the sale or solicited commercial transaction was wrongful;

2. Recall and collect from all persons and entities that have purchased wholesale or are a distributor of any and all products found to infringe the '173 and '627 patents that were made, offered for sale, sold, or otherwise distributed by Alcatel, or anyone acting on its behalf;

3. Destroy or deliver to Labyrinth all infringing products produced by Alcatel; and

4. File with the Court and serve upon Labyrinth, within thirty (30) days after entry of final judgment in this case, a report in writing and subscribed under oath setting forth in detail the form and manner in which Alcatel has complied with the Court's orders as prayed for.

D. Awarding Labyrinth patent infringement damages and pre-judgment interest pursuant to 35 U.S.C. §284 including, but not limited to, lost profits and/or a reasonable royalty;

E. Awarding treble damages for willful infringement pursuant to 35 U.S.C. §284;

F. Declaring the case exceptional and awarding Labyrinth reasonable costs and attorneys fees pursuant to 35 U.S.C. §285;

G. Granting Labyrinth such other and further relief as justice and equity may require.

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**JURY DEMAND**

Labyrinth requests a jury trial.

Respectfully submitted,
Labyrinth Optical Technologies LLC

By its attorneys,
SIMMONS BROWDER GIANARIS
ANGELIDES & BARNERD LLC

Dated: May 10, 2012

By: [signature]

Crystal G. Foley
100 N. Sepulveda Blvd., Suite 1350
El Segundo, California 90245
Telephone: 310-322-3555
Facsimile: 310-322-3655
Email: cfoley@simmonsfirm.com

Paul A. Lesko – *pro hac vice* (pending)
Jo Anna Pollock – *pro hac vice* (pending)
Stephen C. Smith – *pro hac vice* (pending)
One Court Street
Alton, IL 62002
Tel: 618-259-2222
Fax: 618-259-2251
Email: plesko@simmonsfirm.com
jpollock@simmonsfirm.com
ssmith@simmonsfirm.com

# Exhibit A

US008103173B2

(12) **United States Patent**
**Schemmann et al.**

(10) **Patent No.: US 8,103,173 B2**
(45) **Date of Patent: *Jan. 24, 2012**

(54) **METHOD AND SYSTEM FOR A POLARIZATION MODE DISPERSION TOLERANT OPTICAL HOMODYNE DETECTION SYSTEM WITH OPTIMIZED TRANSMISSION MODULATION**

(75) Inventors: **Marcel F. C. Schemmann**, Maria-Hoop (NL); **Zoran Maricevic**, Manlius, NY (US); **Antonije R. Djordjevic**, Belgrade (YU); **Darby Racey**, Cicero, NY (US)

(73) Assignee: **Teradvance Communications, LLC**, Manlius, NY (US)

( * ) Notice: Subject to any disclaimer, the term of this patent is extended or adjusted under 35 U.S.C. 154(b) by 0 days.

This patent is subject to a terminal disclaimer.

(21) Appl. No.: **12/554,241**

(22) Filed: **Sep. 4, 2009**

(65) **Prior Publication Data**

US 2010/0046957 A1 Feb. 25, 2010

**Related U.S. Application Data**

(62) Division of application No. 09/871,216, filed on May 31, 2001, now Pat. No. 7,599,627.

(51) **Int. Cl.**
*H04B 10/04* (2006.01)

(52) **U.S. Cl.** ........ 398/183; 398/188; 398/202; 398/147; 398/184; 398/81; 398/208; 398/209; 398/203; 385/24; 385/27; 385/39; 375/271; 375/302; 375/322

(58) **Field of Classification Search** ................ 398/182, 398/183, 184, 185, 186, 187, 188, 189, 190, 398/192, 194, 191, 202, 203, 204, 205, 206, 398/207, 208, 209, 140, 152, 158, 159, 147, 398/81; 385/24, 27, 39; 375/271, 302, 322
See application file for complete search history.

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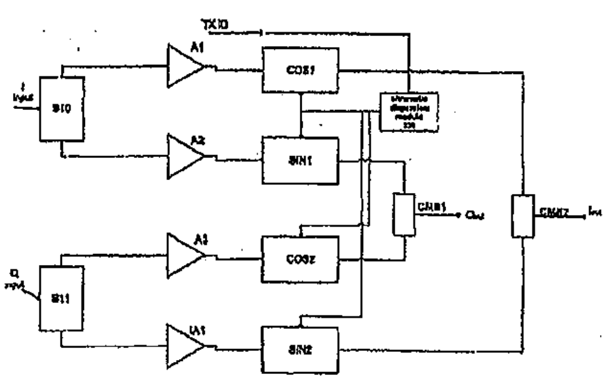
*Primary Examiner* — Hanh Phan
(74) *Attorney, Agent, or Firm* — Kenyon & Kenyon LLP

(57) **ABSTRACT**

An optical homodyne communication system and method in which a side carrier is transmitted along with data bands in an optical data signal, and upon reception, the side carrier is boosted, shifted to the center of the data bands, and its polarization state is matched to the polarization state of the respective data bands to compensate for polarization mode dispersion during transmission. By shifting a boosted side carrier to the center of the data bands, and by simultaneously compensating for the effects of polarization mode dispersion, the provided system and method simulate the advantages of homodyne reception using a local oscillator. The deleterious effects of chromatic dispersion on the data signals within the data bands are also compensated for by applying a corrective function to the data signals which precisely counteracts the effects of chromatic dispersion.

**16 Claims, 10 Drawing Sheets**



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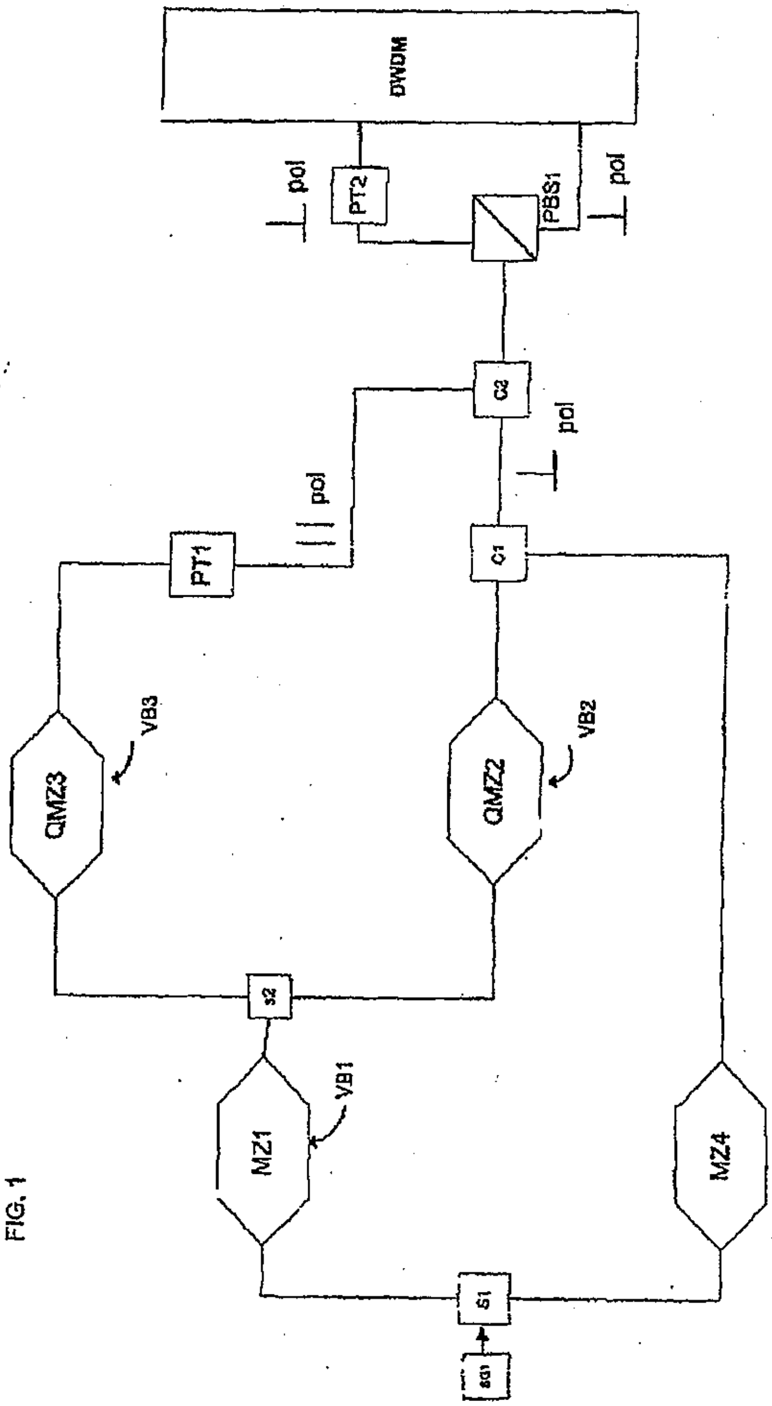

DWDM
PT2
pol
PBS1
pol
C2
pol
pol
PT1
C1
VB3
QMZ3
QMZ2
VB2
S2
VB1
MZ1
MZ4
S1
SG1

FIG. 1

FIG. 2a

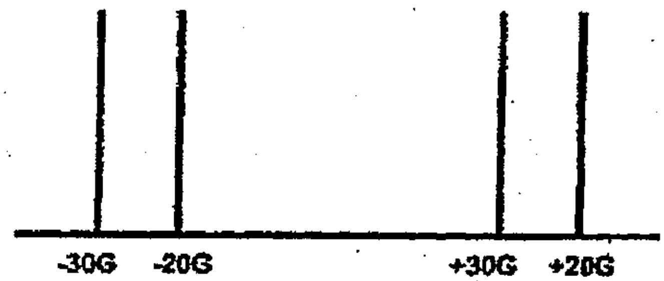



FIG. 2b

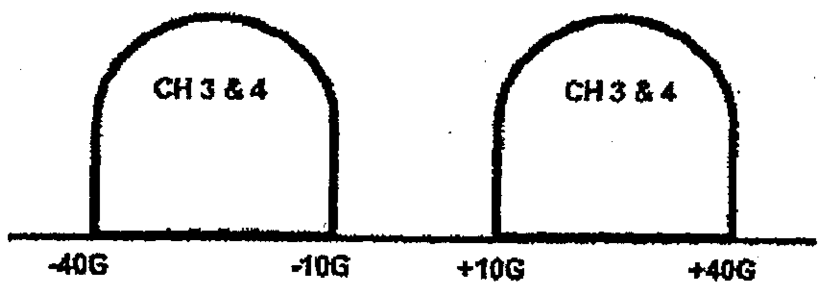



FIG. 2c

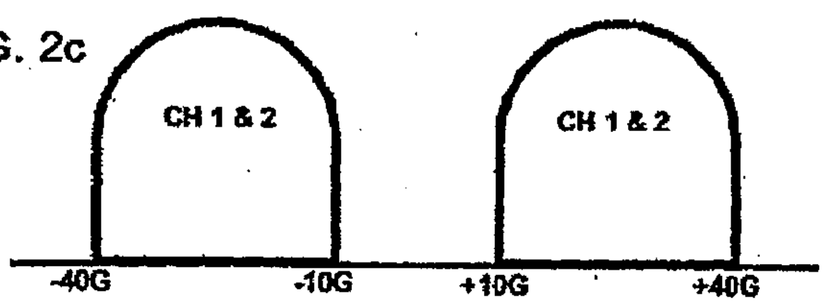


FIG. 3

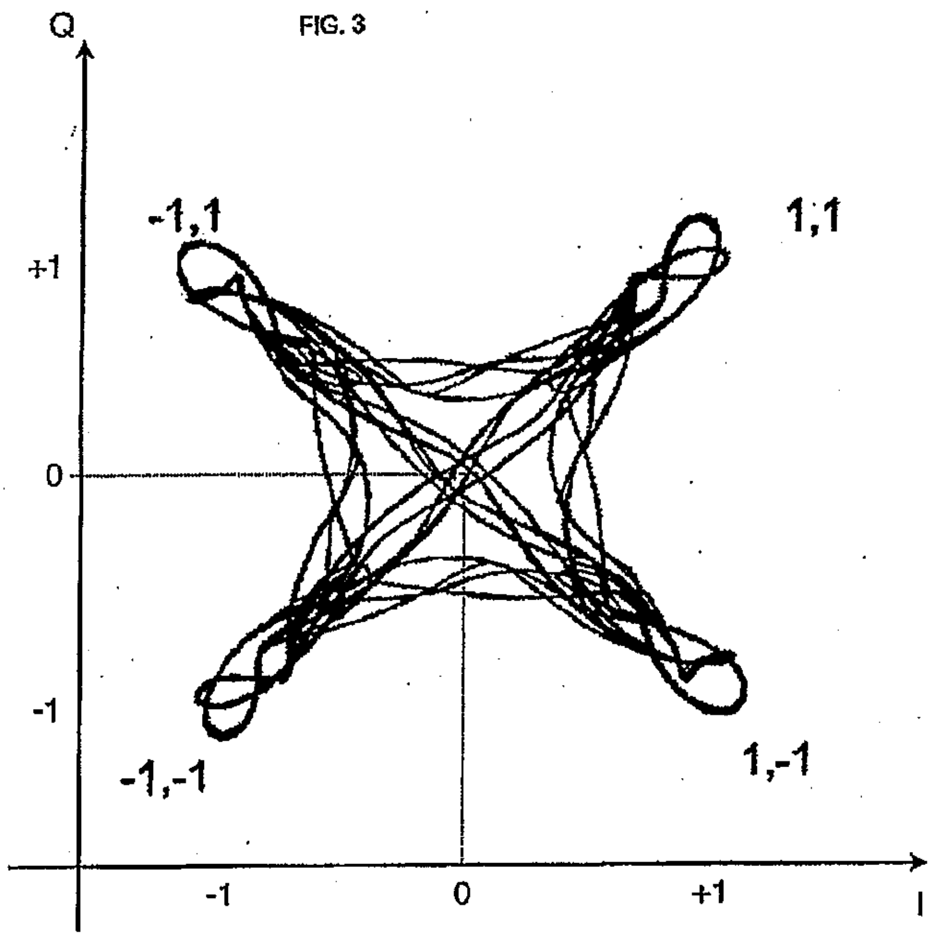


FIG. 4a

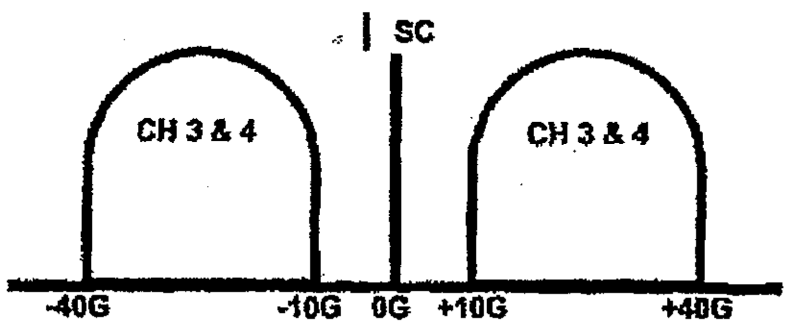



FIG. 4b

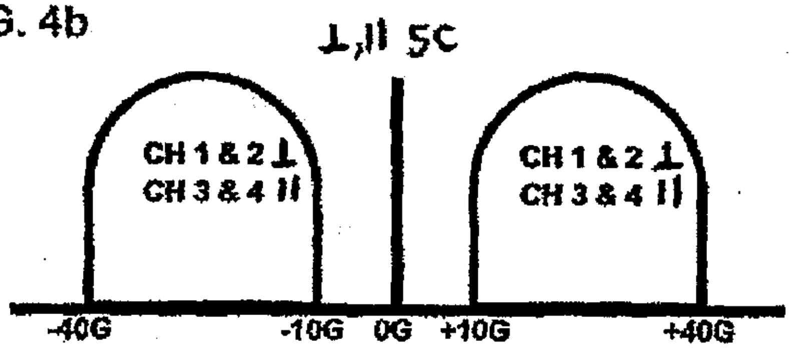
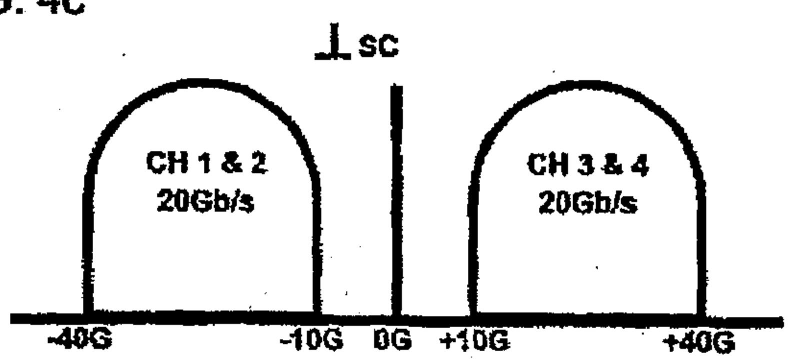



FIG. 4c



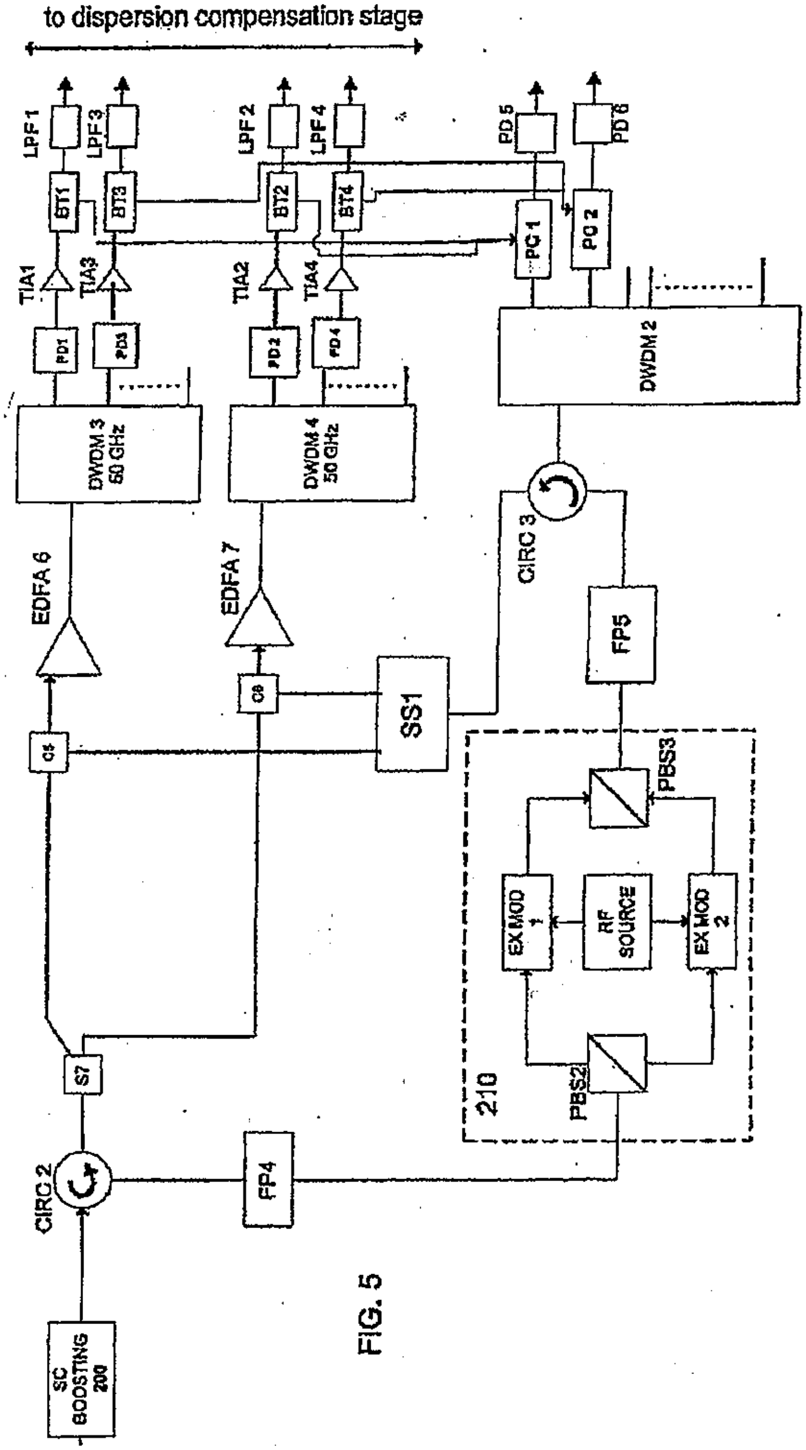

to dispersion compensation stage
LPF1
LPF3
LPF 2
LPF 4
PD 5
PD 6
BT1
BT3
BT2
BT4
PC 1
PC 2
TIA1
TIA3
TIA2
TIA4
PD1
PD3
PD 2
PD4
DWDM 3 50 GHz
DWDM 4 50 GHz
DWDM 2
CIRC 3
EDFA 6
EDFA 7
FP5
C5
C6
SS1
PBS3
EX MOD 1
RF SOURCE
EX MOD 2
210
PBS2
S7
CIRC 2
FP4
SC BOOSTING 200

FIG. 5

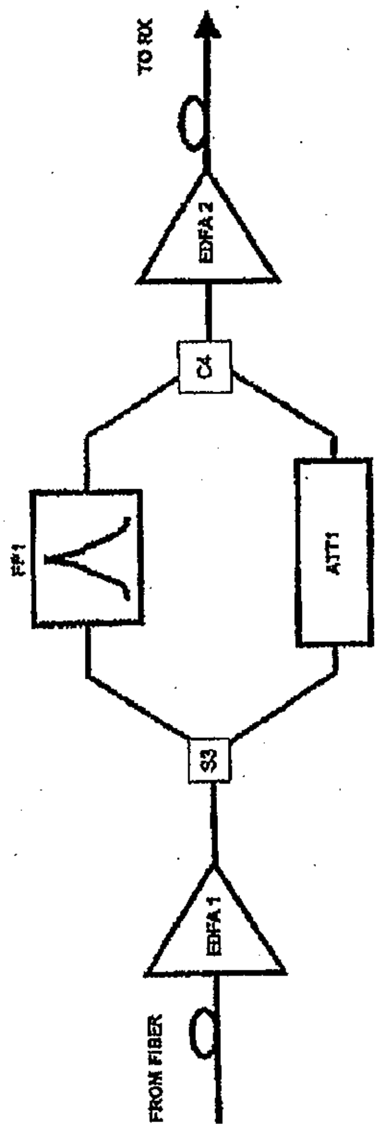



FIG. 6

FIG. 7

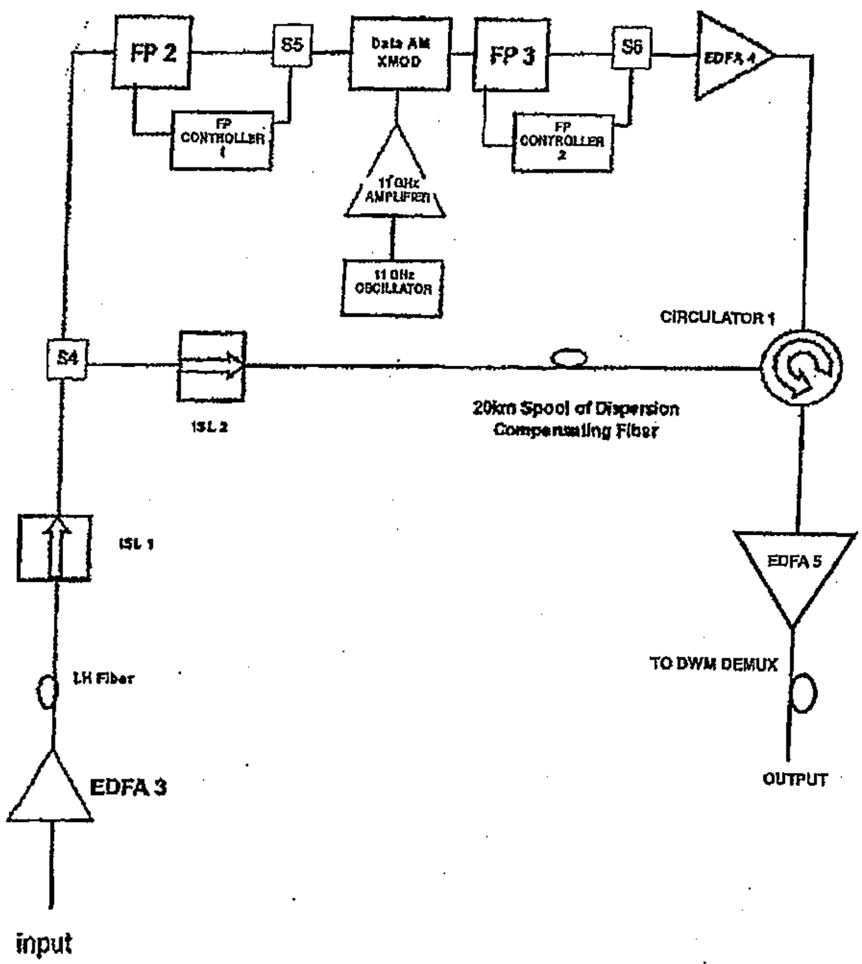

FP 2
S5
Data AM XMOD
FP 3
S6
EDFA 4
FP CONTROLLER 1
FP CONTROLLER 2
11GHz AMPLIFIER
11 GHz OSCILLATOR
CIRCULATOR 1
S4
ISL 2
20km Spool of Dispersion Compensating Fiber
ISL 1
EDFA 5
TO DWM DEMUX
LH Fiber
EDFA 3
OUTPUT
input

FIG. 8a

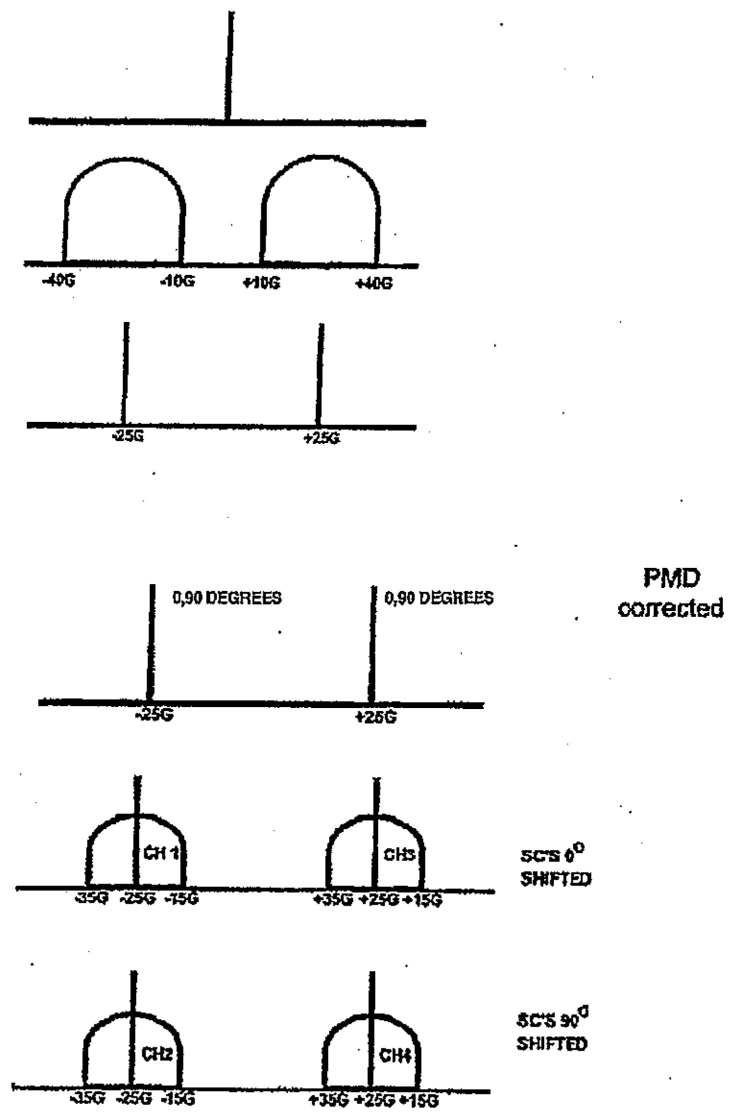
FIG. 8b

FIG. 8c

FIG. 8d

FIG. 8e

FIG. 8f



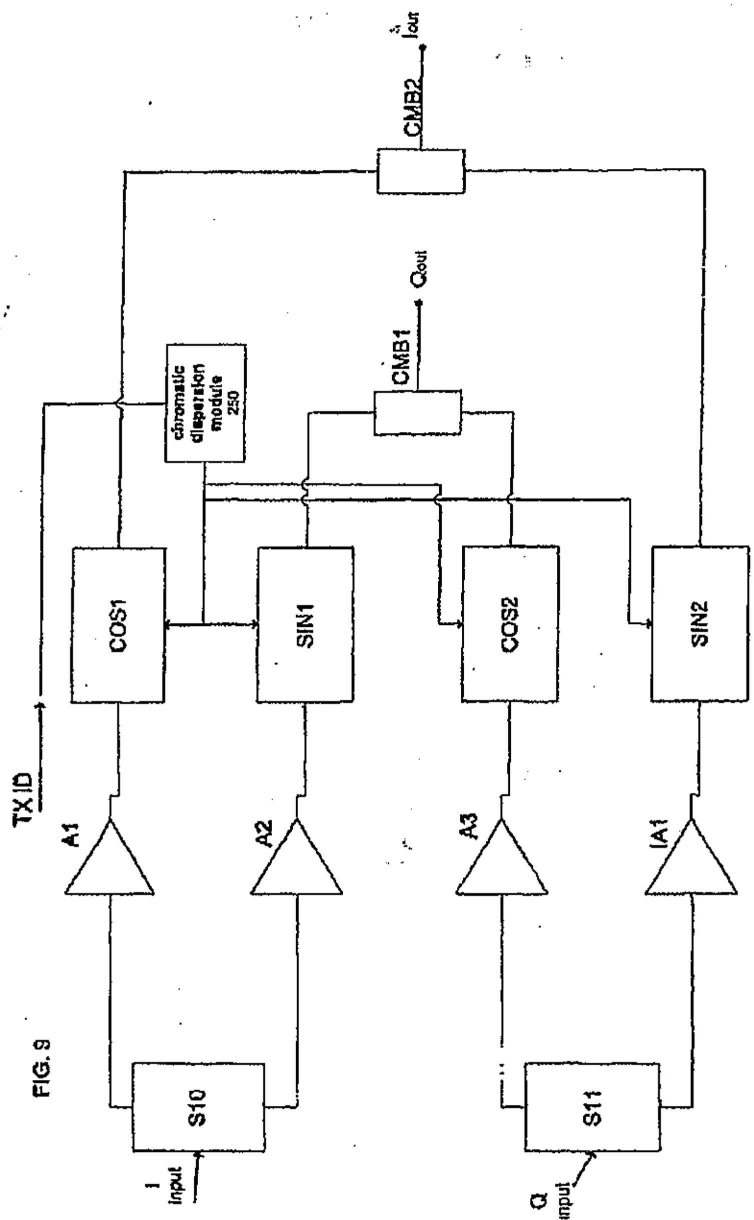

I_out
CMB2
Q_out
CMB1
chromatic dispersion module 250
COS1
SIN1
COS2
SIN2
TX ID
A1
A2
A3
IA1
S10
S11
I input
Q input

FIG. 9

FIG. 10a

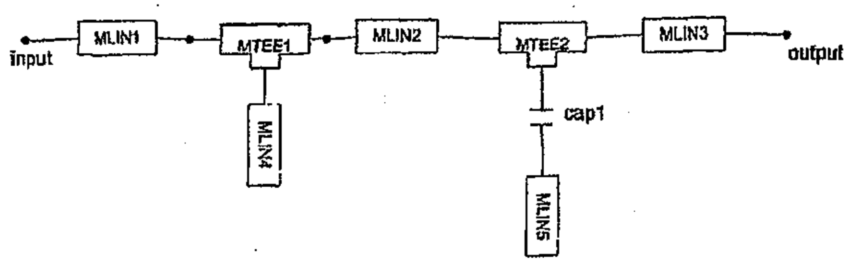
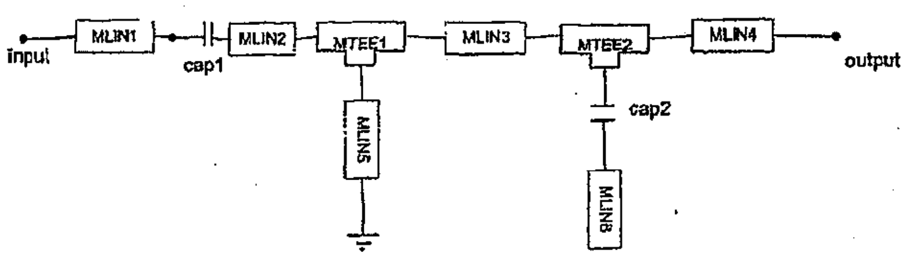



FIG. 10b



# METHOD AND SYSTEM FOR A POLARIZATION MODE DISPERSION TOLERANT OPTICAL HOMODYNE DETECTION SYSTEM WITH OPTIMIZED TRANSMISSION MODULATION

## CROSS-REFERENCES TO RELATED APPLICATIONS

This application is a divisional of U.S. patent application Ser. No. 09/871,216 filed on May 31, 2001, which is related to copending and commonly assigned U.S. patent application Ser. No. 09/748,750, filed in the United States Patent and Trademark office on Dec. 26, 2000, entitled "Method, System and Apparatus for Optically Transferring Information", which is expressly incorporated herein in its entirety by reference thereto.

## FIELD OF THE INVENTION

The present invention relates to optical data communication, and in particular, relates to a method and optical data communication system that improves signal-to-noise ratio of optical data signals, counteracts polarization mode dispersion and improves robustness to fiber nonlinearities.

## BACKGROUND INFORMATION

Currently, optical data communication systems are being upgraded from a 10 Gb/s data transmission rate up to a 40 Gb/s transmission rate. However, data transmission at 40 Gb/s (or higher) presents extensive design challenges because the effects of polarization mode dispersion (PMD), chromatic dispersion and fiber non-linear effects such as cross-phase modulation become more dominant at the higher transmission rates. In particular, the limit of tolerable polarization mode dispersion, usually defined as 14% of the data bit duration, is only 3.5 ps at a 40 Gb/s transmission rate. A 3.5 ps polarization mode dispersion translates to an attainable reach of several hundred kilometers over single mode fiber which has a typical fiber PMD of 0.1 ps/km$^{1/2}$.

Current optical communications systems, such as the PMD compensation arrangement described in U.S. Pat. No. 6,130,766 to Cao, generally attempt to compensate for PMD by splitting received optical signals into x and y mode components having orthogonal polarization, and then adjusting the delay on one of the orthogonal components to align the modes. This arrangement requires significant signal processing and differential delays to cover the range of frequencies carrying data.

Nonlinearities induced during optical transmission are also amplified at higher data rates. While it is necessary for accurate detection that optical data signals be at least 20 dB above background noise, if the data signals are transmitted with too much power, nonlinearities can play a greater role in distorting the signal. In addition, in coherent systems typical heterodyne optical reception systems suffer an inherent 3 dB penalty with respect to homodyne systems and introduce phase noise through use of a local oscillator, and thereby add a further level of complexity and constraints to optical system design.

What is therefore needed is a cost-effective method and system that compensates for PMD, optimizes SNR performance and minimizes phase noise and nonlinearities associated with transmission over fiber at high data transmission rates.



## SUMMARY OF THE INVENTION

The present invention meets the above objectives by providing an optical homodyne communication system and method in which a reduced amplitude side carrier is transmitted along with data bands in an optical data signal, and upon reception, the side carrier is boosted, shifted to the center of the data bands, and its polarization state is matched to the polarization state of the respective data bands to compensate for polarization mode dispersion during transmission. This scheme achieves the signal-to-noise benefits of homodyne reception without incurring the conventional restrictions and complications of homodyne reception such as requiring the phase of a signal from a local oscillator to be locked to the phase of the optical signal.

According to one embodiment, the present invention provides a method of optical communication that begins with providing a quadrature modulated optical data including two data bands separated in frequency, each data band having in-phase and quadrature components. The power of the quadrature modulated optical data signal is limited in order to limit non-linear effects by reducing the power of the optical data signal during transitional states in which data symbols transmitted in the optical data signal change in value, and in particular by reducing the power to zero such that transmitted power decreases to zero at approximately the mid point of the transitional states. The optical data signal is combined with a side carrier at a single frequency between the two data bands of the optical data signal and then transmitted across optical fiber to a receiver.

At the receiver, the side carrier is separated from the two data bands of the combined optical data signal and increased in amplitude relative to the data. The side carriers are then shifted to the middle of each of the respective two data bands. Since the relationship between the polarization state of the side carriers and the polarization state of the data bands does not stay constant during transmission over optical fiber, the polarization state of the shifted side carriers is adjusted to match the polarization state of the data bands at which they are centered.

The present invention further provides a method of compensating for the effects of chromatic dispersion during transmission over optical fiber by separating the in-phase and quadrature components of the two data bands prior to opto-electric conversion, and, after optoelectric conversion, compensating for chromatic dispersion by applying a corrective function to each of the in-phase and quadrature components of the data bands, the corrective function precisely counteracting the effects of chromatic dispersion on the in-phase and quadrature components.

The present invention also provides a method of providing information concerning a transmission device by providing an optical data signal having data bands and a side carrier with the side carrier modulated to carry an identification code, the identification code including information concerning the transmitter. According to an embodiment of the present invention, the information concerning a transmitter embedded in the side carrier includes parameters used in the corrective function to precisely counteract the effects of chromatic dispersion.

An optical data signal transmitter is provided for generating the quadrature modulated optical data signal including at least one side carrier. The transmitter includes a Mach-Zender modulator which generates an optical carrier signal by modulating a pair of side carriers onto an input optical signal. The optical carrier signal is modulated by at least two phase modulators which modulate a pair of data signals, in quadrature, onto the optical carrier signal, outputting an optical data signal including at least two data bands. By spreading the data bands onto the pair of side carriers, the amplitude of the optical data signal is reduced to zero during transitions between data symbols. The transmitter also includes a second Mach-Zender modulator which imprints a low-frequency TX ID (transmitter identification code) side carrier onto the input optical signal. The TX ID signal side carrier then combined with the optical data signal for transmission. The transmitted identification code includes information concerning the transmitter, such as its location, from which the distance between the transmitter and a receiver may be deduced.

The present invention further provides a receiver for implementing homodyne reception. The receiver includes a side carrier boosting module for increasing the amplitude of the side carrier relative to the data bands in the optical data signal. The receiver further includes a side carrier shifting module coupled to the side carrier boosting module which shifts the side carrier into two shifted carriers. Each of the shifted carriers is shifted to the center of one of the data bands. In addition, means for compensating polarization mode dispersion that are coupled to the side carrier shifting module match the polarization states of the shifted carriers to the data bands by adjusting either the polarization state of the shifted carriers or the polarization state of the data bands. After optoelectric conversion of the optical data signal, the receiver employs a chromatic dispersion correction stage that includes circuits that apply transfer functions to the in-phase and quadrature detected data channels

## BRIEF DESCRIPTION OF THE DRAWINGS

FIG. 1 is a block diagram of a transmitter according to an embodiment of the present invention.

FIG. 2*a* shows the spectrum of an optical carrier signal at the output of MZ1 of FIG. 1 according to an embodiment of the present invention.

FIG. 2*b* shows the spectrum of an optical data signal at the output of QMZ3 of FIG. 1 after data modulation in quadrature according to an embodiment of the present invention.

FIG. 2*c* shows the spectrum of an optical data signal at the output of QMZ2 of FIG. 1 according to an embodiment of the present invention.

FIG. 3 shows a 10G symbol per second Quadrature Return to Zero (QRZ) constellation diagram of the output from QMZ2 and QMZ3.

FIG. 4*a* shows the spectrum of an optical data signal at the output of C1 of FIG. 1 according to an embodiment of the present invention.

FIG. 4*b* shows the spectrum of an optical data signal at the output of C2 of FIG. 1 according to an embodiment of the present invention.

FIG. 4*c* shows the spectrum of an optical data signal at the output of the DWDM of FIG. 1 according to an embodiment of the present invention.

FIG. 5 is a block diagram of a receiver according to an embodiment of the present invention.

FIG. 6 is a block diagram of a first embodiment of the side carrier boosting module according to the present invention.

FIG. 7 is a block diagram of a second embodiment of the side carrier boosting module according to the present invention which employs the Stimulated Brillouin Scattering (SBS) effect.

FIG. 8*a* shows the spectrum of an optical carrier signal at the output of the FP4 of FIG. 5 according to an embodiment of the present invention.



FIG. 8*b* shows the spectrum of an optical carrier signal at the output of the S7 of FIG. 5 according to an embodiment of the present invention.

FIG. 8*c* shows the spectrum of an optical carrier signal at the output of the PBS3 of FIG. 5 according to an embodiment of the present invention.

FIG. 8*d* shows the spectrum of an optical carrier signal at the output of the SS1 of FIG. 5 according to an embodiment of the present invention.

FIG. 8*e* shows the spectrum of an optical carrier signal at the output of the C5 of FIG. 5 according to an embodiment of the present invention.

FIG. 8*f* shows the spectrum of an optical carrier signal at the output of the C6 of FIG. 5 according to an embodiment of the present invention.

FIG. 9 is a block diagram of a chromatic dispersion compensation circuit according to an embodiment of the present invention.

FIG. 10*a* is a block diagram of a microstrip implementation of a circuit that applies a COS transfer function to an input signal according to an embodiment of the present invention.

FIG. 10*b* is a block diagram of a microstrip implementation of a circuit that applies a SIN transfer function to an input signal according to an embodiment of the present invention.

## DETAILED DESCRIPTION

### I. Transmission

In accordance with the present invention, at a transmitter, a pair of side carriers is modulated onto each side of a monochromatic optical carrier signal, which is then split into two channels. Each optical carrier signal channel is modulated with two 10 Gb/s data signals in an orthogonal phase relationship to one another. The data signals are spread onto the two side carriers in each channel, and in effect, are spread out by fifty percent in the frequency domain. This spreading is equivalent to multiplication by a sine wave at half the data rate, and results in each data symbol returning to zero between transitions, referred to as quadrature-return-to-zero (QRZ). Using QRZ, the power of the optical data signal is made independent of the data pattern. The polarization of one of the optical data signal channels is then shifted, and one of the channels is combined with a channel of the original monochromatic carrier that has been modulated with a transmission identification carrier of less than 100 kHz.

The two optical data signal bands, which each carry a 20 Gb/s data stream, are combined and either multiplexed with adjacent channels at similar frequency and orthogonal polarization or one of the two channels is shifted in polarization to match the other channel. In either case, the optical data signals are multiplexed according to a Dense Wave Division Mulitplexing (DWDM) scheme and transmitted along long haul fiber to a destination receiver.

FIG. 1 illustrates an embodiment of a transmitter according to the present invention, which may be implemented on a Lithium-Niobate chip, for example. An optical signal generator SG1, which may be a laser, generates a monochromatic, polarized optical carrier at a reference frequency which for purposes of the following discussion is designated as the origin (0 GHz) in terms of relative frequency. The optical signal is thereafter split into two channels, an upper channel going to Mach-Zender modulator MZ1 and a lower channel being transmitted to Mach-Zender modulator MZ4. The division of light intensity between the two channels can be uneven with the lower channel receiving, for example, just 10 percent of the light intensity generated by SG1. At narrow-band modulator MZ4, the lower channel of the optical signal is modulated with a "Transmitter Identification" (TX ID) tone in the frequency range of 10 KHz to 100 KHz above the reference frequency. At modulator MZ1, two sets of side carriers at +/-20 GHz and +/-30 GHz are modulated onto the optical signal. The spectrum for the modulated signal, denoted an optical carrier signal, is shown in FIG. 2*a*. As shown in the figure, the resulting spectrum output from MZ1 shows four peaks, two below the reference frequency at -30 GHz and -20 GHz relative to the reference frequency, and two above the reference frequency at +20 GHz and +30 GHz.

The output of modulator MZ1 is further split into an upper channel which is transmitted to quadrature data modulator QMZ3 and a lower channel which is transmitted to quadrature data modulator QMZ2. Data modulator QMZ2 imprints two individual 10 Gb/s data streams in quadrature (in orthogonal phase relationship) CH.1 and CH. 2 onto each of the pairs of side carriers above and below the reference frequency. Similarly, data modulator QMZ3 imprints individual 10 Gb/s data streams CH.3 and CH.4 onto each of the pairs of side carriers in the optical carrier signal. Respective bias control electrodes VB2 and VB3 assist in keeping the data streams in quadrature. Spectra of the outputs from QMZ3 and QMZ2 are shown in FIG. 2*b* and FIG. 2*c* respectively. As can be discerned in FIG. 2*b* and FIG. 2*c*, the output spectra from QMZ3 and QMZ2 show two data bands, one extending from -40 GHz to -10 GHz and another extending from +10 GHz to +40 GHz relative to the reference frequency.

By imprinting two 10 Gb/s data streams in quadrature, in effect, 20 Gb/s of data are modulated onto each pair of side carriers (-30, -20 GHz and +20, +30 GHz, respectively) and each 20 Gb/s data band covers 30 GHz in the frequency domain. By providing two side carriers, with one side carrier in the pair a clock rate away from the other (i.e., 30 GHz being a clock away from 20 GHz), the data bits in both I and Q format are multiplied in the time domain by a 5 GHz sinusoid which crosses zero every 100 ps. Thus, the total data signal always crosses through zero in between any pair of symbols (any pair of I,Q data), referred to as quadrature-return-to-zero (QRZ) modulation.

FIG. 3 illustrates the key property of the QRZ format, showing that the trajectory between two successive symbols always leads through the I-Q origin. Each corner of the figure represents a pair of I, Q data symbols (e.g., I=1, Q=-1 or I=-1, Q=1). As shown, to get from adjacent corner points I=1, Q=1 (upper right corner) to I=1, Q=-1 (lower right corner) the optical data signal must travel through the origin (0,0). During each trajectory through the origin, the power of the signal, which is proportion to the square of its amplitude, goes to zero.

Returning to FIG. 1, the output from modulator QMZ3 is input to a polarization transformer PT1, which shifts the polarization of the optical data signal output from QMZ3 90 degrees. The polarization of the signal output from PT1 is arbitrarily illustrated by parallel lines as parallel polarization as opposed to a perpendicular polarization of the original optical signal. Furthermore, the output optical data signal from modulator QMZ2 is combined at combiner C1 with the TX ID pilot signal from MZ4. The output from C1 is shown in FIG. 4*a*. As noted above, the intensity of the TX ID signal is reduced in comparison with the optical data signal from QMZ2. It is also noted that the polarization of the output signal from C1 is shown as perpendicular, since the polarization of the output from C1 remains unchanged from the original polarization. Thereafter, the output signal from PT1 is combined with the output signal from combiner C1 at C2. The spectrum of the output signal out of C2 is shown in FIG. 4*b*. As can be discerned, the spectrum includes data channels 1, 2, 3 and 4 in both lower and upper data bands. Channels 1 and 2 are in perpendicular polarization and channels 3 and 4 are in parallel polarization. The reference carrier at approximately 0 GHz from MZ4 is in perpendicular polarization.

According to the illustrated embodiment, the output signal from C2 is input to a polarization beam splitter PBS1 which splits the signal into perpendicular and parallel polarized components, thereby separating the data channels 1 and 2 from channels 3 and 4. The perpendicular component (containing data channels 1 and 2 as well as the central reference frequency) is transmitted along lower path 102 to a first channel of a dense wave division multiplexer DWDM, the parallel component (containing data channels 3 and 4) is input to a polarization transformer PT2, which rotates the polarization of the parallel component back into a perpendicular state. The output from PT2 is then input to a second DWDM channel. Each DWDM channel acts as a band pass filter and passes only frequencies that fall within a 50 GHz band. Assuming for illustrative purposes that DWDM channel 1 passes frequencies from -50 GHz to 0 GHz relative to the reference frequency, and DWDM channel 2 passes frequencies from 0 to +50 GHz, data channels 1 and 2 are passed only in the data band from -40 GHz to -10 GHz and while data channels 3 and 4 are passed only in the data band from +10 GHz to +40 GHz. The DWDM multiplexes each of the passed bands onto a long haul fiber (not shown). The output spectrum from -50 GHz to +50 GHz output from the DWDM is shown in FIG. 4*c*. The adjacent DWDM channels each pass 20 Gb/s of data, combining for a total of 40 Gb/s.

In an alternative embodiment, a polarization multiplexing scheme may be used, making it unnecessary to separate data channels 1 and 2 from data channels 3 and 4. As described in related and commonly owned application [Ser. No. 09/782, 354] hereby incorporated for reference, the pairs of data channels can occupy the same data band if their polarization states remain orthogonal and thus do not interfere with each other. In this implementation, the polarization beam splitter PBS1 is not needed and the output from C2 can be sent directly to one of the DWDM input channels.

II. Reception

In accordance with the present invention, a homodyne reception system is employed to receive the optical data signal generated as described above. Upon reception, the transmitted side carrier at the reference frequency is boosted to increase the signal-to-noise ratio (SNR) of the optical data signal and to compensate for the attenuation of the side carrier in the transmitter. The boosting of the side carrier increases the SNR because of the implementation of homodyne reception in which overall detected signal power is increased in proportion to the power of the local oscillator, or in the present case (as will be discussed below), the transmitted side carrier.

Once the amplitude of the side carrier power is boosted relative to the transmitted data bands, the side carrier is shifted by +/-25 GHz into two side carriers that are each shifted to the center of one of the two data bands to further implement homodyne reception.

After the shifting of the side carriers, the two side carriers are separated and then modified by polarization controllers which match the time-varying polarization state of each the side carriers to the different time-varying polarization state of the respective data bands, thus overcoming the effects of polarization mode dispersion by controlling the polarization at only a single frequency.

According to an embodiment of the present invention, a chromatic dispersion compensation stage is used to counter the effects of dispersion during transmission over long haul fiber. Since the effects of dispersion can be modeled as a transfer function that is applied to the I and Q data signals, the chromatic dispersion compensation stage applies a compensating correction function that effectively counteracts the transfer function, rendering the I and Q data signals into their original non-dispersed state.

FIG. 5 illustrates an embodiment of a homodyne receiver according to the present invention. An optical data signal is received first by a side carrier boosting module 200 for which the present invention provides two exemplary embodiments. In a first embodiment of the side carrier boosting module, shown in FIG. 6, the optical data signal is first input to an optical amplifier EDFA1, which may be, for example, an erbium-doped fiber amplifier (EDFA). It is noted that all further optical amplifiers used in the implementations described below may be implemented as erbium-doped fiber amplifiers. The optical amplifier EDFA1 amplifies the entire spectrum of the received signal by, for example, approximately 15-18 dB. The amplified signal output from EDFA1 is split at S3 between an upper branch that is coupled to a Fabry-Perot resonator FP1 and a lower branch that is coupled to an attenuator ATT1.

The Fabry Perot resonator FP1 functions as a high-Q filter that nearly completely filters out all frequencies excepts for a series of frequencies that are separated by, for example, 100 Ghz which, according to the International Telecommunication Union (ITU) grid, is the amount of bandwidth allocated for each channel. The resonator FP1 is adjusted to pass the side carrier at the reference frequency and filter out the data bands of the optical data signal. It is noted in this regard that it is contemplated that the embodiments of the present invention be used in the context of the ITU grid, and that the reception approach described allows for simultaneous processing of side carriers for a plurality of ITU grid-spaced channels. The lower branch passed to ATT1, which contains both the data bands and the side carrier is attenuated. The signals output from FP1 and ATT1 are combined in combiner C4 and then passed to a further optical amplifier EDFA2 where the combined signal is again amplified by, for example, approximately 15-18 dB. Because the side carrier was isolated and boosted in FP1 and the data bands were attenuated in ATT1, the combined signal contains a side carrier boosted at least 10 dB in amplitude relative to the data bands.

A second embodiment of the side carrier boosting module, which advantageously makes use of the amplitude-enhancing effect of Stimulated Brillouin Scattering (SBS), is shown in FIG. 7. The SBS effect causes a first optical signal having narrow frequency band around frequency X to be amplified when collides with a signal of frequency X+−11 GHz traveling in the opposite direction. Referring to FIG. 7, the received signal is input to optical amplifier EDFA3 which amplifies the entire spectrum of the input signal. The signal output from amplifier EDFA3 is transmitted to optical isolator ISL 1, which permits optical signal to travel only in one direction (the direction indicated by the arrow in the figure) and prevents optical signals being reflected or transmitted back toward the amplifier EDFA3. From the optical isolator ISL 1, the optical data signal is split into two branches at splitter S4.

A first upper branch from splitter S4 leads to Fabry Perot resonator FP2, which passes the side carrier (and other modes in the series of frequencies) in between the data bands. FP controller 1 automatically adjusts the resonator FP2 so that it correctly passes the side carrier using input from splitter S5 and filters out the data bands. The output from FP2 is delivered to external modulator XMOD 1, which also receives an 11 GHz signal from a 11 GHz oscillator through an 11 GHz amplifier. The external modulator XMOD 1 modulates the 11 GHz signal onto the side carrier. The spectrum of the output from the modulator XMOD 1 thereafter contains the reference frequency and two side frequencies located 11 GHz both above and below the reference frequency. This output signal is then transmitted to another resonator FP3, which is adjusted by FP controller 2 to center on (and pass) only the side frequency 11 GHz above the reference side carrier frequency. The resulting signal, carrying substantially a single frequency at the reference frequency +11 GHz, is amplified in optical amplifier EDFA4 and then input to circulator CIRC 1. The circulator passes signals in a counter-clockwise direction. More specifically, CIRC 1 passes the output from EDFA4 leftwards in a counter-clockwise rotation towards the output of optical isolator ISL 2. It is noted that the side carrier boosting scheme is also intended be used in conjunction with a dense wave division multiplexing scheme. Thus, the side carrier boosting module can simultaneously process and boost a plurality of side carriers spaced in frequency according to ITU channel spacing.

Simultaneously, the optical signal in the lower branch from splitter S4 is transmitted through isolator ISL 2 and then meets with the optical signal from the upper branch output from the circulator CIRC 1. This collision of the two optical signals traveling in opposite directions generates the SBS non-linear effect. According to one implementation, the fiber connecting isolator ISL 2 and circulator CIRC 1 can be dispersion compensating fiber which, due to its relatively smaller cross-section, promotes higher intensity and more pronounced non-linear effects such as SBS. When the optical data signal containing the reference side carrier collides with the 11 GHz side frequency signal from CIRC 1, a narrow band including the side carrier in the optical data signal is amplified relative to the data bands due to the SBS effect as explained above. This modified optical data signal then reaches the circulator CIRC 1 from which it passes in the counter-clockwise direction to optical amplifier EDFA5, which amplifies the entire spectrum of the modified optical data signal by 15-18 dB. The output from EDFA5 is the final output of the second embodiment of the side carrier boosting module 200.

Returning to FIG. 5, the optical data signal output from the side carrier boosting module 200 is input to circulator CIRC 2, which in turn transmits the signal in a counter-clockwise direction to Fabry-Perot resonator FP4, having a free spectral range (FSR) of 100 GHz and finesse on the order of 1000. The resonator FP4 is also tuned to select the side carrier at (approximately) the reference frequency (O GHz). FIG. 8*a* shows a spectrum of the signal output from FP4, indicating that the data bands have again been filtered out. The data bands that are filtered out at FP4 are resent back toward circulator CIRC 2, where they are redirected in a counter-clockwise direction towards splitter S7. The spectrum of the output from splitter S7, which includes the two filtered data bands at −40 GHz to −10 GHz and +10 GHz to +40 GHz, is shown in FIG. 8*b*.

It is noted that when the optical data signal is transmitted over long haul fiber between the transmitter and the receiver, the polarization state of the transmitted signal is scrambled, with the result that the received signal has an unknown time-varying polarization state. Since the time-varying polarization state varies with frequency, the side carrier is expected to have a different time-varying polarization state than either of the data bands because it is separated from the centers of data bands by 25 GHz. When the output from resonator FP4 is fed to the side carrier shifting module 210, the side carrier's orthogonal polarization states are split in polarization beam splitter PBS2, and then each of the orthogonal signals are separately modulated by 25 GHz in XMOD 2 and XMOD 3, respectively, and then joined back in PBS3. The output from PBS3 is illustrated in FIG. 8*c*, which shows two side carriers at −25 GHz and +25 GHz from the reference frequency, respectively. The output from PBS2 is passed on to Fabry-Perot filter FP5 (FSR=50 GHz, finesse >500) which passes both the 25 GHz left and right shifted side carriers, and transmits them to circulator CIRC 3. Circulator CIRC 3 delivers shifted SC's to reflective polarization controllers PC 1, PC 2, through respective adjacent 50 GHz-spaced channels of WDM demultiplexer DWDM 2. The polarization controllers PC 1, PC 2 are constructed to provide control of the phase of the signals reflected from the polarization controllers back to the demultiplexer DWDM 2. Such control may be used, for instance, in order to compensate for the effective fiber length between the polarization controllers PC 1, PC 2 and the demultiplexer DWDM 2. In one implementation, the polarization controllers PC 1, PC 2 include mirrors and piezoelectric actuators to adjust the distance the reflected signal travels, which in turn controls the phase of the reflected optical signal.

Each polarization controller PC 1, PC 2 is used to transform the time-varying polarization state of one of the two side carriers so that the polarization states of each side carrier matches the time varying polarization state of the respective data bands which are centered at the side carrier (−25 GHz and +25 GHz). To accomplish this, each polarization controller PC 1, PC2 obtains feedback from the photodiodes that receive the data bands. PC 1 receives the feedback via bias-T couplers BT 1 and BT 3, while PC 2 receives feedback via bias-T couplers BT 2 and BT 4. As will be described below, the demultiplexers at the top of FIG. 5, DWDM 3, DWDM 4, receive both the data bands and the side carriers, filter them into separate, adjacent frequency channels and then effectively multiply the side carrier and data bands together at photodiodes PD1, PD2, PD3 and PD4 (and other photodiodes of adjacent channels that are not shown) which respond to the intensity of the signal (i.e., the square of the amplitude). The product signal output from the photodiodes is delivered to the respective polarization controllers PC 1, PC 2 via bias-T couplers BT 1, BT 2, BT 3 and BT 4. The outputs from BT 1 and BT 3, which contain converted data signals 1 and 2, corresponding to data channels 1 and 2, are combined to provide feedback to polarization controller PC 1, and the outputs from BT 2 and BT 4, which contain data signals 3 and 4, corresponding to data channels 3 and 4, are combined to provide feedback polarization controller PC 2. It is noted that the data signals 1 and 2 are expected to have a similar polarization state since, during transmission, they occupy the same frequency range. Equally, data signals 3 and 4, corresponding to data channels 3 and 4, are expected to have a similar polarization state. At the polarization controllers PC 1, PC 2, the time-varying polarization of the combined product signals are compared to the polarization state of the individual side carrier signals.

By continually adjusting the polarization of the side carrier signal and then comparing the modified polarization state to the combined product signals, the polarization controllers PC 1, PC 2 can accurately match the time-varying polarization state of each of the side carriers with the time-varying polarization state of the corresponding data bands. This technique takes advantage of fact that it is easier to adjust the single polarization state of a single side carrier frequency than to adjust the multitude of polarization states of a band of frequencies, for example, a 20 GHz data band, via wide-band polarization compensation. However, polarization mode dispersion compensation can also be performed here by adjusting the average polarization of the data band, which is treated as having a single polarization, and then matching to the polarization of the side carrier.

Returning once again to FIG. 5, the polarization controllers PC 1, PC 2 output polarization compensated side carrier signals to circulator CIRC 3, from which they are forwarded to splitter SS1. The splitter SS1 also shifts the phase of one of the output branches by 90 degrees relative to other branch. The output spectrum from SS1 is shown in FIG. 8*d*. These 0 degree and 90 degree phase shifted carriers are recombined in combiners C5 and C6, respectively, with the data bands output from splitter S7. In-phase (0 degree shifted) and quadrature (90 degree-shifted) signal spectrums out of outputs of respective combiners C5 and C6 are shown in FIG. 8*e* and FIG. 8*f*. As can be discerned, in each spectrum, a side carrier is positioned in the center of a data band. Each side of the spectra is equivalent to a spectrum generated by a conventional homodyne system in which the local oscillator frequency is matched to the center frequency of the data band. Furthermore, as in conventional homodyne reception, the power of the central carrier frequency is boosted relative to the data portion in order to the improve signal-to-noise ratio of the detected signal. The side carrier that has been shifted 0 degrees can be used to detect the in-phase (I) 10 Gb/s data channels from the transmitter (channels 1, 3) and the side carrier that has been shifted 90 degrees can be used to detect the quadrature (90 degree shifted) 10 Gb/s data channels (channels 2, 4).

The combined signal from C5 is sent through optical amplifier EDFA6 and the combined signal from C6 is sent through optical amplifier EDFA7 to final 50 GHz spaced demultiplexers DWDM 3 and DWDM 4. Each of the demultiplexers DWDM 3, DWDM 4 separate the data bands and side carriers in adjacent channels for electro-optic conversion at photodiodes PD 1, PD 2 and PD 3, PD 4 respectively. In this manner 10 GB/s data channels 1 and 3 are separated in DWDM 3 and 10 Gb/s channels 2 and 4 are separated in DWDM 4, resulting in the output of four separate 10 Gb/s data signals.

In an implementation of the receiver according to the present invention, low-bandwidth photodiodes can be placed at reflective ends of polarization controllers in each leg of WDM demultiplexer to provide monitor outputs proportional to fluctuations in each of carriers, for example caused by cross phase modulation (XPM). Since the respective 10 Gb/s data channels corresponding to the side carriers generally fluctuate in sympathy, the effect of carrier fluctuation can be removed if the monitor output fluctuations are subtracted from the outputs of the respective received 10 Gb/s output channels.

After the converted data signals are further processed through trans-impedance amplifiers TIA1, TIA2, TIA 3, TIA 4 and low pass filters LPF1, LPF2, LPF3, LPF4, they are input to a chromatic dispersion compensation stage shown schematically in FIG. 9. It is noted in this context that the dispersion compensation stage can equally be implemented at the quadrature data modulators on the transmitter side instead of, or in addition to, implementation at the receiver. The effects of fiber-induced chromatic dispersion on quadrature-modulated sinusoidal data signals can be described by the following matrix equation:

$$\begin{bmatrix} I\_out(D, L, f) \\ Q\_out(D, L, f) \end{bmatrix} = \begin{bmatrix} \cos\phi 1(D, L, f) & \sin\phi 1(D, L, f) \\ -\sin\phi 1(D, L, f) & \cos\phi 1(D, L, f) \end{bmatrix} \begin{bmatrix} I\_in(f) \\ Q\_in(f) \end{bmatrix} \quad (1)$$

where I_out(f) and Q_out(f) are frequency domain representations of output I and Q signals, which are modified from frequency domain representations of input I and Q signals, I_in(f) and Q_in(f), by the dispersion matrix, for which

$$\Phi 1(D,L,f) = D \cdot L \cdot \frac{0.8}{4 \cdot \pi} \cdot 10^{-26} \cdot (2\pi f)^2 \quad (2)$$

D denotes the fiber dispersion in units of ps/nm*km, L stands for fiber length in meters and f stands for frequency in Hz.

The dispersion matrix can be interpreted as a transfer function which applies a clockwise rotation angle that is proportional to the square of the frequency of the transmitted sinusoid. To counter the dispersion effect, it is feasible to apply an inverse transfer function, which can be interpreted as a counterclockwise rotation, also proportional to the square of the frequency. This counter-dispersion, or correction function may be described by the following matrix equation:

$$\text{disp\_corr}(D,L,f) = \begin{bmatrix} \cos(\phi 1(D,L,f)) & -\sin(\phi 1(D,L,f)) \\ \sin(\phi 1(D,L,f)) & \cos(\phi 1(D,L,f)) \end{bmatrix} \quad (3)$$

Therefore to correct the I and Q data signal for the effects of chromatic dispersion, the correction function is applied to the I and Q input signals (again, either at the transmitter or at the receiver, as is shown). Multiplying the correction function by the input signals yields:

$$I\_out = \cos\Phi 1(D,L,f) \cdot I\_in - \sin\Phi 1(D,L,f) \cdot Q\_in$$

$$Q\_out = \sin\Phi 1(D,L,f) \cdot I\_in + \cos\Phi 1(D,L,f) \cdot Q\_in \quad (4)$$

From equation (4), it is clear that dispersion compensation can be obtained by modifying the input I and Q data signals with an appropriate transfer function and then combining the modified signal. An embodiment of a dispersion correction circuit that performs these operations is shown in FIG. 9. As shown, the I input signal is input to a splitter S10, from which an upper branch is delivered to amplifier A1 and a lower branch is delivered to an amplifier A2 in order to boost the signal. The upper branch is transmitted to a COS1 circuit which applies the cosine portion of the dispersion correction function cos Φ1(D,L,f) to the input data signal as will be described further below. The lower branch from the splitter S10 is fed to a SIN1 circuit which applies the complementary sine portion of the dispersion correction function.

The Q data signal is concurrently input to splitter S11 and broken up into an upper branch which is fed through amplifiers A3, and a lower branch which is delivered to inverting amplifier IA1 which, in addition to boosting the signal, also shifts the phase of the signal by 180 degrees. The upper and lower branches are thereafter input to respective COS2 and SIN2 circuits which perform the same functions as the COS1 and SIN1 circuits, respectively. As shown, the modified signal from the SIN1 circuit, which is the product I_in times sin Φ1(D,L,f), is combined with the output from COS2, the product, Q_in times cos Φ1(D,L,f), at combiner CMB1. Comparison with equation (4), shows that the output of combiner CMB1 matches the desired Q_out output for dispersion compensation. Similarly, the combination at CMB2, containing the products I_in times cos Φ1(D,L,f) and Q_in times −sin Φ1(D,L,f), matches the desired I_out output for dispersion compensation.

Furthermore, the TX ID pilot signal, which, as noted above, is modulated onto the reference frequency +/−10-100 kHz, is received at the polarization controllers PC1, PC2 and converted to the RF domain at photodetectors PD3 and PD4. The TX pilots may be coded by frequency modulation or by another code modulation technique. The TX ID identifies the particular transmitter sending the signal, allowing information, such as the length of optical fiber between the transmitter and the receiver (which is the same as the parameter, L, used in the dispersion correction function), to be extracted from the coded signal. This information is transmitted to the chromatic dispersion compensation stage where it is received by a chromatic dispersion module 250. The chromatic dispersion module, in turn, is coupled to the SIN and COS circuits and causes adjustments to be made to the respective transfer functions applied to the I and Q inputs in accordance with the information extracted from the TX ID.

According to an embodiment of the present invention, the SIN and COS circuits of FIG. 9 are implemented as microstrip circuits which use layers or regions of copper deposited on a circuitboard having various widths and lengths, to adjust electromagnetic effects that modify signals sent through the copper layers or regions. FIG. 10*a* and FIG. 10*b* illustrate implementations of the sin Φ1(D,L,f) and cos Φ1(D,L,f) transfer functions respectively. As is known in the art, various combinations of linear strips, (denoted as MLIN), t-junctions (denoted as MTEE), and capacitive elements (cap1, cap2), again having various adjustable lengths and widths are used to fine-tune the electromagnetic wave effects in the copper regions to simulate the desired transfer functions.

In the foregoing description, the method and system of the invention have been described with reference to a number of examples that are not to be considered limiting. Rather, it is to be understood and expected that variations in the principles of the method and apparatus herein disclosed may be made by one skilled in the art and it is intended that such modifications, changes, and/or substitutions are to be included within the scope of the present invention as set forth in the appended claims. For example, although only a 10 Gbp/s digital baseband is discussed, the inventive principles herein may be applied to higher or lower data rates as the case may be.

What is claimed is:

1. A method of compensating a quadrature modulated optical data signal for effects of chromatic dispersion occurring during transmission over optical fiber, the method comprising the steps of:

separating in-phase and quadrature components of the optical data signal;

optoelectrically converting the in-phase and quadrature components of the optical data signal into in-phase and quadrature data signals;

applying a corrective function to the in-phase and quadrature data signals, the corrective function modifying the in-phase and quadrature data signals in a manner that precisely counteracts effects of chromatic dispersion on the in-phase and quadrature components of the optical data signal.

2. The method of claim 1, wherein the corrective function is a function of a coefficient of fiber dispersion, a length of the optical fiber, and frequency of the optical data signal.

3. A receiver for receiving and processing an optical data signal, the optical data signal including at least two data bands and at least one side carrier, each of the at least two data bands including a pair of quadrature modulated data signals, the receiver comprising:

a side carrier boosting module, the side carrier boosting module for increasing an amplitude of the at least one side carrier relative to the at least two data bands;

a side carrier shifting module coupled to the side carrier boosting module, the side carrier shifting module for shifting the at least one side carrier into at least two shifted carriers, each of the at least two shifted carriers shifted to a center of one of the at least two data bands; and

means for compensating polarization mode dispersion coupled to the side carrier shifting module, the means for compensating adjusting a polarization state of one of:

a) each of the at least two shifted carriers to match a polarization state of one of the at least two data bands; and

b) the at least two data bands to match a polarization state of the at least two shifted carriers.

4. The receiver of claim 3, wherein the side carrier boosting module includes:

a splitter for splitting the received optical data signal and transmitting the optical data signal into an upper branch and a lower branch;

a Fabry-Perot resonator coupled to the upper branch for filtering the at least one side carrier from the at least two data bands in the optical data signal fed to the upper branch;

an attenuator coupled to the lower branch for attenuating the optical data signal transmitted via the lower branch;

a combiner coupled to both the upper and lower branches, the combiner combining and outputting the optical data signals transmitted via each of the upper and lower branches; and

an optical amplifier coupled to the combiner for amplifying the output of the combiner;

wherein an amplitude of the at least one side carrier is increased relative to an amplitude of the at least two data bands.

5. The receiver of claim 3, wherein the side carrier boosting module includes:

a splitter for splitting the received optical data signal and transmitting the optical data signal into an upper branch and a lower branch; and

a Fabry-Perot resonator coupled to the upper branch for filtering the at least one side carrier from the at least two data bands in the optical data signal fed to the upper branch;

a modulator coupled to the Fabry-Perot resonator for modulating an 11 GHz signal onto the at least one side carrier output from the Fabry-Perot resonator;

a further Fabry-Perot resonator coupled to an output of the modulator for selecting a frequency 11 GHz above the at least one side carrier; and

a circulator coupled to both an output of the further Fabry-Perot resonator and the lower branch, the circulator sending the output of the further Fabry-Perot resonator in along the lower branch in a direction opposite to a transmission direction of the optical data signal;

wherein the optical data signal collides with the output of the further Fabry-Perot resonator inducing a Stimulated Brillouin Scattering effect, the effect enhancing an amplitude of the at least one side carrier in the optical data signal relative to an amplitude of the at least two data bands in the optical data signal.

6. The receiver of claim 5, wherein the side carrier boosting module includes:

an amplifier for amplifying the output from the further Fabry-Perot resonator;



an isolator in the lower branch downstream of the splitter, the isolator blocking the progress of the output from the further Fabry-Perot resonator along the lower branch; and

dispersion compensating fiber coupling the circulator with the isolator along the lower branch, the dispersion compensating fiber enhancing Stimulated Brillouin Scattering events occurring within the fiber.

7. The receiver of claim 3, further comprising:

a chromatic dispersion compensation stage, the chromatic dispersion stage receiving as input in-phase and quadrature-phase signals of the quadrature modulated data signals, the chromatic dispersion correction stage including:

a first splitter for splitting the input in-phase signal into a first branch and a second branch;

a first COS circuit coupled to the first splitter for applying a COS transfer function to the in-phase signal in the first branch;

a first SIN circuit coupled to the first splitter for applying a first SIN transfer function to the in-phase signal in the second branch;

a second splitter for splitting the input quadrature-phase signal into a first quadrature branch and a second quadrature branch;

an inverter coupled to the second quadrature branch for changing the phase of the quadrature signal in the second branch 180 degrees;

a second COS circuit coupled to the first splitter for applying a COS transfer function to the quadrature signal in the first branch;

a second SIN circuit coupled to the first splitter for applying a SIN transfer function to the quadrature signal in the second branch;

a first combiner for combining output from the first SIN circuit with output from the second COS circuit into a corrected quadrature output signal; and

a second combiner for combining output from the first COS circuit with output from the second SIN circuit into a corrected in-phase output signal.

8. The receiver of claim 7, wherein the received optical data signal includes a transmitter identification code embedded in one of the at least one side carrier and the chromatic dispersion compensation stage further includes:

a chromatic dispersion module coupled to an input for receiving the transmitter identification and also coupled to the first and second COS circuits and the first and second SIN circuits;

wherein the chromatic dispersion module is operative to transmit signals to the first and second COS circuits and the first and second SIN circuits, the signal effectuating adjustments to the respective transfer functions applied by the first and second COS circuits and the first and second SIN circuits in accordance with information extracted from the transmitter identification.

9. The receiver of claim 8, wherein the extracted information includes information describing the location of a transmitter from which the received optical data signal originates.

10. The receiver of claim 8, wherein the first and second COS circuits and the first and second SIN circuits include microstrip elements, the microstrip elements having variable lengths and widths and modifying input signals according to the variable lengths and widths.

11. The receiver of claim 3, wherein means for compensating polarization mode dispersion include:

a frequency filter coupled to an output of the side carrier shifting module; and at least two polarization controllers, the at least two polarization controllers coupled to the frequency filter and to a photodetector output, each polarization controller receiving one of the two shifted side carriers and altering a polarization state of the received shifted side carrier to match a polarization state of the data band at which the shifted side carrier is centered, the polarization state of the data band being received via feedback from the photodetector output.

12. The receiver of claim 11, further comprising:

a phase shifter coupled to and receiving output side carriers from the at least two polarization controllers, the phase shifter splitting the received shifted side carrier signals into a first branch and a second branch, the second branch signal being shifted 90 degrees with respect to the first branch signal;

a first combiner for combining the first branch with the data bands of the optical data signal;

a second combiner for combining the second branch with the data bands of the optical data signal; and

a first demultiplexer coupled to the first combiner and filtering output from the first combiner into first and second in-phase channels according to frequency, the first and second in-phase channels each including a data band and a shifted side carrier;

a second demultiplexer coupled to the second combiner and filtering output from the second combiner into third and fourth quadrature-phase channels according to frequency, the third and fourth quadrature-phase channels each including a data band and a shifted side carrier; and

at first set of photodetectors coupled to the first demultiplexer for optoelectrically converting the first and second in-phase channels; and

a second set of photodetectors coupled to the second demultiplexer for optoelectrically converting the third and fourth quadrature-phase channels;

wherein output from the first and second set of photodetectors is provided to the at least two polarization controllers, the polarization controllers match polarization states of the first, second, third and fourth channels with the respective side carrier within each of the channels.

13. The receiver of claim 12, wherein the first and second demultiplexers are dense wave division demultiplexers.

14. A method of correcting a quadrature modulated optical data signal for effects of chromatic dispersion comprising the steps of:

deriving in-phase and quadrature data signals via a homodyne reception system; and

applying a corrective function to the in-phase and quadrature data signals, the corrective function modifying the in-phase and quadrature data signals in a manner that precisely counteracts effects of chromatic dispersion on the in-phase and quadrature components of the optical data signal.

15. A method of correcting in-phase and quadrature data signals for effect of chromatic dispersion prior to modulation onto an optical data signal, comprising the steps of:

providing an in-phase data signal on a first input and providing a quadrature data signal on a second input; and

applying a corrective function to the in-phase and quadrature data signals, the corrective function modifying the in-phase and quadrature data signals in a manner that precisely counteracts effects of chromatic dispersion occurring when the in-phase and quadrature data signals are modulated onto the optical data signal and transmitted across optical fiber.

16. A receiver for receiving and processing an optical data signal, the optical data signal including at least two data bands and at least one side carrier, each of the at least two data bands including a pair of quadrature modulated data signals, the receiver comprising:

a side carrier boosting module, the side carrier boosting module for increasing an amplitude of the at least one side carrier relative to the at least two data bands;

a side carrier shifting module coupled to the side carrier boosting module, the side carrier shifting module for shifting the at least one side carrier into at least two shifted carriers, each of the at least two shifted carriers shifted to a center of one of the at least two data bands; and

a chromatic dispersion compensation stage, the chromatic dispersion stage receiving as input in-phase and quadrature-phase signals of the quadrature modulated data signals, the chromatic dispersion correction stage including:

a first splitter for splitting the input in-phase signal into a first branch and a second branch;

a first COS circuit coupled to the first splitter for applying a COS transfer function to the in-phase signal in the first branch;

a first SIN circuit coupled to the first splitter for applying a first SIN transfer function to the in-phase signal in the second branch;

a second splitter for splitting the input quadrature-phase signal into a first quadrature branch and a second quadrature branch;

an inverter coupled to the second quadrature branch for changing the phase of the quadrature signal in the second branch 180 degrees;

a second COS circuit coupled to the first splitter for applying a COS transfer function to the quadrature signal in the first branch;

a second SIN circuit coupled to the first splitter for applying a SIN transfer function to the quadrature signal in the second branch;

a first combiner for combining output from the first SIN circuit with output from the second COS circuit into a corrected quadrature output signal; and

a second combiner for combining output from the first COS circuit with output from the second SIN circuit into a corrected in-phase output signal.

* * * * *

# Exhibit B

US007599627B2

(12) **United States Patent**
Schemmann et al.

(10) **Patent No.:** **US 7,599,627 B2**
(45) **Date of Patent:** **Oct. 6, 2009**

(54) **METHOD AND SYSTEM FOR A POLARIZATION MODE DISPERSION TOLERANT OPTICAL HOMODYNE DETECTION SYSTEM WITH OPTIMIZED TRANSMISSION MODULATION**

(75) Inventors: **Marcel F. C. Schemmann**, Maria-Hoop (NL); **Zoran Maricevic**, Manlius, NY (US); **Antonije R. Djordjevic**, Belgrade (YU); **Darby Racey**, Cicero, NY (US)

(73) Assignee: **Teradvance Communications, LLC**, Manlius, NY (US)

(*) Notice: Subject to any disclaimer, the term of this patent is extended or adjusted under 35 U.S.C. 154(b) by 274 days.

(21) Appl. No.: **09/871,216**

(22) Filed: **May 31, 2001**

(65) **Prior Publication Data**

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(51) **Int. Cl.**
*H04B 10/04* (2006.01)

(52) **U.S. Cl.** ........................ 398/183; 398/147; 398/184; 398/185; 398/188; 398/202; 385/24; 385/27; 385/39; 375/271; 375/302; 375/322; 359/326

(58) **Field of Classification Search** ................. 398/147, 398/152, 158, 163, 182, 184, 188, 194, 192, 398/202, 203, 183, 185, 186, 187, 189, 190, 398/191, 204, 205, 206, 207, 208, 209, 140, 398/159, 79, 81; 375/271, 302, 322; 359/326; 385/24, 3, 27, 39

See application file for complete search history.

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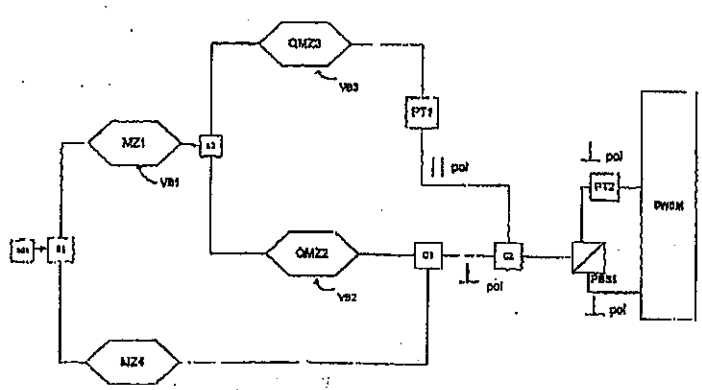
*Primary Examiner*—Hanh Phan
(74) *Attorney, Agent, or Firm*—Kenyon & Kenyon LLP

(57) **ABSTRACT**

An optical homodyne communication system and method in which a side carrier is transmitted along with data bands in an optical data signal, and upon reception, the side carrier is boosted, shifted to the center of the data bands, and its polarization state is matched to the polarization state of the respective data bands to compensate for polarization mode dispersion during transmission. By shifting a boosted side carrier to the center of the data bands, and by simultaneously compensating for the effects of polarization mode dispersion, the provided system and method simulate the advantages of homodyne reception using a local oscillator. The deleterious effects of chromatic dispersion on the data signals within the data bands are also compensated for by applying a corrective function to the data signals which precisely counteracts the effects of chromatic dispersion.

**22 Claims, 10 Drawing Sheets**



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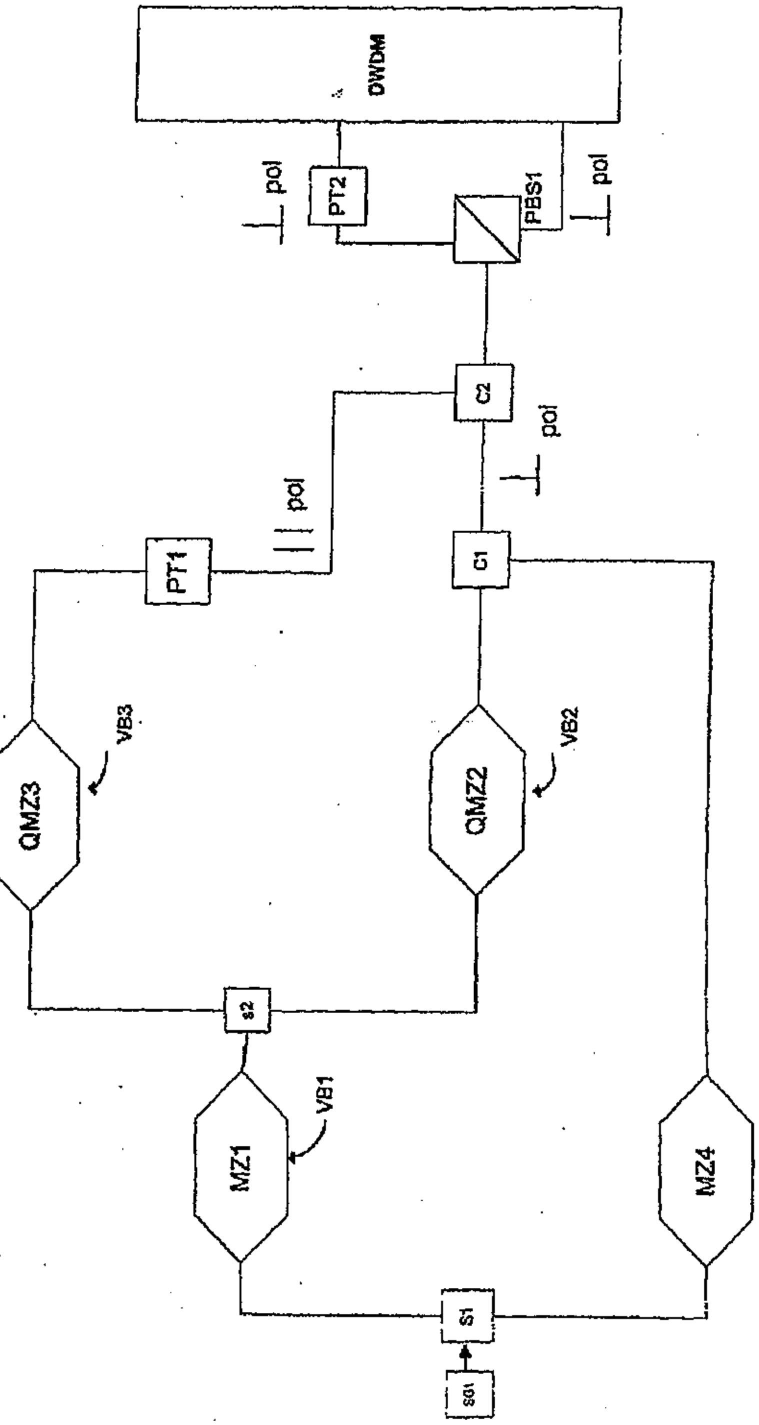

DWDM
PT2
pol
PBS1
pol
C2
pol
PT1
pol
C1
VB3
QMZ3
QMZ2
VB2
s2
VB1
MZ1
MZ4
S1
SG1

FIG. 1

FIG. 2a

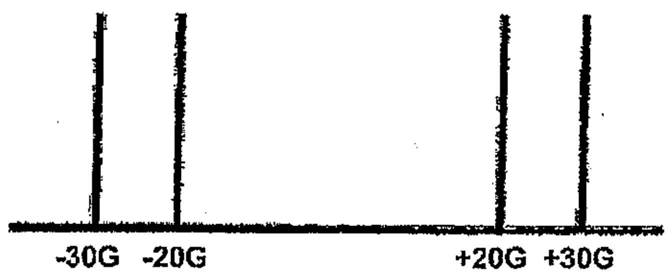



FIG. 2b

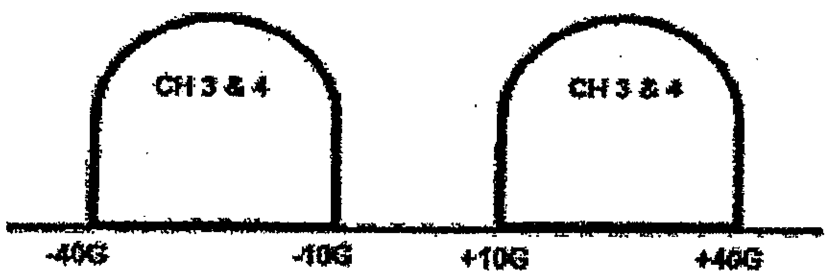



FIG. 2c

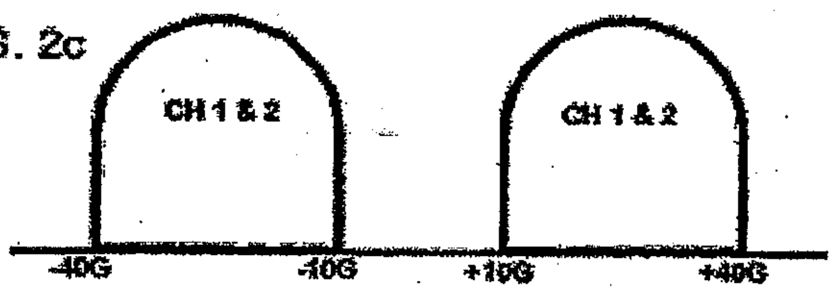


FIG. 3

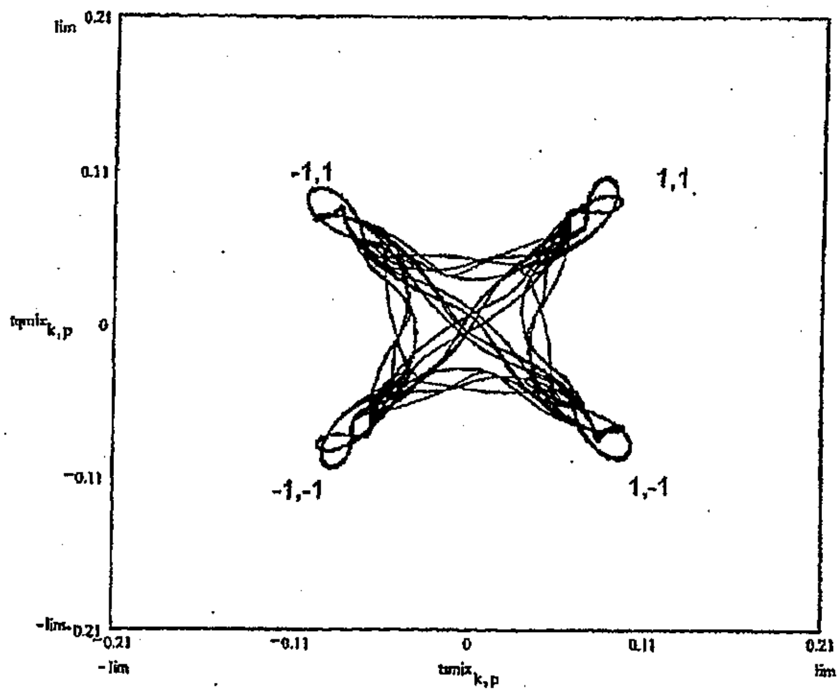


FIG. 4a

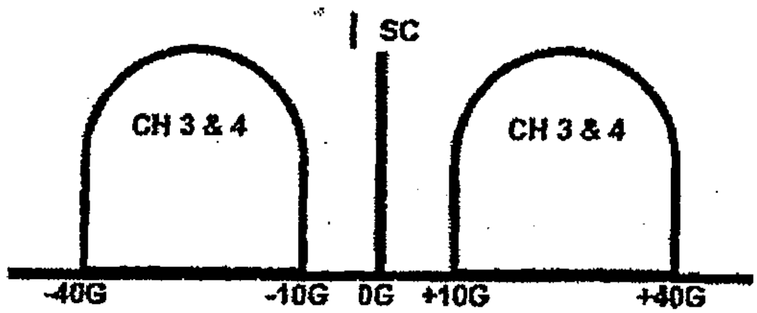



FIG. 4b

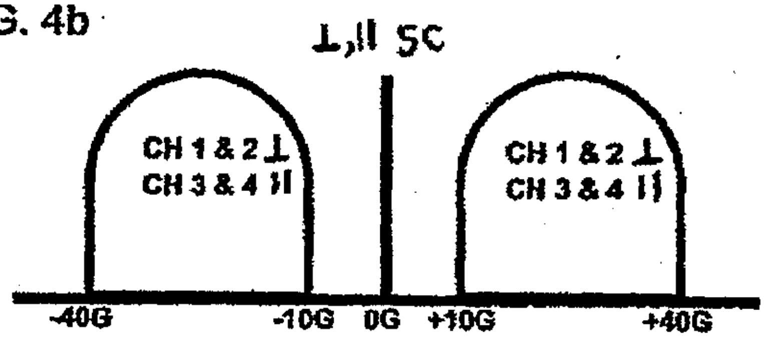
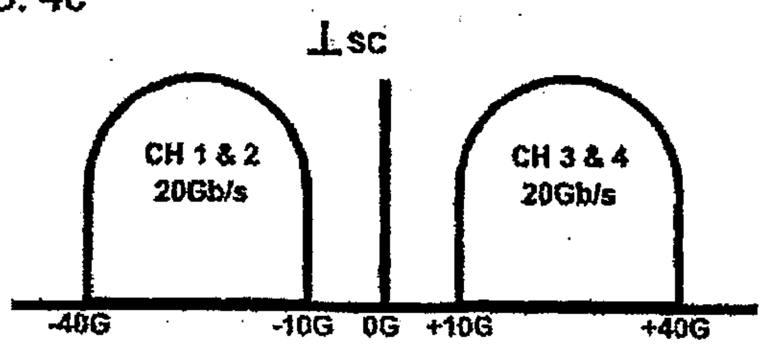



FIG. 4c



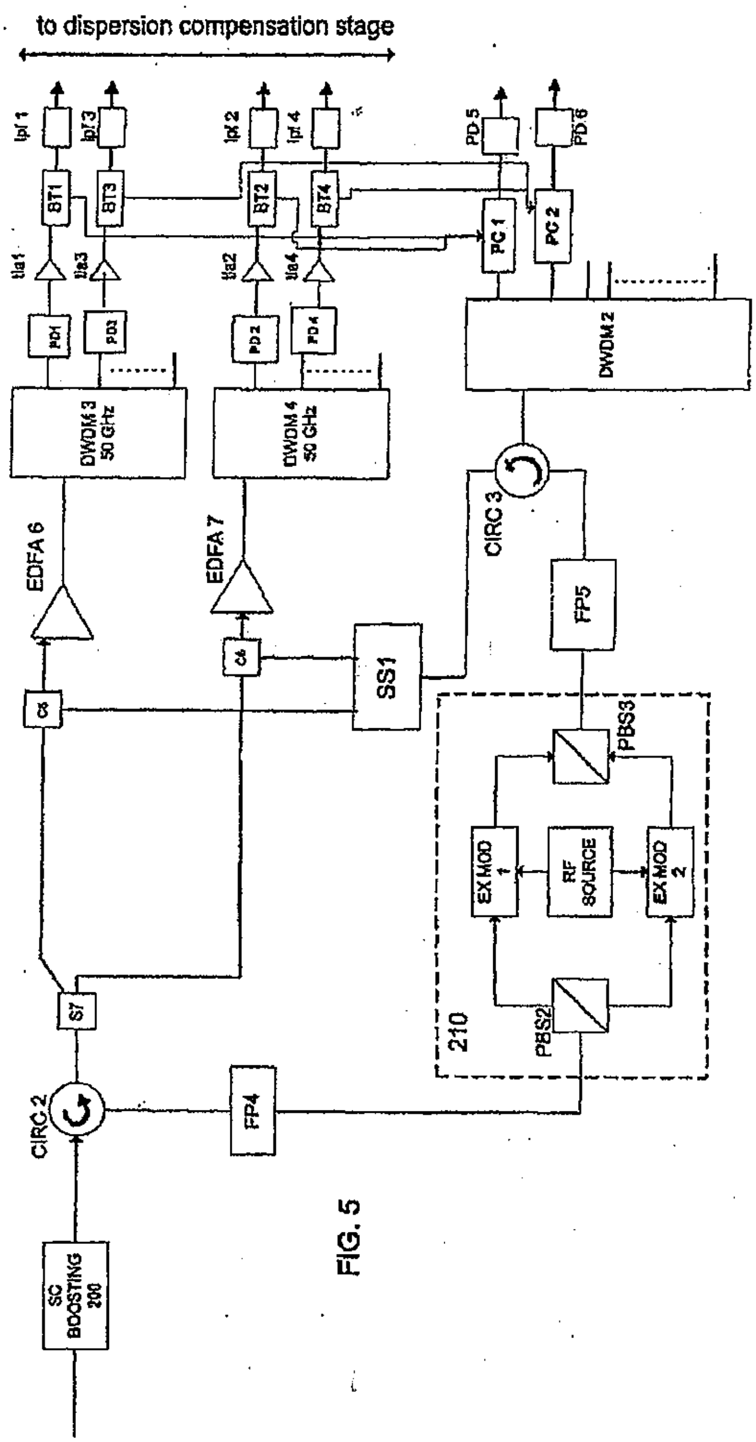

to dispersion compensation stage
SC BOOSTING 200
CIRC 2
S7
FP4
EDFA 6
EDFA 7
SS1
CIRC 3
FP5
DWDM 3 50 GHz
DWDM 4 50 GHz
DWDM 2
PD5
PD6
PC 1
PC 2
BT1
BT2
BT3
BT4
PBS2
PBS3
EX MOD 1
EX MOD 2
RF SOURCE
210

FIG. 5

FIG. 6

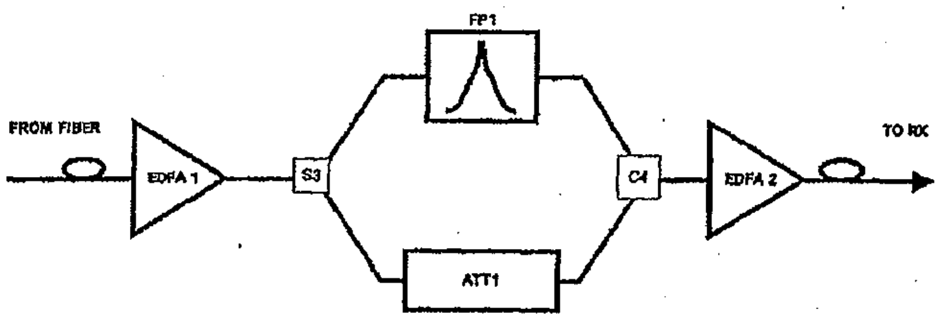


FIG. 7

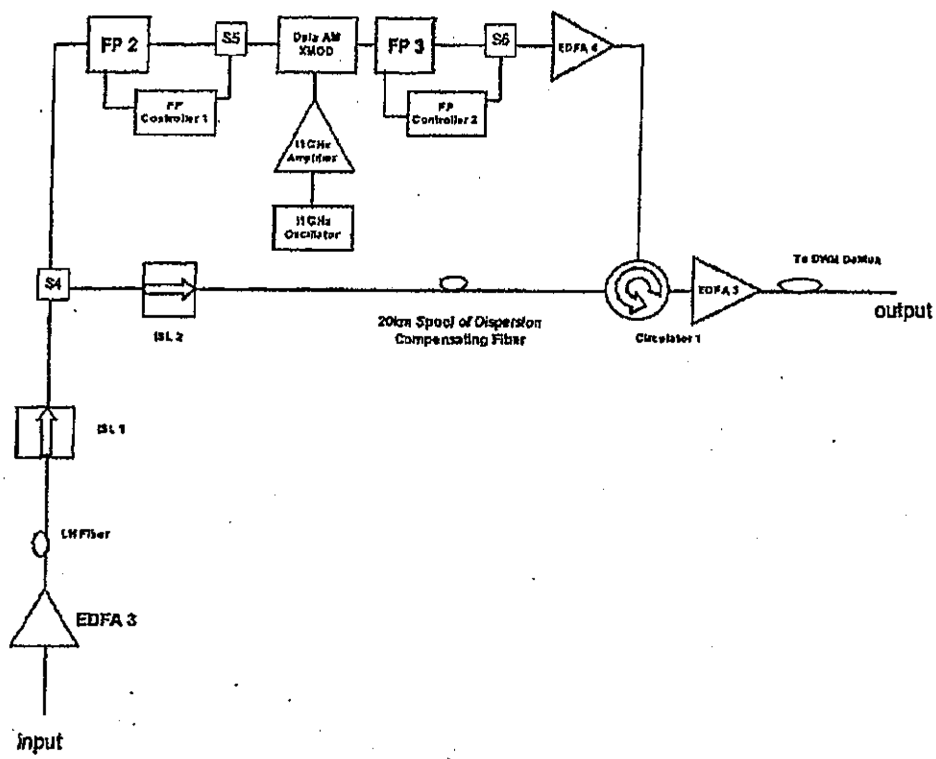

FP 2
S5
Data AM XMOD
FP 3
S6
EDFA 4
FP Controller 1
FP Controller 2
11GHz Amplifier
11GHz Oscillator
S4
ISL 2
20km Spool of Dispersion Compensating Fiber
Circulator 1
EDFA 3
To DWDM DeMux
output
ISL 1
LH Fiber
EDFA 3
input

FIG. 8a

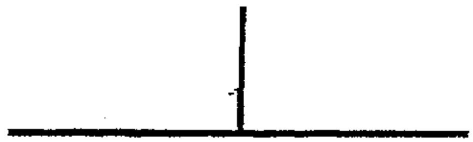


FIG. 8b

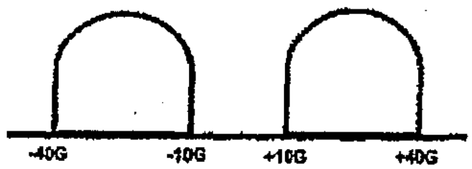



FIG. 8c

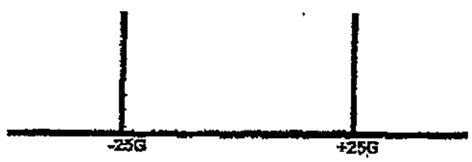
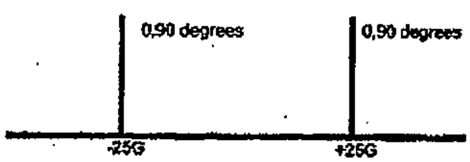
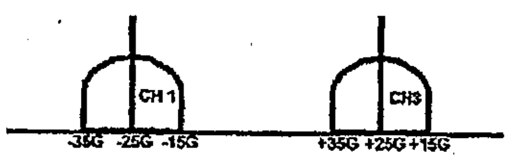



FIG. 8d




PMD corrected

FIG. 8e




SC'S 0° SHIFTED

FIG. 8f


SC'S 90° SHIFTED

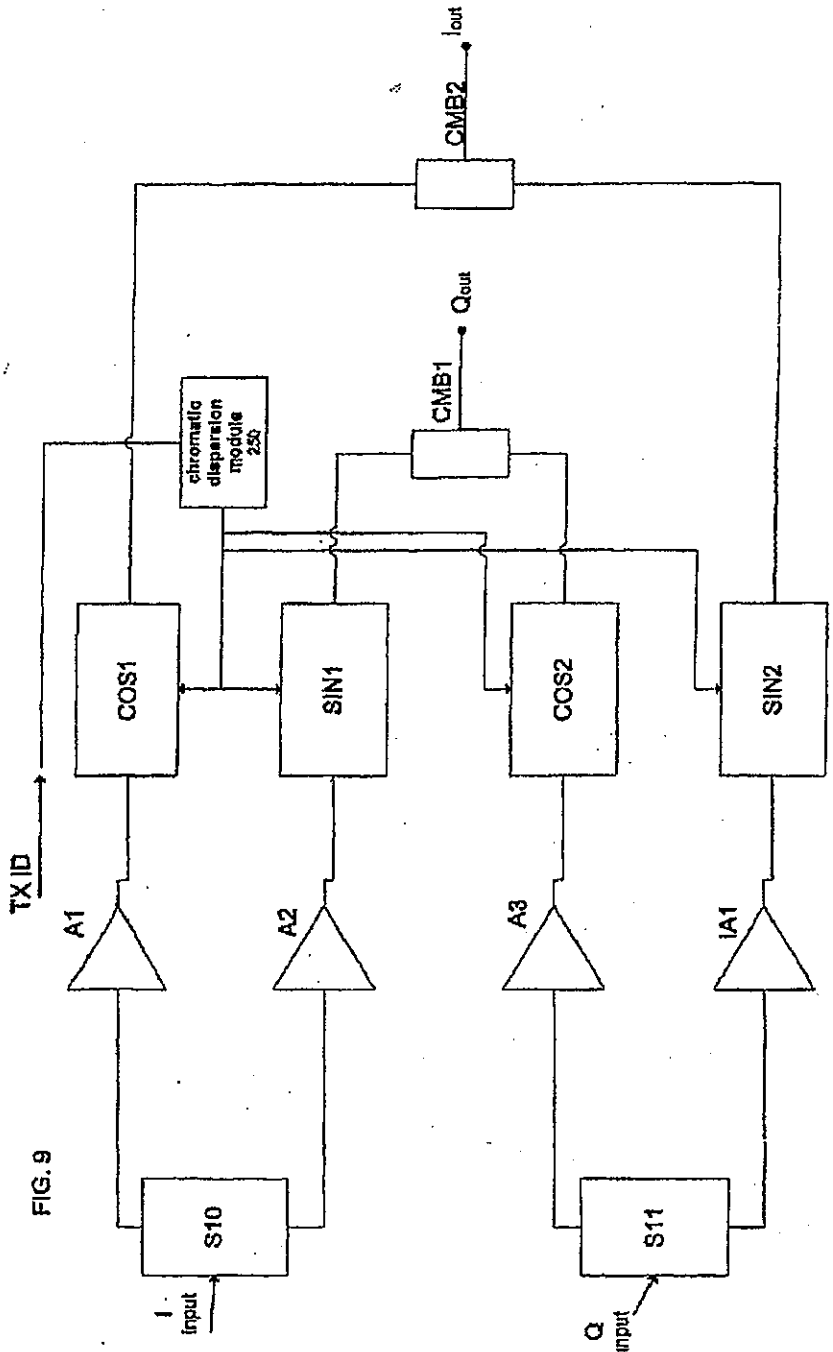

Iout
CMB2
Qout
CMB1
chromatic dispersion module 250
COS1
SIN1
COS2
SIN2
TX ID
A1
A2
A3
IA1
S10
S11
I input
Q input

FIG. 9

FIG. 10a

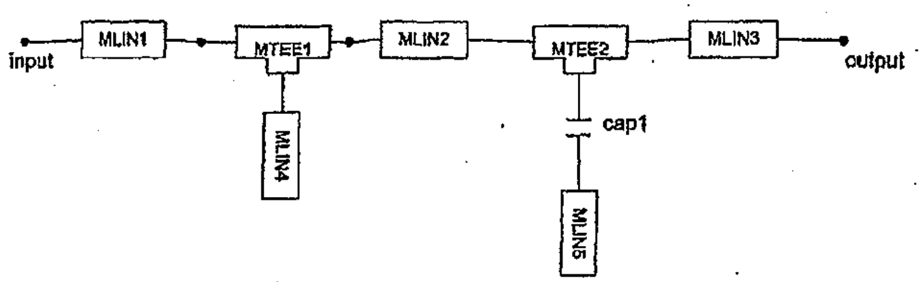
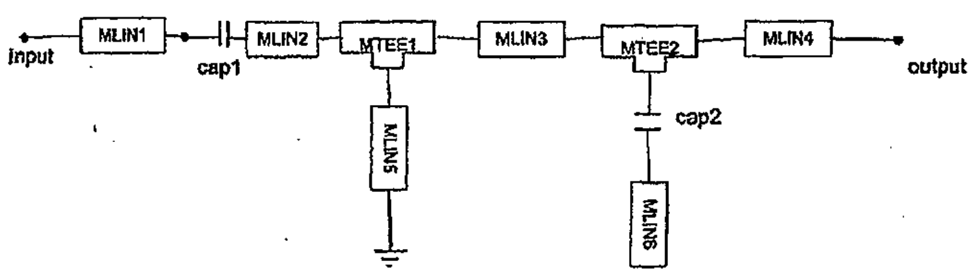



FIG. 10b



# METHOD AND SYSTEM FOR A POLARIZATION MODE DISPERSION TOLERANT OPTICAL HOMODYNE DETECTION SYSTEM WITH OPTIMIZED TRANSMISSION MODULATION

## CROSS-REFERENCES TO RELATED APPLICATIONS

This application is related to copending and commonly assigned U.S. patent application Ser. No. 09/748,750, filed in the United States Patent and Trademark office on Dec. 26, 2000, entitled "Method, System and Apparatus for Optically Transferring Information".

## FIELD OF THE INVENTION

The present invention relates to optical data communication, and in particular, relates to a method and optical data communication system that improves signal-to-noise ratio of optical data signals, counteracts polarization mode dispersion and improves robustness to fiber nonlinearities.

## BACKGROUND INFORMATION

Currently, optical data communication systems are being upgraded from a 10 Gb/s data transmission rate up to a 40 Gb/s transmission rate. However, data transmission at 40 Gb/s (or higher) presents extensive design challenges because the effects of polarization mode dispersion (PMD), chromatic dispersion and fiber non-linear effects such as cross-phase modulation become more dominant at the higher transmission rates. In particular, the limit of tolerable polarization mode dispersion, usually defined as 14% of the data bit duration, is only 3.5 ps at a 40 Gb/s transmission rate. A 3.5 ps polarization mode dispersion translates to an attainable reach of several hundred kilometers over single mode fiber which has a typical fiber PMD of 0.1 ps/km$^{1/2}$.

Current optical communications systems, such as the PMD compensation arrangement described in U.S. Pat. No. 6,130,766 to Cao, generally attempt to compensate for PMD by splitting received optical signals into x and y mode components having orthogonal polarization, and then adjusting the delay on one of the orthogonal components to align the modes. This arrangement requires significant signal processing and differential delays to cover the range of frequencies carrying data.

Nonlinearities induced during optical transmission are also amplified at higher data rates. While it is necessary for accurate detection that optical data signals be at least 20 dB above background noise, if the data signals are transmitted with too much power, nonlinearities can play a greater role in distorting the signal. In addition, in coherent systems typical heterodyne optical reception systems suffer an inherent 3 dB penalty with respect to homodyne systems and introduce phase noise through use of a local oscillator, and thereby add a further level of complexity and constraints to optical system design.

What is therefore needed is a cost-effective method and system that compensates for PMD, optimizes SNR performance and minimizes phase noise and nonlinearities associated with transmission over fiber at high data transmission rates.

## SUMMARY OF THE INVENTION

The present invention meets the above objectives by providing an optical homodyne communication system and



method in which a reduced amplitude side carrier is transmitted along with data bands in an optical data signal, and upon reception, the side carrier is boosted, shifted to the center of the data bands, and its polarization state is matched to the polarization state of the respective data bands to compensate for polarization mode dispersion during transmission. This scheme achieves the signal-to-noise benefits of homodyne reception without incurring the conventional restrictions and complications of homodyne reception such as requiring the phase of a signal from a local oscillator to be locked to the phase of the optical signal.

According to one embodiment, the present invention provides a method of optical communication that begins with providing a quadrature modulated optical data including two data bands separated in frequency, each data band having in-phase and quadrature components. The power of the quadrature modulated optical data signal is limited in order to limit non-linear effects by reducing the power of the optical data signal during transitional states in which data symbols transmitted in the optical data signal change in value, and in particular by reducing the power to zero such that transmitted power decreases to zero at approximately the mid point of the transitional states. The optical data signal is combined with a side carrier at a single frequency between the two data bands of the optical data signal and then transmitted across optical fiber to a receiver.

At the receiver, the side carrier is separated from the two data bands of the combined optical data signal and increased in amplitude relative to the data. The side carriers are then shifted to the middle of each of the respective two data bands. Since the relationship between the polarization state of the side carriers and the polarization state of the data bands does not stay constant during transmission over optical fiber, the polarization state of the shifted side carriers is adjusted to match the polarization state of the data bands at which they are centered.

The present invention further provides a method of compensating for the effects of chromatic dispersion during transmission over optical fiber by separating the in-phase and quadrature components of the two data bands prior to optoelectric conversion, and, after optoelectric conversion, compensating for chromatic dispersion by applying a corrective function to each of the in-phase and quadrature components of the data bands, the corrective function precisely counteracting the effects of chromatic dispersion on the in-phase and quadrature components.

The present invention also provides a method of providing information concerning a transmission device by providing an optical data signal having data bands and a side carrier with the side carrier modulated to carry an identification code, the identification code including information concerning the transmitter. According to an embodiment of the present invention, the information concerning a transmitter embedded in the side carrier includes parameters used in the corrective function to precisely counteract the effects of chromatic dispersion.

An optical data signal transmitter is provided for generating the quadrature modulated optical data signal including at least one side carrier. The transmitter includes a Mach-Zender modulator which generates an optical carrier signal by modulating a pair of side carriers onto an input optical signal. The optical carrier signal is modulated by at least two phase modulators which modulate a pair of data signals, in quadrature, onto the optical carrier signal, outputting an optical data signal including at least two data bands. By spreading the data bands onto the pair of side carriers, the amplitude of the optical data signal is reduced to zero during transitions between data symbols. The transmitter also includes a second Mach-Zender modulator which imprints a low-frequency TX ID (transmitter identification code) side carrier onto the input optical signal. The TX ID signal side carrier then combined with the optical data signal for transmission. The transmitted identification code includes information concerning the transmitter, such as its location, from which the distance between the transmitter and a receiver may be deduced.

The present invention further provides a receiver for implementing homodyne reception. The receiver includes a side carrier boosting module for increasing the amplitude of the side carrier relative to the data bands in the optical data signal. The receiver further includes a side carrier shifting module coupled to the side carrier boosting module which shifts the side carrier into two shifted carriers. Each of the shifted carriers is shifted to the center of one of the data bands. In addition, means for compensating polarization mode dispersion that are coupled to the side carrier shifting module match the polarization states of the shifted carriers to the data bands by adjusting either the polarization state of the shifted carriers or the polarization state of the data bands. After optoelectric conversion of the optical data signal, the receiver employs a chromatic dispersion correction stage that includes circuits that apply transfer functions to the in-phase and quadrature detected data channels

## BRIEF DESCRIPTION OF THE DRAWINGS

FIG. 1 is a block diagram of a transmitter according to an embodiment of the present invention.

FIG. 2*a* shows the spectrum of an optical carrier signal at the output of MZ1 of FIG. 1 according to an embodiment of the present invention.

FIG. 2*b* shows the spectrum of an optical data signal at the output of QMZ3 of FIG. 1 after data modulation in quadrature according to an embodiment of the present invention.

FIG. 2*c* shows the spectrum of an optical data signal at the output of QMZ2 of FIG. 1 according to an embodiment of the present invention.

FIG. 3 shows a 10G symbol per second Quadrature Return to Zero (QRZ) constellation diagram of the output from QMZ2 and QMZ3.

FIG. 4*a* shows the spectrum of an optical data signal at the output of C1 of FIG. 1 according to an embodiment of the present invention.

FIG. 4*b* shows the spectrum of an optical data signal at the output of C2 of FIG. 1 according to an embodiment of the present invention.

FIG. 4*c* shows the spectrum of an optical data signal at the output of the DWDM of FIG. 1 according to an embodiment of the present invention.

FIG. 5 is a block diagram of a receiver according to an embodiment of the present invention.

FIG. 6 is a block diagram of a first embodiment of the side carrier boosting module according to the present invention.

FIG. 7 is a block diagram of a second embodiment of the side carrier boosting module according to the present invention which employs the Stimulated Brillouin Scattering (SBS) effect.

FIG. 8*a* shows the spectrum of an optical carrier signal at the output of the FP4 of FIG. 5 according to an embodiment of the present invention.

FIG. 8*b* shows the spectrum of an optical carrier signal at the output of the S7 of FIG. 5 according to an embodiment of the present invention.

FIG. 8*c* shows the spectrum of an optical carrier signal at the output of the PBS3 of FIG. 5 according to an embodiment of the present invention.

FIG. 8*d* shows the spectrum of an optical carrier signal at the output of the SS1 of FIG. 5 according to an embodiment of the present invention.

FIG. 8*e* shows the spectrum of an optical carrier signal at the output of the C5 of FIG. 5 according to an embodiment of the present invention.

FIG. 8*f* shows the spectrum of an optical carrier signal at the output of the C6 of FIG. 5 according to an embodiment of the present invention.

FIG. 9 is a block diagram of a chromatic dispersion compensation circuit according to an embodiment of the present invention.

FIG. 10*a* is a block diagram of a microstrip implementation of a circuit that applies a COS transfer function to an input signal according to an embodiment of the present invention.

FIG. 10*b* is a block diagram of a microstrip implementation of a circuit that applies a SIN transfer function to an input signal according to an embodiment of the present invention.

## DETAILED DESCRIPTION

### I. Transmission

In accordance with the present invention, at a transmitter, a pair of side carriers is modulated onto each side of a monochromatic optical carrier signal, which is then split into two channels. Each optical carrier signal channel is modulated with two 10 Gb/s data signals in an orthogonal phase relationship to one another. The data signals are spread onto the two side carriers in each channel, and in effect, are spread out by fifty percent in the frequency domain. This spreading is equivalent to multiplication by a sine wave at half the data rate, and results in each data symbol returning to zero between transitions, referred to as quadrature-return-to-zero (QRZ). Using QRZ, the power of the optical data signal is made independent of the data pattern. The polarization of one of the optical data signal channels is then shifted, and one of the channels is combined with a channel of the original monochromatic carrier that has been modulated with a transmission idenfitication carrier of less than 100 kHz.

The two optical data signal bands, which each carry a 20 Gb/s data stream, are combined and either multiplexed with adjacent channels at similar frequency and orthogonal polarization or one of the two channels is shifted in polarization to match the other channel. In either case, the optical data signals are multiplexed according to a Dense Wave Division Mulitplexing (DWDM) scheme and transmitted along long haul fiber to a destination receiver.

FIG. 1 illustrates an embodiment of a transmitter according to the present invention, which may be implemented on a Lithium-Niobate chip, for example. An optical signal generator SG1, which may be a laser, generates a monochromatic, polarized optical carrier at a reference frequency which for purposes of the following discussion is designated as the origin (0 GHz) in terms of relative frequency. The optical signal is thereafter split into two channels, an upper channel going to Mach-Zender modulator MZ1 and a lower channel being transmitted to Mach-Zender modulator MZ4. The division of light intensity between the two channels can be uneven with the lower channel receiving, for example, just 10 percent of the light intensity generated by SG1. At narrow-band modulator MZ4, the lower channel of the optical signal is modulated with a "Transmitter Identification" (TX ID) tone in the frequency range of 10 KHz to 100 KHz above the reference frequency. At modulator MZ1, two sets of side carriers at +/-20 GHz and +/-30 GHz are modulated onto the optical signal. The spectrum for the modulated signal, denoted an optical carrier signal, is shown in FIG. 2*a*. As shown in the figure, the resulting spectrum output from MZ1 shows four peaks, two below the reference frequency at -30 GHz and -20 GHz relative to the reference frequency, and two above the reference frequency at +20 GHz and +30 GHz.

The output of modulator MZ1 is further split into an upper channel which is transmitted to quadrature data modulator QMZ3 and a lower channel which is transmitted to quadrature data modulator QMZ2. Data modulator QMZ2 imprints two individual 10 Gb/s data streams in quadrature (in orthogonal phase relationship) CH.1 and CH.2 onto each of the pairs of side carriers above and below the reference frequency. Similarly, data modulator QMZ3 imprints individual 10 Gb/s data streams CH.3 and CH.4 onto each of the pairs of side carriers in the optical carrier signal. Respective bias control electrodes VB2 and VB3 assist in keeping the data streams in quadrature. Spectra of the outputs from QMZ3 and QMZ2 are shown in FIG. 2*b* and FIG. 2*c* respectively. As can be discerned in FIG. 2*b* and FIG. 2*c*, the output spectra from QMZ3 and QMZ2 show two data bands, one extending from -40 GHz to -10 GHz and another extending from +10 GHz to +40 GHz relative to the reference frequency.

By imprinting two 10 Gb/s data streams in quadrature, in effect, 20 Gb/s of data are modulated onto each pair of side carriers (-30,-20 GHz and +20, +30 GHz, respectively) and each 20 Gb/s data band covers 30 GHz in the frequency domain. By providing two side carriers, with one side carrier in the pair a clock rate away from the other (i.e., 30 GHz being a clock away from 20 GHz), the data bits in both I and Q format are multiplied in the time domain by a 5 GHz sinusoid which crosses zero every 100 ps. Thus, the total data signal always crosses through zero in between any pair of symbols (any pair of I,Q data), referred to as quadrature-return-to-zero (QRZ) modulation.

FIG. 3 illustrates the key property of the QRZ format, showing that the trajectory between two successive symbols always leads through the I-Q origin. Each corner of the figure represents a pair of I, Q data symbols (e.g., I=1,Q=-1 or I=-1, Q=1). As shown, to get from adjacent corner points I=1, Q=1 (upper right corner) to I=1, Q=-1 (lower right corner) the optical data signal must travel through the origin (0,0). During each trajectory through the origin, the power of the signal, which is proportion to the square of its amplitude, goes to zero.

Returning to FIG. 1, the output from modulator QMZ3 is input to a polarization transformer PT1, which shifts the polarization of the optical data signal output from QMZ3 90 degrees. The polarization of the signal output from PT1 is arbitrarily illustrated by parallel lines as parallel polarization as opposed to a perpendicular polarization of the original optical signal. Furthermore, the output optical data signal from modulator QMZ2 is combined at combiner C1 with the TX ID pilot signal from MZ4. The output from C1 is shown in FIG. 4*a*. As noted above, the intensity of the TX ID signal is reduced in comparison with the optical data signal from QMZ2. It is also noted that the polarization of the output signal from C1 is shown as perpendicular, since the polarization of the output from C1 remains unchanged from the original polarization. Thereafter, the output signal from PT1 is combined with the output signal from combiner C1 at C2. The spectrum of the output signal out of C2 is shown in FIG. 4*b*. As can be discerned, the spectrum includes data channels 1, 2, 3 and 4 in both lower and upper data bands. Channels 1 and 2 are in perpendicular polarization and channels 3 and 4 are in parallel polarization. The reference carrier at approximately 0 GHz from MZ4 is in perpendicular polarization.

According to the illustrated embodiment, the output signal from C2 is input to a polarization beam splitter PBS1 which splits the signal into perpendicular and parallel polarized components, thereby separating the data channels 1 and 2 from channels 3 and 4. The perpendicular component (containing data channels 1 and 2 as well as the central reference frequency) is transmitted along lower path 102 to a first channel of a dense wave division multiplexer DWDM, the parallel component (containing data channels 3 and 4) is input to a polarization transformer PT2, which rotates the polarization of the parallel component back into a perpendicular state. The output from PT2 is then input to a second DWDM channel. Each DWDM channel acts as a band pass filter and passes only frequencies that fall within a 50 GHz band. Assuming for illustrative purposes that DWDM channel 1 passes frequencies from -50 GHz to 0 GHz relative to the reference frequency, and DWDM channel 2 passes frequencies from 0 to +50 GHz, data channels 1 and 2 are passed only in the data band from -40 GHz to -10 GHz and while data channels 3 and 4 are passed only in the data band from +10 GHz to +40 GHz. The DWDM multiplexes each of the passed bands onto a long haul fiber (not shown). The output spectrum from -50 GHz to +50 GHz output from the DWDM is shown in FIG. 4*c*. The adjacent DWDM channels each pass 20 Gb/s of data, combining for a total of 40 Gb/s.

In an alternative embodiment, a polarization multiplexing scheme may be used, making it unnecessary to separate data channels 1 and 2 from data channels 3 and 4.

As described in related and commonly owned application Ser. No. 09/782,354 hereby incorporated for reference, the pairs of data channels can occupy the same data band if their polarization states remain orthogonal and thus do not interfere with each other. In this implementation, the polarization beam splitter PBS1 is not needed and the output from C2 can be sent directly to one of the DWDM input channels.

II. Reception

In accordance with the present invention, a homodyne reception system is employed to receive the optical data signal generated as described above. Upon reception, the transmitted side carrier at the reference frequency is boosted to increase the signal-to-noise ratio (SNR) of the optical data signal and to compensate for the attenuation of the side carrier in the transmitter. The boosting of the side carrier increases the SNR because of the implementation of homodyne reception in which overall detected signal power is increased in proportion to the power of the local oscillator, or in the present case (as will be discussed below), the transmitted side carrier.

Once the amplitude of the side carrier power is boosted relative to the transmitted data bands, the side carrier is shifted by +/-25 GHz into two side carriers that are each shifted to the center of one of the two data bands to further implement homodyne reception.

After the shifting of the side carriers, the two side carriers are separated and then modified by polarization controllers which match the time-varying polarization state of each the side carriers to the different time-varying polarization state of the respective data bands, thus overcoming the effects of polarization mode dispersion by controlling the polarization at only a single frequency.

According to an embodiment of the present invention, a chromatic dispersion compensation stage is used to counter the effects of dispersion during transmission over long haul fiber. Since the effects of dispersion can be modeled as a transfer function that is applied to the I and Q data signals, the chromatic dispersion compensation stage applies a compensating correction function that effectively counteracts the transfer function, rendering the I and Q data signals into their original non-dispersed state.

FIG. 5 illustrates an embodiment of a homodyne receiver according to the present invention. An optical data signal is received first by a side carrier boosting module 200 for which the present invention provides two exemplary embodiments. In a first embodiment of the side carrier boosting module, shown in FIG. 6, the optical data signal is first input to an optical amplifier EDFA1, which may be, for example, an erbium-doped fiber amplifier (EDFA). It is noted that all further optical amplifiers used in the implementations described below may be implemented as erbium-doped fiber amplifiers. The optical amplifier EDFA1 amplifies the entire spectrum of the received signal by, for example, approximately 15-18 dB. The amplified signal output from EDFA1 is split at S3 between an upper branch that is coupled to a Fabry-Perot resonator FP1 and a lower branch that is coupled to an attenuator ATT1.

The Fabry Perot resonator FP1 functions as a high-Q filter that nearly completely filters out all frequencies excepts for a series of frequencies that are separated by, for example, 100 Ghz which, according to the International Telecommunication Union (ITU) grid, is the amount of bandwidth allocated for each channel. The resonator FP1 is adjusted to pass the side carrier at the reference frequency and filter out the data bands of the optical data signal. It is noted in this regard that it is contemplated that the embodiments of the present invention be used in the context of the ITU grid, and that the reception approach described allows for simultaneous processing of side carriers for a plurality of ITU grid-spaced channels. The lower branch passed to ATT1, which contains both the data bands and the side carrier is attenuated. The signals output from FP1 and ATT1 are combined in combiner C4 and then passed to a further optical amplifier EDFA2 where the combined signal is again amplified by, for example, approximately 15-18 dB. Because the side carrier was isolated and boosted in FP1 and the data bands were attenuated in ATT1, the combined signal contains a side carrier boosted at least 10 dB in amplitude relative to the data bands.

A second embodiment of the side carrier boosting module, which advantageously makes use of the amplitude-enhancing effect of Stimulated Brillouin Scattering (SBS), is shown in FIG. 7. The SBS effect causes a first optical signal having narrow frequency band around frequency X to be amplified when collides with a signal of frequency X+-11 GHz traveling in the opposite direction. Referring to FIG. 7, the received signal is input to optical amplifier EDFA3 which amplifies the entire spectrum of the input signal. The signal output from amplifier EDFA3 is transmitted to optical isolator ISL 1, which permits optical signal to travel only in one direction (the direction indicated by the arrow in the figure) and prevents optical signals being reflected or transmitted back toward the amplifier EDFA3. From the optical isolator ISL 1, the optical data signal is split into two branches at splitter S4.

A first upper branch from splitter S4 leads to Fabry Perot resonator FP2, which passes the side carrier (and other modes in the series of frequencies) in between the data bands. FP controller 1 automatically adjusts the resonator FP2 so that it correctly passes the side carrier using input from splitter S5 and filters out the data bands. The output from FP2 is delivered to external modulator XMOD 1, which also receives an 11 GHz signal from a 11 GHz oscillator through an 11 GHz amplifier. The external modulator XMOD 1 modulates the 11 GHz signal onto the side carrier. The spectrum of the output from the modulator XMOD 1 thereafter contains the reference frequency and two side frequencies located 11 GHz both above and below the reference frequency. This output signal is then transmitted to another resonator FP3, which is adjusted by FP controller 2 to center on (and pass) only the side frequency 11 GHz above the reference side carrier frequency. The resulting signal, carrying substantially a single frequency at the reference frequency +11 GHz, is amplified in optical amplifier EDFA4 and then input to circulator CIRC 1. The circulator passes signals in a counter-clockwise direction. More specifically, CIRC 1 passes the output from EDFA4 leftwards in a counter-clockwise rotation towards the output of optical isolator ISL 2. It is noted that the side carrier boosting scheme is also intended be used in conjunction with a dense wave division multiplexing scheme. Thus, the side carrier boosting module can simultaneously process and boost a plurality of side carriers spaced in frequency according to ITU channel spacing.

Simultaneously, the optical signal in the lower branch from splitter S4 is transmitted through isolator ISL 2 and then meets with the optical signal from the upper branch output from the circulator CIRC 1. This collision of the two optical signals traveling in opposite directions generates the SBS non-linear effect. According to one implementation, the fiber connecting isolator ISL 2 and circulator CIRC 1 can be dispersion compensating fiber which, due to its relatively smaller cross-section, promotes higher intensity and more pronounced non-linear effects such as SBS. When the optical data signal containing the reference side carrier collides with the 11 GHz side frequency signal from CIRC 1, a narrow band including the side carrier in the optical data signal is amplified relative to the data bands due to the SBS effect as explained above. This modified optical data signal then reaches the circulator CIRC 1 from which it passes in the counter-clockwise direction to optical amplifier EDFA5, which amplifies the entire spectrum of the modified optical data signal by 15-18 dB. The output from EDFA5 is the final output of the second embodiment of the side carrier boosting module 200.

Returning to FIG. 5, the optical data signal output from the side carrier boosting module 200 is input to circulator CIRC 2, which in turn transmits the signal in a counter-clockwise direction to Fabry-Perot resonator FP4, having a free spectral range (FSR) of 100 GHz and finesse on the order of 1000. The resonator FP4 is also tuned to select the side carrier at (approximately) the reference frequency (O GHz). FIG. 8*a* shows a spectrum of the signal output from FP4, indicating that the data bands have again been filtered out. The data bands that are filtered out at FP4 are resent back toward circulator CIRC 2, where they are redirected in a counter-clockwise direction towards splitter S7. The spectrum of the output from splitter S7, which includes the two filtered data bands at −40 GHz to −10 GHz and +10 GHz to +40 GHz, is shown in FIG. 8*b*.

It is noted that when the optical data signal is transmitted over long haul fiber between the transmitter and the receiver, the polarization state of the transmitted signal is scrambled, with the result that the received signal has an unknown time-varying polarization state. Since the time-varying polarization state varies with frequency, the side carrier is expected to have a different time-varying polarization state than either of the data bands because it is separated from the centers of data bands by 25 GHz. When the output from resonator FP4 is fed to the side carrier shifting module 210, the side carrier's orthogonal polarization states are split in polarization beam splitter PBS2, and then each of the orthogonal signals are separately modulated by 25 GHz in XMOD 2 and XMOD 3, respectively, and then joined back in PBS3. The output from PBS3 is illustrated in FIG. 8*c*, which shows two side carriers at −25 GHz and +25 GHz from the reference frequency, respectively. The output from PBS2 is passed on to Fabry-Perot filter FP5 (FSR=50 GHz, finesse>500) which passes both the 25 GHz left and right shifted side carriers, and transmits them to circulator CIRC3. Circulator CIRC3 delivers shifted SC's to reflective polarization controllers PC 1, PC 2, through respective adjacent 50 GHz-spaced channels of WDM demultiplexer DWDM 2. The polarization controllers PC 1, PC 2 are constructed to provide control of the phase of the signals reflected from the polarization controllers back to the demultiplexer DWDM 2. Such control may be used, for instance, in order to compensate for the effective fiber length between the polarization controllers PC 1, PC 2 and the demultiplexer DWDM 2. In one implementation, the polarization controllers PC 1, PC 2 include mirrors and piezoelectric actuators to adjust the distance the reflected signal travels, which in turn controls the phase of the reflected optical signal.

Each polarization controller PC 1, PC 2 is used to transform the time-varying polarization state of one of the two side carriers so that the polarization states of each side carrier matches the time varying polarization state of the respective data bands which are centered at the side carrier (−25 GHz and +25 GHz). To accomplish this, each polarization controller PC 1, PC2 obtains feedback from the photodiodes that receive the data bands. PC 1 receives the feeback via bias-T couplers BT 1 and BT 3, while PC 2 receives feedback via bias-T couplers BT 2 and BT 4. As will be described below, the demultiplexers at the top of FIG. 5, DWDM 3, DWDM 4, receive both the data bands and the side carriers, filter them into separate, adjacent frequency channels and then effectively multiply the side carrier and data bands together at photodiodes PD1, PD2, PD3 and PD4 (and other photodiodes of adjacent channels that are not shown) which respond to the intensity of the signal (i.e., the square of the amplitude). The product signal output from the photodiodes is delivered to the respective polarization controllers PC 1, PC 2 via bias-T couplers BT 1, BT 2, BT 3 and BT 4. The outputs from BT 1 and BT 3, which contain converted data signals 1 and 2, corresponding to data channels 1 and 2, are combined to provide feedback to polarization controller PC 1, and the outputs from BT 2 and BT 4, which contain data signals 3 and 4, corresponding to data channels 3 and 4, are combined to provide feedback polarization controller PC 2. It is noted that the data signals 1 and 2 are expected to have a similar polarization state since, during transmission, they occupy the same frequency range. Equally, data signals 3 and 4, corresponding to data channels 3 and 4, are expected to have a similar polarization state. At the polarization controllers PC 1, PC 2, the time-varying polarization of the combined product signals are compared to the polarization state of the individual side carrier signals.

By continually adjusting the polarization of the side carrier signal and then comparing the modified polarization state to the combined product signals, the polarization controllers PC 1, PC 2 can accurately match the time-varying polarization state of each of the side carriers with the time-varying polarization state of the corresponding data bands. This technique takes advantage of fact that it is easier to adjust the single polarization state of a single side carrier frequency than to adjust the multitude of polarization states of a band of frequencies, for example, a 20 GHz data band, via wide-band polarization compensation. However, polarization mode dispersion compensation can also be performed here by adjusting the average polarization of the data band, which is treated as having a single polarization, and then matching to the polarization of the side carrier.

Returning once again to FIG. 5, the polarization controllers PC 1, PC 2 output polarization compensated side carrier signals to circulator CIRC 3, from which they are forwarded to splitter SS1. The splitter SS1 also shifts the phase of one of the output branches by 90 degrees relative to other branch. The output spectrum from SS1 is shown in FIG. 8*d*. These 0 degree and 90 degree phase shifted carriers are recombined in combiners C5 and C6, respectively, with the data bands output from splitter S7. In-phase (0 degree shifted) and quadrature (90 degree-shifted) signal spectrums out of outputs of respective combiners C5 and C6 are shown in FIG. 8*e* and FIG. 8*f*. As can be discerned, in each spectrum, a side carrier is positioned in the center of a data band. Each side of the spectra is equivalent to a spectrum generated by a conventional homodyne system in which the local oscillator frequency is matched to the center frequency of the data band. Furthermore, as in conventional homodyne reception, the power of the central carrier frequency is boosted relative to the data portion in order to the improve signal-to-noise ratio of the detected signal. The side carrier that has been shifted 0 degrees can be used to detect the in-phase (I) 10 Gb/s data channels from the transmitter (channels 1, 3) and the side carrier that has been shifted 90 degrees can be used to detect the quadrature (90 degree shifted) 10 Gb/s data channels (channels 2, 4).

The combined signal from C5 is sent through optical amplifier EDFA6 and the combined signal from C6 is sent through optical amplifier EDFA7 to final 50 GHz spaced demultiplexers DWDM 3 and DWDM 4. Each of the demultiplexers DWDM 3, DWDM 4 separate the data bands and side carriers in adjacent channels for electro-optic conversion at photodiodes PD 1, PD 2 and PD 3, PD 4 respectively. In this manner 10 GB/s data channels 1 and 3 are separated in DWDM 3 and 10 Gb/s channels 2 and 4 are separated in DWDM 4, resulting in the output of four separate 10 Gb/s data signals.

In an implementation of the receiver according to the present invention, low-bandwidth photodiodes can be placed at reflective ends of polarization controllers in each leg of WDM demultiplexer to provide monitor outputs proportional to fluctuations in each of carriers, for example caused by cross phase modulation (XPM). Since the respective 10 Gb/s data channels corresponding to the side carriers generally fluctuate in sympathy, the effect of carrier fluctuation can be removed if the monitor output fluctuations are subtracted from the outputs of the respective received 10 Gb/s output channels.

After the converted data signals are further processed through trans-impedance amplifiers TIA1, TIA2, TIA 3, TIA 4 and low pass filters LPF1, LPF2, LPF3, LPF4, they are input to a chromatic dispersion compensation stage shown schematically in FIG. 9. It is noted in this context that the dispersion compensation stage can equally be implemented at the quadrature data modulators on the transmitter side instead of, or in addition to, implementation at the receiver. The effects of fiber-induced chromatic dispersion on quadrature-modulated sinusoidal data signals can be described by the following matrix equation:

$$\begin{bmatrix} I\_out(D, L, f) \\ Q\_out(D, L, f) \end{bmatrix} = \begin{bmatrix} \cos\phi 1(D, L, f) & \sin\phi 1(D, L, f) \\ -\sin\phi 1(D, L, f) & \cos\phi 1(D, L, f) \end{bmatrix} \begin{bmatrix} I\_in(f) \\ Q\_in(f) \end{bmatrix} \quad (1)$$

where I_out(f) and Q_out(f) are frequency domain representations of output I amd Q signals, which are modified from frequency domain representations of input I and Q signals, I_in(f) and Q_in(f), by the dispersion matrix, for which

$$\phi 1(D, L, f) = D \cdot L \cdot \frac{0.8}{4 \cdot \pi} \cdot 10^{-26} \cdot (2\pi f)^2 \quad (2)$$

D denotes the fiber dispersion in units of ps/nm*km, L stands for fiber length in meters and f stands for frequency in Hz.

The dispersion matrix can be interpreted as a transfer function which applies a clockwise rotation angle that is proportional to the square of the frequency of the transmitted sinusoid. To counter the dispersion effect, it is feasible to apply an inverse transfer function, which can be interpreted as a counterclockwise rotation, also proportional to the square of the frequency. This counter-dispersion, or correction function may be described by the following matrix equation:

$$\text{disp\_corr}(D, L, F) = \begin{bmatrix} \cos(\phi 1(D, L, f)) & -\sin(\phi 1(D, L, f)) \\ \sin(\phi 1(D, L, f)) & \cos(\phi 1(D, L, f)) \end{bmatrix} \quad (3)$$

Therefore to correct the I and Q data signal for the effects of chromatic dispersion, the correction function is applied to the I and Q input signals (again, either at the transmitter or at the receiver, as is shown). Multiplying the correction function by the input signals yields:

$$\begin{aligned} \text{I\_out} &= \cos\phi 1(D, L, f) \cdot \text{I\_in} - \sin\phi 1(D, L, f) \cdot \text{Q\_in} \\ \text{Q\_out} &= \sin\phi 1(D, L, f) \cdot \text{I\_in} + \cos\phi 1(D, L, f) \cdot \text{Q\_in} \end{aligned} \quad (4)$$

From equation (4), it is clear that dispersion compensation can be obtained by modifying the input I and Q data signals with an appropriate transfer function and then combining the modified signal. An embodiment of a dispersion correction circuit that performs these operations is shown in FIG. 9. As shown, the I input signal is input to a splitter **S10**, from which an upper branch is delivered to amplifier A1 and a lower branch is delivered to an amplifier A2 in order to boost the signal. The upper branch is transmitted to a COS1 circuit which applies the cosine portion of the dispersion correction function cosϕ1 (D,L,f) to the input data signal as will be described further below. The lower branch from the splitter **S10** is fed to a SIN1 circuit which applies the complementary sine portion of the dispersion correction function.

The Q data signal is concurrently input to splitter **S11** and broken up into an upper branch which is fed through amplifiers A3, and a lower branch which is delivered to inverting amplifier IA1 which, in addition to boosting the signal, also shifts the phase of the signal by 180 degrees. The upper and lower branches are thereafter input to respective COS2 and SIN2 circuits which perform the same functions as the COS1 and SIN1 circuits, respectively. As shown, the modified signal from the SIN1 circuit, which is the product I_in times sinϕP1 (D,L,f), is combined with the output from COS2, the product, Q_in times cosϕ1(D,L,f), at combiner CMB1. Comparison with equation (4), shows that the output of combiner CMB1 matches the desired Q_out output for dispersion compensation. Similarly, the combination at CMB2, containing the products I_in times cosϕ1(D,L,f) and Q_in times −sinϕ1(D, L,f), matches the desired I_out output for dispersion compensation.

Furthermore, the TX ID pilot signal, which, as noted above, is modulated onto the reference frequency +/−10-100 kHz, is received at the polarization controllers PC **1**, PC **2** and converted to the RF domain at photodetectors PD3 and PD4. The TX pilots may be coded by frequency modulation or by another code modulation technique. The TX ID identifies the particular transmitter sending the signal, allowing information, such as the length of optical fiber between the transmitter and the receiver (which is the same as the parameter, L, used in the dispersion correction function), to be extracted from the coded signal. This information is transmitted to the chromatic dispersion compensation stage where it is received by a chromatic dispersion module **250**. The chromatic dispersion module, in turn, is coupled to the SIN and COS circuits and causes adjustments to be made to the respective transfer functions applied to the I and Q inputs in accordance with the information extracted from the TX ID.

According to an embodiment of the present invention, the SIN and COS circuits of FIG. 9 are implemented as microstrip circuits which use layers or regions of copper deposited on a circuitboard having various widths and lengths, to adjust electromagnetic effects that modify signals sent through the copper layers or regions. FIG. **10***a* and FIG. **10***b* illustrate implementations of the sinϕ1(D,L,f) and cosϕ1(D,L,f) transfer functions respectively. As is known in the art, various combinations of linear strips, (denoted as MLIN), t-junctions (denoted as MTEE), and capacitive elements (cap1, cap2), again having various adjustable lengths and widths are used to fine-tune the electromagnetic wave effects in the copper regions to simulate the desired transfer functions.

In the foregoing description, the method and system of the invention have been described with reference to a number of examples that are not to be considered limiting. Rather, it is to be understood and expected that variations in the principles of the method and apparatus herein disclosed may be made by one skilled in the art and it is intended that such modifications, changes, and/or substitutions are to be included within the scope of the present invention as set forth in the appended claims. For example, although only a 10 Gbp/s digital baseband is discussed, the inventive principles herein may be applied to higher or lower data rates as the case may be.

What is claimed is:

1. A method of optical communication in an optical communication system, comprising the steps of:

providing a quadrature modulated optical data signal by a transmitter, the optical data signal including two data bands separated in frequency, each data band having in-phase and quadrature components;

during transitional states of the quadrature modulated optical data signal in which data symbols change in value, reducing, by the transmitter, the power to zero such that transmitted power decreases to zero at approximately a mid point of the transitional states;

combining the optical data signal with a side carrier at a single frequency between the two data bands of the optical data signal;

transmitting, by the transmitter, the combined optical data signal;

receiving, by a receiver, the combined optical data signal;

separating, at the receiver, the side carrier from the two data bands of the combined optical data signal;

increasing an amplitude of the side carrier;

modulating the side carrier into two shifted side carriers, one of the two shifted carriers being shifted in frequency to the middle of each of the respective two data bands; and correcting, at the receiver, for polarization mode dispersion on the combined signal by adjusting a polarization state of each of the two shifted side carriers to match a polarization state of the one of the two data bands at which the respective shifted side carrier is centered.

2. The method of claim 1, further comprising the steps of:

separating the in-phase and quadrature components of the two data bands after optoelectric conversion; and

after optoelectric conversion, compensating for chromatic dispersion by applying a corrective function to each of the in-phase and quadrature components of the data bands, the corrective function precisely counteracting the effects of chromatic dispersion on the in-phase and quadrature components.

3. The method of claim 1, further comprising the steps of:

before transmission, separating signals in quadrature in each of the two data bands of the combined optical data signal into separate first and second signals; and

inputting the first and second signals into respective first and second channels of a dense wave division multiplexer.

4. The method of claim 3, further comprising the steps of:

during modulation, imprinting a first data signal in-phase and a second data signal in quadrature phase onto two data channels on data bands of a first quadrature modulated optical data signal;

during modulation, imprinting a third data signal in-phase and a fourth data signal in quadrature-phase onto each of two data channels on data bands of a second quadrature modulated optical data signal;

encoding the first modulated optical data signal with a first polarization state; and

encoding the second modulated optical data signal with a second polarization state.

5. The method of claim 4, further comprising the steps of:

combining the first and second quadrature modulated optical data signals;

separating the first and second quadrature modulated optical data signals according to polarization state, the first and second data channels in the data bands having a first polarization state, the third and fourth data channels in the data bands having a second polarization state;

before transmission, filtering the separated signals according to frequency.

6. The method of claim 1, further comprising the step of:

before transmission, reducing an amplitude of the side carrier.

7. The method of claim 1, wherein the step of compensating for polarization mode dispersion on the combined signal includes the steps of:

mixing the optical data signal with one of the two shifted side carriers, the shifted side carrier having a second polarization state;

adjusting the second polarization state of the shifted side carrier;

determining, through feedback from the mixing step, whether the adjustment to the second polarization state of the carrier signal has brought the second polarization state in alignment with the first polarization state; and

repeating the previous steps until the second polarization state is in alignment with the first polarization state.

8. The method of claim 1, wherein the step of compensating for polarization mode dispersion on the combined signal includes the steps of:

mixing the optical data signal with one of the two data bands of the optical data signal, the one of the two data bands having a first polarization state;

adjusting the first polarization state of the one of the two data bands;

determining, through feedback from the mixing step, whether the adjustment to the first polarization state of the one of the two data bands has brought the first polarization state in alignment with the second polarization state; and

repeating the previous step until the first polarization state is in alignment with the second polarization state.

9. The method of claim 1, wherein after reception, the side carrier is separated from the two data bands of the combined optical data signal by filtering the combined optical signal using a Fabry-Perot resonator.

10. The method of claim 1, further comprising the step of:

prior to transmission, modulating the side carrier with an identification code, the identification code including information concerning a transmitter performing the step of transmitting the combined optical data signal.

11. The method of claim 10, further comprising the steps of:

separating the in-phase and quadrature components of the two data bands after optoelectric conversion; and

compensating for chromatic dispersion by applying a corrective function to each of the in-phase and quadrature components of the data bands, the corrective function precisely counteracting effects of chromatic dispersion on the in-phase and quadrature components;

wherein the information concerning a transmitter includes parameters used in the corrective function to precisely counteract the effects of chromatic dispersion.

12. A method of reducing the transmitted power of a quadrature modulated optical data signal, comprises the steps of:

providing a quadrature modulated optical data signal by a transmitter;

during all transitional states of the quadrature modulated optical data signal in which data symbols can change in value, reducing, by the transmitter, the power to zero such that transmitted power decreases to zero at approximately a mid point of each of the transitional states;

combining the quadrature modulated optical data signal with a side carrier; and

transmitting the side carrier with the quadrature modulated optical data signal.

13. The method of claim 12, wherein the transmitted power is independent of a data pattern of the quadrature modulate optical data signal.

14. An optical data signal transmitter comprising:

a Mach-Zender modulator, the Mach-Zender modulator receiving an input optical signal and modulating a pair of side carriers onto the input optical signal, outputting an optical carrier signal; and

at least two phase modulators, the at least two phase modulators receiving the optical carrier signal and each generating an optical data signal by modulating a pair of data signals onto at least two data bands;

wherein the data bands are spread in frequency when modulated onto the optical carrier signal, the spreading causing an amplitude of the optical data signal to be reduced to zero during all transitional state between any pair of data symbol, in which the data symbols can change in value.

15. An optical data signal transmitter comprising:

a Mach-Zender modulator, the Mach-Zender modulator receiving an input optical signal and modulating a pair of side carriers onto the input optical signal, outputting an optical carrier signal;

at least two phase modulators, the at least two phase modulators receiving the optical carrier signal and each generating an optical data signal by modulating a pair of data signals onto at least two data bands;

a second Mach-Zender modulator, the second Mach-Zender modulator imprinting the input optical signal with an identification code to generate a TX ID, the identification code including information concerning the transmitter; and

a combiner, the combiner attaching the TX ID to the optical data signal;

wherein the data bands are spread in frequency when modulated onto the optical carrier signal, the spreading causing an amplitude of the optical data signal to be reduced to zero during transitions between data symbols.

16. The transmitter of claim 15, further comprising:

a polarization transformer;

wherein the at least two phase modulators generate a first optical data signal including data bands imprinted with a first pair of data channels, the first optical data signal having a first polarization state, and a second optical data signal including data bands imprinted with a second pair of data channels, the second optical data signal having a first polarization state, the polarization transformer altering a polarization state of the first optical data signal from the first polarization state to a second polarization state.

17. The transmitter of claim 16, further comprising

a dense wave division multiplexing unit; and

means for separating the first pair of data channels from the second pair of data channels based upon differing polarization states of the first and second optical data signals;

wherein the first and second pairs of data channels are input to separate channels of the dense wave division multiplexing unit.

18. An optical data signal comprising:

a Mach-Zender modulator, the Mach-Zender modulator receiving an input optical signal and modulating a pair of side carriers onto the input optical signal, outputting an optical carrier signal; and

at least two phase modulators, the at least two phase modulators receiving the optical carrier signal and each generating an optical data signal by modulating a pair of data signals onto at least two data bands;

wherein the data bands are spread in frequency when modulated onto the optical carrier signal, the spreading causing an amplitude of the optical data signal to be reduced to zero during transitions between data symbols; and

wherein the pair of side carriers is modulated onto the input optical signal at both above and below a reference frequency of the input optical signal.

19. The transmitter of claim 18, wherein a first side carrier of the pair of side carriers is modulated onto the input optical signal at 30 Ghz above and below the reference frequency, and a second side carrier of the pair of side carriers is modulated onto the input optical signal at 20 Ghz above and below the reference frequency.

20. A method of reducing the transmitted power of a quadrature modulated optical data signal, comprising the steps:

providing a quadrature modulated optical data signal by a transmitter;

during all transitional states of the quadrature modulated optical data signal in which data symbols can change in value, reducing, by the transmitter, the power to zero such that transmitted power decreases to zero at approximately a mid point of each of the transitional states; and

spreading orthogonal data signals onto two side carriers of an optical signal to obtain the quadrature modulated optical data signal.

21. The method of claim 20, wherein the two side carriers are separated from one another by a clock rate.

22. A method of reducing the transmitted power of a quadrature modulated optical data signal, comprising the steps:

providing a quadrature modulated optical data signal by a transmitter;

during all transitional states of the quadrature modulated optical data signal in which data symbols can change in value, reducing, by the transmitter, the power to zero such that transmitted power decreases to zero at approximately a mid point of each of the transitional states, where data signals are in effect spread out by approximately fifty percent in the frequency domain equivalent to a multiplication by a sine wave at half the data rate, and results in each symbol returning to zero at approximately a mid-point of the transitional states.

* * * * *

UNITED STATES PATENT AND TRADEMARK OFFICE

# CERTIFICATE OF CORRECTION

PATENT NO. : 7,599,627 B2
APPLICATION NO. : 09/871216
DATED : October 6, 2009
INVENTOR(S) : Schemmann et al.

Page 1 of 1

It is certified that error appears in the above-identified patent and that said Letters Patent is hereby corrected as shown below:

On the Title Page:

The first or sole Notice should read --

Subject to any disclaimer, the term of this patent is extended or adjusted under 35 U.S.C. 154(b) by 875 days.

Signed and Sealed this

Twenty-eighth Day of September, 2010

David J. Kappos

David J. Kappos
*Director of the United States Patent and Trademark Office*

# Exhibit C

JOURNAL OF LIGHTWAVE TECHNOLOGY, VOL. 30, NO. 4, FEBRUARY 15, 2012 547

# Transmission of Mixed 224-Gb/s and 112-Gb/s PDM-QPSK at 50-GHz Channel Spacing Over 1200-km Dispersion-Managed LEAF® Spans and Three ROADMs

Chongjin Xie, *Senior Member, IEEE*, Gregory Raybon, *Member, IEEE*, and Peter J. Winzer, *Fellow, IEEE*

***Abstract*—By using asymmetric interleavers, carrier-suppressed polarization-division-multiplexed quadrature-phase-shift-keying (CSRZ-PDM-QPSK), and coherent detection, we successfully transmit a mix of 224-Gb/s and 112-Gb/s PDM-QPSK channels at a 50-GHz channel spacing and 3-b/s/Hz spectral efficiency over 1200-km dispersion-managed LEAF® spans with three ROADMs and over 2000 km without ROADMs.**

***Index Terms*—Coherent detection, fiber nonlinearities, filtering, modulation formats, optical communications, ROADM.**

## I. Introduction

THE demand for high capacity communication services has spurred intense research on high spectral efficiency (SE) and high data rate fiber-optic networks. In research experiments, high SE with a channel spacing close to the symbol rate has been demonstrated by using either orthogonal frequency division multiplexing (OFDM) or complicated digital signal processing (DSP) techniques, achieving SEs close to 4 b/s/Hz over long-haul distances, and up to 11 b/s/Hz at shorter reaches [1]–[4]. In contrast, the highest-SE commercial system available today supports 100-Gb/s polarization-division-multiplexed quadrature-phase-shift keying (PDM-QPSK) on a 50-GHz wavelength-division-multiplexing (WDM) grid and at a SE of 2 b/s/Hz. One way to increase the SE of current commercial systems is to use higher-order modulation formats such as 16-ary quadrature-amplitude modulation (16-QAM), but higher-order modulation formats require higher optical signal-to-noise ratios (OSNRs) and has lower tolerances to fiber nonlinearities, which makes them less suitable for long haul systems over legacy fiber infrastructure. Another approach is to reduce the channel spacing of current PDM-QPSK systems [5]. By using Nyquist spectral shaping techniques, a long-haul 100-Gb/s PDM-QPSK system with a channel spacing of 1.1 the symbol rate has been achieved without using complicated DSP at the receiver [6]. One issue of this approach voiced by carriers is that the channels do not fall on the WDM ITU grid and/or the channel bit rates are not compatible with current standards. Here, we investigate a third approach and demonstrate a record SE of 3 b/s/Hz on a commercial all-Raman optical transport platform [7]–[10], using a widely deployed optical fiber type and dispersion map, without the need to resort to dispersion-compensation-free green field deployments often discussed in the context of high-SE systems. To increase the SE from 2 b/s/Hz to 3 b/s/Hz and at the same time follow the 50-GHz WDM ITU grid and standard bit rates, we alternate 50-GHz spaced 224-Gb/s and 112-Gb/s PDM-QPSK channels using asymmetric interleavers that are an integral part of this system [7]. Carrier-suppressed return-to-zero (CSRZ) pulse shaping is used to reduce the penalty caused by narrow bandwidth filtering. By using coherent detection, we successfully transmit the mix of 224-Gb/s and 112-Gb/s PDM-QPSK signals over 1200-km dispersion-managed LEAF® spans with three reconfigurable optical add/drop multiplexers (ROADMs), and over 2000 km without ROADMs, respectively.

## II. Experimental Setup

The experimental setup is shown in Fig. 1. Ten L-band channels on a 50-GHz channel spacing ranging from 190.50 to 190.95 THz (1570.01 to 1573.71 nm) were separated into two groups of five channels. Nine channels were from distributed feedback (DFB) lasers and the channel under test was from a tunable external cavity laser (ECL) with a linewidth of ~ 100 kHz. To combine a mix of 224-Gb/s and 112-Gb/s PDM-QPSK channels at 50-GHz channel spacing on the WDM ITU grid, an asymmetric interleaver, which was part of the emulated commercial system [7], was used. The passband characteristics of the asymmetri interleaver are shown in Fig. 2, with a wide bandwith (3-dB bandwidth of 62.1-GHz) for even channels and a narrow bandwidth (3-dB bandwidth of 37.1-GHz) for odd channels [7]–[10]. The five even and five odd channels were modulated by a 56-Gbaud and a 28-Gbaud nested Mach–Zehnder modulator (MZM) to generate 112-Gb/s and 56-Gb/s QPSK signals, respectively. Each of the inphase/quadrature (I/Q) drive signals was formed by electronically multiplexing four delay-decorrelated copies of a 14-Gb/s and 7-Gb/s $2^{16}-1$ pseudo-random bit-sequence (PRBS) for the 112-Gb/s and 56-Gb/s modulators. The multiplexing delays for the four 14-Gb/s tributaries to generate the 56-Gb/s drive signals were 19, 0, 15, and 32 bits for the I branch and 15, 12, 0, and 32 bits for Q branch. The multiplexing delays for the four 7-Gb/s tributaries to generate the 28-Gb/s drive signals were 5, 0, 16, and 27 bits for the I branch and 14, 0, 18, and 8 bits for the

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The authors are with Bell Labs, Alcatel-Lucent, Holmdel, NJ 07733 USA (e-mail: chongjin.xie@alcatel-lucent.com).

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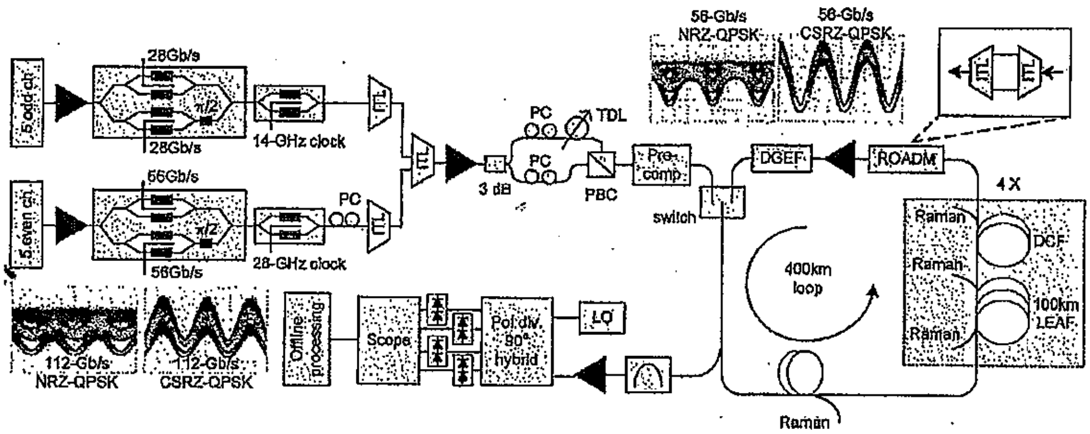


Fig. 1. The experimental setup. ITL: interleaver, PC: polarization controller, TDL: tunable delay line, PBC: polarization beam combiner, DGEF: dynamic gain equalizer filter, LO: local oscillator. Raman is Raman pump. The insets are the eye-diagrams of the 56-Gb/s and 112-Gb/s NRZ-QPSK and CSRZ-QPSK signals before the interleavers.

Q branch. The 112-Gb/s and 56-Gb/s QPSK signals were then pulse-carved with MZMs biased at the transmission minimum and sinusoidally driven at 28-GHz and 14-GHz, respectively, to generate CSRZ-QPSK. The insets in Fig. 1 show eye-diagrams of 56-Gb/s and 112-Gb/s NRZ-QPSK and CSRZ-QPSK signals before the interleavers. As expected, the eye-diagrams of 112-Gb/s QPSK are not as clear as those of 56-Gb/s QPSK due to hardware limitations. To reduce crosstalk, the even and odd channels were pre-filtered and combined with two cascaded asymmetric interleavers. One common polarization multiplexer with 10.357-ns delay (290 symbols for 28-Gbaud signals) between two polarization tributaries was used for all channels, and a tunable delay line was inserted in one polarization tributary to adjust the relative time delay since it has been shown that time interleaving two polarizations of return-to-zero (RZ) PDM-QPSK by half a symbol period can significantly reduce inter-channel nonlinearities in a dispersion-managed system [11], [12]. As one polarization multiplexer cannot time interleave 112-Gb/s and 224-Gb/s PDM-QPSK signals simultaneously, and as inter-channel nonlinearities from higher symbol rate channels are in general smaller than those from lower symbol rate channels, we adjusted the tunable delay line to time interleave the two polarizations by half a symbol at 112-Gb/s PDM-QPSK in this experiment. Therefore, the two polarization tributaries of the 224-Gb/s PDM-QPSK signal were aligned in time.

Transmission was conducted in a recirculating loop, which consisted of four 100-km dispersion-managed LEAF® spans with all-Raman amplification, to emulate a commercial all-Raman amplified optical transport system [7], [8]. The dispersion of each span was compensated with dispersion compensating fiber (DCF), with a residual dispersion per span of about 30 ps/nm. The LEAF® spans have a CD coefficient of about 7 ps/(nm.km) at a wavelength of 1570 nm, a loss coefficient of about 0.21 dB/km, and an effective area of about 72 $\mu m^2$. The DCF has a CD coefficient of about −100 ps/(nm.km) at a wavelength of 1570 nm, a loss coefficient of about 1.0 dB/km, and an effective area of about 15 $\mu m^2$. The system also included −300-ps/nm dispersion

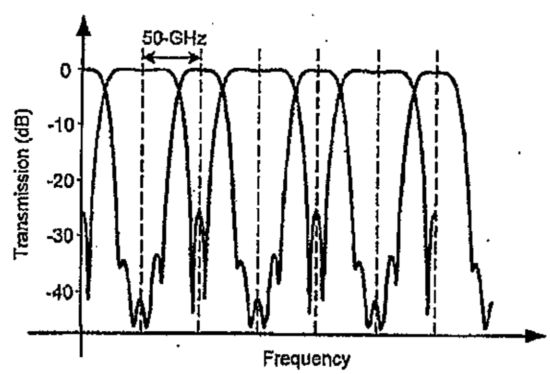


Fig. 2. Optical passband of the asymmetrical interleaver with 50-GHz channel spacing.

pre-compensation, as is typical for installed systems of this kind [7]. The LEAF® spans were bi-directionally pumped with approximately 4.5-dB and 15.0-dB on/off gain from forward Raman pumping and backward Raman pumping, respectively, and the DCFs were backward pumped. The launch power to the DCFs was about 2-dB lower than that to the spans. After each loop, the signal was sent to a ROADM, which consisted of a pair of the asymmetric interleavers, as shown in Fig. 1, with a 3-dB bandwidth of 56.5-GHz and 31.6-GHz for even and odd channels, respectively. The signal spectrum was then flattened by a dynamic gain equalizing filter (DGEF). An erbium-doped-fiber amplifier (EDFA) after the ROADM and a Raman amplifier before the spans were used to compensate for the losses induced by the DGEF, the ROADM, the loop switch and the coupler. An additional lumped Raman amplifier (cf. Fig. 1) was composed of a 5-km Raman fiber and a 5-km standard single-mode fiber (SSMF) to compensate for the CD in the Raman fiber, and was backward pumped.

In the receiver, the signal was first filtered by an amplified spontaneous emission (ASE) noise filter and amplified by an EDFA, then mixed with a free-running ECL local oscillator (LO) in a polarization diversity 90-degree hybrid, followed by

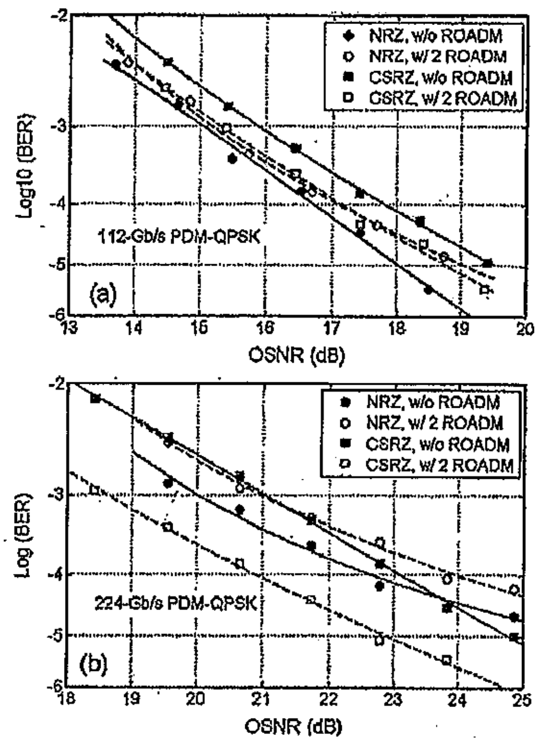


Fig. 3. Performance in back-to-back configuration without (solid) and with (dashed and open) 2 ROADMs for 112-Gb/s (a) and 224-Gb/s (b) NRZ- and CSRZ-PDM-QPSK.

four balanced detectors with bandwidths of ~ 40 GHz. The four signal components were captured by two 2-channel 80-GSamples/s real-time oscilloscopes with 30-GHz bandwidths and an effective number of bits (ENoB) larger than 4.5 [13]. For the 112-Gb/s PDM-QPSK, the oscilloscope bandwidth was reduced to 20-GHz. The captured signal was processed offline. The sampling skew was first corrected and the signal was synchronously re-sampled to 2 samples per symbol. After dispersion compensation, a butterfly equalizer with 19 taps, adapted via the constant modulus algorithm (CMA), was used for polarization demultiplexing [14], [15], residual dispersion compensation and inter-symbol interference (ISI) mitigation. We found that 19 taps were sufficient to mitigate all the ISI caused by residual CD, PMD, nonlinearity and filtering effects in our experiments. A phase increment frequency estimation algorithm was used for frequency estimation [16], and carrier phase estimation was performed using a decision-directed algorithm [17].

## III. Results and Discussion

We first measured the tolerance towards narrow bandwidth filtering of non-return-to-zero (NRZ) QPSK and CSRZ-QPSK. Fig. 3 shows the back-to-back performance without any ROADMs and with two ROADMs (i.e., 4 asymmetric interleavers) between the transmitter and the receiver. The 112-Gb/s and 224-Gb/s PDM-QPSK signals were set at an odd channel and an even channel, respectively. The figure shows that the performance of 112-Gb/s and 224-Gb/s PDM-QPSK is slightly different with two ROADMs. Due to hardware limitations, the 224-Gb/s PDM-QPSK requires 5-dB higher optical signal-to-noise-ratio (OSNR) than the 112-Gb/s PDM-QPSK when there is no ROADM. This reflects a 2-dB higher implementation penalty at 56 Gbaud compared to 28 Gbaud. In the back-to-back case without ROADMs, CSRZ-PDM-QPSK requires about 1-dB higher OSNR than NRZ-PDM-QPSK at bit-error-ratio (BER) of $10^{-3}$ for both the 112-Gb/s and 224-Gb/s signals. This is because that CSRZ-PDM-QPSK has a wider bandwidth than NRZ-PDM-QPSK and that the receiver with its limited bandwidth cannot capture the entire signal spectrum. After the two ROADMs, the performance of NRZ-PDM-QPSK is degraded, but the performance of CSRZ-PDM-QPSK is improved. The improvement for 224-Gb/s CSRZ-PDM-QPSK is much larger than that for 112-Gb/s CSRZ-PDM-QPSK. For 224-Gb/s CSRZ-PDM-QPSK, the required OSNR at a BER of $10^{-3}$ is reduced by about 2.5 dB after two ROADMs compared to that without ROADMs and is about 2.5 dB less than that for 224-Gb/s NRZ-PDM-QPSK after two ROADMs. We also note that 224-Gb/s NRZ-PDM-QPSK has a higher error floor than 224-Gb/s CSRZ-PDM-QPSK. In contrast, for 112-Gb/s CSRZ-PDM-QPSK, the required OSNR at a BER of $10^{-3}$ is reduced only by about 0.5 dB after two ROADMs compared to that without ROADMs and is close to that for 112-Gb/s NRZ-PDM-QPSK after two ROADMs. We further found that the best performance can be achieved for 112-Gb/s and 224-Gb/s CSRZ-PDM-QPSK after four and three ROADMs, respectively, but for NRZ-PDM-QPSK, a higher penalty is induced when there are more ROADMs (not shown here). Note that the optimum number of ROADMs depends on the signal spectrum, the ROADM characteristics, and the receiver response. Fig. 3 clearly indicates that CSRZ-QPSK can tolerate much narrower filtering than NRZ-QPSK.

The results in Fig. 3 can be explained by the spectra of the signals, which are given in Fig. 4. The ROADM passbands of the odd and even channels are also shown in the figure for reference. The normalized bandwidth of 224-Gb/s NRZ-PDM-QPSK is narrower than that of 112-Gb/s NRZ-PDM-QPSK. Due to the bandwidth limitation of the 224-Gb/s data modulator, after the pulse carver, the spectrum of 224-Gb/s CSRZ-PDM-QPSK spectrum has a dip in the middle. This is similar to transmit-side equalization and helps to make the overall spectrum flat after filtering at both transmitter and receiver, which is beneficial for narrow bandwidth filtering [5]. The spectra in the figure also explain why we used CSRZ modulation here. A CSRZ pulse carver generates two tones if higher harmonics are neglected, so the spectrum of a CSRZ modulation is the convolution of the data spectrum from the data modulator and the two tones from the CSRZ pulse carver. Therefore, the shape of the overall spectrum can be easily controlled by changing the bandwidth of the data spectrum to make it flat-top or V-shaped, as shown by the spectra of the 112-Gb/s and 224-Gb/s CSRZ-PDM-QPSK, which has a significant impact on the signal's tolerance to filtering.

The negative penalty of the 224-Gb/s CSRZ-PDM-QPSK comes partly from the excessive bandwidth of the original CSRZ signal and partly from the shape of the ROADM passband. For 112-Gb/s CSRZ-PDM-QPSK, as the normalized bandwidth of the data modulator is wider, there is no dip in the middle of the spectrum, but it has a much flatter top than that

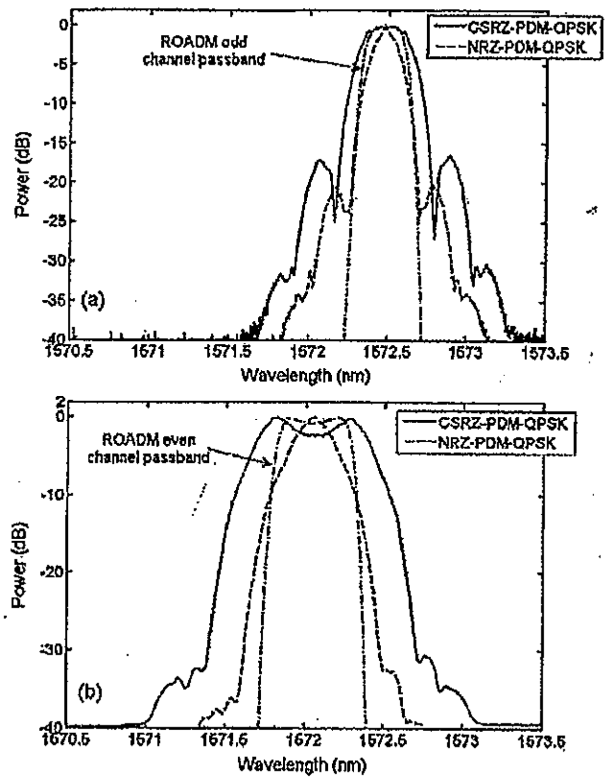


Fig. 4. Spectra of 112-Gb/s (a) and 224-Gb/s (b) NRZ- and CSRZ-PDM-QPSK. The dash-dotted lines are the ROADM passband of odd and even channels in (a) and (b) respectively.

of 112-Gb/s NRZ-PDM-QPSK. In the following transmission experiments, we use CSRZ for both the 224-Gb/s and the 112-Gb/s PDM-QPSK channels. Figs. 3 and 4 also indicate that the system performance can be optimized by optimizing spectrum shapes of signals at transmitters and by taking into account filtering effects in systems.

The signal spectrum at the input of the loop is depicted in Fig. 5. As the odd and even channels were not combined with any WDM multiplexer, there is some crosstalk among neighboring 224-Gb/s CSRZ-PDM-QPSK channels. As shown in Fig. 5, the crosstalk is lower than −20 dB. In a real system that uses WDM multiplexers, the crosstalk can be effectively eliminated by multiplexer filters.

Fig. 6 shows the recovered x- and y-polarization constellations of the 224-Gb/s and 112-Gb/s CSRZ-PDM-QPSK signals at the input of the loop. The signal constellation clouds of the 224-Gb/s signal are much bigger than those of the 112-Gb/s signal, which is caused by the following few factors: 1) limited bandwidth of the transmitter (as shown by the eye-diagrams in Fig. 1 and signal spectra in Fig. 2); 2) limited bandwidth of the receiver (30-GHz for the 224-Gb/s signal and 20-GHz for the 112-Gb/s signal); 3) reduced sampling speed at the receiver (1.43 samples/symbol for the 224-Gb/s signal and 2.86 samples/symbol for the 112-Gb/s signal).

The output spectra after 1600-km transmission with and without ROADMs are depicted in Fig. 7. The ROADM filtering effect is clearly seen in the spectrum.

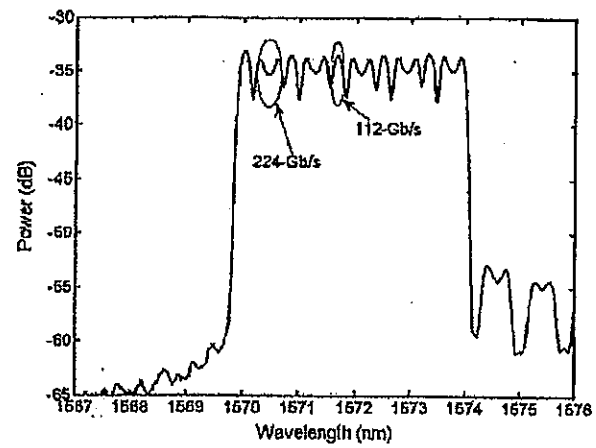


Fig. 5. Signal spectrum at the input of the loop.

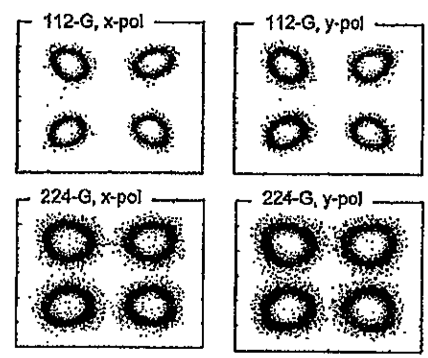


Fig. 6. Signal constellations of 112-Gb/s and 224-Gb/s CSRZ-PDM-QPSK at the input of the loop.

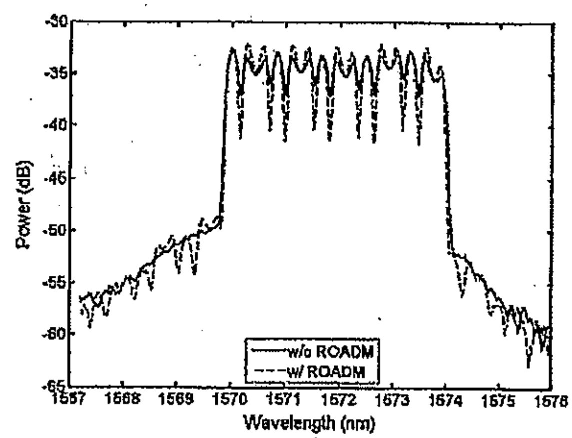


Fig. 7. Signal spectrum after 1600-km transmission with and without ROADMs.

Fig. 8 shows the $Q^2$-factor (obtained from measured BER after offline processing) for a central 224-Gb/s channel (190.70 THz) in WDM transmission after 1200 km with three ROADMs and 1600 km without any ROADMs as a function of the launch power per 224-Gb/s channel. The launch power of

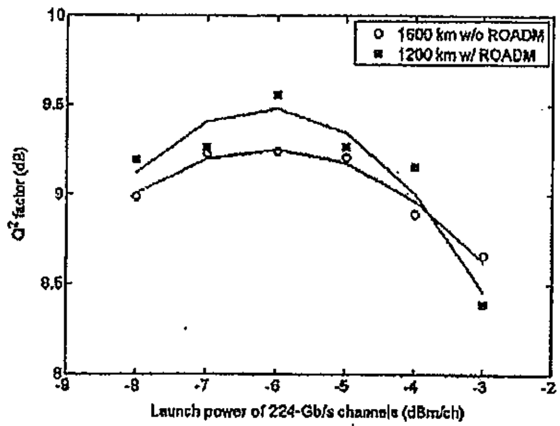


Fig. 8. $Q^2$-factor versus launch power of 224-Gb/s channels at 1200 km with ROADMs.

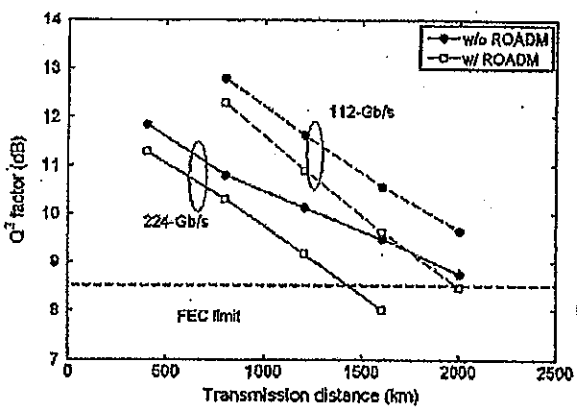


Fig. 9. $Q^2$-factor versus distance for 224-Gb/s and 112-Gb/s channels for the system with and without ROADMs.

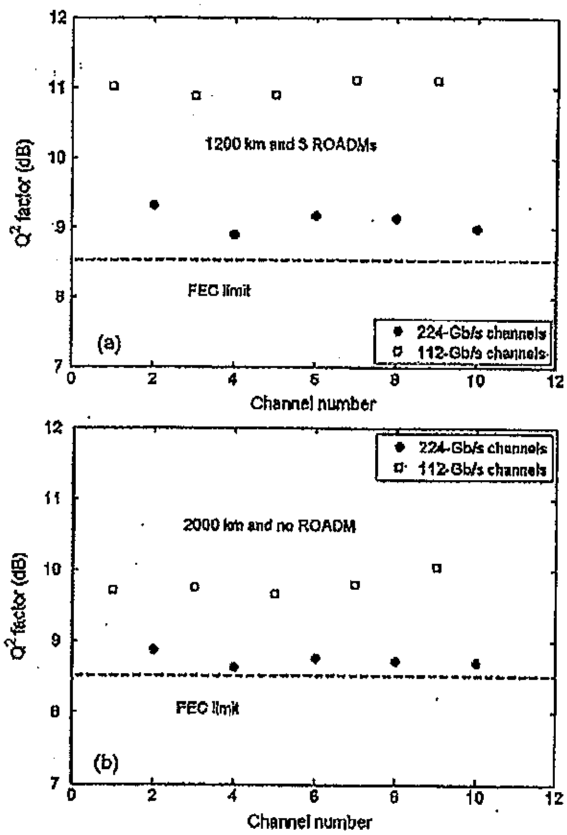


Fig. 10. $Q^2$-factor of all the 10 channels at 1200 km with three ROADMs and 2000 km without ROADMs.

the 112-Gb/s channels was chosen about 2 dB lower than that of the 224-Gb/s channel, motivated by the fact that the 112-Gb/s channels require lower OSNR than the 224-Gb/s channels, which allows for a reduction in launch power to obtain a similar transmission reach while reducing the inter-channel nonlinearities from the 112-Gb/s channels onto the 224-Gb/s channels. The optimum launch powers for the 224-Gb/s channels in both cases shown in Fig. 8 are the same, −6 dBm per channel. We hence used −6-dBm and −8-dBm as the per channel launch powers for the 224-Gb/s and the 112-Gb/s channels, respectively. Fig. 9 gives the $Q^2$-factor versus transmission distance for both the 224-Gb/s (190.70 THz) and 112-Gb/s (190.75 THz) channels in WDM transmission with and without ROADMs in the loop. As expected, the 112-Gb/s channel performs better than the 224-Gb/s channel. Assuming a forward-error-correction (FEC) BER threshold of $3.8 \times 10^{-3}$ (a $Q^2$ value of 8.53 dB), the system can transmit 1200 km with three ROADMs and 2000 km without ROADMs on this legacy, dispersion-managed fiber infrastructure. Fig. 9 also shows that the performance difference between the system with and without ROADMs for the 224-Gb/s channel is larger than that for the 112-Gb/s channel. This is because the ROADM bandwidth normalized by the symbol rate is smaller for the 224-Gb/s channel than that for the 112-Gb/s channel, as discussed in the context of Figs. 3 and 4 above.

Fig. 9 shows that the system with ROADMs performs worse in the transmission than that without ROADMs, which is different from the back to back performance of CSRZ-PDM-QPSK shown in Fig. 3. This is because of two reasons. One is that the optimum ROADM numbers are 4 and 3 for 112-Gb/s and 224-Gb/s CSRZ-PDM-QPSK, respectively in the back to back operation, and after those, the performance starts to be degraded with more ROADMs. Note that the interleavers at the transmitter are effectively one ROADM. The second reason is fiber nonlinear effects. ROADMs reduce the signal bandwidth and at the same time increase the peak to average power ratio of the signal, and the increased peak to average power ratio enhances fiber nonlinear effects. As shown in Fig. 8, the performance with ROADMs is reduced at high power due to fiber nonlinear effects.

The $Q^2$-factor of all 10 channels after WDM transmission at 1200 km with three ROADMs and at 2000 km without ROADMs is given in Fig. 10. The per-channel launch powers for the 224-Gb/s and 112-Gb/s channels are −6 dBm and −8 dBm, respectively. The figure shows that all the channels achieve performance above the FEC limit and that the 112-Gb/s channels can achieve 1 to 2 dB higher $Q^2$-factor than the

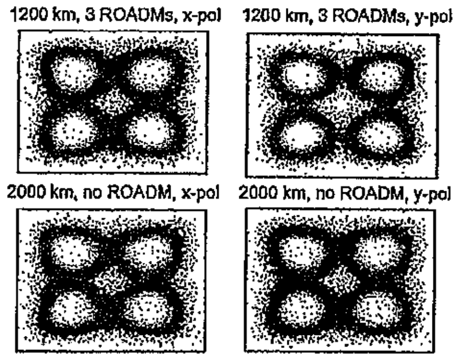


Fig. 11. Signal constellations of 224-Gb/s CSRZ-PDM-QPSK signals after 1200 km with three ROADMs and 2000 km without ROADM transmission.

224-Gb/s channels, as expected. The signal constellations of the 224-Gb/s PDM-QPSK (channel 6) after transmission over 1200-km with three ROADMs and over 2000-km without ROADMs are shown in Fig. 11.

## IV. Conclusion

By using asymmetrical interleavers, CSRZ-PDM-QPSK and coherent detection, we have successfully transmitted, on a legacy long-haul transmission system, a mix of 224-Gb/s and 112-Gb/s signals at 50-GHz channel spacing over 1200-km dispersion-managed LEAF® spans with three bandwidth-managed asymmetric ROADMs and over 2000 km without ROADMs. This is the highest spectral efficiency reported on a commercial all-Raman optical transport platform using a widely deployed, dispersion-compensated fiber infrastructure.

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**Chongjin Xie** (M'01–SM'05) was born in Maanshan, Anhui province, China in 1970. He received his M.Sc. in 1996 and Ph.D. in 1999 from Beijing University of Posts and Telecommunications, Beijing, China.

From 1999 to 2001, he was with the Photonics Laboratory, Chalmers University of Technology, Gothenburg, Sweden, for one and half years to conduct post-doctorate research. He joined Bell Laboratories, Lucent Technologies (now Alcatel-Lucent), Holmdel, NJ, as a Member of Technical Staff in 2001. His research interests are in fiber optical communication systems and networks, including high-speed lightwave transmission, polarization mode dispersion, polarization dependent loss, modulation formats, coherent detection, optical performance monitoring, etc. He has authored and coauthored more than 150 journal and conference publications and two book chapters in the field of optical communications.

Dr. Xie serves as a reviewer for IEEE Photonics Technology Letters and the Journal of Lightwave Technology.

**Gregory Raybon** (M'00) biography not available at the time of publication.

**Peter J. Winzer** (F'09) received the Ph.D. degree in electrical engineering from the Vienna University of Technology, Vienna, Austria, in 1998.

Supported by the European Space Agency, he investigated space-borne Doppler lidar and laser communications using high-sensitivity digital modulation and detection. In 2000, he joined Bell Laboratories, Alcatel-Lucent, Holmdel, NJ, where his research focused on many aspects of fiber-optic networks, including Raman amplification, optical modulation formats, advanced optical receiver concepts, digital signal processing and coding, as well as on robust network architectures for dynamic data services. He demonstrated several high-speed and high-capacity optical transmission records from 10 to 100 Gb/s and beyond, including the first 100G and the first 400G electronically multiplexed optical transmission systems and the first field trial of live 100G video traffic over an existing carrier network. In 2007, he became the Distinguished Member of Technical Staff, Bell Laboratories and since 2010 he has been the Head of the Optical Transmission Systems and Networks Research Department. He has widely published and patented.

Dr. Winzer is a member of the Optical Society of America (OSA). He is actively involved in technical and organizational tasks with the IEEE Photonics Society and the OSA.

# UNITED STATES DISTRICT COURT
# CENTRAL DISTRICT OF CALIFORNIA

## NOTICE OF ASSIGNMENT TO UNITED STATES MAGISTRATE JUDGE FOR DISCOVERY

This case has been assigned to District Judge Andrew Guilford and the assigned discovery Magistrate Judge is Marc Goldman.

The case number on all documents filed with the Court should read as follows:

**SACV12- 759 AG (MLGx)**

Pursuant to General Order 05-07 of the United States District Court for the Central District of California, the Magistrate Judge has been designated to hear discovery related motions.

All discovery related motions should be noticed on the calendar of the Magistrate Judge

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**NOTICE TO COUNSEL**

*A copy of this notice must be served with the summons and complaint on all defendants (if a removal action is filed, a copy of this notice must be served on all plaintiffs).*

Subsequent documents must be filed at the following location:

[ ] **Western Division**
**312 N. Spring St., Rm. G-8**
**Los Angeles, CA 90012**

[X] **Southern Division**
**411 West Fourth St., Rm. 1-053**
**Santa Ana, CA 92701-4516**

[ ] **Eastern Division**
**3470 Twelfth St., Rm. 134**
**Riverside, CA 92501**

Failure to file at the proper location will result in your documents being returned to you.

# UNITED STATES DISTRICT COURT, CENTRAL DISTRICT OF CALIFORNIA
## CIVIL COVER SHEET

| I (a) PLAINTIFFS (Check box if you are representing yourself ☐) | DEFENDANTS |
|---|---|
| Labyrinth Optical Technologies LLC | Alcatel-Lucent USA, Inc. |
| (b) Attorneys (Firm Name, Address and Telephone Number. If you are representing yourself, provide same.)<br>Simmons Browder Gianaris Angelides & Barnerd LLC, 100 N. Sepulveda Blvd., Suite 1350, El Segundo, CA 90245; Tel. 310.322.3555 | Attorneys (If Known) |

**II. BASIS OF JURISDICTION** (Place an X in one box only.)

- ☐ 1 U.S. Government Plaintiff
- ☒ 3 Federal Question (U.S. Government Not a Party)
- ☐ 2 U.S. Government Defendant
- ☐ 4 Diversity (Indicate Citizenship of Parties in Item III)

**III. CITIZENSHIP OF PRINCIPAL PARTIES - For Diversity Cases Only** (Place an X in one box for plaintiff and one for defendant.)

| | PTF | DEF | | PTF | DEF |
|---|---|---|---|---|---|
| Citizen of This State | ☐ 1 | ☐ 1 | Incorporated or Principal Place of Business in this State | ☐ 4 | ☐ 4 |
| Citizen of Another State | ☐ 2 | ☐ 2 | Incorporated and Principal Place of Business in Another State | ☐ 5 | ☐ 5 |
| Citizen or Subject of a Foreign Country | ☐ 3 | ☐ 3 | Foreign Nation | ☐ 6 | ☐ 6 |

**IV. ORIGIN** (Place an X in one box only.)

☒ 1 Original Proceeding ☐ 2 Removed from State Court ☐ 3 Remanded from Appellate Court ☐ 4 Reinstated or Reopened ☐ 5 Transferred from another district (specify): ☐ 6 Multi-District Litigation ☐ 7 Appeal to District Judge from Magistrate Judge

**V. REQUESTED IN COMPLAINT: JURY DEMAND:** ☒ Yes ☐ No (Check 'Yes' only if demanded in complaint.)

**CLASS ACTION under F.R.C.P. 23:** ☐ Yes ☒ No ☐ **MONEY DEMANDED IN COMPLAINT: $** ____________

**VI. CAUSE OF ACTION** (Cite the U.S. Civil Statute under which you are filing and write a brief statement of cause. Do not cite jurisdictional statutes unless diversity.)

Patent Infringement

**VII. NATURE OF SUIT** (Place an X in one box only.)

**OTHER STATUTES**
- ☐ 400 State Reapportionment
- ☐ 410 Antitrust
- ☐ 430 Banks and Banking
- ☐ 450 Commerce/ICC Rates/etc.
- ☐ 460 Deportation
- ☐ 470 Racketeer Influenced and Corrupt Organizations
- ☐ 480 Consumer Credit
- ☐ 490 Cable/Sat TV
- ☐ 810 Selective Service
- ☐ 850 Securities/Commodities/ Exchange
- ☐ 875 Customer Challenge 12 USC 3410
- ☐ 890 Other Statutory Actions
- ☐ 891 Agricultural Act
- ☐ 892 Economic Stabilization Act
- ☐ 893 Environmental Matters
- ☐ 894 Energy Allocation Act
- ☐ 895 Freedom of Info. Act
- ☐ 900 Appeal of Fee Determination Under Equal Access to Justice
- ☐ 950 Constitutionality of State Statutes

**CONTRACT**
- ☐ 110 Insurance
- ☐ 120 Marine
- ☐ 130 Miller Act
- ☐ 140 Negotiable Instrument
- ☐ 150 Recovery of Overpayment & Enforcement of Judgment
- ☐ 151 Medicare Act
- ☐ 152 Recovery of Defaulted Student Loan (Excl. Veterans)
- ☐ 153 Recovery of Overpayment of Veteran's Benefits
- ☐ 160 Stockholders' Suits
- ☐ 190 Other Contract
- ☐ 195 Contract Product Liability
- ☐ 196 Franchise

**REAL PROPERTY**
- ☐ 210 Land Condemnation
- ☐ 220 Foreclosure
- ☐ 230 Rent Lease & Ejectment
- ☐ 240 Torts to Land
- ☐ 245 Tort Product Liability
- ☐ 290 All Other Real Property

**TORTS — PERSONAL INJURY**
- ☐ 310 Airplane
- ☐ 315 Airplane Product Liability
- ☐ 320 Assault, Libel & Slander
- ☐ 330 Fed. Employers' Liability
- ☐ 340 Marine
- ☐ 345 Marine Product Liability
- ☐ 350 Motor Vehicle
- ☐ 355 Motor Vehicle Product Liability
- ☐ 360 Other Personal Injury
- ☐ 362 Personal Injury- Med Malpractice
- ☐ 365 Personal Injury- Product Liability
- ☐ 368 Asbestos Personal Injury Product Liability

**IMMIGRATION**
- ☐ 462 Naturalization Application
- ☐ 463 Habeas Corpus- Alien Detainee
- ☐ 465 Other Immigration Actions

**TORTS — PERSONAL PROPERTY**
- ☐ 370 Other Fraud
- ☐ 371 Truth in Lending
- ☐ 380 Other Personal Property Damage
- ☐ 385 Property Damage Product Liability

**BANKRUPTCY**
- ☐ 422 Appeal 28 USC 158
- ☐ 423 Withdrawal 28 USC 157

**CIVIL RIGHTS**
- ☐ 441 Voting
- ☐ 442 Employment
- ☐ 443 Housing/Accommodations
- ☐ 444 Welfare
- ☐ 445 American with Disabilities - Employment
- ☐ 446 American with Disabilities - Other
- ☐ 440 Other Civil Rights

**PRISONER PETITIONS**
- ☐ 510 Motions to Vacate Sentence Habeas Corpus
- ☐ 530 General
- ☐ 535 Death Penalty
- ☐ 540 Mandamus/ Other
- ☐ 550 Civil Rights
- ☐ 555 Prison Condition

**FORFEITURE/ PENALTY**
- ☐ 610 Agriculture
- ☐ 620 Other Food & Drug
- ☐ 625 Drug Related Seizure of Property 21 USC 881
- ☐ 630 Liquor Laws
- ☐ 640 R.R. & Truck
- ☐ 650 Airline Regs
- ☐ 660 Occupational Safety /Health
- ☐ 690 Other

**LABOR**
- ☐ 710 Fair Labor Standards Act
- ☐ 720 Labor/Mgmt. Relations
- ☐ 730 Labor/Mgmt. Reporting & Disclosure Act
- ☐ 740 Railway Labor Act
- ☐ 790 Other Labor Litigation
- ☐ 791 Empl. Ret. Inc. Security Act

**PROPERTY RIGHTS**
- ☐ 820 Copyrights
- ☒ 830 Patent
- ☐ 840 Trademark

**SOCIAL SECURITY**
- ☐ 861 HIA (1395ff)
- ☐ 862 Black Lung (923)
- ☐ 863 DIWC/DIWW (405(g))
- ☐ 864 SSID Title XVI
- ☐ 865 RSI (405(g))

**FEDERAL TAX SUITS**
- ☐ 870 Taxes (U.S. Plaintiff or Defendant)
- ☐ 871 IRS-Third Party 26 USC 7609

SACV12-759

**FOR OFFICE USE ONLY:** Case Number: ____________________

**AFTER COMPLETING THE FRONT SIDE OF FORM CV-71, COMPLETE THE INFORMATION REQUESTED BELOW.**

UNITED STATES DISTRICT COURT, CENTRAL DISTRICT OF CALIFORNIA
CIVIL COVER SHEET

VIII(a). IDENTICAL CASES: Has this action been previously filed in this court and dismissed, remanded or closed? ☑ No ☐ Yes
If yes, list case number(s): ____

VIII(b). RELATED CASES: Have any cases been previously filed in this court that are related to the present case? ☑ No ☐ Yes
If yes, list case number(s): ____

**Civil cases are deemed related if a previously filed case and the present case:**

(Check all boxes that apply) ☐ A. Arise from the same or closely related transactions, happenings, or events; or
☐ B. Call for determination of the same or substantially related or similar questions of law and fact; or
☐ C. For other reasons would entail substantial duplication of labor if heard by different judges; or
☐ D. Involve the same patent, trademark or copyright, and one of the factors identified above in a, b or c also is present.

IX. VENUE: (When completing the following information, use an additional sheet if necessary.)

(a) List the County in this District; California County outside of this District; State if other than California; or Foreign Country, in which EACH named plaintiff resides.
☐ Check here if the government, its agencies or employees is a named plaintiff. If this box is checked, go to item (b).

| County in this District:* | California County outside of this District; State, if other than California; or Foreign Country |
|---|---|
| Orange County | |

(b) List the County in this District; California County outside of this District; State if other than California; or Foreign Country, in which EACH named defendant resides.
☐ Check here if the government, its agencies or employees is a named defendant. If this box is checked, go to item (c).

| County in this District:* | California County outside of this District; State, if other than California; or Foreign Country |
|---|---|
| Orange County | |

(c) List the County in this District; California County outside of this District; State if other than California; or Foreign Country, in which EACH claim arose.
**Note: In land condemnation cases, use the location of the tract of land involved.**

| County in this District:* | California County outside of this District; State, if other than California; or Foreign Country |
|---|---|
| Orange County | |

*** Los Angeles, Orange, San Bernardino, Riverside, Ventura, Santa Barbara, or San Luis Obispo Counties**
Note: In land condemnation cases, use the location of the tract of land involved

X. SIGNATURE OF ATTORNEY (OR PRO PER): [signature] Date 5/10/12

**Notice to Counsel/Parties:** The CV-71 (JS-44) Civil Cover Sheet and the information contained herein neither replace nor supplement the filing and service of pleadings or other papers as required by law. This form, approved by the Judicial Conference of the United States in September 1974, is required pursuant to Local Rule 3-1 is not filed but is used by the Clerk of the Court for the purpose of statistics, venue and initiating the civil docket sheet. (For more detailed instructions, see separate instructions sheet.)

Key to Statistical codes relating to Social Security Cases:

| Nature of Suit Code | Abbreviation | Substantive Statement of Cause of Action |
|---|---|---|
| 861 | HIA | All claims for health insurance benefits (Medicare) under Title 18, Part A, of the Social Security Act, as amended. Also, include claims by hospitals, skilled nursing facilities, etc., for certification as providers of services under the program. (42 U.S.C. 1935FF(b)) |
| 862 | BL | All claims for "Black Lung" benefits under Title 4, Part B, of the Federal Coal Mine Health and Safety Act of 1969. (30 U.S.C. 923) |
| 863 | DIWC | All claims filed by insured workers for disability insurance benefits under Title 2 of the Social Security Act, as amended; plus all claims filed for child's insurance benefits based on disability. (42 U.S.C. 405(g)) |
| 863 | DIWW | All claims filed for widows or widowers insurance benefits based on disability under Title 2 of the Social Security Act, as amended. (42 U.S.C. 405(g)) |
| 864 | SSID | All claims for supplemental security income payments based upon disability filed under Title 16 of the Social Security Act, as amended. |
| 865 | RSI | All claims for retirement (old age) and survivors benefits under Title 2 of the Social Security Act, as amended. (42 U.S.C. (g)) |