All-Order Polarization Mode Dispersion Compensation

As bit rates increase, all order polarization mode dispersion (PMD) compensation appears to be the premier way to increase the length of fiber communications. A demand exists for a technology that can perform all-order PMD compensation in existing fiber communication systems. A limitation of current algorithms is their differential group delay (DGD), which must be in the tens of picoseconds for them to be useful for real applications.

Purdue University researchers have demonstrated a novel and robust algorithm for all-order PMD compensation that could be applied to real fiber communication systems. This algorithm can be applied with much larger DGD values than previous test algorithms and can reduce the response time of the communication device.

Advantages:
- Further reaching fiber optics
- Lowered response time

Innovator Biography

Dr. Andrew M. Weiner is the Scifres Distinguished Professor of Electrical and Computer Engineering at Purdue University. He earned his S.B., S.M., and Sc.D. from Massachusetts Institute of Technology. Dr. Weiner received the Purdue University Herbert Newby McCoy Award, the IEEE Photonics Society Quantum Electronics Award, a National Security Science and Engineering Faculty Fellowship from the U.S. Department of Defense, and selected into the National Academy of Engineering. His research focuses on ultrafast optics, femtosecond pulse shaping, high-speed fiber communications, radio-frequency photonics, and optical frequency combs.
SYSTEM AND METHOD FOR PROGRAMMABLE POLARIZATION-INDEPENDENT PHASE COMPENSATION OF OPTICAL SIGNALS

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Notice: Subject to any disclaimer, the term of this patent is extended or adjusted under 35 U.S.C. 154(b) by 14 days.

Appl. No.: 10/178,949
Filed: Jun. 24, 2002

Related U.S. Application Data
Provisional application No. 60/303,763, filed on Jul. 6, 2001.

Int. Cl. 7 .......................... G02F 1/01; G02B 26/00
U.S. Cl. ..................................... 359/279; 398/81
Field of Search .......................... 359/279; 398/81; 372/28, 29:023

References Cited
U.S. PATENT DOCUMENTS

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ABSTRACT
A system and method for programmable phase compensation of optical signals is disclosed. The systems and methods include the use of a polarization-independent spatial light modulator (PI-SLM), so that the state of polarization (SOP) of the incoming optical signal need not be known. The system includes a first dispersive module that spatially separates the optical signal into its frequency components. The frequency components are spread over the active area of the PI-SLM. The active area of the PI-SLM includes an array of independently programmable addressable regions capable of altering the phase of the light incident thereto. An exemplary application of the invention is chromatic dispersion compensation by knowing the amount of chromatic dispersion in the optical signal, or alternatively, by knowing the amount of chromatic dispersion to be introduced into the optical signal downstream, the appropriate phase adjustments can be made to each frequency component of the signal. The phase-adjusted frequency components are then recombined via a second dispersive module to form a compensated optical signal.

58 Claims, 14 Drawing Sheets
SYSTEM AND METHOD FOR PROGRAMMABLE POLARIZATION-INDEPENDENT PHASE COMPENSATION OF OPTICAL SIGNALS

CROSS-REFERENCE TO RELATED APPLICATION

This application claims priority under 35 U.S.C. 119(e) from U.S. Provisional Application Ser. No. 60/303,763, filed Jul. 6, 2001, which application is incorporated herein by reference.

FIELD OF THE INVENTION

The present invention relates to optical communications and the processing of optical signals, and in particular relates to systems and methods for adjusting the phase of optical signals having an arbitrary polarization.

BACKGROUND OF THE INVENTION

The transmission of information over optical fibers is becoming pervasive. This is motivated, at least in part, because optical fiber offers much larger bandwidths than electrical cable. Moreover, optical fiber can connect nodes over long distances and transmit optical information between such nodes at the speed of light.

There are, however, a number of physical effects that limit the ability to transmit large amounts of information over an optical fiber. One such effect is called “chromatic dispersion,” which refers to the spreading of a pulse of light (i.e., an “optical signal” or “lightwave signal”) due to the variation in the propagation velocity of the different optical frequencies (or equivalently, wavelengths) making up the pulse.

Chromatic dispersion has two root causes. The first is due to the fact that silica of the optical fiber, like any optical material, has an index of refraction that is frequency-dependent. This is referred to as “material dispersion.” The second cause is due to the nature of the propagation of light down the fiber and is referred to as “waveguide dispersion.” The power distribution of the light between the core and the cladding of the fiber is a function of frequency. This means the “effective index” or “propagation constant” of the waveguide mode is a function of frequency as well, which causes the optical signal to disperse as it travels down the fiber.

In optical fiber communication systems, chromatic dispersion causes individual bits to broaden, since each bit is composed of a range of optical frequencies that separate due to their different propagation velocities. Such broadening eventually leads to intersymbol interference due to overlap of adjacent bits, which results in unacceptable data transmission errors. Chromatic dispersion compensation is usually needed to obtain the required performance in lightwave transmission systems operating at per channel data rates of 10 Gb/s or above. For example, the dispersion of a standard single mode fiber (SMF) at the key lightwave communications wavelength of 1550 nm is roughly 17 ps/km-km. For a 10 Gb/s transmission system, the optical bandwidth per channel is typically a minimum of 0.1 nm, and is often greater. Transmission through a 30 km span of SMF would lead to a chromatic dispersive broadening of the signal of 51 ps, which is 50% of the bit period (100 ps).

Such a broadening is unacceptably large and would lead to a large error rate. The problem becomes much more acute with higher data rates, such as 40 Gb/s per channel systems currently under development. The problem will even become more acute for the anticipated higher data rate systems presently being contemplated. Further details about the nature of chromatic dispersion in optical fibers and the consequences for optical networks can be found in the book by Ramaswami and Sivarajan, entitled Optical Networks, a Practical Perspective, Morgan Kaufmann Publishers, in chapter 2.3.

Efforts have been made in the past to develop systems and methods for compensating for the effects of chromatic dispersion. For example, dispersion-compensating fibers (DCF) have been developed that have the opposite sign of dispersion compared to conventional single mode fibers have been developed and are widely deployed as compensators. However, the DCF technique lacks the ability to easily fine tune the spectral variation of the dispersion and involves a relatively large insertion loss for long fiber links. Chirped fiber Bragg gratings can also compensate fixed amounts of dispersion, but only for one WDM channel at a time. Both techniques lack the ability to reprogram or programmably fine tune the amount of dispersion and its spectral profile, which is likely to be needed to develop higher rate lightwave communication systems.

A number of workers have used programmable pulse shapers to programmably compensate chromatic dispersion in high-power femtosecond pulse amplifiers and in nonlinear optical pulse compression systems. A variety of spatial light modulator (SLM) types have been used, including liquid crystals, acousto-optic modulators, and deformable mirrors.

By way of examples, the use of a deformable-mirror SLM to correct chromatic dispersion is described in the paper by E. Zeek et al., *Pulse compression by use of deformable mirrors*, Opt. Lett. 24, 493–495 (1999). The use of an arrayed waveguide grating (AWG) rather than a bulk diffraction grating as the spectral disperser is described in the paper by H. Takenouchi et al., entitled *2x40-channel dispersion-slope compensator for 40-Gbit/s WDM transmission systems covering entire C- and L-bands*, presented at the Optical Fiber Communications Conference (OFC) sponsored by the Optical Society of America, Anaheim, Calif., March 2001; however, in this paper a fixed phase mask is used in place of an SLM, with the result that the dispersion is not programmable. Further, the article by C. Chang et al. entitled *Dispersion-free fiber transmission for femtosecond pulses by use of a dispersion-compensating fiber and a programmable pulse shaper*, Opt. Lett. 23, 283–285 (1998) describes chromatic dispersion compensation using a liquid crystal SLM.

These and the other efforts described in the cited references all have the shortcoming that the operation of the dispersion compensation system depends on the SOP and/or that the system is not sufficiently programmable to handle the dispersion slope and higher-order dispersion terms or to reprogram the dispersion profile to accommodate changes in the length of optical fiber links in a switched optical networking environment. The dependence of a chromatic dispersion compensation system on the SOP of the input lightwave is a major shortcoming because the SOP of light having traveled through an optical fiber system is scrambled and can vary with time, resulting in polarization-dependent loss (PDL). Further, the inability to robustly perform phase encoding of the signal reduces the ability to accurately compensate for the chromatic dispersion characteristics of a given optical fiber system.

Accordingly, what is needed is a system and method that can programmably compensate, with a high degree of
accuracy, an optical signal for chromatic dispersion effects of an optical fiber, while also being insensitive to the SOP of the light signal being processed.

**SUMMARY OF THE INVENTION**

The present invention relates to optical communications and the processing of optical signals, and in particular relates to systems and methods for adjusting the phase of optical signals having an arbitrary polarization. The present invention finds particularly utility in correcting, reducing or otherwise adjusting chromatic dispersion in optical signals.

The present invention provides the capability to programmably control pulse broadening due to chromatic dispersion in chromatically dispersive media, and in particular in optical fiber communications systems and networks. This capability allows optical fiber communication systems to operate at higher speeds or longer distances by compensating chromatic dispersion, which is regarded as a key impairment for high-performance lightwave communication systems. The present invention can be applied both to very high-speed time-division multiplexed (TDM) and to wavelength division multiplexed (WDM) optical communications. In the case of WDM systems, several WDM channels can be independently compensated and can be programmed to achieve nearly arbitrary dispersion profiles in order to match the system requirements. The chromatic dispersion compensator can handle input optical signals with arbitrary and unspecified state of polarization, and may be configured to produce substantially zero PDL.

Accordingly, a first aspect of the invention is a system for programmably adjusting the phase of the frequency components of an optical signal of arbitrary polarization. The system includes a first dispersive module arranged to receive and disperse the optical signal into its frequency components. A polarization-independent spatial light modulator (PI-SLM) having an active area comprising a plurality of independently programmable addressable regions is arranged to receive the frequency components on the active area. The PI-SLM may be, for example, a liquid-crystal SLM adapted for polarization-independent operation, or a programmable deformable mirror. A controller is coupled to the PI-SLM. During operation of the system, the controller causes the PI-SLM to independently adjust the phase of one or more of the frequency components.

In an example embodiment of the invention, the phase-adjustment is performed to alter chromatic dispersion in the optical signal.

A second aspect of the invention is a method of programmably adjusting the phase of the frequency components of an optical signal of arbitrary polarization to adjust the amount of chromatic dispersion in the signal. The method includes dispersing the optical signal onto a polarization-independent spatial light modulator (PI-SLM) over an active area having a plurality of independently programmable addressable regions. The method further includes independently adjusting one or more of the addressable regions to alter the phase of the corresponding frequency components incident thereon. The phase-altered signals are then recombined to produce a compensated optical signal.

A third aspect of the invention includes the above described method, and involves adjusting the polarization of the optical signal frequency components so as to reduce any polarization-dependent loss (PDL) due to dispersing the optical signal into its frequency components and/or recombining the phase-altered frequency components to form the compensated optical signal.

A fourth aspect of the invention involves using the chromatic dispersion compensation system of the present invention to compensate for chromatic dispersion in channel optical signals in a wavelength-division multiplexed (WDM) signal. This is accomplished by dividing up the active area of the PI-SLM into sets of addressable regions corresponding to the frequency components of the different channel optical signals, and then compensating the frequency components of each channel signal. The compensated channel signals can then be detected, transferred to another optical system, or recombined with a multiplexer to form a compensated WDM signal.

**BRIEF DESCRIPTION OF THE DRAWINGS**

**FIG. 1** is a schematic diagram of the chromatic dispersion compensation system of the present invention as part of a larger lightwave optical system for reducing chromatic dispersion in an optical signal caused, for example, by transmission through an optical system with chromatic dispersion;

**FIG. 2A** is a close-up perspective view of a liquid-crystal-based SLM that is adaptable as one type of polarization-insensitive SLM (PI-SLM) suitable for use in the chromatic dispersion compensation system of **FIG. 1**;

**FIG. 2B** is an exploded perspective view of a reflective single liquid crystal layer PI-SLM that includes a polarization-adjusting element between the liquid crystal array of addressable regions and the reflecting member;

**FIG. 3** is a schematic diagram of a transmission-mode embodiment of the chromatic dispersion compensation system of **FIG. 1** that employs the two-layer liquid-crystal SLM of **FIG. 2A**, which is adapted to be polarization-independent, the system further including diffraction gratings in the dispersive modules;

**FIG. 4** is a schematic diagram of an on-axis reflection-mode embodiment of the chromatic dispersion compensation system of **FIG. 1** that employs a single optical fiber as the input and output optical fiber, and a circulator connected to first and second optical fibers and the single optical fiber;

**FIG. 5A** is a schematic diagram of an on-axis reflection-mode embodiment of a chromatic dispersion compensation system similar to that of **FIG. 4**, but that includes an optical system having magnification to reduce the overall size of the system;

**FIG. 5B** is a schematic diagram of an example telescope embodiment of the magnification optical system of the chromatic dispersion compensation system of **FIG. 5A**;

**FIG. 6** is a schematic diagram of an off-axis reflection-mode embodiment of the chromatic dispersion compensation system of **FIG. 1** similar to that of **FIG. 4** and that employs input and output optical fibers;

**FIG. 7A** is a schematic diagram of an optical processing system that includes the chromatic dispersion compensation system of the present invention, wherein the latter is used to perform post-compensation of an optical signal having passed through an optical system with chromatic dispersion;

**FIG. 7B** is a schematic diagram of an optical processing system that includes the chromatic dispersion compensation system of the present invention, wherein the latter is used to perform pre-compensation of an optical signal to be passed through an optical system with chromatic dispersion;

**FIGS. 7C and 7D** are schematic diagrams of embodiments of optical processing systems that includes the chromatic dispersion compensation system of the present invention, wherein a detection system is used to interrogate the optical
system to measure its chromatic dispersion and to provide information for the chromatic dispersion compensation system to perform post-compensation (FIG. 7C) or pre-compensation (FIG. 7D) of an optical signal.

FIG 8A is an embodiment of an optical processing system that includes the chromatic compensation system of the present invention, wherein the signals associated with different WDM channels are individually compensated for chromatic dispersion and then received by respective optical systems.

FIG. 8B is an embodiment of an optical processing system similar to that of FIG. 8A, but further including a multiplexer connected to each of the optical fibers that are connected to the respective chromatic dispersion compensation systems for multiplexing the compensated signals.

FIG. 9 is a close-up view of the first dispersive module and PI-SLM of system of FIG. 1 as used to perform chromatic dispersion compensation for a WDM signal having different channel optical signals, wherein the PI-SLM includes sets of addressable regions corresponding to the frequency components associated with each channel optical signal.

Like reference symbols in the various drawings indicate like elements.

**DETAILED DESCRIPTION OF THE INVENTION**

The present invention relates to optical communications and the processing of optical signals, and in particular relates to systems and methods for adjusting the phase of optical signals having an arbitrary polarization. In the following detailed description of the embodiments of the invention, reference is made to the accompanying drawings that form a part hereof, and in which is shown by way of illustration specific embodiments in which the invention may be practiced. These embodiments are described in sufficient detail to enable those skilled in the art to practice the invention, and it is to be understood that other embodiments may be utilized and that changes may be made without departing from the scope of the present invention. The following detailed description is, therefore, not to be taken in a limiting sense, and the scope of the present invention is defined only by the appended claims.

With reference to FIG. 1, there is shown a phase vs. frequency compensation system 100 according to the present invention as part of an optical processing system 106. System 100 is illustrated in transmission mode for the sake of convenience and illustration, and one skilled in the art will appreciate that there are associated folded reflection-mode systems that have the identical or analogous properties as represented in the transmission mode schematic diagram of FIG. 1. Such systems are discussed below and shown in FIGS. 3-6.

System 100 can be used, for example, to compensate, reduce or otherwise alter the chromatic dispersion in an optical signal 10. As chromatic dispersion is a variation in the propagation velocity of the different frequency (or, equivalently, wavelength) components making up the optical signal, chromatic dispersion can be adjusted by imparting an appropriate phase to one or more of the frequency components based on a desired phase vs. frequency relationship. The discussion of system 100 and the various implementations of system 100 emphasizes polarization-independent chromatic dispersion compensation because the present invention is eminently suited to such a function. However, it will be apparent to one skilled in the art that system 100 can perform other polarization-independent phase vs. frequency adjustment functions, such as for example wavefront reconstruction, wavefront alteration, and pulse shaping.

Chromatic dispersion may be present in optical signal 10 and caused, for example, by the signal having passed through a first optical system 120 having chromatic dispersion. Optical system 120 may include, for example, a distance of optical fiber 132 having chromatic dispersion. Optical system 120 may also include other optical components, e.g., laser sources, amplifiers, switches, gratings, routers, lenses, couplers etc., collectively shown as an element 124, that are capable of introducing additional amounts of chromatic dispersion. Optical system 120 thus produces chromatic dispersion in optical signal 110 from one or more sources that, absent compensation, limits the bandwidth and/or fidelity of optical signal 110 as a whole. In particular, chromatic dispersion causes pulse-broadening that, absent compensation, sets an upper limit for the bit rate period because of intersymbol interference.

A preferred consequence of compensating chromatic dispersion in optical processing system 106 is that it can optimize the usable bandwidth of optical signal 110. For example, performing chromatic dispersion compensation of optical signal 110 to form a compensated (i.e., phase-adjusted) signal 126 may be necessary to successfully transmit information through a second optical system 130, which may itself include sources of chromatic dispersion, such as an optical fiber 132 as well as other sources 124 of chromatic dispersion.

With continuing reference to FIG. 1, system 100 includes in order along an optical axis A1, a first dispersive module 136, and a polarization-independent spatial light modulator (PI-SLM) 140 having an active region 144 comprising an array 145 of independently programmable addressable regions 146. Also included downstream from PI-SLM 140 is a second dispersive module 148. Dispersive module 136 serves to spatially separate optical signal 110 into its frequency components 200 and direct these components onto active area 144 of PI-SLM 140. PI-SLM 140 is electronically connected to a controller 150 that controls the operation of the PI-SLM, as described below.

PI-SLM 140 may be one of a number of spatial light modulators that do not depend on the polarization of the input light signal, and that do not impart a polarization to a light signal. More generally, as used herein, a PI-SLM is any component or aggregation of components that defines an active area 144 having multiple, addressable regions 146 for adjusting the phase, and/or amplitude of light wavefronts incident on the regions. For example, the PI-SLM can have multiple, independently addressable regions such as a discrete array of independently addressable, addressable regions. Alternatively, the PI-SLM can have multiple, addressable regions that partially overlap. For example, the PI-SLM can be a deformable mirror having multiple, addressable actuators that deform overlap regions of the active area. Furthermore, other PI-SLMs can vary the phase, for example, by varying the refractive index of the addressable regions. In the example embodiment shown in FIG. 1, PI-SLM 140 is electronically addressable through its connection with controller 150. In other embodiments, however, the SLM may be optically addressable. Dispersive module 136 directs frequency components 200 onto the multiple regions of SLM 140 so that there is a known relationship between each addressable region 146 and the particular frequency component or frequency components 200 incident on that region.
Thus, the PI-SLM can adjust the phase, and/or amplitude of the incident frequency components by, e.g., reflection, transmission, diffraction, or some combination thereof. As described further below, in many embodiments, the PI-SLM involves one or more liquid crystal layers, whose birefringence and/or orientation are controlled to provide a desired series of adjustments for each SLM addressable region. For example, the liquid-crystal PI-SLM may include twisted nematic liquid crystals, non-twisted nematic liquid crystals, and/or ferroelectric liquid crystals. In further embodiments, the PI-SLM can include an inorganic electro-optic modulator, e.g., a lithium niobate crystal coupled to a generator providing a spatially addressable E-field, or an acousto-optic modulator coupled to a transducer providing a spatially addressable acoustic wave.

In one example embodiment, PI-SLM 140 is a multi-layer liquid-crystal modulator, such as described in U.S. Pat. No. 5,719,650 (the ‘650 patent), which patent is incorporated herein by reference. As described in the ‘650 patent and as illustrated in FIG. 2A, liquid-crystal PI-SLM 140 includes in active region 144 first and second arrays 160 and 162 of adjacent polarization rotating or adjustable birefringent elements (addressable regions) 166. Elements 166 are aligned along a first axis in array 160 and along a second axis (preferably, 90-degrees with respect to the first axis) in array 162.

In the present invention, liquid-crystal-based PI-SLM 140 of FIG. 2A needs to be adapted for use in system 100 so that it can be operated without concern for polarization effects, and in particular, without regard to the polarization of optical signal 110.

Specifically, if the liquid crystal alignment directions (axes) of arrays 160 and 162 are described as x and y, then the polarization transfer matrix M(ω) for the two-layered liquid crystal PI-SLM 140 is given by:

\[ M(ω) = \begin{pmatrix} e^{iφ_{x}(ω)} & 0 \\ 0 & e^{iφ_{y}(ω)} \end{pmatrix} \]  

where \( e^{iφ_{x}(ω)} \) and \( e^{iφ_{y}(ω)} \) are the phases shifts imparted by the SLM for array 160 and 162, respectively.

Thus, to obtain the output electric field vector \( E_{OUT}(ω) \) from the input electric field vector \( EIN(ω) \) the following operation is performed:

\[ E_{OUT}(ω) = M(ω)E_{IN}(ω) \]  

By setting \( φ_{x}(ω) = φ_{y}(ω) \), \( M(ω) \) becomes:

\[ M(ω) = \begin{pmatrix} 1 & 0 \\ 0 & 1 \end{pmatrix} \]  

Thus, in the case of the liquid-crystal-based PI-SLM 140 of FIG. 2A, Equation 3 reveals that PI-SLM 140 can be arranged so that it does not change the SOP of light passing therethrough. Thus, the phase shift imparted by liquid-crystal PI-SLM 140 of FIG. 2A can be made independent of the polarization of the input electric field, by aligning the respective liquid crystal axes of element 166 in array 160 and 162 at 90-degrees with respect to one another.

With reference now to FIG. 2B, this effect can be achieved by a reflective SLM having a single array of liquid crystal addressable regions, wherein light passes twice through elements 166 in single array 160, and wherein a 90-degree polarization change is imparted to the light prior to it passing back through the array. This can be achieved, for example, by providing a polarization-adjusting element 168 (e.g., a wave-plate) between array 160 and reflective member 170 (e.g., a mirror), wherein the polarization-adjusting element is designed to impart a total of 90-degrees of polarization rotation upon the light passing twice through the element. As one example, this can be achieved by passing twice through a properly oriented quarter wave plate. As a second example, this can be achieved by the use of a Faraday mirror providing a total of 90-degrees of polarization rotation. In the latter case, polarization-adjustment element 168 and reflecting member 170 are combined.

For a given SLM element 166, both \( φ_{x}(ω) \) and \( φ_{y}(ω) \) can be adjusted by applying the appropriate voltage according to a phase vs. voltage calibration. Such voltage can be provided by controller 150, which is calibrated with the necessary pixel phase vs. voltage data, e.g., as look-up table. As long as elements 166 offer a range of phase variation greater than 2π, \( φ_{x}(ω) \) can be made equal to \( φ_{y}(ω) \) and can be programmed to any desired value (modulo 2π).

With reference again to FIG. 1, since PI-SLM 140 in general is made up of an array 145 of independently programmable addressable regions 146, different addressable regions can be programmed via controller 150 to impart different phases independently using different driving voltages. Combined with the spatial dispersion of frequencies (or equivalently, wavelength) afforded by dispersive module 136, different optical frequencies \( ω \) are mapped onto different addressable regions 146. This allows for the arbitrary specification of phase vs. wavelength, i.e., a programmable phase versus optical frequency function that is independent of the SOP of input optical signal 110. Again, calibration of the phase vs. voltage can be readily performed and the data stored (e.g., as a look-up table) so that the precise phase can be encoded onto the signal.

Ideally, one would like to avoid PDL in any of the elements in system 100. As the input SOP cannot be specified in system 100, one desires zero PDL, as with any optical processing system where the SOP is not maintained. However, first dispersive module 136 used for spectral dispersion can have an associated PDL. As PI-SLM 140 of the present invention is of the type that does not alter the SOP, one can optionally compensate for dispersive-module-induced PDL by inserting a half-wave (f2) polarization-adjusting element 176 (e.g., a half-wave plate, Faraday rotator, etc.) anywhere in system 100 between dispersive modules 130 and 148 (in FIG. 1, element 176 is shown in phantom between PI-SLM 140 and dispersive module 148). In a reflective arrangement, half-wave polarization-adjusting element 176 becomes a quarter-wave polarization-adjusting element, as discussed below. Further, as element 176 can be shown to introduce a simple rotation in polarization in compensated lightwave 126, a second half-wave polarization-adjusting element (not shown) can optionally be inserted after second dispersive module 148 to restore the polarization. A half-wave polarization-adjusting element gives a 90-degree rotation for the correct orientation of axes and a single pass. A quarter-wave polarization-adjusting element provides 90-degrees of polarization rotation with two passes for the correct orientation of the element.

With continuing reference to FIG. 1, controller 150 is programmed to cause PI-SLM 140 to selectively and independently adjust the phase (and optionally the amplitude) of different subsets of spatially separated frequency (or equivalently, wavelength) components 200 associated with addressable regions 146 to produce phase-adjusted, spatially-separated frequency components 204. Dispersive
module 148 then spatially recombines adjusted frequency components 204 to produce an optical signal 126 that is compensated for chromatic dispersion (or, as discussed below, restored to its original state of not having any chromatic dispersion).

The phase to be imparted to each frequency component 200 of optical signal 110 can be based on information about the chromatic dispersion properties of a particular optical system (e.g., system 120 or 130) as measured or calculated (e.g., based on a model of chromatic dispersion effects of an optical system). Alternatively, information about chromatic dispersion can be acquired empirically by propagating a known optical signal (e.g., optical signal 110 or a test signal) through an optical system and measuring the chromatic dispersion effect.

In an exemplary embodiment of system 100, controller 150 controls PI-SLM 140 based at least in part on a feed forward detection signal from a detection system 220, which samples a portion of optical signal 110 to characterize its chromatic dispersion. In another exemplary embodiment, controller 150 controls PI-SLM 140 based at least in part on a feedback detection signal from detection system 230 that samples a portion of compensated optical signal 126 to characterize the effective reduction in the chromatic dispersion from system 100.

Furthermore, in another exemplary embodiment, controller 150 controls PI-SLM 140 based at least in part on signals from both detection systems 220 and 230.

Controller 150 includes the necessary power source and logic for independently applying electric fields (voltages) to each of respective addressable regions 146. Suitable power sources and logic are commercially available, e.g., from Cambridge Research and Instrumentation (CRI), Woburn, Mass. Controller 150 can also store appropriate calibration curves for array 145 so that the voltage necessary to impart a desired phase retardance is known. The algorithms can be implemented in computer programs or dedicated integrated circuits or computer-readable media (e.g., floppy disks or compact disks) using standard programming techniques.

Thus, in an exemplary embodiment of the present invention, controller 150 includes a computer system 258 (or may be linked to a computer system) that may be, for example, any digital or analog processing unit, such as a personal computer, workstation, a portion of a console, a mainframe server, server-computer, laptop or the like capable of embodying the programmable aspect of invention described herein. In an example embodiment, computer 258 includes a processor 260, a memory device 262, and a data storage unit 264, all electrically interconnected. Data storage unit 264 may be for example, a hard drive, CD-ROM drive, or a floppy disk drive that contains or is capable of accepting and reading a computer-readable medium 268. In an example embodiment, computer-readable medium 268 is a hard disk, a CD, a floppy disk or the like. Computer-readable medium 268 may contain computer-executable instructions to cause controller 150 to perform the methods described herein. An example computer 258 is a Dell personal computer (PC) or Workstation, available from Dell Computer, Inc., Austin, Texas.

In another example embodiment, computer-readable medium 268 comprises a signal 270 traveling on a communications medium 272. In one example embodiment, signal 270 is an electrical signal and communications medium 272 is a wire, while in another example embodiment, the communications medium is an optical fiber and the signal is an optical signal. Signal 270 may, in one example, be transmitted over the Internet 276 to computer 258 and optionally onward to controller 150.

As described above in connection with system 100 of FIG. 1, controller 150 may receive feed forward or feedback signals from detection systems 220 and 230, respectively, which characterize the chromatic dispersion in optical signals 10 and 126, respectively. In relatively simple embodiments with few degrees of freedom, detection system 230 can monitor the mean pulse dispersion in an adjusted optical signal 126 and provide a detection signal indicative of that dispersion to controller 150, which varies the adjustments imparted by PI-SLM 140 to minimize the pulse broadening due to chromatic dispersion (e.g., vary the phase imparted to each frequency by controlling the voltage provided to each pixel 146). In more complex embodiments, one or both of detection systems 220 and 230 can spectrally characterize the respective lightwave samples to provide sensing data to controller 150 for each of the spatially separated frequency components 200 incident on PI-SLM 140.

Preferably, one or both of detection systems 220 and 230 sense the spectral phase of the particular optical signal 110 and/or 126 on a wavelength-by-wavelength basis. Sensing of the spectral phase (or equivalently the frequency-dependent delay τ(ω)) can be achieved by using spectral interferometry techniques, cross-correlation techniques, and/or self-referencing measurement techniques, such as frequency resolved optical gating. Such techniques are described in, e.g., L. Lepetit et al., J. Opt. Soc. Am. B. 12, 2467–2474 (1995), K. Nagamura et al., Opt. Lett. 15, 393–395 (1990), and R. Tchino et al., Rev. Sci. Instrum. 68, 3277–3295 (1997), respectively.

With continuing reference to FIG. 1, dispersive modules 130 and 148 can include any dispersive element capable of spatially separating frequency components present in an optical signal. For example, they can include a diffraction grating (e.g., a reflective grating, transmissive grating, an amplitude grating, a phase grating, a holographic grating, echelle grating, arrayed-waveguide grating, etc.), a chromatic prism, and/or a virtually imaged phased array (VIPA). VIPAs are described in, for example, M. Shirasaki, Opt. Lett., 21, 366 (1996), and Shirasaki et al., IEEE Phot. Tech. Lett. 11, 1443 (1999).

Dispersive modules 130 and 148 may further include one or more imaging or relaying optics (e.g., lenses, mirrors, apertures, etc.) for directing the frequency components spatially separated by the dispersive element in module 130 onto PI-SLM 140 or for directing the adjusted frequency components from PI-SLM 140 to the dispersive element in dispersive module 148. Moreover, in additional exemplary embodiments of the present invention, the dispersive modules can be a single optical element that combines the dispersing and directing functions, such as a diffractive optical element (DOE).

Even where individual addressable regions of PI-SLM 140 provide many degrees of control over incident frequency components, the maximum amount of chromatic dispersion that can be compensated or reduced is limited by the spectral resolution of system 100. Generally, the parameters of dispersive module 136 are selected to fully exploit the entire pixel array 145 of PI-SLM 140. In other words, one tries to minimize the range of frequency components 200 on any pixel 146 while also insuring that all frequency components of interest are incident on at least one pixel. Accordingly, spectral resolution can be made to scale with the number of independently addressable addressable regions 146 of PI-SLM 140.

For example, PI-SLM 140 may have, e.g., at least 2, 4, or 8 addressable regions, and preferably many more, e.g., 64,
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128, etc. In any case, to avoid aliasing, spectral variations in the chromatic dispersion of the signal should be slow compared to the frequency width, denoted $f_0$, of one pixel $146$. This is equivalent to the requirement that the total duration of the signal to be compensated should be significantly below $1/2f_0$. The situation may be modified somewhat for embodiments in which the chromatically dispersed optical signal includes multiple signals on separate wavelength bands. In this case, dispersive modules $130$ and $148$ and PI-SLM $140$ can be tailored to optimize spectral resolution within each band, whereas regions between separate bands may be ignored. Thus, the PI-SLM can have multiple sets of arrays $145$, with each array dedicated to a particular wavelength band.

With continuing reference again to FIG. 1, dispersive module $136$ and PI-SLM $140$ combine to function as a programmable spectral phase equalizer by independently adjusting the phase of optical signal $126$ on a wavelength-by-wavelength basis. The approach allows compensation of time-varying chromatic dispersion effects, at least down to the response time of PI-SLM $140$. For a nematic liquid-crystal based PI-SLM (FIG. 2A), this response time is on the order of tens of milliseconds, which is fast enough to handle the majority of effects that cause chromatic dispersion.

It is worth remarking on the relationship between delay and spectral phase. For complete phase control, PI-SLM $140$ only needs to vary the phase at each pixel $146$ over a $0-2\pi$ radian range, which by itself constitutes a small phase delay. The frequency dependent group delay, however, varies as the derivative of the phase with respect to frequency. In particular, frequency-dependent delay $\tau(\omega)$ is related to a spectral phase variation $\Psi(\omega)$ as shown in EQ. 4:

$$\tau(\omega) = -\frac{\delta\Psi(\omega)}{\delta\omega}$$  \hspace{1cm} (EQ. 4)

Therefore, even relatively large group delays that may be associated with chromatic dispersion, e.g., in the tens of picoseconds range, can be compensated using physical phase delays no larger than $2\pi$. For visible and near infrared wavelengths, such phase delays correspond to a physical phase delay of only a few femtoseconds.

EXAMPLE EMBODIMENTS

As mentioned above, there are many specific examples of system $100$ of FIG. 1. Several of these examples are described below for the sake of illustration, and one skilled in the art will appreciate that the examples provided in no way limit the general teaching of the chromatic dispersion compensation system of the present invention.

Transmission System with Liquid Crystal PI-SLM and Diffraction Gratings

Referring now to FIG. 3, a first exemplary embodiment of system $100$ is shown. In this embodiment, first dispersive module $136$ includes a first grating $300$ for receiving optical signal $110$ and angularly dispersing its frequency components $200$, and a first lens $306$ having a focal length $F_1$ for collimating the angularly dispersed frequency components and focusing them onto a liquid-crystal-based PI-SLM $140$, and in particular onto first and second arrays $160$ and $162$ of elements $166$ (FIG. 2A).

Optical signal $110$ emanates from the end of an output optical fiber $122$ as part of optical system $120$ and is incident on first grating $300$. The collimation and focusing of frequency components $200$ can be accomplished by spacing lens $306$ from each of grating $300$ and PI-SLM $140$ by a distance equal to its focal length $F_1$. Thus, the grating and lens map the frequency content (i.e., components $200$) of optical signal $110$ onto SLM arrays $160$ and $162$. Moreover, because of the positioning of lens $306$, grating $300$, and PI-SLM $140$, the spatial extent of any individual frequency component on arrays $160$ and $162$ is minimized. For each pixel, PI-SLM $140$ independently adjusts the phase (and optionally the amplitude) of the frequency components $200$ incident on the pixel (in FIG. 2A, only two frequency components $220$ are shown for simplicity).

Second dispersive module $148$ includes a second grating $320$ and a second lens $326$ having a focal length $F_2$ for recombining the adjusted spatially-separated frequency components $204$ into adjusted optical signal $126$, which can then be coupled to an optical fiber $132$ as part of second optical system $130$. Like first dispersive module $136$, lens $326$ is preferably spaced from each of PI-SLM $140$ and grating $320$ by a distance equal to its focal length $F_2$. In an example embodiment, the focal length of lenses $306$ and $326$ are the same (i.e., $F_1=F_2=F$), and thus the gratings, lenses, and SLM define a “4-F” arrangement.

An advantage of the present invention is that gratings $300$ and $320$ need not be polarization insensitive, since system $10$ as a whole does not rely on knowledge of SOP of optical signal $110$.

In other embodiments of system $100$ of FIG. 3, for example, lenses $306$ and/or $326$ can be replaced with curved mirrors having a radius of curvature equal to $2F$, in which case the arrangement is folded. Similarly, the arrangement can be folded by using a reflective PI-SLM, as discussed below. Also, transmission gratings may be used instead of reflective gratings $300$ and $320$. One skilled in the art will appreciate the basic equivalency between folded reflected systems and unfolded transmission systems. Moreover, in additional embodiments, the dispersive modules and PI-SLM may be implemented, in whole or in part, as an integrated waveguide structure.

Depending on the nature of gratings $200$, PDL can be significant. Thus, optionally included in system $100$ of FIG. 3 is half-wave polarization-adjusting member $176$ shown in phantom just downstream of PI-SLM $140$, in order to reduce any PDL from gratings $200$ and $320$.

On-axis Reflection System with Diffraction Gratings

With reference now to FIG. 4, an on-axis reflective system $100$ is illustrated. System $100$ of FIG. 4 is similar to the transmissive system of FIG. 3 in that it is an optically folded version thereof. In particular, system $100$ of FIG. 4 includes a single optical fiber $122$ serving as both the input and output fiber. This is made possible by connecting optical fiber $122$ to a circulator $400$ to which is also connected a first optical fiber $406$ and a second optical fiber $408$. A chromatically dispersed input optical signal $110$ is provided by first optical fiber $406$, and is passed to optical fiber $122$ by circulator $400$. Optical signal $110$ is dispersed by grating $300$ into its constituent frequency components $200$ and imaged by lens $306$ onto active area $144$ of reflective PI-SLM $140$. Addressable regions $146$ of reflective PI-SLM $140$ are programmed to impart the appropriate phase for each frequency, as described above, to create dispersion-compensated signal components $204$ and reflect the components through lens $306$ and to grating $300$. A half-wave phase plate $410$ (shown in phantom) is optionally provided to provide a total of half-wave (i.e., 90-degrees) of total polarization rotation over two passes of the light through the plate, to limit PDL, as discussed above. The combination of lenses $306$ and grating $300$ serves to recombine the frequency components to form compensated optical signal $126$ and relay the optical signal
back to optical fiber 122. Optical signal 126 propagates along optical fiber 122 until it encounters circulator 400, which directs optical signal 126 to second optical fiber 408.

On-axis Reflection System with Magnification

With continuing reference to FIG. 4, in order to disperse a given wavelength band across active area 144 of PI-SLM 140, lens 306 needs to have a certain focal length F1. The larger PI-SLM 140 and the narrower the wavelength band of optical signal 110, the longer focal length F1 must be. For many diffraction gratings, F1 must be on the order of 10 m to disperse a 1 nm band across a 1 cm active area 144. This makes for a very long optical path for system 100.

Accordingly with reference now to FIG. 5A, a compact on-axis reflective system 100 is illustrated. System 100 of FIG. 5A is similar to the reflective system of FIG. 4, except that magnification is introduced to shorten the system. Note that reflective designs by nature are more compact than transmissive designs, and also tend to be more economical because the components can be employed to perform "double duty" by passing light through select components in two different directions.

Magnification is achieved in the present invention by forming an intermediate image 11 at an intermediate image plane P1 of spectral components 200 formed by grating 300 located at a plane P0. Image 11 is then used as an object for forming a magnified image I2 of the frequency components 200 at a second image plane P2 coincident with active area 144 of PI-SLM 140 using a magnifying optical system 460 arranged between planes P1 and P2. Thus, magnifying optical system 460 relays with magnification frequency components 200 onto active area 144. In general, the magnification provided is such that the optical path of system 100 is shortened as compared to the optical path without the introduction of magnification. The necessary magnification will depend, in part, on the size of active area 144 of PI-SLM 140 and the amount of dispersion of the frequency components provided by dispersive module 136.

With reference to FIG. 5B, in an example embodiment optical system 460 includes a telescope with a first lens 470 having a focal length F4 and a second lens 476 having a focal length F5. Lens 306 has a focal length F1. In a preferred embodiment, the distance between planes P0 and P1 is 2F1 and the distance between plane P1 and P2 is set to 2(F4+F1). One skilled in the art will appreciate that the judicious arrangement and choice of lenses 306 and the elements making up optical system 460 can significantly reduce the length of system 100 should the system otherwise prove to be too long for the particular application. Also, the magnification technique used in this reflective embodiment as an example is equally applicable to a transmissive system (e.g., system 100 of FIG. 2A).

Because the size of system 100 scales with the size of the active area 144 of PI-SLM 140, it can also be made compact by using an SLM with a smaller active area (i.e., aperture 144 and smaller addressable regions 146 in addition to, or as an alternative to providing magnification. For example, certain liquid crystal SLMs have addressable regions (pixels) of typically about 100 microns, but also as small as 25 microns, which allowing 512 pixels to fit into a 12.8 mm aperture. Such an SLM is available from the Raytheon Company in Lexington, Mass. A similar SLM with 128 pixels would have an aperture of approximately 3 mm. A liquid crystal SLM from Boulder Nonlinear Systems, Boulder, Colo., has 4096 pixels, with a center-to-center pixel spacing of 1.8 microns and an aperture of 7.4 mm.

Thus, a small PI-SLM 140 has an aperture size of about 5 mm across, and in an example embodiment, has an aperture size of 3 mm or less. With a reflective system 100, using a PI-SLM having an active area of (3 mm x 3 mm) and a magnification of 10 can result in system 100 having an overall length as small as, for example, 40 cm, for a 1 nm bandwidth. This system could be made more compact by folding the optical path using, for example, fold mirrors or fold prisms.

Off-Axis Reflection System

With reference now to FIG. 6, there is shown another example embodiment of system 100 of the present invention that utilizes an off-axis reflective design. System 100 of FIG. 6 is similar to that of FIG. 4, except that reflective PI-SLM 140 is tilted relative to axis A1, so that the return path of light rays 480 from PI-SLM associated with compensated optical signal 126 are not coincident with the incident path of light rays 490 associated with incident optical signal 110. This allows for different input and output fibers 112 and 132 to be used, rather than a single fiber.

Optical Processing Systems Implementing the System 100

System 100 can also be implemented in optical processing system configurations other than that shown in FIG. 1. In particular, rather than compensating or reducing chromatic dispersion in an optical signal after it has passed through the optical system, system 100 can be used to pre-compensate an optical signal prior to its transmission through an optical system having chromatic dispersion. Furthermore, in addition to post-compensation and pre-compensation, system 100 can be used in an implementation that interrogates the optical system having chromatic dispersion, rather than sensing or detecting the actual optical signal itself. In addition, system 100 can be used to perform independent chromatic dispersion control of optical signals for independent WDM channels.

These various implementations are now described in greater detail below.

Pre-Compensation Implementation

With reference now to FIG. 7A, there is shown a source 510 for providing an undistorted optical signal 516, which passes through an optical system 520 having chromatic dispersion to produce a chromatically dispersed optical signal 530, akin to optical signal 110 of FIG. 1. Optical signal 530 then passes through system 100 (e.g., as shown generically in FIG. 1 or any of the specific embodiments thereof discussed above in the ensuing Figures) to reduce the chromatic dispersion in the signal and produce an adjusted optical signal 126. Signal 126 is detected by detection system 230 to monitor the degree of compensation and allow for iterative measurements and compensations to provide an optimally reduced chromatic dispersion. Signal 530 may also be detected by detection system 220 to determine the amount of compensation needed to be applied to signal 530 by system 100.

Pre-Compensation Implementation

With reference now to FIG. 7B, there is shown a pre-compensation implementation of chromatic dispersion compensation system 100. In particular, undistorted optical signal 516 first passes through system 100 that is adapted to alter signal 516 in a predetermined manner to counteract the anticipated effects of downstream optical system 520. The result is an optical signal 550 that includes a predetermined amount of chromatic dispersion. Optical signal 550 then passes through optical system 520. The chromatic dispersion imparted to signal 550, however, was selected to offset or reduce the impact of the chromatic dispersion caused by optical system 520. Thus, an optical signal 516 emerges from optical system 520 having reduced, if not fully compensated, chromatic dispersion. Accordingly, optical...
signal 516 closely resembles signal 516, if not identical thereto. In an exemplary embodiment, chromatic dispersion compensator 100 is guided by detection system 230, which provides a precompensation signal to controller 150 representative of the state of chromatic dispersion of optical signal 516, which is indicative of the chromatic dispersion effects in downstream optical system 520.

Optical System Compensation Implementation

With reference now to FIGS. 7C and 7D, there are shown optical processing systems involving post-compensation and pre-compensation implementations wherein the compensation of the optical signal is determined by interrogating optical system 520 directly, rather than by sensing or detecting an optical signal using detection systems (sensors) 220 and 230.

Accordingly, a sensor 580 is arranged to be in optical communication with optical system 520 and system 100, wherein the sensor is adapted to sense the chromatic dispersion of the optical system. This may carried out, for example, by providing one or more lightweight test signals 586 having particular characteristics (e.g., a set bandwidth, pulse length and/or pulse shape) through optical system 520, and measuring the amount of chromatic dispersion induced using system 100. System 100, via controller 150, processes the measurements and determines the amount of pre-compensation (FIG. 7D) or post-compensation (FIG. 7C) for chromatic dispersion is required for system 520. Once the amount of compensation is determined, the actual input signal 516 can be compensated (FIG. 510).

WDM Optical Processing System Implementation

Although the preceding paragraphs refer to compensation of pulse broadening caused by chromatic dispersion, it is noted that optical signals 110 and 126 (FIG. 1) may carry such pulse information on one or more different wavelength bands (channels). Thus, in one limit, the entire frequency bandwidth of the optical signal may be used to carry high-bandwidth pulsed information (e.g., time-domain multiplexing or TDM), whereas, in the opposite limit, the frequency bandwidth of the optical signal is divided into separate wavelength bands, each simultaneously carrying lower-bandwidth pulsed information (e.g., wavelength-division multiplexing or WDM).

Thus, with reference to FIGS. 8A and 8B, there is shown an optical processing system-level view of a system implementation that allows for independently compensating the optical signal associated with different WDM channels ("channel optical signals"). The system includes upstream optical system 120 and a multiplexed optical signal 604 comprising channel optical signals 110a, 110b and 110c centered at wavelengths λa, λb and λc, respectively, and each having a wavelength band Δλ. In an example embodiment, the channel spacing is 0.8 nm (i.e., 100 GHz), the wavelength band Δλ=0.1 nm (i.e., 12.5 GHz) λa, λb and λc=1550 nm, 1550.8 nm and 1551.6 nm. Three channel optical signals are used for the sake of illustration; clearly, greater or fewer channels optical signals can be used.

Channel optical signals 110a, 110b and 110c pass through a demultiplexer 600, which separates the channel signals so that they can be coupled into corresponding optical fibers 610a, 610b and 610c. Each of fibers 610a, 610b and 610c is coupled to a system 100. Systems 100, as described above, each adjusting the phase of the frequency components of the corresponding channel optical signal so that the signal is compensated for chromatic dispersion, as described above. The result is compensated channel signals 126a, 126b and 126c traveling along optical fibers 610a, 610b and 610c.

With reference now to FIG. 8A, compensated channel signals 126a, 126b and 126c are then received by respective receiving optical systems 130, which in the present embodiment may simply be optical detectors that detect the optical signal and convert it to an electrical signal programmed to process.

With reference now to FIG. 8B, the optical processing system of the present implementation may further include a multiplexer 620 that multiplexes compensated signals 126a, 126b and 126c to form a compensated WDM signal 628, which can then be passed along to optical system 130. The optical processing systems of FIGS. 8A and 8B can be used in either the pre-compensation or post-compensation modes.

WDM Compensation Using a Single PI-SLM

With reference now to FIG. 9, there is shown a close-up view of a portion of system 100 of FIG. 1, wherein multiplexed optical signal 604 comprising channel optical signals 110a, 110b and 110c centered at wavelengths λa, λb and λc, respectively, and each having a wavelength bandwidth Δλ. Three channel optical signals are used for the sake of illustration; clearly, greater or fewer channels optical signals can be used.

Multiplexed optical signal 604 is incident on dispersive module 136. The latter is designed to disperse not only the frequency components 200a-200c of the individual channel optical signals 110a, 110b and 110c, but also to disperse the different channel signals relative to one another. Thus, the different channel optical signals 110a-110c of multiplexed signal 604 are dispersed to different zones 630 (e.g., 630a-630c) on PI-SLM 140, with each zone containing a set of addressable regions 146. Thus, the addressable regions 146 in zones 630a-630c are dedicated to compensating the optical frequencies in the wavelength band Δλ centered around each wavelength λa-λc, respectively. This allows different channel optical signals centered at different wavelengths to be independently and simultaneously compensated and optimized. This is advantageous because chromatic dispersion properties vary across the wavelength spectrum, so that different optical signals centered around different wavelength bands will generally require different amounts of chromatic dispersion compensation.

It should be noted that this WDM chromatic dispersion correction approach requires a trade-off between the number of addressable regions per channel optical signal and the number of channel optical signals in the WDM signal. In an example embodiment, the number of addressable regions per channel optical signal is preferably between about 8 and 16. Further, the total number of addressable regions is preferably about 128 or greater.

CONCLUSION

The invention provides the capability to programmably control pulse broadening due to chromatic dispersion in optical fiber communication and networking systems. This capability allows optical fiber lightweight communication systems to run at higher speeds over longer distances by compensating chromatic dispersion, which is regarded as a key impairment for high performance lightweight communication systems.

The present invention can be applied both to very high-speed time-division multiplexed (TDM) and to wavelength division multiplexed (WDM) optical communications. In the case of WDM systems, several WDM channels can be compensated independently and can be programmed to achieve nearly arbitrary dispersion profiles in order to match the system requirements. The chromatic dispersion compensation system of the present invention can handle input optical signals with an arbitrary and unspecified SOP, and may be configured to provide substantially zero PDL. The programmable nature of the present invention allows for
chromatic dispersion to be compensated under a variety of conditions and situations, including re-programming the chromatic dispersion compensation system when there is a change in the optical processing system configuration (e.g., the length of the network) that results in a change in the system chromatic dispersion.

A number of embodiments of the invention have been described. Nevertheless, it will be understood that various modifications may be made without departing from the spirit and scope of the invention. For example, some embodiments may incorporate both pre-compensation and post-compensation. In such case, a pre-compensation system may be used to match the wavelength-by-wavelength chromatic dispersion of an optical signal to the wavelength-by-wavelength chromatic dispersion of a downstream optical system. Thereafter, a post-compensation system can further reduce chromatic dispersion in the optical signal caused by the optical system.

Thus, while the present invention has been described in connection with preferred embodiments, it will be understood that it is not so limited. On the contrary, it is intended to cover all alternatives, modifications and equivalents as may be included within the spirit and scope of the invention as defined in the appended claims.

What is claimed is:

1. A system for programmably adjusting the phase of the frequency components of an optical signal of arbitrary polarization, comprising:
   a first dispersive module arranged to receive and disperse the optical signal into its frequency components;
   a polarization-independent spatial light modulator (PI-SLM) having an active area comprising a plurality of independently programmable addressable regions, the PI-SLM arranged to receive the frequency components on the active area; and
   a controller coupled to the PI-SLM wherein during operation the controller causes the PI-SLM to independently adjust the phase of one or more of the frequency components.

2. A system according to claim 1, wherein the PI-SLM is operated by the controller to alter chromatic dispersion in the optical signal.

3. A system according to claim 1, wherein the PI-SLM includes a multi-layer liquid-crystal spatial light modulator adapted to be polarization insensitive.

4. A system according to claim 1, wherein the PI-SLM is a programmably deformable mirror.

5. A system according to claim 1, wherein the PI-SLM includes a single liquid crystal layer, a polarization adjusting member and a reflective element, wherein the polarization-adjusting member imparts a total polarization rotation of 90 degrees to light passing twice therethrough.

6. A system according to claim 1, wherein the controller includes information pertaining to the amount of voltage to be supplied to each pixel to introduce a predetermined amount of phase change per pixel.

7. A system according to claim 1, further including a computer coupled to the controller, the computer capable of receiving and storing instructions for operating the controller.

8. A system according to claim 1, further including a second dispersive module downstream of the PI-SLM for re-combining the phase-adjusted frequency components to form a phase-adjusted optical signal.

9. A system according to claim 2, further including a polarization-adjusting element arranged between the first and second dispersive modules.

10. A system according to claim 9, wherein the PI-SLM is reflective and the polarization-adjusting element imparts a total of 90-degrees of polarization rotation so as to reduce polarization-dependent loss (PDL).

11. A system according to claim 9, wherein the PI-SLM is transmissive and the polarization-adjusting element imparts a total of 90-degrees of polarization rotation so as to reduce polarization-dependent loss (PDL).

12. A system according to claim 1, further including a first detection system coupled to the controller for detecting properties of the optical signal.

13. A system according to claim 12, further including a second detection system coupled to the controller for detecting properties of the phase-adjusted optical signal.

14. A system according to claim 1, wherein the first dispersive module includes one of a diffraction grating, a chromatic prism, an arrayed waveguide grating, and a virtually imaged phased array.

15. A system according to claim 1, wherein the PI-SLM is reflective.

16. A system according to claim 15, wherein the PI-SLM is one of a programmably deformable mirror, a micromirror array, a liquid-crystal based SLM, an electro-optic modulator and an acousto-optic modulator.

17. A system according to claim 1, wherein the PI-SLM is transmissive.

18. A system according to claim 17, wherein the PI-SLM is one of a programmably deformable mirror, a micromirror array, a liquid-crystal based SLM, an electro-optic modulator and an acousto-optic modulator.

19. A system according to claim 8, wherein the optical signal is emitted from a single optical fiber and a phase-corrected optical signal is received by the single optical fiber.

20. A system according to claim 19, further including a circulator to which the single optical fiber is coupled, and further including first and second optical fibers coupled to the circulator for respectively inputting the optical signal and outputting the phase-corrected optical signal.

21. A system according to claim 1, further including a polarization-adjusting member between the first dispersive module and the PI-SLM to reduce polarization-dependent loss (PDL).

22. A system according to claim 15, wherein the PI-SLM is arranged at an angle relative to an axis passing normally through the active area so that the optical signal and the phase-corrected optical signal do not traverse the same optical path.

23. A system according to claim 1, further including a magnification optical system arranged downstream of the first dispersive module and designed to relay with magnification the frequency components onto the active area of the PI-SLM.

24. A system according to claim 1, wherein the PI-SLM has an active area with a dimension of 5 mm or less.

25. A system according to claim 24, wherein the addressable regions each have a dimension of about 100 microns or less.

26. A system according to claim 24, wherein the PI-SLM is reflective, and further including a magnification optical system arranged between the first dispersive module and the PI-SLM, wherein the magnification of the magnification optical system is designed to make the system shorter than it would be without the magnification optical system.

27. A system according to claim 26, wherein the magnification optical system includes a telescope.

28. A system according to claim 1, wherein the optical signal is a multiplexed optical signal comprising different
channel optical signals centered around different wavelengths and wherein the active area is divided up into sets of addressable regions corresponding to frequency components of the different channel optical signals.

29. An optical processing system for at least partially pre-compensating an optical signal for chromatic dispersion effects present in a downstream optical system, the system comprising:

a first dispersive module positioned to receive the optical signal and spatially separate frequency components of the optical signal;

a polarization-independent spatial light modulator (PILSLM) having an active area comprising a plurality of independently programmable addressable regions, the PILSLM arranged to receive the spatially separated components in the active area; and

a controller coupled to the PILSLM and configured to receive a compensation signal indicative of the chromatic dispersion effects in the downstream optical system that allows for the PILSLM to independently adjust the phase of one or more addressable regions in order to at least partially compensate the optical signal for chromatic dispersion of the downstream optical system.

30. A system according to claim 29, wherein the downstream optical system includes an optical fiber.

31. A system according to claim 29, wherein the compensation signal is obtained by providing a test signal to the downstream optical system.

32. An optical processing system for at least partially post-compensating an optical signal for chromatic dispersion effects present in an upstream optical system, the system comprising:

a first dispersive module positioned to receive the optical signal and spatially separate frequency components of the optical signal;

a polarization-independent spatial light modulator (PILSLM) having an active area comprising a plurality of independently programmable addressable regions, the PILSLM arranged to receive the spatially separated frequency components in the active area; and

a controller coupled to the PILSLM and configured to receive a compensation signal indicative of the chromatic dispersion effects in the upstream optical system that allows for the PILSLM to independently adjust the phase of one or more addressable regions in order to at least partially compensate the optical signal for chromatic dispersion of the upstream optical system.

33. A system according to claim 32, wherein the upstream optical system includes an optical fiber.

34. A system according to claim 32, wherein the compensation signal is obtained by providing a test signal to the upstream optical system.

35. A method of programmably adjusting the phase of the frequency components of an optical signal of arbitrary polarization, comprising:

spatially dispersing frequency components of the optical signal onto a polarization-independent spatial light modulator (PILSLM) over an active area having a plurality of independently programmable addressable regions; and

independently adjusting one or more of the addressable regions to alter the phase of the corresponding frequency components incident thereon.

36. A method according to claim 35, further including recombining the phase-altered frequency components to produce a compensated optical signal.

37. A method according to claim 35, wherein the independently adjusting the one or more addressable regions is performed as post-compensation for chromatic dispersion present in the optical signal.

38. A method according to claim 35, wherein independently adjusting the one or more addressable regions is performed as pre-compensation for chromatic dispersion anticipated to be introduced into the optical signal.

39. A method according to claim 35, wherein adjusting of the one or more addressable regions is performed in response to monitoring the chromatic dispersion effects of an optical system.

40. A method according to claim 35, wherein adjusting the one or more addressable regions is performed in response to monitoring the chromatic dispersion in the optical signal having passed through an optical system.

41. A method according to claim 35, wherein adjusting the one or more addressable regions is performed in response to monitoring the chromatic dispersion in the optical signal prior to the optical signal passing through an optical system.

42. A method according to claim 35, wherein adjusting of the one or more addressable regions is performed in response to a control signal provided to the PILSLM by a controller.

43. A method according to claim 42, wherein the control signal includes information based on a look-up table that relates an induced phase per pixel to a voltage provided to the addressable regions.

44. A method according to claim 35, wherein adjusting of the one or more addressable regions is based on a model of chromatic dispersion effects of an optical system.

45. A method according to claim 35, wherein the optical signal is a multiplexed optical signal comprising channel optical signals centered around different wavelengths, and wherein spatially dispersing the frequency components of the optical signal includes dividing up the active area of the PILSLM into sets of addressable regions corresponding to the frequency components of the different channel optical signals.

46. A method according to claim 45, wherein independently adjusting the one or more addressable regions includes further includes selectively phase-adjusting the frequency components of the channel optical signals using the corresponding sets of addressable regions to correct for chromatic dispersion present in the respective channel optical signals.

47. A method according to claim 35, wherein the PILSLM includes liquid crystal addressable regions arranged to ensure the PILSLM is polarization-insensitive.

48. A method according to claim 47, wherein the PILSLM is reflective and includes a single array of liquid crystal addressable regions, a polarization-adjusting element, and a reflective member, wherein the polarization adjusting element is designed to provide a total polarization rotation of 90-degrees for light passing twice there through.

49. A method according to claim 35, wherein spatially dispersing the optical signal is performed by using a grating, a prism, an arrayed waveguide grating or a virtually imaged phase array.

50. A method according to claim 36, including adjusting the polarization to reduce polarization-dependent loss due to spatially dispersing the frequency components and/or recombining the phase-altered frequency components.

51. A method of reducing the chromatic dispersion in optical signals traveling in different WDM channels in a multiplexed optical signal, comprising:

demultiplexing the optical signals in the multiplexed optical signal; and
performing chromatic dispersion compensation for each channel optical signal by spatially dispersing frequency components of each channel optical signal onto a polarization-independent spatial light modulator (PILS LM) over an active area having a plurality of independently programmable addressable regions, and independently adjusting one or more of the addressable regions to alter the phase of the corresponding frequency components incident thereon, and then recombining the phase-altered components to form a compensated channel optical signal.

52. A method according to claim 51, further including separately detecting each compensated channel optical signal.

53. A method according to claim 51, further including: multiplexing the compensated channel optical signals to form a compensated multiplexed optical signal.

54. A method according to claim 51, wherein performing chromatic dispersion compensation includes altering the phase of the frequency components of the channel optical signals to compensate for chromatic dispersion effects induced by an upstream optical system.

55. A method according to claim 51, wherein performing chromatic dispersion compensation includes altering the phase of the frequency components of the channel optical signals to compensate for anticipated chromatic dispersion effects of a downstream optical system.

56. A method of programmably adjusting the phase of the frequency components of an optical signal of arbitrary polarization over a short optical path, comprising: spatially dispersing frequency components of the optical signal onto a polarization-independent spatial light modulator (PILS LM) over an active area having a dimension of 5 mm or less and a plurality of independently programmable addressable regions within the active area; and independently adjusting one or more of the addressable regions to alter the phase of the corresponding frequency components incident thereon.

57. A method according to claim 56, further including relaying the spatially dispersed frequency components to the active area with magnification so that the optical path is shortened as compared to the optical path without magnification.

58. A method according to claim 56, wherein the PILS LM is reflective.

* * * * *
Polarization Mode Dispersion Compensation

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Notice: Subject to any disclaimer, the term of this patent is extended or adjusted under 35 U.S.C. 154(b) by 730 days.

Appl. No.: 12/425,919
Filed: Apr. 17, 2009

Prior Publication Data

Related U.S. Application Data
Provisional application No. 61/046,128, filed on Apr. 18, 2008.

Int. Cl. H04B 10/2569 (2013.01)
U.S. Cl. USPC ........... 398/208; 398/147; 398/152; 398/159; 398/184; 398/194

Field of Classification Search
USPC ................... 398/159, 147, 152, 184, 194, 208

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Abstract
An apparatus and method for correcting for the polarization mode distortion of an optical signal is described. The optical data signal to be transmitted is processed by a switch configured to place the signal into a plurality of polarization states on a periodic basis. At the receiving end of the system, a portion of the signal is coupled to a polarimeter and the wavelength-dependent state of polarization (SOP) of the received signal determined for the plurality of polarization states imposed on the transmitted signal. The data for two of the transmitted polarization states is selected to be used as the basis for correcting the SOP so as to compensate for the wavelength dependence thereof. The corrections may be applied in an optical pulse shaper.

42 Claims, 7 Drawing Sheets
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* cited by examiner
Polarization Mode Dispersion Compensation

This application claims the benefit of priority to U.S. provisional application Ser. No. 61/046,128 filed on Apr. 18, 2008, which is incorporated herein by reference.

STATEMENT OF GOVERNMENT SPONSORSHIP

This invention was made with Government support under contract 9501366-LCS awarded by the National Science Foundation. The Government has certain rights in this invention.

TECHNICAL FIELD

The present application may relate to the measurement and correction of dispersion in optical systems, and in particular to the use in telecommunications or sensing.

BACKGROUND

Optical telecommunications systems may use single-mode or multimode optical fibers to guide light having data modulations imposed thereon so as to transmit information over a distance. Typically the transmission distance is limited by such factors as power loss in the fiber, and the dispersion or distortion of the signal due to intrinsic properties of the optical waveguide, or imperfections in the fiber due to manufacturing defects, the environment, or non-linear effects such as four-wave mixing. Two types of linear distortion mechanisms are chromatic and polarization mode dispersion.

Chromatic, or intramodal, dispersion occurs in both single mode and multimode optical fibers. Chromatic dispersion occurs because different wavelengths of light travel through the fiber waveguide at different speeds. Since the different wavelengths of light have different velocities, some wavelengths of a signal arrive at the fiber end before others. This delay difference leads to pulse broadening.

In an ideal optical fiber, the light-guiding core has a perfectly circular cross-section, and the fundamental electromagnetic propagating mode may be described as having two orthogonal polarizations that travel at the same velocity at each wavelength. The orientation of the polarization axes with respect to the local fiber axis is not a consideration, as the two polarizations propagate with identical properties due to the circular symmetry of the fiber. However, in practice, this ideal state is not achieved, and there are asymmetrical propagation properties with respect to the polarization components.

Symmetry-breaking imperfections fall into several categories: geometric asymmetry: e.g., slightly elliptical cores; and, stress-induced material birefringence. These can arise from either imperfection in manufacturing (which is never perfect or stress-free) or from thermal and mechanical stresses imposed on the fiber when installed is a system. The latter stresses may vary with time, for example, as the temperature changes. These effects cause the polarization and delay of a signal transmitted over a distance to vary as a function of wavelength and time in an apparently random manner, and is called polarization mode dispersion (PMD). PMD is a factor limiting the upgrade of existing optical fiber communication systems and on the transmission bandwidth in new designs. Traditional PMD compensators typically work in a low-order (first- and second-order as function of wavelength) PMD approximation. In the first-order approximation, the effect of PMD is modeled as a birefringence with frequency-independent magnitude and with frequency-independent axes (which are often called the principal states of polarization (PSP)). However, as the bandwidth of telecommunication systems increases, higher-order PMD effects become increasingly important, and the PSPs and the magnitude of the equivalent birefringence become strongly frequency dependent.

SUMMARY

An apparatus for compensating distortion of an optical signal is disclosed, including a receiver, adapted to accept the optical signal from a proximal end of an optical network. The receiver includes a polarimeter for characterizing the wavelength dependent state of polarization of the received signal. A controller is configured to analyze the polarimeter data so as to determine the wavelength dependent optical network characteristics and the corrections needed to compensate such characteristics. A pulse shaper is controlled to perform the compensation so that the effects of the optical network are mitigated. The optical signal transmitted over the optical network may have data modulated thereon. At the transmitting end of the optical network the state of polarization (SOP) of the optical signal is modified by a polarization transfer matrix switch such that there are at least two states of polarization, prior to coupling the optical signal to the optical network.

In another aspect, an apparatus for transmitting an optical signal having a data modulation includes a polarization transfer matrix switch, the switch being configurable to modify the SOP of the optical signal to at least two polarization states prior to transmission over an optical fiber, and a switching rate of the polarization transfer matrix switch is substantially lower than a data rate of the data modulated on the optical signal.

In yet another aspect, a system for compensation of distortion of an optical signal includes a transmitting portion and a receiving portion. The transmitting portion may include a polarization transfer matrix switch, the switch being configurable to periodically modify the state of polarization (SOP) of an input optical signal between at least two output optical signal polarization states. The switch output signal may be coupled to an input of an optical transmission device. The receiving portion is adapted to receive an optical signal output by the optical transmission device, and further comprises a polarimeter and a pulse shaper.

A method of compensating for distortion of an optical signal used for transmitting data includes receiving an output optical signal from an optical fiber. A state-of-polarization (SOP) of the input optical signal to the optical fiber is periodically modified by a Jones matrix switch prior to transmission over the optical fiber so as to have at least two different polarization states. The SOP of the received optical signal is measured as a function of wavelength for the different transmitted polarization states. A wavelength dependent polarization and phase correction to the polarization and phase of the output signal is determined so that the polarization state becomes frequency independent. The computed corrections are used to modify the received signal in a pulse shaper.

In another aspect, a method of transmitting an optical signal includes accepting an optical signal modulated at a data rate; and, periodically modifying the state of polarization (SOP) of the optical signal into a plurality of polarization states using a polarization transfer matrix switch. The optical signal having a sequence of polarization states is coupled to an optical transmission device. The rate of switching the
polarization transfer switch is substantially lower than a data rate of the data to be transmitted on the optical signal.

A computer program product having instructions, stored on a machine readable medium, is described. The instructions configure a computer to receive a measurement output of a polarimeter, measuring a received signal from a transmission system, and to determine a first wavelength-dependent Jones matrix characterizing the transmission system, wherein a state of polarization of the received optical signal has been modified in a periodic manner to at least two states of polarization prior to transmission. A second wavelength dependent Jones matrix is computed such that a third Jones matrix being the concatenation of the first Jones matrix and the second Jones matrix is a frequency independent Jones matrix. The computer is further configured to control a pulse shaper capable of modifying a polarization of a received optical signal based on the second Jones matrix on a wavelength dependent basis.

BRIEF DESCRIPTION OF THE DRAWINGS

FIG. 1 illustrates the relationship of the Poincare sphere to the Stokes vectors, showing the principal states of polarization along the orthogonal axes and elliptical polarization elsewhere;

FIG. 2 is a Poincare sphere representation showing the effect of polarization-mode-dispersion of an 800 fs optical pulse passed through a PMD simulator with a mean differential group delay (DGD) of about 5.5 ps;

FIG. 3 is a block diagram of an experimental example of correction of polarization mode distortion according to an embodiment;

FIG. 4 is a Poincare sphere representation of PMD simulator output SOP spectra corresponding to the 4 FLC states 00, 01, 10, and 11 over a spectrum range is 1545.5-1554.7 nm, and each point corresponds to a measured SOP vector at a specified wavelength;

FIG. 5 shows (A) the output pulses for two fixed states of polarization at the input of the PMD simulator and (B), the pulses for the two fixed states of polarization after correction for PMD as described herein; and

FIG. 6 shows simplified block diagram of a wavelength-parallel polarimeter; and

FIG. 7 shows a block diagram of an optical telecommunications system with PMD correction capability.

DESCRIPTION

Exemplary embodiments may be better understood with reference to the drawings, but these examples are not intended to be of a limiting nature. Like numbered elements in the same or different drawings perform equivalent functions. When a specific feature, structure, or characteristic is described in connection with an example, it will be understood that one skilled in the art may effect such feature, structure, or characteristic in connection with other examples, whether or not explicitly stated herein. Embodiments of this invention may be implemented in hardware, firmware, software, or any combination thereof, and may include instructions stored on a machine-readable medium, which may be read and executed by one or more processors.

Optical components may be discrete, as in bulk optics components, or incorporated as functions in integrated modules. Light propagation may be in free space, or waveguide constrained, where the constraining means includes optical fiber, planar waveguides, arrayed wavelength gratings (AWG), dispersive media, or the like. The descriptions herein generally use the laboratory apparatus for the experiments described, however such equipment descriptions are not meant to be limiting.

In the interest of clarity, not all the routine features of the implementations described herein are described. It will of course be appreciated that in the development of any such actual implementation, numerous implementation-specific decisions must be made to achieve a developers' specific goals, such as compliance with system and business related constraints, and that these goals will vary from one implementation to another. Moreover, it will be appreciated that such a development effort might be complex and time-consuming, but would nevertheless be a routine undertaking of engineering for those of ordinary skill in the art having the benefit of this disclosure.

There are a variety of mathematical schemas used to characterize the polarization properties of an electromagnetic signal, and the description herein could have equally been presented in any of a variety of such systems. Therefore the use of such constructs as a Poincare sphere, Stokes parameters, Jones matrix, polarization transfer switch, and the like is not intended to be a limitation on the scope of the subject matter described herein. The terms frequency-dependent and wavelength-dependent are sometimes used to describe characteristics of the optical signals, transmission media, or devices, and a person of ordinary skill in the art will understand that these are equivalent ways of describing the characteristics, the frequency and wavelength being inversely proportional to each other. Similarly, optical signals, lightwave signals, and the like, are used generally without intending to distinguish between the usage.

The polarization properties of an optical signal may be described as a vector combination of two orthogonal signals, where the amplitude and relative phase of the signals produces a linear, circular, or elliptically polarized result. One way of visualizing the signal is a Poincare sphere and Stokes coordinate system as shown in FIG. 1. The orthogonal axis system represents linear horizontal and vertical polarizations, slant 45° polarizations, and right and left hand circular polarizations along the positive and negative principal axes, and elliptical polarization, with varying ellipticity, for the vector space that is off-axis. The state of polarization (SOP) of a signal may be represented by a point on the sphere, and the SOP may be shown, for example, as a function of time, or of wavelength. In the present discussion, the SOP of a light signal will be shown as a function of wavelength at a particular epoch.

In an aspect, polarized light may be represented as a Jones vector,

$$\begin{cases} E_{x}(t) \\ E_{y}(t) \end{cases}$$

where $E_{x}(t)$ and $E_{y}(t)$ are the transverse x and y components of the electric field of the light wave. Passive optical elements may be characterized based on their effect on the polarization of an optical signal passing therethrough, so that the effects of optical elements such as a quarter wave plate, a half wave plate, a polarizer, or the like may be represented by a Jones matrix multiplication operation.

FIG. 2 shows the effect of polarization-mode-dispersion of an 800 fs optical pulse passed through a PMD simulator with a mean differential group delay (DGD) of about 5.5 ps. The points on the surface of the Poincare sphere represent the frequency-dependent SOP of the signal over a frequency
range of about 1.2 THz at a central wavelength of about 1549.6 nm. FIG. 2A shows the results which obtain when the input SOP is linear, and FIG. 2B shows the results which obtain when the input SOP is right hand circular (RHC). To obtain this data, the input states of polarization were wavelength independent, and the input state of polarization at the transmission end of the system corresponding to each of the wavelength-dependent polarization plots of the output data shown in FIG. 2 would be a single point on the Poincare sphere. This illustrates that the output SOP depends on the input SOP to the PMD simulator, where the PMD simulator represents the transmission system. As such, a single wavelength-independent compensation would not be effective in correcting PMD.

The Jones matrix characterization of an optical path (excluding the isotropic chromatic dispersion and losses) can be written as:

\[
J_\nu = \begin{bmatrix} \cos \theta & -\sin \theta e^{j\varphi} \\ \sin \theta e^{j\varphi} & \cos \theta \end{bmatrix},
\]

where \(\theta\), \(\varphi\), and \(\varphi\) are frequency dependent angles. The Jones matrix itself is independent of the input polarization and represents the characteristics of the physical system; however output polarization of a signal transmitted through the system depends on the input polarization through the Jones matrix transformation. By measuring the output state-of-polarization (output SOP) corresponding to 0° linear and 45° linear input states of polarization (input SOP) to a device or optical path, one can determine \(\theta\), \(\varphi\), and \(\varphi\) as a function of frequency. PMD may be associated with the wavelength dependence of the Jones matrix and wavelength-dependent compensation of the PMD can be achieved by correcting the Jones matrix to a constant, wavelength-independent matrix. Where the term wavelength independent is used, a person of skill in the art would recognize that the ability to render the resultant signal wavelength independent is influenced by measurement errors such as due to signal-to-noise ratio, bandwidth, resolution of the polarization measurements, the rate of temporal change of the system characteristics, and the like.

The wavelength dependence of the Jones matrix, may be characterized by sequentially transforming an arbitrary input SOP from an optical source or modulator to at least two different SOPs, launching the optical signal into the fiber link, and measuring the output SOP as a function of wavelength. In the experiments described herein, four states of a polarization transfer (Jones matrix) switch were used.

At the receiving end of the transmission path (simulated by passing the optical signal through the PMD simulator), two output SOP wavelength-dependent polarization spectra whose relative angle is closest to 90° on the Poincare sphere are selected. By associating one of the selected output SOP spectra with a 0° linear input SOP, and the normalized cross product of the two selected output SOPs with a 45° linear input SOP; a correction matrix to the wavelength-dependent Jones matrix \(J_\nu \cdot J_\nu\) is obtained, where \(J_\nu\) is a frequency independent matrix and \(J_\nu\) would transform one of the selected SOPs to a 0° linear state and the normalized cross product of the two selected SOPs to a 45° linear state. The effect of noise on the measurement of the cross product is reduced when the angle between the two selected to be approximately 90°, although relative angles of between 60° and 120° may be used.

The inverse of

\[
J_\nu^{-1} = \begin{bmatrix} \frac{\exp(-j\theta)}{\cos \theta} & 0 \\ 0 & \frac{\exp(-j\theta)}{\cos \theta} \end{bmatrix}
\]

where \(\theta_1 = (\phi + \psi)/2 + \pi/4\), \(\theta_2 = \theta\), and \(\theta_3 = (\phi - \psi)/2 - \pi/4\) and each of these angles is wavelength dependent. To achieve wavelength-by-wavelength Jones matrix correction, the optical frequency components of the received signal are spatially dispersed in a pulse shaping configuration so that small wavelength intervals within the signal bandwidth may be individually corrected and then recombined.

A 4-layer liquid crystal modulator array (LCM) as the spatial light modulator (SLM) may be used to realize the three elementary rotation matrices of equation (2), which allows full compensation of the PMD in a single pulse shaper apparatus. Formally, the adjustments effected by each wavelength resolution element of the SLM can be expressed as a polarization transfer matrix \(M\). Because a dispersive module maps different optical wavelength components onto the different pixels of SLM the effective polarization transfer matrix of the SLM becomes frequency dependent, \(M(\omega)\). The electric field \(E_{\text{field}}(\omega)\) of adjusted optical signal following transmission through a compensation system can be expressed as:

\[
E_{\text{field}}(\omega) = M(\omega)E_{\text{field}}(\omega)
\]

where \(E_{\text{field}}(\omega)\) is the electric field vector of the PMD-distorted lightwave signal. Matrix \(M\) is a 2-by-2 Hermitian matrix; it has four degrees of freedom and its elements may take on complex values. When each pixel of SLM independently controls all four degrees of freedom of the polarization transfer matrix, the SLM can independently control the SOP of phase of the spatially dispersed frequency components, and thereby completely compensate for the wavelength-dependent polarization effects imparted by optical system. Even when the pixels of the SLM control less than all four of the degrees of the polarization transfer matrix, the distortions caused by optical system can be reduced, if not completely compensated. Both the SOP and the phase or only the SOP may be corrected.

Each LCM layer of an LCM functions as a linear retarder array having, for example, 128 active regions with a fixed fast axis and arbitrarily adjustable retardance in the slow axis. The orientations of the fast axis of each of the four LCM layers may be 0°, 45°, 90°, and 180°, respectively with respect to a reference direction perpendicular to the light path. The first three layers (0°, 45°, -45°) may be operated to produce the three elementary rotation matrices on the right side of Eq (2). After that operation, the isotropic residual spectral phase of \((-\theta_0 + \theta_3 + \theta_4\)) remains, which may be considered an isotropic or chromatic phase and which may include any residual chromatic dispersion not otherwise compensated.

The third and fourth LCM layers may be programmed in a common-mode configuration to have a value opposite of the residual phase, thus removing the remaining isotropic phase, and the phase of the third LCM layer may also be pro-
A controller causes a spatial light modulator (SLM) 140 to independently adjust one or more properties of the spatially-separated wavelength components to produce PMD-compensated wavelength components. The dispersive module 160 then spatially recombines the adjusted wavelength components to produce a compensated lightwave signal, which may be coupled out of the pulse shaper 80 as a beam which may propagate in a fiber. The effect of the compensation system is to reduce the distortions in the lightwave signal caused by the transmission system (represented here by the PMD simulator 70 and polarization controller 55). In a telecommunications system, the transmission system may include an optical fiber, and interface equipment which may include frequency division multiplexers (FDM), add-drop multiplexers, fixed dispersion compensators, optical routing switches, and the like.

The modules 130 and 160 may include dispersive elements for spatially separating or combining wavelength components. For example, the modules may include a diffraction grating (e.g., a reflective grating, transmissive grating, an amplitude grating, a phase grating, a holographic grating, echelle grating, arrayed-waveguide grating, or the like), a chromatic prism, and/or a virtually imaged phased array (VIPA). The dispersive modules may further include one or more imaging optics components 120, 150 (e.g., lenses, mirrors, apertures, etc.) for directing the frequency components that have been spatially separated by the dispersive element in module 130 onto the LCM 140, and for directing the adjusted wavelength components from SLM 140 to the dispersive element in module 160. In an aspect, the dispersive modules can be a single optical element that combines the dispersing and directing functions, e.g., the dispersive module can be a diffractive optical element (DOE).

The term "pulse shaper", as used herein, is intended to denote an ability to modify the spectral properties of a broadband optical signal. The optical signal may be spread over an optical bandwidth by on-off pulse modulation, phase modulation, amplitude modulation, or a combination of such modulation techniques. The pulse shaper 80 is representative of devices that can process such broadband signals and modify the properties selectable wavelength regions of the signal. The examples shown herein are for optical pulses, as such pulses and the distortion effects thereof are familiar to persons of skill in the art, and the effect of the apparatus and method described herein would be more easily understood. A constant amplitude signal having an equivalent bandwidth could equivalently be processed.

The spatial light modulator 140 (SLM) may be a liquid crystal modulator (LCM) and may include at least one liquid crystal layer. For example, the SLM may include four liquid crystal (LC) layers, wherein the LC molecules in each of the LC layers are oriented along an axis, and wherein the axis for each of the LC layers may be different from the axis of another of the adjacent LC layers. In some embodiments, the axes may differ from one another by an absolute amount of about 45° or a multiple thereof. The number of active elements in the modulator, and the spatial distribution of the elements depend on the specific design of the compensation module, and the wavelength range to be compensated.

At present, the use of SLM which is an LCD is convenient due to the state of development of the apparatus, however, SLM may use other materials and construction, including, for example, ferro-optoelectric materials, such as lithium niobate, optically active polymers, or the like, having the same or similar effect.

The specific correction to be applied to each of the wavelength components is determined by measurements made using a polarimeter. In the experimental data described herein
a grating-based wavelength-parallel polarimeter was used. Another configuration of wavelength-parallel polarimeter having a VIPA dispersive element is shown in Fig. 6c, see, for example, U.S. Pat. No. 7,166,419, issued to one of the present inventors, and incorporated herein by reference. A non-polarizing beam splitter 170 (NPBS) may direct a fraction of the light to the polarimeter 180 for SOP sensing. The beamsplitter 170 may be integrated into the compensation module 80, as shown, so as to use the input dispersive module 130 to spatially separate the input signal for the purposes of polarization measurement as well as the purpose of applying the corrections of the correction module.

Alternatively, the sample of the light which is to be measured by the polarimeter may be obtained by a beamsplitter located prior to the input of the pulse shaper 80. The beamsplitter may be any of the techniques that are capable of obtaining a sample of the signal output from the transmission system, and may include partial mirrors, prisms, directional couplers and the like which may be implemented in bulk optics, integrated optical module, optical fiber, or the like, or a combination thereof.

Temporal profiles of pulses before and after PMD compensation may be measured by, for example, an intensity cross-correlation technique. In the examples shown, the overall chromatic dispersion of the entire apparatus was pre-compensated.

The input SOP prior to the Jones matrix switch 60, may be arbitrary so long as the input SOP is substantially constant during each measurement cycle. A Jones matrix (polarization) switch may be comprised of a plurality of FLC retarders. Each FLC may be configured to act as a quarter-wave retarder at 1550 nm and may have two stable optic-axis orientations separated by approximately 45°. The switching time of the present Jones matrix switch is about 70 μs. The orientations of the axes of the two FLC’s were 0° (state 0), −45° (state 1), and 45° (state 0), −90° (state 1). The SOP transformations may be denoted by the combination of the states of the FLC as 90, 01, 10, and 11.

While a light source 50 such as a laser may be strongly polarized, the light may be transmitted between the laser, a data modulator, and the Jones matrix switch using single mode (non-polarization maintaining fiber) and the state of polarization SOP at the input to the Jones matrix switch may vary depending on the optical components disposed between the light source 50 and the Jones matrix switch 60 and may also vary with time due to environmental effects, such as temperature, and stress. The Jones matrix switching rate and the update rate of the polarimeter are selected to be sufficiently rapid such that the measurements made represent the temporal dependence of the PMD of the transmission system. This may permit the combination of a plurality of individual modulated optical central frequencies to be combined in a wavelength division multiplexer (WDM) prior to the Jones matrix switch.

Under such circumstances, where four Jones matrix switch states are configured, having approximately orthogonal properties on the Poincare sphere, numerical simulation studies have shown that that, for any input SOP to the Jones matrix switch, there are at least two Jones matrix switch states yielding SOPs from the output from the transmission system (here simulated by the PMD simulator 70) separated by an angle in the range between 60° and 120° on the Poincare sphere. The output light of the optical fiber (or PMD simulator 70) is connected to a fiber-pigtailed pulse shaper incorporating SLM which is a four-layer liquid-crystal modulator (LCM). This LCM is presently a laboratory device, specially fabricated by CRI. Inc. (Woburn, Mass.). A commercial two-layer version is available, of which two were packaged together to form the apparatus used. A multi-layer LCM array is described in U.S. Pat. No. 5,719,691 to Weifers et al., which is incorporated herein by reference.

FIG. 4 shows an example of four Poincare sphere plots (corresponding to the four states of the Jones matrix switch used in the experiment) of the wavelength dependence of the SOP when distorted by the PMD of the simulator. Each dot on the sphere represents a wavelength that has been measured at an equally-spaced interval in the wavelength domain, and adjacent wavelength measurements for the same input SOP are connected by lines. The strong wavelength-dependent variation of the output SOPs is indicative of significant all-order PMD effects. That is, the PMD characteristic has a wavelength dependence which, if described in a power series expansion, would have more than a constant and a linear term, and the higher order terms may have significant effects.

The average measured angles between data from FLC states 00-01, 00-10, 01-10, 01-11, and 10-11 were computed as 89.2°, 107.9°, 107.2°, 159.4°, 108.9°, and 59.0°. Data from 00-01 states, having an average angle difference of 89.2°, was selected for control of the PMD compensator.

The PMD distorted signal was launched into a grating-based transmission-type pulse shaper incorporating the 4-layer LCM as the SLM for PMD compensation. Each LCM layer functions as a linear retarder array (128 independently addressable pixels) with a specified fast axis and adjustable slow axis retardance. The retardance is controlled by a microprocessor applied to each stripe of each layer of the LCM, and is determined by a computer, which may be a microprocessor.

FIGS. 5A and 5B show the PMD distorted pulses and the restored pulses after PMD compensation, respectively. Temporal profiles of pulses before and after PMD compensation were measured using an intensity cross-correlation technique. Since the PMD-distorted pulses are input-polarization dependent, the temporal intensity profiles of the pulses were measured at two orthogonal input polarization states (0° and 90° linear) selected by a polarizer. During this portion of the experiment, the FLC retarders of the Jones matrix switch 70 at the transmission end were stable (00 state).

The peak intensity of the restored pulse at 0° linear SOP is normalized to 1. After compensation, the pulse has been compressed from more than 10 ps (10% intensity) to 825 fs full-width at half maximum (FWHM). The output SOP of state 00 is corrected to 0° linear state at the output of the pulse shaper, as predicted in theory. Similar results were obtained for other Jones matrix switching states where the average angle differences were between 60° and 120°.

The same experiment was repeated with more than 20 independent PMD profiles and input SOPs to the Jones matrix switch. Each time, the pulses were compressed to about 800 fs duration after PMD compensation.

The PMD compensation apparatus is compatible with simultaneous real-time and compensation. To demonstrate this, the intensity profiles of the restored pulses were measured while switching states of the Jones matrix at a rate of up to 2000 Hz during the experiments. No significant change in the restored pulse width was observed. The value of 2000 Hz was chosen for experimental convenience and is not meant to be a limitation.

An example of a wavelength-parallel polarimeter shown in FIG. 6A, where a first stage is a polarization component selector, having a pair of fast-switching ferroelectric liquid crystal (FLC) retarders 510 and a polarizer 515. The FLCs were anti-reflection coated, and had a fixed quarter-wave phase retardation for 1550 nm light. The fast optical axis of the first FLC was switched between 90° and 135°, the fast
optical axis of the second FLC was switched between 135° and 180°, and the polarizer was fixed at horizontal (0°). The FLC pair and the polarizer were used to sequentially transform the SOP of the analyzed light, permitting determination of four polarization components of the light under being measured. With the knowledge of these four polarization components, the polarization Stokes parameters of the light can be found.

In the second stage of the polarimeter 180, the light is wavelength dispersed onto a photo-detector array for wavelength-parallel operation. High spectral resolution over a broad bandwidth may be obtained by using a 2-D spectral dispersion geometry in a virtually-imaged phased array and a diffraction grating. The light beam is focused onto a VIPA 530 (Avanex, Freemont, Calif.) by a cylindrical lens 520. The VIPA has a free spectral range (FSR), thus spectrally periodically dispersing segments of the bandwidth in an x-direction. A diffraction grating 540 is placed so as to spatially separate the FSRs of the VIPA in a y-direction. In order to improve FSR isolations, a beam expander 550 may be inserted prior to the grating 540 to increase the beam width at the grating so as to result in higher spectral resolution in the grating dispersion direction. A lens 570 may direct the two-dimensional spectral patterns onto photodetector 580, which may be a camera having an InGaAs detector array (such as the Indigo Alpha NIR™, Photon, San Jose, Calif.). The signal intensities measured by the camera may be communicated to a computer or controller (not shown) that analyzes the data to compute the required wavelength-dependent Stokes parameters. FIG. 6A shows schematically a representation of the 2D image which would be formed on the detector array of the camera 580, where the spectrum is segmented in intervals corresponding to the FSR of the VIPA 530, and the intensity represents the signal strength as a function of wavelength.

Other types of polarimeter may be used depending on the response time, resolution, and bandwidth of the system for which they are intended. Such polarimeters may, for example, measure the properties of the signal in a wavelength-sequential manner, or may sample the wavelength spectrum.

Similarly to the use of two-dimensional spectral dispersal for polarimetry, an optical signal whose PMD is to be compensated could dispersive in two-dimensions in the pulse shaper so as to either increase the spectral resolution of the compensation or to increase the bandwidth over which PMD compensation can be provided using a single apparatus. Such wide-bandwidth uses may be compatible with the concept of wavelength division multiplexing (WDM) where a plurality of optical signals, each having a different central wavelength, are multiplexed with data, optically multiplexed, and transmitted over the same optical fiber.

The composite optical signal at the transmitting end may be processed in the Jones matrix switch as described above at the sending end, and a polarimeter and pulse shaper may be used to process the received optical signal at the receiving end before the received optical signal is separated into the individual WDM channels for further processing.

The pulse shaper may be a two dimensional LCD array, having a pixelated construction, so as to individually compensate each wavelength interval in the two-dimensionally-dispersed spectrum. Gaps in the wavelength coverage may correspond to guard bands between the individual WDM channels.

The concepts described above may be used in an optical telecommunications or sensing system to correct for polarization distortions, such as polarization mode distortion (PMD) occurring in the fiber, or in other components of the optical system. FIG. 7 shows a block diagram of an optical telecommunications system 700 having an optical source 710, which may be, for example a semiconductor laser or fiber laser. The light is modulated with a signal representing the data information content to be transmitted from the transmitting end to the receiving end. The signal may be amplitude or phase modulated onto the optical source signal in a modulator 720, which may be an integrated optics device using interferometric or other techniques, an absorptive modulator, a switch, or the like, and routed through a Jones matrix switch 730, to periodically modify the polarization state of the signal at the input to the optical fiber transmission system 740. The optical fiber transmission system 740 may have one or more components exhibiting PMD.

The multiple-polarization-state modulated signal output from the Jones matrix switch 730 may be coupled directly to an optical fiber at a proximal end, or may be coupled to the fiber through ancillary terminal equipment such as a wavelength division multiplexer (WDM) or other interface equipment (not shown), as is known in the art. At the distal end of the telecommunications link path where the optical signal is to be recovered, the optical signal output from the fiber or the distal-end WDM equipment may be coupled to the PMD compensator 800.

The PMD compensator may include a pulse shaper 840, which may be a grating based pulse shaper similar to that described above, a VIPA based pulse shaper, or any apparatus capable of performing a polarization transfer matrix operation on an optical data signal, as is known in the art. A sample of the received signal is also routed to a polarimeter 820, to measure the wavelength-dependent state-of-polarization (SOP) of the received signal. The coupling of the signal to the polarimeter may be by a prism, a partially reflecting surface, a directional coupler or similar device (not shown).

The wavelength-dependent Stokes parameters obtained by the polarimeter may be used to compute the corrections to the Jones matrix so as to render it wavelength-independent over the bandwidth being compensated. The compensation computation is performed by a computer or controller 850 executing stored instructions to configure the computer 850 to receive the output of the polarimeter 820 and to control the pulse shaper 840, the pulse shaper having wavelength dispersing modules and a spatial light modulator operable to apply a correction to the signal on a wavelength-by-wavelength basis, with a resolution consistent with the remainder of the system design. After being initialized, the variation in PMD may be continually compensated using the output of the polarimeter to adjust the parameters for correcting the Jones matrix to a frequency independent state and controlling the pulse shaper accordingly, as the changes in PMD, and any polarization changes at the input to the Jones matrix switch at the transmitting end or in the transmission system are slow with respect to the Jones matrix switching rate.

The resultant compensated optical output will have a polarization state corresponding to the polarization states that were imposed on the signal at the sending end. However, the polarization states will be substantially independent of the effects of PDM associated with the transmission path. If the state of polarization at the input to the Jones matrix switch at the transmitting end is controllable, similar results may be obtainable using only two orthogonal states of the Jones matrix switch. If such a PMD-compensated signal were to be displayed in a Poincare sphere, the wavelength-dependent polarization characteristic of the output of the transmission system would not be observed, as the polarizations would be collapsed into the same number of discrete polarizations as were imposed on the signal by the Jones matrix switch at the transmitting end.
A method of correcting for polarization mode distortion (PMD) comprises the steps of: using a Jones matrix polarization state switch to modify the polarization state of a transmitted signal in a known sequence of states; coupling the output of the Jones matrix switch to an optical transmission system, which may be a fiber optic telecommunications system; and, coupling the output of the optical transmission at the receiving end of the system path to a polarization mode dispersion compensator.

In an aspect, the polarization mode dispersion compensator performs the steps of coupling a portion of the output signal to a polarimeter where the wavelength-dependent state of polarization (SOP) is measured for each of at least two states of polarization of the transmitted signal. A further step of selecting the two SOP measurements corresponding to transmitted polarization states and having a difference angle on the Poincare sphere closest to 90° and, at each wavelength, the step of computing the cross product of the two selected SOP data sets is performed. One of the two selected SOPs is associated with the output SOP for 0° linear input, and the cross product is associated with the output SOP for slant 45° linear input. The SOP data are used to compute a wavelength-dependent Jones matrix. In another step, a Jones matrix is computed such that the concatenation of the computed Jones matrix and the wavelength-dependent Jones matrix becomes frequency independent. The computed Jones matrix is used to control the compensations applied to the pulse shaper.

In an aspect, the pairs of data to be associated with the input switched states of polarization may have difference angles in the range of about 60° to about 120°. Depending on the state of polarization of the optical signal at the input to the transmitting Jones matrix switch, a different pair of the four states may be selected to have the appropriate difference angle.

The method and apparatus provides for wavelength-parallel Jones matrix (or equivalently Muller matrix) sensing of an optical signal with an arbitrary input SOP, and all-order PMD compensation based on a computed wavelength-dependent Jones matrix (or equivalently Muller matrix) to control the correction of the received signal.

In another aspect, a method of compensating for PMD includes: providing a pre-compensation signal indicative of wavelength-dependent polarization effects in an optical system; spatially dispersing wavelength components of an optical signal in a spatial light modulator (SLM) disposed at a transmitting end thereof; and independently adjusting the polarization transfer matrix of multiple regions of the SLM to pre-compensate the optical signal for distortions caused by the wavelength-dependent polarization effects in the optical system. In this configuration, the PMD is measured as before, at the receiving end, and a low-bandwidth signal transmitted from the receiving end to the transmitting end so as to control the Jones matrix properties of the SLM. This may fully or partially pre-compensate for the transmission system induced PMD.

While the methods disclosed herein have been described and shown with reference to particular steps performed in a particular order, it will be understood that these steps may be combined, sub-divided, or reordered to from an equivalent method without departing from the teachings of the present invention. Accordingly, unless specifically indicated herein, the order and grouping of steps is not a limitation of the present invention.

The apparatus and methods described herein may be controlled by a microprocessor controller, computer, or the like, which may be either a separate unit or integral to one of the other component units. The instructions for implementing processes of the apparatus or method may be provided on computer-readable storage media or memories, such as a cache, buffer, RAM, removable media, hard drive or other computer-readable storage media. Computer-readable storage media may include various types of volatile and nonvolatile storage media. The functions, acts or tasks illustrated in the figures or described herein may be executed in response to one or more sets of instructions stored in or on computer-readable storage media. The functions, acts or tasks may be independent of the particular type of instruction set, storage media, processor or processing strategy and may be performed by software, hardware, integrated circuits, firmware, micro code and the like, operating alone or in combination. Some aspects of the functions, acts, or tasks may be performed by dedicated hardware.

In an embodiment, the instructions may be stored on a removable media device for reading by local or remote systems. In other embodiments, the instructions may be stored in a remote location for transfer through a computer network, a local or wide area network, by wireless techniques, or over telephone lines. In yet other embodiments, the instructions are stored within a given computer, system, or device.

In an aspect, a computer, controller, or similar programmable device may be used to receive the output of a polarimeter, compute the corrections to be applied to the received signal, and to control the operation of a pulse shaper so as to compensate for wavelength-dependent polarization-mode-related distortions of a signal received over a transmission system.

Although the present invention has been explained by way of the embodiments described above, it should be understood to the ordinary skilled person in the art that the invention is not limited to the embodiments, but rather that various changes or modifications thereof are possible without departing from the spirit of the invention. Accordingly, the scope of the invention shall be determined only by the appended claims and their equivalents.

What is claimed is:
1. An apparatus for compensating distortion of an optical signal, comprising:
   a receiver, adapted to accept the optical signal from a proximal end of an optical fiber, further comprising: a polarimeter;
   a pulse shaper; and
   a controller configured to use wavelength-dependent polarization measurements output by the polarimeter to control the pulse shaper,
   wherein the optical signal is controlled to have at least two discrete states of polarization (SOP) prior to coupling the optical signal to a distal end of the optical fiber.
2. The apparatus of claim 1, wherein the SOP is controlled by a polarization transfer matrix switch.
3. The apparatus of claim 1, wherein the pulse shaper is comprised of a plurality of optical filters, spaced apart in wavelength and having substantially the same bandwidth.
4. The apparatus of claim 1, wherein the pulse shaper is configured to compensate the received signal for all orders of polarization mode distortion (PMD) consistent with the bandwidth of the optical filters.
5. The apparatus of claim 1, wherein the SOP has at least two discrete states that are substantially orthogonal to each other when displayed on a Poincare sphere.
6. The apparatus of claim 1, wherein a rate of modifying the optical signal is substantially less than the data rate of data to be modulated onto the optical signal prior to coupling to the distal end of the optical fiber.
7. The apparatus of claim 1, wherein the pulse shaper includes a spatial light modulator (SLM).
8. The apparatus of claim 7, wherein the SLM is a liquid crystal modulator (LCM).

9. The apparatus of claim 8, wherein the LCM has four layers, each layer oriented at a fixed angle with respect to the adjacent layer.

10. The apparatus of claim 7, wherein the pulse shaper disperses a beam of the accepted optical signal, adjusts at least a polarization of the optical signal at a plurality of wavelengths, and converts the adjusted optical signal to another beam.

11. The apparatus of claim 10, wherein the pulse shaper adjusts a phase of the optical signal at a plurality of wavelengths.

12. The apparatus of claim 10, wherein another beam is coupleable to a photodetector.

13. The apparatus of claim 10, wherein another beam is coupleable to an input to another optical fiber.

14. The apparatus of claim 1, wherein the pulse shaper is controlled to compensate for a wavelength-dependent polarization characteristic of the coupled optical signal at the proximal end of the optical fiber.

15. The apparatus of claim 14, wherein the optical signal is compensated for a wavelength-dependent phase.

16. The apparatus of claim 14, wherein the compensated optical signal has a substantially wavelength-independent polarization characteristic.

17. The apparatus of claim 1, wherein a correction Jones matrix to a measured wavelength-dependent Jones matrix is determined such that a concatenation of the correction Jones matrix and the wavelength-dependent Jones matrix is wavelength independent, and the pulse shaper is controlled based on the correction Jones matrix.

18. The apparatus of claim 1, wherein the polarimeter measures the SOP of the optical signal at the proximal end of the optical fiber in a wavelength-parallel manner.

19. The apparatus of claim 18, wherein the measurement time of the polarimeter is shorter than a time duration of a state of the polarization transfer matrix switch.

20. The apparatus of claim 1, wherein a first polarization state of the light at the distal end of the fiber is about linear 0° and a second polarization state of the light at the distal end of the optical fiber is about linear 45° with respect to the first polarization.

21. The apparatus of claim 1, wherein at least two of the discrete polarization states are substantially orthogonal to each other on the Poincare sphere when measured at the distal end of the optical fiber.

22. A method of compensating for distortion of an optical signal used for transmitting data, comprising the acts of:

receiving an output optical signal from an optical transmission system, wherein a state-of-polarization (SOP) of an input optical signal to the transmission system is periodically modified to have at least two discrete polarization states prior to transmission;

measuring a SOP of the output optical signal as a function of wavelength for a plurality of input SOP states to determine a first frequency dependent Jones matrix representing the transmission system;

determining a second Jones matrix such that a concatenation of a first Jones matrix and the second Jones matrix is frequency independent and;

adjusting the polarization of the output signal using a wavelength-dependent correction determined from the second Jones matrix.

23. The method of claim 22, wherein a wavelength-dependent phase adjustment performed.

24. The method of claim 22, wherein the SOP of the input optical signal is periodically modified to at least two predetermined polarization states.

25. The method of claim 22, wherein a periodic modification rate is low compared with a data rate of data modulated on the optical signal.

26. The method of claim 22, further comprising: for a pair of output signals associated with a pair of Jones matrix switch states, computing an average wavelength-dependent dependent difference angle on a Poincare sphere.

27. The method of claim 26, wherein the pair of output signals having an average difference angle of approximately 90° is selected, and a first signal of the pair of signals is associated with a 0° linear input SOP state and a cross-product between the first and a second signal of the pair of signals is associated with a 45° input SOP state.

28. The method of claim 27 wherein the SOP of the first signal and the cross-product of the first signal and the second signal are used to compute a wavelength-dependent Jones matrix characterizing the transmission system and a correction Jones matrix so as to minimize a wavelength dependence of the concatenation of the transmission system Jones matrix and the correction Jones matrix.

29. The method of claim 27, wherein the average difference angle between the pair of output signals selected is between about 60° and about 120°.

30. The method of claim 22, wherein the correction to the received optical signal is performed in an optical pulse shaper.

31. An apparatus for transmitting an optical signal having data modulated thereon, comprising:

a polarization controller, the controller being configurable to repeatedly modify a SOP of the optical signal to at least two discrete polarization states, wherein a switching rate of the polarization controller is substantially lower than a data rate of the data modulated on the optical signal, and an output of the polarization controller is coupleable to a transmission system.

32. The apparatus of claim 31, further comprising an optical modulator adapted to accept an optical signal and to modulate data onto the optical signal.

33. The apparatus of claim 31, wherein the SOP has at least two discrete states which are orthogonal on a Poincare sphere.

34. The apparatus of claim 31, wherein the at least two discrete polarization states are four discrete polarization states.

35. A method of transmitting an optical signal, comprising the steps of:

accepting the optical signal modulated with data at a data rate;

periodically modifying the state-of-polarization (SOP) of the optical signal into repeatable discrete polarization states using a polarization controller; and

coupling the optical signal to an optical transmission device, wherein a rate of switching of the polarization controller is substantially lower than the data rate of the data.

36. A system for compensation of distortion of an optical signal, comprising:

a transmitting portion, further comprising:

a polarization controller, the controller being configurable to periodically modify the state of polarization (SOP) of an input optical signal between at least two discrete output optical signal polarization states, the output optical signal being coupleable to an input of an optical transmission device; and

a receiving portion adapted to receive an optical signal output by the optical transmission device, further comprising;
a polarimeter; and
a pulse shaper.
37. The system of claim 36, wherein the transmitting portion further comprises:
a modulator adapted to receive the optical signal and to
modulate data onto the optical signal, the optical signal
being couplable to an input of the polarization transfer
matrix switch.
38. The system of claim 36, wherein the transmission system is an optical fiber.
39. A computer program product, stored on a non-transitory computer-readable medium, comprising:
instructions for configuring a computer to:
receive a measurement output of a polarimeter measuring
an optical signal received from a transmission system;
determine a wavelength-dependent Jones matrix of the
transmission system using the polarimeter measurement output; and
determine a correction Jones matrix such that a concatenate
of the transmission system Jones matrix and the correction Jones matrix is a wavelength-independent
Jones matrix;
wherein a state of polarization of the optical signal has
been modified in a periodic manner to at least two
discrete states of polarization prior to transmission.
40. The computer program product of claim 39, further comprising instructions configuring the computer to control a
pulse shaper, the pulse shaper configured to adjust a polarization of the received optical signal based on the correction
Jones matrix.

41. The computer program product of claim 40, wherein a wavelength-dependent phase of the received optical signal is
adjusted.
42. A system for transmission of signals over an optical fiber, comprising:
a transmitting portion, further comprising:
an optical signal generator to generate an optical signal;
and
a polarization modulator configured to periodically modify an SOP of the optical signal to at least two
discrete polarization states; and
a receiving portion adapted to receive an optical signal, further comprising:
a processor,
a polarimeter adapted to measure a SOP of a received
optical signal as a function of wavelength for the at
least two discrete polarization states of the optical signal produced by the polarization modulator to permit the computation of a first frequency dependent
Jones matrix representing a transmission system disposed
between the transmitting portion and the receiving portion;
the processor configured to compute a second Jones
matrix such that a concatenation of the first Jones
matrix and the second Jones matrix is a frequency
independent Jones matrix; and
a pulse shaper;
wherein the pulse shaper is configured to adjust a polarization of the received optical signal based on the frequency
independent Jones matrix.
It is certified that error appears in the above-identified patent and that said Letters Patent is hereby corrected as shown below:

In the Claims

In column 14, claim 1, line 49, after “to a distal end” insert --of--.

In column 15, claim 23, line 67, after “phase adjustment” insert --is--.

In column 16, claim 26, line 10, before “angle on a Poincare” delete “difference”.

Signed and Sealed this
Twenty-seventh Day of May, 2014

Michelle K. Lee
Deputy Director of the United States Patent and Trademark Office