



System for transmitting and receiving multi-polarized signals

Usuga Castaneda, Mario A.

Publication date:
2016

Document Version
Publisher's PDF, also known as Version of record

[Link back to DTU Orbit](#)

Citation (APA):
Usuga Castaneda, M. A. (2016). System for transmitting and receiving multi-polarized signals. (Patent No. WO2016046315).

General rights

Copyright and moral rights for the publications made accessible in the public portal are retained by the authors and/or other copyright owners and it is a condition of accessing publications that users recognise and abide by the legal requirements associated with these rights.

- Users may download and print one copy of any publication from the public portal for the purpose of private study or research.
- You may not further distribute the material or use it for any profit-making activity or commercial gain
- You may freely distribute the URL identifying the publication in the public portal

If you believe that this document breaches copyright please contact us providing details, and we will remove access to the work immediately and investigate your claim.

(12) INTERNATIONAL APPLICATION PUBLISHED UNDER THE PATENT COOPERATION TREATY (PCT)

(19) World Intellectual Property

Organization

International Bureau



WIPO | PCT



(10) International Publication Number

WO 2016/046315 A1

(43) International Publication Date

31 March 2016 (31.03.2016)

(51) International Patent Classification:

H04J 14/06 (2006.01) G02B 6/27 (2006.01)

(21) International Application Number:

PCT/EP2015/071972

(22) International Filing Date:

24 September 2015 (24.09.2015)

(25) Filing Language:

English

(26) Publication Language:

English

(30) Priority Data:

14186191.4 24 September 2014 (24.09.2014) EP

(71) Applicant: DANMARKS TEKNISKE UNIVERSITET

[DK/DK]; Bygning 101A, Anker Engelundsvej 1, DK-2800 Kgs. Lyngby (DK).

(72) Inventor: USUGA CASTANEDA, Mario A.; Brønshøj,

Denmark, Husumvej 67, 1.tv., DK-2700 Brønshøj (DK).

(74) Agent: HØIBERG A/S; St. Kongensgade 59 A, DK-1264

Copenhagen K (DK).

(81) Designated States (unless otherwise indicated, for every

kind of national protection available): AE, AG, AL, AM, AO, AT, AU, AZ, BA, BB, BG, BH, BN, BR, BW, BY,

BZ, CA, CH, CL, CN, CO, CR, CU, CZ, DE, DK, DM, DO, DZ, EC, EE, EG, ES, FI, GB, GD, GE, GH, GM, GT, HN, HR, HU, ID, IL, IN, IR, IS, JP, KE, KG, KN, KP, KR, KZ, LA, LC, LK, LR, LS, LU, LY, MA, MD, ME, MG, MK, MN, MW, MX, MY, MZ, NA, NG, NI, NO, NZ, OM, PA, PE, PG, PH, PL, PT, QA, RO, RS, RU, RW, SA, SC, SD, SE, SG, SK, SL, SM, ST, SV, SY, TH, TJ, TM, TN, TR, TT, TZ, UA, UG, US, UZ, VC, VN, ZA, ZM, ZW.

(84) Designated States (unless otherwise indicated, for every kind of regional protection available): ARIPO (BW, GH, GM, KE, LR, LS, MW, MZ, NA, RW, SD, SL, ST, SZ, TZ, UG, ZM, ZW), Eurasian (AM, AZ, BY, KG, KZ, RU, TJ, TM), European (AL, AT, BE, BG, CH, CY, CZ, DE, DK, EE, ES, FI, FR, GB, GR, HR, HU, IE, IS, IT, LT, LU, LV, MC, MK, MT, NL, NO, PL, PT, RO, RS, SE, SI, SK, SM, TR), OAPI (BF, BJ, CF, CG, CI, CM, GA, GN, GQ, GW, KM, ML, MR, NE, SN, TD, TG).

Declarations under Rule 4.17:

— of inventorship (Rule 4.17(iv))

Published:

— with international search report (Art. 21(3))

(54) Title: SYSTEM FOR TRANSMITTING AND RECEIVING MULTI-POLARIZED SIGNALS

(57) Abstract: The present disclosure relates to: an optical receiver, configured to receive at least three multiplexed, differently polarized, optically transmitted signals, each signal associated with a predefined state of polarization, said receiver comprising a multi-polarization analyzer for obtaining an analyzed signal for each of said polarized signals, wherein at least one of said analyzed signals comprises data in the full Stokes space; an optical transmitter, configured to transmit at least three multiplexed, differently polarized, optically transmitted signals, wherein at least one of said polarized signals comprises data in the full Stokes space; a system configured to communicate optically over a communication link, comprising: an optical transmitter, configured to generate and multiplex at least three independent data signals having different states of polarization into a multiplexed signal, and an optical receiver, configured to receive the transmitted signal, said receiver comprising a demultiplexer for polarization demultiplexing the multiplexed signal into three or more polarized signals, said receiver further comprising at least three signal detectors.



WO 2016/046315 A1

System for transmitting and receiving multi-polarized signals

Field of invention

The present disclosure relates to an optical receiver, configured to receive multi-polarized signals, an optical transmitter, configured to transmit multi-polarized signals, and a system, configured to transmit and receive optical multi-polarized signals over a communication link.

Background of invention

In recent years system capacity in terms of bandwidth in communication systems have been significantly improved to meet the demands of data traffic. The need for systems capable of handling higher data rates is likely to keep growing. There are many techniques for increasing bandwidth, including time division multiplexing, wavelength division multiplexing, polarization-division multiplexing (PDM), frequency-division multiplexing, various modulation formats, and combinations thereof.

Some of these techniques are reaching their maximum theoretical capacity. Others require installation of new fiber-optic infrastructure. Digging for installing new optical fiber is relatively expensive. Some of the available techniques also require additional complex signal processing, which could be costly both in terms of implementation and transmitting and receiving equipment.

Fiber-optic communication is a method of transmitting information from one place to another by sending pulses of light through an optical fiber. Modern fiber-optic communication systems generally include an optical transmitter to convert an electrical signal into an optical signal to send into the optical fiber, a cable containing bundles of multiple optical fibers that is routed through underground conduits and buildings, multiple kinds of amplifiers, and an optical receiver to recover the signal as an electrical signal. The information transmitted is typically digital information generated by computers, telephone systems, and cable television companies.

Polarization is a property of waves that can oscillate with more than one orientation. Electromagnetic waves, such as light, is one example of waves that may be polarized. One technique for increasing the bandwidth of a communication system is using two

orthogonal states of polarization (SOP). Such polarization may be combined with for example phase key shifting modulation, forming coherent transceiver systems.

5 The performance of optical transmission system in terms of signal quality and bit rate is limited by the optical properties of the line, which is subject to physical phenomena which degrade the optical signals. As bit rates increase to meet expanding demand, systems have become increasingly sensitive to polarization-related effects related to the optical properties of the line. This is particularly valid for the system using two orthogonal SOPs since for example the fiber may cause polarization rotation.

10

Summary of invention

The present disclosure relates to an optical receiver, configured to receive at least three multiplexed, differently polarized, optically transmitted signals, an optical transmitter, configured to transmit at least three multiplexed, differently polarized, 15 optically transmitted signals having a wavelength suitable for fiber optic based communication, such as between 200 nm and 3 μ m, or such as between 800 nm and 1800 nm, and a system, configured to communicate optically over a communication link, comprising an optical transmitter, configured to generate and multiplex at least three independent data signals having different states of polarization into a multiplexed 20 signal, and an optical receiver, configured to receive the transmitted signal, said receiver comprising a demultiplexer for demultiplexing the multiplexed signal into three or more polarized signals, said receiver further comprising at least three signal detectors.

25 By simultaneously using at least three general states of polarizations the invention presents a low-cost solution for increasing bandwidth in communications systems, including optical and radio communication. At the heart of the invention is also the powerful yet simple solution for compensation of induced polarization effects in the communication link, which allows the invention to operate in realistic scenarios such as 30 waveguides, optical fiber or freespace communication channels, including incoherent communication systems. The inventor has realized, and demonstrated in experiments, that with compensation of the channel-induced polarization rotation, using a multi-polarization analyzer (preferably a Stokes analyzer) and a simple tracking algorithm at the receiver side, combined with transmitting a multiplexed multi-polarized transmitted 35 signal, significantly higher bandwidth can be achieved. The system works for coherent

and incoherent communication systems, exhibiting single or multiple sources respectively. The generalized polarization demultiplexing stage avoids the complications of a coherent receiver.

5 The invention has several advantages and presents a number of opportunities and applications. Since the presently disclosed invention may operate on an existing communication link, it does not require expensive replacement of already deployed optical fibers or other communication links. The invention presents a comparable alternative to mature standards such as DP-QPSK at a lower cost. Relatively
10 inexpensive modification on the transmitter and receiver side is sufficient to achieve higher bandwidth. Also, compared to existing alternative solutions for achieving higher bandwidth in an existing channel, using coherent transmitter/receiver for communication, the present invention presents advantages. The receiver in the present invention is applicable on incoherent systems with direct detection, which means that
15 extra lasers (local oscillators), required for phase reference in traditional coherent systems can be avoided, which simplifies the digital signal processing. One embodiment of the presently disclosed receiver therefore comprises a demultiplexer configured to demultiplex the at least three multiplexed, differently polarized, optically transmitted signals without explicit phase reference. In one embodiment of the
20 presently disclosed receiver, the signals are received and demodulated incoherently. Hence the components to be replaced in the transmitter and receiver are less complex and cheaper. Furthermore, the present invention may be used in a wide range of communication scenarios, including but not limited to: radio communication, fiber optics based communication (short to long haul communication, including active optical
25 cables, freespace optical communication, integrated photonic chips and quantum communication.

Description of drawings

30 The invention will in the following be described in greater detail with reference to the drawings. The drawings are exemplary and are intended to illustrate some of the features of the present method and unit and are not to be construed as limiting to the presently disclosed invention.

Fig. 1a shows a schematic diagram of a receiver according to the present invention.

Fig. 1b shows an example of a configuration of a receiver according to the present invention, including demultiplexing of a multi-polarized signal, detectors and a DSP.

Fig. 2 shows an example of an incoherent version of a communication system according to the present invention, using three polarizations, including three light sources, three individually modulated signals, a multiplexer, a transmission line, a demultiplexing and demodulation stage at the receiver and signal detectors.

Fig. 3 shows an example of a coherent version of a communication system according to the present invention, using three polarizations, including one light source, three individually modulated signals, a multiplexer, a transmission line, a demultiplexing and demodulation stage at the receiver and signal detectors.

Fig. 4 shows an example of an RF communication system according to the present invention, using three polarizations in three dimensions in the RF domain, a demultiplexing stage at the receiver, wherein the receiver is further connected to an optical link

Fig. 5 shows a conceptual illustration of an example of communication according to the present invention using four different SOPs, where the SOPs rotate in the transmission channel as indicated by the vectors in the Poincaré sphere.

Fig. 6 shows a schematic of an example of an experimental setup using four different SOPs.

Fig. 7a shows the bit-error-rate (BER) performance versus input power into the receiver for perfect polarization rotation compensation of a communication system according to the present invention, using four different SOPs.

Fig. 7b shows the accumulated BER over time for a 4-SOP configuration with and without rotation compensation according to the present invention.

Detailed description of the invention

One aspect of the presently disclosed invention relates to an optical receiver, configured to receive at least three multiplexed, differently polarized, optically transmitted signals, each signal associated with a predefined state of polarization, said receiver comprising a multi-polarization analyzer for obtaining an analyzed signal for each of said polarized signals, wherein at least one of said analyzed signals comprises data in the full Stokes space. Until now only two orthogonal SOPs are available in traditional PDM systems. The inventor has realized that it is possible to use multi-polarized multiplexed signals in transceiver systems, using the full Poincaré sphere and still be able to operate on both coherent and incoherent systems. With the proposed

solution it is possible to multiplex the multi-polarized signals into a shared channel, for example fiber-optic data link and compensate for channel-induced polarization effects.

There are a number of wavelength ranges for fiber-optic communication. Broadly, optical fiber communications typically operate in a wavelength region of approximately 800-1800 nm. In optical fibers, the loss comes from a combination of Rayleigh scattering, oxygen absorption and the fundamental absorption of the silica material. Optical fiber communications typically operate in a wavelength region corresponding to one of the following windows:

- First window - 800-900 nm. Losses are high in this region so this window is used primarily for short-distance communications.
- Second window – approximately 1300 nm, where the loss of silica fibers is lower and the fibers' chromatic dispersion is very weak. Low dispersion is not necessarily ideal for long-haul dispersion.
- Third window utilizes wavelengths around 1500 nm. The losses of silica fibers are lowest in this region, and erbium-doped fiber amplifiers are available which offer very high performance.

The second and third windows are further divided into the wavelength bands of Table 1.

Band	Description	Wavelength range
O	Original	1260-1360 nm
E	Extended	1360-1460 nm
S	Short wavelengths	1460-1530 nm
C	Conventional (erbium window)	1530-1565 nm
L	Long wavelengths	1565-1625 nm
U	Ultralong wavelengths	1625-1675 nm

Table 1

In one embodiment, the presently disclosed receiver, transmitter and system operate on optical signals having a wavelength between 800 nm and 1800 nm.

- In one embodiment of the presently disclosed optical receiver, said receiver operates on optically transmitted signals having a wavelength between 200 nm and 3 μ m, or between 1260 nm and 1675 nm, or between 1530 nm and 1625 nm, or between 1000

nm and 1800 nm, or between 1000 nm and 1700 nm, or between 1200 nm and 1700 nm, such as 1550 nm. Similarly, in one embodiment of the optical transmitter, said transmitter operates on optically transmitted signals having a wavelength between 1260 nm and 1675 nm, or between 1530 nm and 1625 nm, or between 1000 nm and 1800 nm, or between 1000 nm and 1700 nm, or between 1200 nm and 1700 nm, such as 1550 nm.

More specifically, in one embodiment of the presently disclosed invention the multi-polarization analyzer is a Stokes analyzer. In a Stokes analyzer the optical power is split in four paths. Three of them end with vertical, horizontal and circular polarizers, respectively, while the fourth path is not polarized. The four signals originating from each path are directly related to the Stokes parameters. This configuration allows fast and simple measurements.

The Poincare sphere is one of the conventional ways of describing the polarization and changes in polarization of a propagating electromagnetic wave. It provides a convenient way of predicting how any given retarder will change a state of polarization. Any given polarization state corresponds to a unique point on the sphere.

The receiver according to the presently disclosed invention includes a multi-polarization analyzer in the demultiplexing stage mentioned above. The multi-polarization may be for example a Stokes analyzer. The multi-polarization analyzer is responsible for detecting signal components along predefined SOPs. As an example, a 4-SOP system may use a Stokes analyzer configuration for detecting signal components along SOPs X, 135°, right circular (RC) together with instantaneous total intensity, see fig. 6. The signal components are transferred into a three-dimensional Stokes space. The inclusion of circular states of polarization, and more generally, any configuration of SOP, is what makes the system more powerful than traditional orthogonal dual-polarization systems.

In one embodiment of the presently disclosed invention the receiver is configured to receive at least four, or at least five or at least six multiplexed, differently polarized signals. Operating on more than three SOPs implies the use of non-coplanar states in the Poincaré sphere.

The receiver also comprises compensation means, configured for compensating for induced polarization effects during transmission. As a consequence of at least one of the analyzed signals from the multi-polarization analyzer comprising data in the full Stokes space, the compensation has to take into account the full Stokes space, allowing exact rotation compensation of the Poincaré sphere. In other words, the multi-polarized receiver may operate in the full Poincaré sphere, which provides high robustness due to its ability for polarization rotation compensation. The compensation means may be a digital signal processor or an application specific integrated circuit, configured to perform polarization tracking to compensate for the channel-induced polarization rotation. The polarization tracking accounts for the compensation of the Poincaré sphere rotation after channel propagation and works for both coherent and incoherent realizations of the system. Polarization rotation compensation of 2-SOP signals has been described in the prior art, however with complex matrix inversions. In the present invention the number of tracked Stokes vectors is at least three, the number depending on the number of SOPs, hence allowing exact rotation compensation of the Poincaré sphere. Therefore, in the presently disclosed invention, the compensation means comprises calculating means for calculating at least three Stokes vectors and (real-time) polarization tracking the at least three vectors. This also enables simple signal demodulation beyond dual-polarization.

As a consequence of the abovementioned at least three Stokes vectors allowing exact rotation compensation of the Poincaré sphere and simple signal demodulation beyond dual-polarization, the presently disclosed invention also relates to the receiver further comprising demodulation means for demodulating the received different polarization signals based on the analyzed signals, wherein at least one of said analyzed signals comprises data in the full Stokes space. This could be a rather simple demodulation stage comprising a static and pre-defined multiple-input-multiple-output (MIMO) process. The at least three multiplexed, differently polarized received signals have a predefined state of polarization, which means that the system operates with SOPs that are known to the receiver. Since the mapping from the transmitter SOPs to Stokes space and from Stokes space to the received signals are known in advance, a low computational load is required and the associated matrices do not need to be inverted in real time. This results in a low computational load which makes implementation possible in for example low-speed digital processors. Therefore, in one embodiment of the presently disclosed receiver, the predefined states of polarization of the signals are represented by a predefined demapping matrix capable of demapping the received

signals from the full Stokes space, said demapping matrix having reference to a mapping matrix corresponding to the mapping of states of polarization of a transmitter to the full Stokes space. Operating in Stokes space allows tracking and compensation of polarization rotation without requiring any phase information with low computational load, which enables application in real scenarios.

A receiver according to the description above is capable of handling complete polarization rotation on the Poincaré sphere. The ability to handle such polarization rotation is also what makes the receiver capable of receiving and rotation compensating at least four multiplexed, differently polarized signals. Therefore in one embodiment of the present invention the receiver is configured to receive at least four multiplexed, differently polarized signals.

Typical use of the presently disclosed receiver would be in an optical system. Therefore, in one embodiment, the receiver is an optical receiver, and the signal is an optically transmitted signal. The induced polarization effects may be fiber-induced effects, and/or polarization rotation, and/or non-linear polarization rotation. The typical use also includes intensity modulation and direct detection (IM/DD) since these are the predominant technologies in optical data links.

In a further embodiment of the present invention the receiver comprises at least three signal detectors, or at least four signal detectors. The detectors may be for example photodiodes, which are typically used in IM/DD systems. In one embodiment of the presently disclosed system for optical communication over a communication link, the system is an incoherent IM/DD system. Such an incoherent system, operating with a Stokes-based tracking algorithm, allows tracking and compensation of polarization rotation without requiring any explicit phase information with low computational load.

A further aspect of the presently disclosed invention relates to a transmitter, configured to transmit at least three multiplexed, differently polarized signals, wherein at least one of said polarized signals comprises data in the full Stokes space. For the reasons mentioned above the inventor has realized that it is an advantage to use multi-polarized multiplexed signals in transceiver systems, using the full Poincaré sphere and still be able to operate on both coherent and incoherent systems. The fact that at least one of the polarized signals comprises data in the full Stokes space means that one of the at least three signals is non-coplanar with the others and no more than 3 SOPs are

coplanar. This enables a possibility to increase the data throughput of the system and works for both coherent and incoherent systems.

5 With the proposed solution it is possible to multiplex the multi-polarized signals into a shared channel, for example fiber-optic data link and compensate for channel-induced polarization effects. Therefore, preferably the transmitter works with a receiver as described above, and the transmitted signals may be optically transmitted signals.

10 In one embodiment of the transmitter the signals are polarized using the states of polarization X, Y, 45° and right circular. This 4-polarization configuration may be used in an intensity modulated direct detection-based system and provides a working, functional embodiment of the presently disclosed invention operating in the non-linear and/or non-coplanar domain for four SOPs, or with four SOPs where no more than three are coplanar.

15 In one embodiment of the presently disclosed invention the transmitter is configured to transmit at least four, or at least five, or at least six multiplexed, differently polarized signals. Operating on more than three SOPs implies the use of non-coplanar states in the Poincaré sphere.

20 A further aspect of the presently disclosed invention relates to a system, configured to communicate over a communication link, comprising:

- 25 - a transmitter, configured to generate and multiplex at least three independent data signals having different states of polarization into a multiplexed signal;
- a receiver, configured to receive the transmitted signal, said receiver comprising a demultiplexer for polarization demultiplexing the multiplexed signal into three or more polarized signals, said receiver further comprising at least three signal detectors.

30 By transmitting at least three independent data signals having different states of polarization the bandwidth may be increased significantly compared to a conventional system using only one or two polarizations. The simplicity of the system originates from the fact that it is fully based on polarization operations (generation, transmission and reception) and that is able to avoid the use of a coherent receiver, which means that
35 this system requires relatively simpler algorithms for recovering the data. In the present invention the whole Poincaré sphere is used to polarize the signal on the transmitter

side, i.e. the transmitter is configured to generate signals in the full Stokes space. Therefore, the transmitter in the system may be the transmitter described above, i.e. configured to transmit at least three multiplexed, differently polarized signals, wherein at least one of said polarized signals comprises data in the full Stokes space.

5

In one embodiment of the present invention the receiver in the system is the receiver as described above, i.e. configured to receive at least three multiplexed, differently polarized signals, each signal associated with a predefined state of polarization, said receiver comprising a multi-polarization analyzer for obtaining an analyzed signal for
10 each of said polarized signals, wherein at least one of said analyzed signals comprises data in the full Stokes space. The receiver may also comprise compensation means, configured for compensating for induced polarization effects during transmission, using the data in the full Stokes space.

15 The information about the mapping from the transmitter SOPs to Stokes space is considered to be known. This information can be used together with the mapping from Stokes space to the received signals, which is determined on the receiver side, for demodulation of the signals on the receiver side. Therefore, in one embodiment of the abovementioned system comprising a transmitter and receiver, the different states of
20 polarization of the at least three independent data signals are represented by predefined mapping and demapping matrices, wherein said mapping matrix is capable of mapping the at least three independent data signals to the full Stokes space, and wherein said predefined demapping matrix is capable of demapping the received three or more polarized signals from the full Stokes space.

25

The system may be used for a wide range of applications. The system may be an optical communication system, such as a fiber link or a freespace link, wherein the transmitter comprises at least one light source, such as a laser diode. However, the system may also be an RF system or a combination (radio-over-fiber, microwave
30 photonics). The system may use intensity modulated signals and direct detection on the receiver side.

The present invention also relates to an active cable comprising a receiver according to the presently disclosed invention and/or a transmitter according to the presently
35 disclosed invention, or a system according to the presently disclosed invention. Active cables are cables for transmission including integrated photonic chips on the

transmitter and receiver side, used for example for inter-rack and intra-rack connections in datacenters. Active optical cable is a cabling technology that accepts same electrical inputs as a traditional copper cable, but uses optical fiber between the connectors. Active optical cables use electrical-to-optical conversion on the cable ends to improve speed and distance performance of the cable without sacrificing compatibility with standard electrical interfaces. The cable may comprise one or more optical fibers and optoelectric modules at the ends of the cable. The active optical cable may also several/receivers/transmitters at each end.

10 Examples

Fig. 1a shows a schematic diagram of a receiver according to the present invention, including a generalized multi-polarization analyzer an electronic demultiplexer stage. The device receives the combined signal after transmission (composed of N multiplexed signals having polarization rotation due to transmission medium), splits them and evaluates their components along the M selected directions on the Poincaré sphere.

Fig. 1b shows an example of a configuration of a receiver according to the present invention, including demultiplexing of a multi-polarized signal, detectors and a DSP. The device receives the combined signal after transmission (composed of N multiplexed signals having polarization rotation due to transmission medium), splits them and evaluates their components along the M selected directions on the Poincaré sphere (Pol-Sels and detectors). The DSP performs polarization tracking and demodulation. This figure presents a direct detection type of receiver that performs M generalized projections on the Poincaré sphere which is used for the polarization demultiplexing of the N original signals.

Fig. 2 shows a simple example of incoherent communication according to the present invention, using three polarizations, including three light sources, three individually modulated signals, a multiplexer, a transmission line, a demultiplexing and demodulation stage at the receiver and signal detectors.

Fig. 3 shows a simple example of a coherent communication system according to the present invention, using three polarizations, including one light source, three individually modulated signals, a multiplexer, a transmission line, a demultiplexing and

demodulation stage at the receiver and signal detectors. This system has only one light source and requires the use of the full Poincare sphere.

Fig. 4 shows an example of a RF communication according to the present invention, using three polarizations in three dimensions in the RF domain, a demultiplexing stage at the receiver, wherein the receiver is further connected to an optical link. Each of the three depicted antennas does not necessarily represent a physical antenna but rather a dimension in the RF domain that may include different carriers, polarizations, etc. Additional components that are not shown in the figure but would be possible to include are optical to electric converters (O/E) and analog or digital processing units (A/D) that may include filters, amplifiers etc.

The inventor has conducted experiments to verify the performance of the presently disclosed invention. In a demonstration of IM/DD links using four states of polarization, fiber-Induced polarization rotation was compensated with a simple tracking algorithm operating on the Stokes space. The principle was proven at 128 Gb/s (4*32 Gb/s) over 2-km standard single-mode fiber (SSMF).

A Stokes analyzer was used on the receiver side and a 4-SOP tracking algorithm for data recovery. The proposed four state polarization (4-SOP) transmission system is illustrated conceptually in **fig.5**. Four independently intensity-modulated optical signals in four different SOPs are simultaneously transmitted over SSMF, where the SOPs rotate (as indicated by the vectors in the Poincaré sphere in **fig. 5**). At the receiver, signal components along SOPs X, 45° and RC (or orthogonal counterparts) are detected, together with the instantaneous total intensity in a Stokes analyzer. Subsequently, polarization rotation compensation and demodulation are performed in the digital domain.

The polarization rotation compensation accounts for the compensation of the Poincaré sphere rotation after fiber propagation. The number of tracked Stokes vectors are three, hence allowing exact rotation compensation of the Poincaré sphere. This also enables simple signal demodulation beyond dual-polarization (4 SOPs in this case). The demodulation stage consists of a static and pre-defined 4x4 multiple-input-multiple-output (MIMO) process. Because the mapping from the transmitter SOPs to Stokes space and from Stokes space to the received signals are known *a priori*, the associated matrices do not need to be inverted in real time. This results in a low

computational load which indicates the implementation feasibility in low-speed digital or analog processors.

Fig. 6 shows the schematic of the experimental setup. At the transmitter side, four distributed feedback lasers 1 are used as light sources. For the proof-of-concept, the outputs of the DFBs are externally modulated with four integrated Mach-Zehnder modulators (MZM) with ~30-GHz analog bandwidth (BW). No DSP is needed at the transmitter. Each of the modulated optical outputs from the MZMs is aligned to the chosen SOPs (X, Y, 45° and left-circular) with polarization controllers (PCs) in a polarization stage 2 and combined by means of standard 4x1 optical couplers in a combiner stage 3. The output from the transmitter is passed through a power equalization stage 4 before fiber transmission in a 2-km SSMF 5. A polarization scrambler 6 is installed at the end of the link for experimental demonstration of the polarization tracking algorithm. Demultiplexing of the polarized signals is performed in the demultiplexing stage 7, including a Stokes analyzer and four photodiodes. The DSP 8 comprises means for resampling, low-pass-filtering, symbol demapping and error counting.

Fig. 7a shows the bit-error-rate (BER) performance of the system versus input power into the receiver for perfect polarization rotation compensation. Measured results for both back-to-back (B2B) and transmission after 2-km SSMF are presented for the two cases of study. Hard decision 7% and 20% overhead forward error-correcting (FEC) thresholds ($4.4 \cdot 10^{-3}$ and $1.1 \cdot 10^{-2}$ respectively) are depicted for the reference. The experimental demonstration of the Stokes-based polarization tracking algorithm is realized with the help of a polarization scrambler. The fastest rotation rate the scrambler can achieve is on the order of radians per second, which is much slower than what can be captured within the digital sampling oscilloscope's maximum observation window. Polarization drifts occur on much longer timescales than the symbol period, hence it is not necessary to update the rotation matrix for every sample. Accordingly, a total of 120 16000-bit long frames were processed every 75 ms, resulting in an equivalent angular velocity magnitude in the order of Mrad/s. **Fig.7b** illustrates the accumulated BER over time for the 4-SOPx32GBd configuration at 25.5dB SNR per symbol, subjected to the aforementioned microsecond-timescale polarization rotations. The results obtained with and without the polarization tracking algorithm clearly show: (i) the need for rotation compensation to accomplish correct signal recovery and (ii) the successful and stable below-FEC performance achieved

with the proposed algorithm under conditions far more demanding than can be expected in 2-km SSMF transmission links.

In one example of an IM/DD setup, four states of polarization are used. Operating on more than three SOPs implies the use of non-coplanar states in the Poincaré sphere. Hence, scaling the system beyond three polarizations requires the aggregate SOP to be described by strictly more than three independent parameters. Mathematically, this allows the construction of the characteristic matrix (whose coefficients are associated with physically meaningful independent variables) of a consistent system of more than three equations with a unique solution. This matrix is referred as mapping matrix and its inverse as demapping matrix.

One transmission matrix for X, Y, 45° and left circular (LC) could therefore be:

$$Tx = \begin{matrix} X \\ 45 \\ Y \\ LC \end{matrix} \begin{pmatrix} X & Y \\ 1 & 0 \\ \cos \frac{\pi}{2} & \sin \frac{\pi}{4} \\ 0 & 1 \\ \cos \frac{\pi}{4} & -i \cdot \sin \frac{\pi}{4} \end{pmatrix}$$

15

It can be seen that the optical phase is indirectly exploited as an independent parameter by encoding part of the information on a circular SOP. Operating on the optical phase through SOP manipulation avoids the use of complex and costly coherent receivers. This particular configuration (along with the corresponding one at the receiver side) makes demultiplexing possible for up to four different SOPs that now can be simultaneously transmitted over the same medium.

On the receiver side, in one configuration Three of the polarizers at the receiver are aligned to X or Y, 45° or 135° and RC or LC respectively. The remaining photodiode captures the instantaneous total power (no polarizer). This general structure is named Stokes analyzer, In one embodiment the polarizers of the Stokes analyzer are aligned to X, 135° and RC. The corresponding Jones vectors describing the polarization of the field at the input of the Stokes analyzer's branches are:

25

$$Rx = \frac{X}{RC} \begin{pmatrix} X & Y \\ 1 & 1 \\ 1 & 0 \\ \cos \frac{3\pi}{4} & \sin \frac{3\pi}{4} \\ \cos \frac{\pi}{4} & -i \cdot \sin \frac{\pi}{4} \end{pmatrix}$$

Further details of the invention

The invention will now be described in further detail with reference to the following items:

- 5 1. A receiver, configured to receive at least three multiplexed, differently polarized signals, each signal associated with a predefined state of polarization, said receiver comprising a multi-polarization analyzer for obtaining an analyzed signal for each of said polarized signals, wherein at least one of said analyzed
10 signal comprises data in the full Stokes space.
2. The receiver according to any of the preceding items, wherein the multi-polarization analyzer is a Stokes analyzer.
- 15 3. The receiver according to any of the preceding items, further comprising compensation means, configured for compensating for induced polarization effects during transmission.
- 20 4. The receiver according to any of the preceding items, configured to receive at least four, or at least five, or at least six multiplexed, differently polarized signals.
5. The receiver according to any of the preceding items, wherein the receiver is an optical receiver, and wherein the signal is an optically transmitted signal.
25
6. The receiver according to any of the preceding items, wherein the compensation means comprises calculating means for calculating at least three Stokes vectors and polarization tracking the at least three vectors.

- 5
7. The receiver according to any of the preceding items, further comprising demodulation means for demodulating the received different polarization signals based on the analyzed signals, wherein at least one of said analyzed signal comprises data in the full Stokes space.
8. The receiver according to any of the preceding items, wherein the induced polarization effects are fiber-induced effects, and/or polarization rotation, and/or polarization rotation on the Poincaré sphere.
- 10
9. The receiver according to any of the preceding items, said receiver further comprising at least three signal detectors, or at least four signal detectors.
10. The receiver according to any of the preceding items, wherein the means for rotation compensating the signal comprises a digital processor.
- 15
11. A transmitter, configured to transmit at least three multiplexed, differently polarized signals, wherein at least one of said polarized signals comprises data in the full Stokes space.
- 20
12. The transmitter according to item 11, wherein the signals are optically transmitted signals.
13. The transmitter according to any of items 11-12, wherein the signals are polarized using the states of polarization X, Y, 45° and right circular.
- 25
14. The transmitter according to any of items 11-13, configured to transmit at least four, or at least five, or at least six multiplexed, differently polarized signals.
15. A system, configured to communicate over a communication link, comprising:
- 30
- a transmitter, configured to generate and multiplex at least three independent data signals having different states of polarization into a multiplexed signal;
 - a receiver, configured to receive the transmitted signal, said receiver comprising a demultiplexer for polarization demultiplexing the multiplexed
- 35
- signal into three or more polarized signals, said receiver further comprising at least three signal detectors.

16. The system according to item 15, wherein the transmitter is a transmitter according to items 11-14.
- 5 17. The system according to any of items 15-16, wherein the transmitter comprises at least one light source, such as a laser diode.
18. The system according to any of items 15-17, wherein the receiver is a receiver according to items 1-10.
- 10 19. The system according to any of items 15-18, wherein the link is an optical link, such as a freespace link or a fiber link, or a wireless link, or a link comprising an optical waveguide, or a combination, such as radio-over-fiber or microwave photonics.
- 15 20. The system according to any of items 15-19, wherein the multiplexed signal is intensity modulated.
- 20 21. The system according to any of items 15-20, wherein the three or more data signals are independently modulated.
22. The system according to any of items 15-21, wherein the signal detectors are photodiodes.
- 25 23. The system according to any of items 15-22, said system configured for bidirectional communication.
24. The system according to any of items 15-23, said system configured to operate with an optical waveguide as transmission medium.
- 30 25. The system according to any of items 15-24, said system configured for quantum communication.
- 35 26. An active cable comprising the receiver according to items 1-10 and/or the transmitter according to items 11-14, or the system according to any of items 15-25.

27. The active cable according to item 26, wherein the cable is optical.

Claims

1. An optical receiver, configured to receive at least three multiplexed, differently polarized, optically transmitted signals having a wavelength suitable for fiber optic based communication, such as between 200 nm and 3 μ m, or such as
5 between 800 nm and 1800 nm, each signal associated with a predefined state of polarization, said receiver comprising a multi-polarization analyzer for obtaining an analyzed signal for each of said polarized signals, wherein at least one of said analyzed signals comprises data in the full Stokes space.
- 10 2. The receiver according to any of the preceding claims, wherein the multi-polarization analyzer is a Stokes analyzer.
3. The receiver according to any of the preceding claims, further comprising compensation means, such as a digital signal processor, configured for
15 compensating for induced polarization effects during transmission.
4. The receiver according to any of the preceding claims, configured to receive at least four, or at least five, or at least six multiplexed, differently polarized signals.
20
5. The receiver according to any of the preceding claims, wherein the wavelength is between 1260 nm and 1675 nm, or between 1530 nm and 1625 nm, or between 1000 nm and 1800 nm, or between 1000 nm and 1700 nm, or between 1200 nm and 1700 nm, such as 1550 nm.
25
6. The receiver according to any of the preceding claims, wherein the compensation means comprises calculating means for calculating at least three Stokes vectors and (real-time) polarization tracking the at least three vectors.
- 30 7. The receiver according to any of the preceding claims, further comprising demodulation means for demodulating the received differently polarized signals based on the analyzed signals, wherein at least one of said analyzed signal comprises data in the full Stokes space.

8. The receiver according to claim 7, wherein the demodulation stage comprises a static and predefined 4x4 multiple-input multiple-output (MIMO) process.
- 5 9. The receiver according to any of claims 7-8, wherein the signals are received and demodulated incoherently.
- 10 10. The receiver according to any of the preceding claims, further comprising a demultiplexer configured to demultiplex the at least three multiplexed, differently polarized, optically transmitted signals without explicit phase reference.
- 15 11. The receiver according to any of the preceding claims, wherein the predefined states of polarization of the signals are represented by a predefined demapping matrix capable of demapping the received signals from the full Stokes space, said demapping matrix having reference to a mapping matrix corresponding to the mapping of states of polarization of a transmitter to the full Stokes space.
- 20 12. The receiver according to any of the preceding claims, wherein the induced polarization effects are fiber-induced effects, and/or polarization rotation, and/or polarization rotation on the Poincaré sphere.
- 25 13. The receiver according to any of the preceding claims, wherein the means for rotation compensating the signal comprises a digital processor.
- 30 14. An optical transmitter, configured to transmit at least three multiplexed, differently polarized, optically transmitted signals having a wavelength suitable for fiber optic based communication, such as between 200 nm and 3 μ m, or such as between 800 nm and 1800 nm, wherein at least one of said polarized signals comprises data in the full Stokes space.
15. The transmitter according to claim 14, configured to transmit at least four, or at least five, or at least six multiplexed, differently polarized signals.
16. A system, configured to communicate optically over a communication link, comprising:

- An optical transmitter, configured to generate and multiplex at least three independent data signals having different states of polarization into a multiplexed signal;
- An optical receiver, configured to receive the transmitted signal, said receiver comprising a demultiplexer for polarization demultiplexing the multiplexed signal into three or more polarized signals, said receiver further comprising at least three signal detectors.

17. The system according to claim 16, wherein the transmitter is a transmitter according to any of claims 14-15.

18. The system according to any of claims 16-17, wherein the receiver is a receiver according to any of claims 1-13.

19. The system according to any of claims 16-18, wherein said system is an incoherent intensity modulation direct detection (IM/DD) system.

20. The system according to any of claims 16-19, wherein the different states of polarization of the at least three independent data signals are represented by predefined mapping and demapping matrices, wherein said mapping matrix is capable of mapping the at least three independent data signals to the full Stokes space, and wherein said predefined demapping matrix is capable of demapping the received three or more polarized signals from the full Stokes space.

21. The system according to any of claims 16-20, said system configured for bidirectional communication, or quantum communication, or configured to operate with an optical waveguide as transmission medium.

22. An active cable comprising the receiver according to any of claims 1-13, and/or the transmitter according to any of claims 14-15, or the system according to any of claims 16-21.

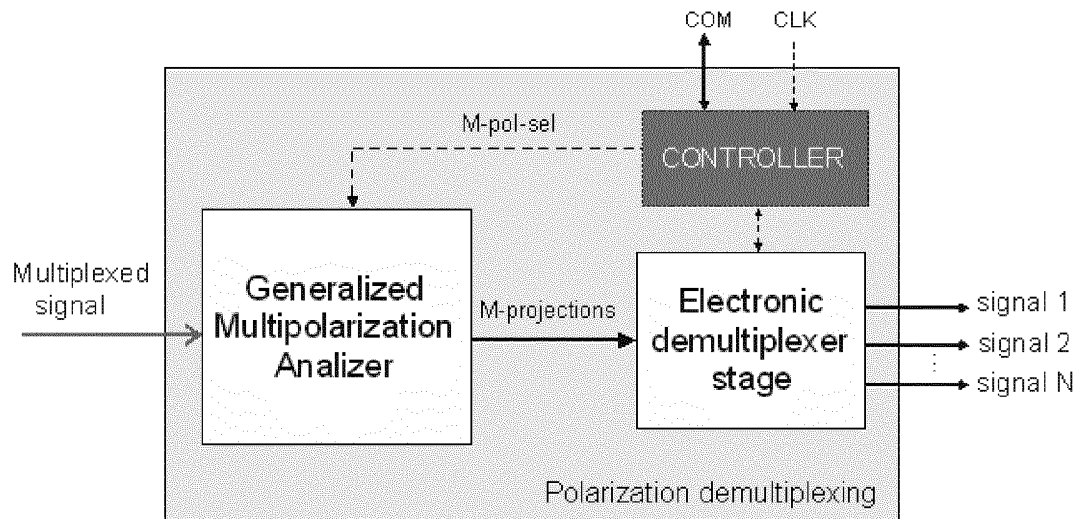


Fig. 1a

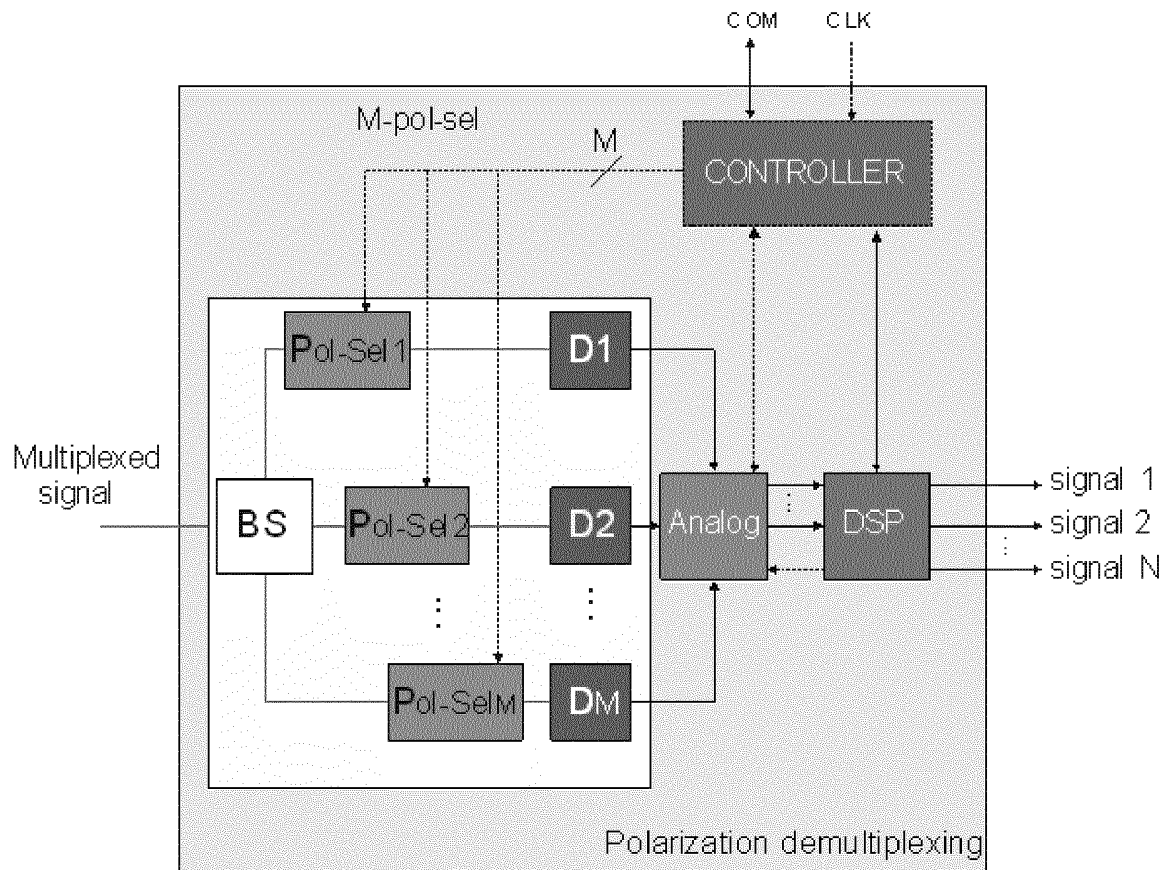


Fig. 1b

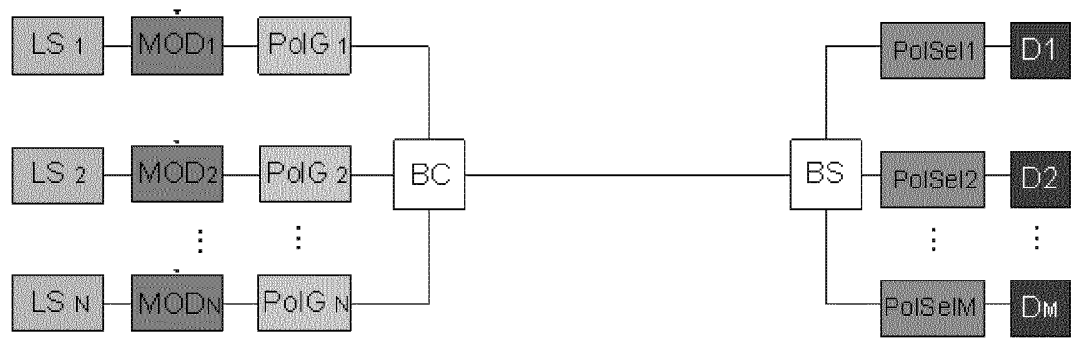


Fig. 2

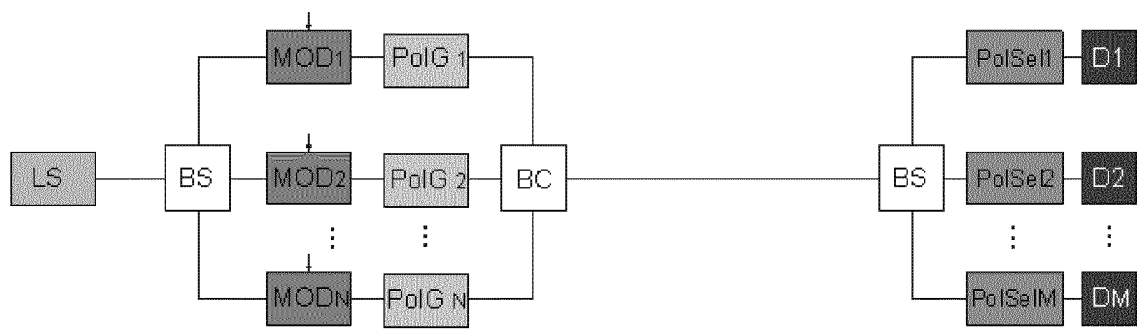


Fig. 3

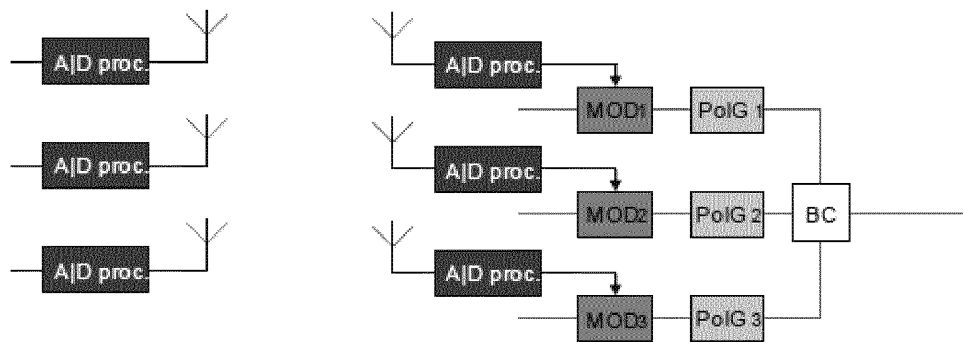


Fig. 4

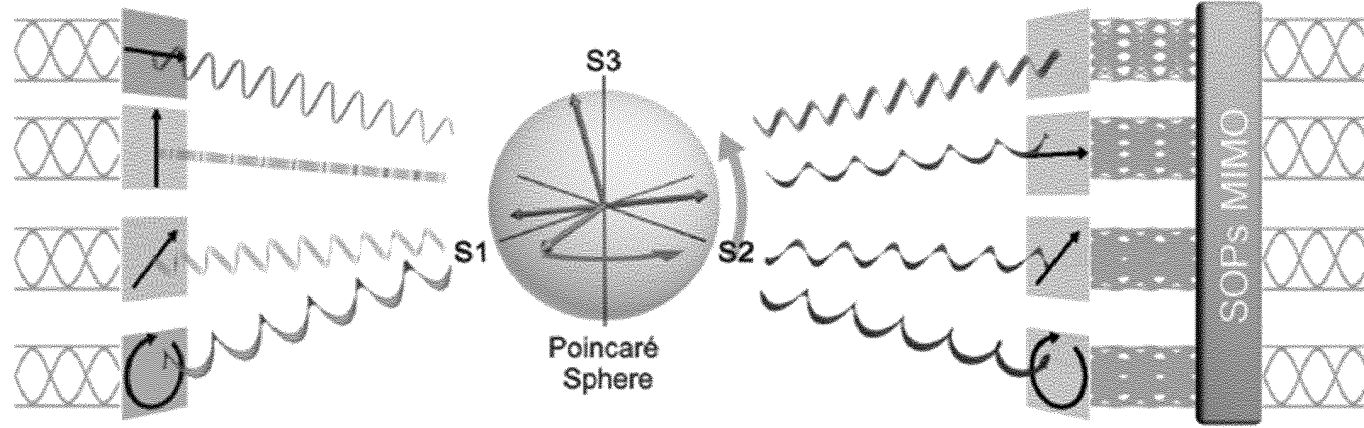


Fig. 5

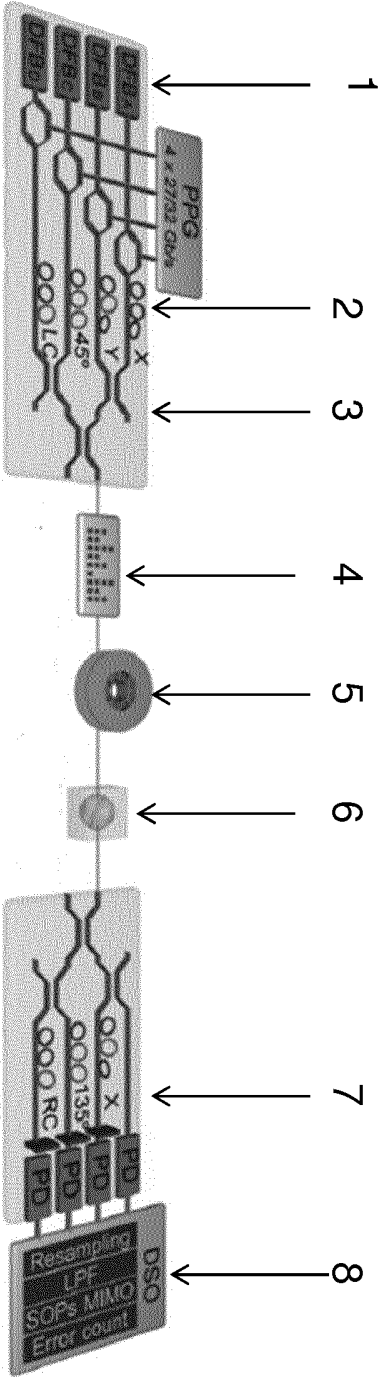


Fig. 6

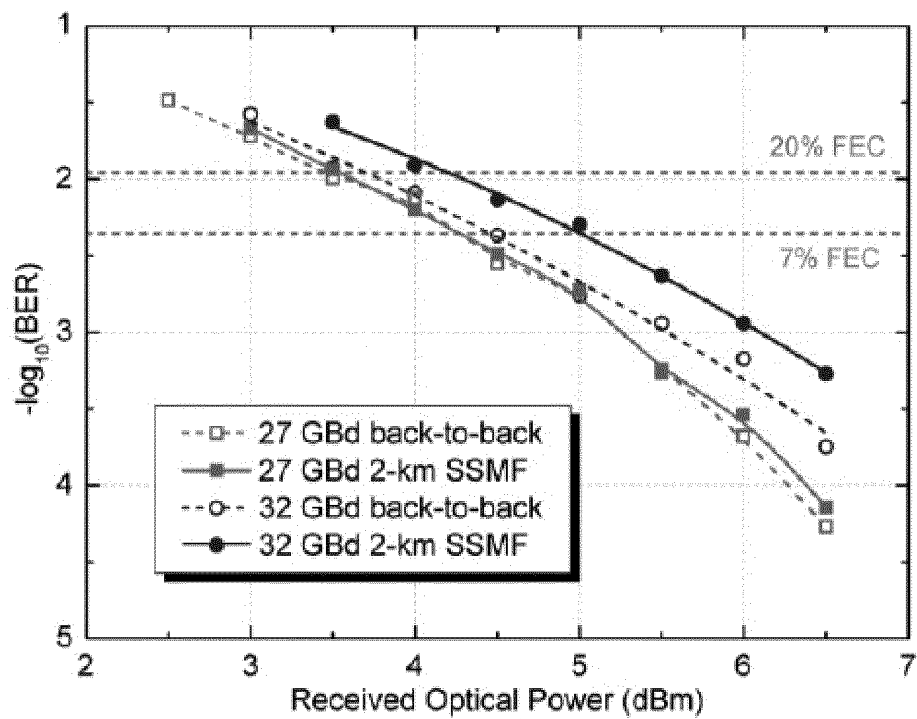


Fig. 7a

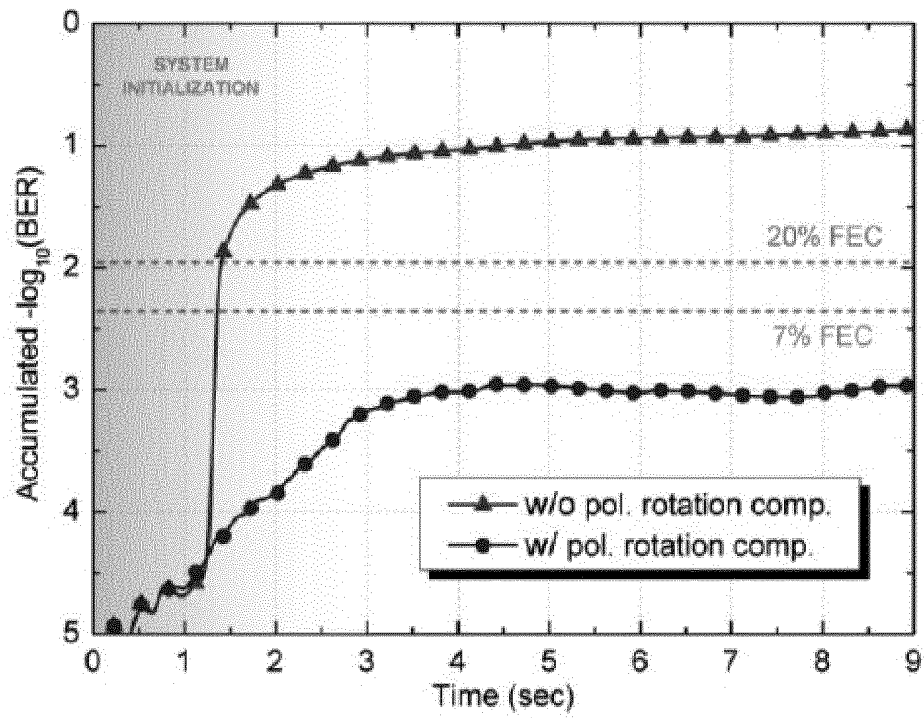


Fig. 7b

INTERNATIONAL SEARCH REPORT

International application No

PCT/EP2015/071972

A. CLASSIFICATION OF SUBJECT MATTER

INV. H04J14/06 G02B6/27
ADD.

According to International Patent Classification (IPC) or to both national classification and IPC

B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)

G02B H04J

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched

Electronic data base consulted during the international search (name of data base and, where practicable, search terms used)

EPO-Internal, WPI Data

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
X	US 2007/279284 A1 (KARAYIL THEKKOOTT NARAYANAN MA [IN]) 6 December 2007 (2007-12-06)	1,4,5, 7-11, 14-22
Y	the whole document	2,3,12, 13
Y	----- WO 2010/061247 A1 (ALCATEL LUCENT [FR]; BUELOW HENNING [DE]; JAEGER PIERRE [DE]) 3 June 2010 (2010-06-03)	2,3,12, 13
A	----- EP 2 109 233 A1 (ALCATEL LUCENT [FR]) 14 October 2009 (2009-10-14)	1-22
A	----- US 2004/218933 A1 (FLUDGER CHRISTOPHER [GB] ET AL) 4 November 2004 (2004-11-04)	1-22
	----- the whole document	



Further documents are listed in the continuation of Box C.



See patent family annex.

* Special categories of cited documents :

"A" document defining the general state of the art which is not considered to be of particular relevance

"E" earlier application or patent but published on or after the international filing date

"L" document which may throw doubts on priority claim(s) or which is cited to establish the publication date of another citation or other special reason (as specified)

"O" document referring to an oral disclosure, use, exhibition or other means

"P" document published prior to the international filing date but later than the priority date claimed

"T" later document published after the international filing date or priority date and not in conflict with the application but cited to understand the principle or theory underlying the invention

"X" document of particular relevance; the claimed invention cannot be considered novel or cannot be considered to involve an inventive step when the document is taken alone

"Y" document of particular relevance; the claimed invention cannot be considered to involve an inventive step when the document is combined with one or more other such documents, such combination being obvious to a person skilled in the art

"&" document member of the same patent family

Date of the actual completion of the international search

15 December 2015

Date of mailing of the international search report

23/12/2015

Name and mailing address of the ISA/

European Patent Office, P.B. 5818 Patentlaan 2
NL - 2280 HV Rijswijk
Tel. (+31-70) 340-2040,
Fax: (+31-70) 340-3016

Authorized officer

Albayrak, Charlotte

INTERNATIONAL SEARCH REPORT

Information on patent family members

International application No

PCT/EP2015/071972

Patent document cited in search report	Publication date	Patent family member(s)	Publication date
US 2007279284 A1	06-12-2007	US 2007279284 A1	06-12-2007
		WO 2005099129 A1	20-10-2005
-----	-----	-----	-----
WO 2010061247 A1	03-06-2010	CN 102227660 A	26-10-2011
		JP 2012510747 A	10-05-2012
		US 2011229143 A1	22-09-2011
		WO 2010061247 A1	03-06-2010
-----	-----	-----	-----
EP 2109233 A1	14-10-2009	AT 476801 T	15-08-2010
		CN 101557260 A	14-10-2009
		EP 2109233 A1	14-10-2009
		JP 4955125 B2	20-06-2012
		JP 2011517222 A	26-05-2011
		KR 20110009139 A	27-01-2011
		US 2009257755 A1	15-10-2009
		WO 2009124861 A1	15-10-2009
-----	-----	-----	-----
US 2004218933 A1	04-11-2004	NONE	
-----	-----	-----	-----