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Combat Polarization Impairments with Dynamic Polarization Controllers

Polarization related impairments have become the major obstacles to the increase of transmission rates in WDM systems. Such impairments include polarization mode dispersion (PMD) in optical fibers, polarization dependent loss (PDL) in passive optical components, polarization dependent modulation (PDM) in electro-optic modulators, and polarization dependent gain (PDG) in optical amplifiers. A dynamic polarization controller is identified as the single most important element in various schemes for overcoming these impairments.

The cause for these polarization impairments is the imperfection of the optical fibers. If the fibers were perfect, the state of polarization (SOP) of the light signal transmitting in the fiber would remain constant and the effects of PMD, PDL, PDM, and PDG could easily be eliminated. Unfortunately, the SOP of light propagating in a length of standard communication fiber varies along the fiber due to the random birefringence induced by the thermal stress, mechanical stress, and irregularities of the fiber core. Generally, at the output end of the fiber the light is elliptically polarized, with varying degrees of ellipticity, and with the major elliptical axis at an arbitrary angle relative to some reference orientation. Worst of all, the induced birefringence changes with temperature, pressure, stress and other environmental variations, making polarization related impairments time dependent.

Polarization Mode Dispersion (PMD)

PMD is often cited as the next critical hurdle for the high bit rate transmission systems (10Gb/s and higher) after chromatic dispersion and fiber nonlinearity impairments are successfully managed. As illustrated in Fig. 1, a fiber link can be considered as a concatenation of many, randomly oriented retardation plates. In the absence of PDL or PDG in the fiber link, these retardation plates are optically equivalent to a single retardation plate with an effective DGD and a pair of effective orthogonal principal axes (can either be linear or circular) for a given optical frequency. Upon entering the retardation plate, an optical pulse is decomposed into two polarization components along the two axes. Because the two components travel with different speeds in the retardation plate, they exit the plate with a relative time delay called Differential Group Delay (DGD). When DGD is comparable with the bit separation of a data stream, bit error rate may significantly increase.
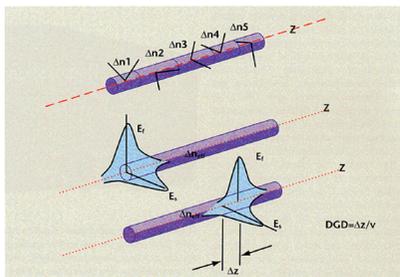
Fig. 1 A real fiber is like many retardation plates with different orientations and birefringences placed in serial. It is equivalent to a single retardation plate having a slow and fast axis and an equivalent birefringence. An optical pulse broadens because the two polarization components travel at different speeds.

The rms value of the DGD is often referred to as first order PMD. Similar to the famous random walk problem in which the rms distance of a drunken man to the origin is proportional to the square-root of the number of walking steps, PMD is proportional to the square-root of the number of cascaded retardation plates, or equivalently, to the square-root of the fiber length.

Contrary to the case of a true retardation plate, the DGD and the principal axes of the fiber link depend on the wavelength and fluctuate in time as a result of temperature variations and external constraints. Consequently, the corresponding pulse broadening is random, both as a function of wavelength at a given time and as a function of time at a given wavelength. As a rule of thumb, the maximum tolerable DGD value is 14% of the bit duration to ensure an outage probability of less than 5 minutes per year at a 3-dB power penalty. This translates to 14ps for a 10Gb/s system and 3.5ps for a 40Gb/s system. Unfortunately, for link distance greater than 300 km, 20% of the installed fiber plant is not suitable for 10Gb/s transmission and 75% is not suitable for 40Gb/s transmission at this outage tolerance level. Therefore, PMD compensation is required for these fiber links.

Unlike the effects of chromatic dispersion and fiber nonlinearity, which are deterministic and stable in time, the PMD-induced penalty can be totally absent at any given moment and adversely large enough several days later to cause an unacceptable bit-error-rate for no apparent reason. To ensure an acceptable outage probability for the fiber optic system, PMD compensation must be dynamic in nature and adaptive to the random time variations. Various schemes for mitigating the effect of PMD are illustrated in Fig. 2.
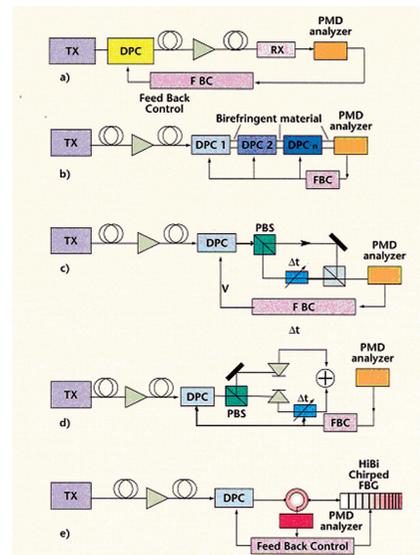
Fig. 2 Various PMD mitigation schemes: a) Principal state transmission method; b) Multiple retardation plates method; c) Optical delay line method; d) Electrical delay line method; e) Chirped HiBi fiber grating method. In all schemes, dynamic polarization controllers (DPC) having fast speed, low PDL, and low activation loss are required.

The schemes generally contain three key components: 1) the dynamic polarization controller (DPC), 2) the PMD analyzer, and 3) the feedback circuit. For some schemes, the dynamic variable delay line may also be required. The low insertion loss specification of the fiber squeezer based device becomes even more attractive for the schemes that require multiple polarization controllers capable of compensating higher order PMD effects. As will be discussed below, low PDL and low activation loss are

also important parameters for the DPC to function properly in the feedback loops.

Polarization Dependent Loss (PDL)

The PDL of an optical component is defined as the difference between the maximum and the minimum insertion losses for all possible input SOPs. Optical components with PDL act as partial polarizers with two orthogonal axes (either linear or circular). A light signal experiences a maximum loss if its SOP is aligned with one axis and a minimum loss if aligned with the other axis.

Almost all fiber optic components have PDL and the causes may be different for different components. First of all, when light passes from an optical medium with an index of n1 to another medium with an index n2, reflection occurs. The reflection coefficients for the polarization states perpendicular and parallel to the plane of incidence are different if the angle of incidence is not normal (many fiber components have angled input and output surfaces for increased return loss.) Such a difference in reflection results in a difference in transmission loss or PDL. For example, an 8° angle polished connector (FC/APC or SC/APC) has a PDL of 0.022 dB. Fiber grating based devices may also exhibit PDL if the grating is not normal to the fiber longitudinal axis.

Second, for many optical components, such as isolators and circulators, birefringent crystals are often used. Because a birefringent crystal has two principal axes with different indexes of refraction, n_o and n_e, the Fresnel reflection coefficients of two polarization states perpendicular and parallel to the principal axes are different even at normal incidence, resulting in different transmission loss. The corresponding PDL is thus:

$$PDL = 20 * \log|(n_e-1)(n_o+1)/(n_o-1)(n_e+1)|$$

Anti-reflection (AR) coatings can greatly reduce the reflection, however, they may not totally eliminate PDL because the optimal coating layer thickness is determined by the refractive index of the coated material: it is either optimized for n_o or n_e.

Diffraction grating based optical components or instruments generally have high PDL because the diffraction efficiencies for the two polarization states perpendicular and parallel to the plane of incidence are different.

Finally, any fiber component containing a dichroic material also has PDL. A dichroic material has two principal axes with different absorption or attenuation coefficients. The principal axes can either be linear (linear dichroism) or circular (circular dichroism). For example, the LiNbO$_3$ waveguide made with the proton exchange method exhibit strong linear dichroism and acts just like a polarizer.

In a fiber link which contains many optical components with different PDL values, the total PDL value depends on the SOPs of the light signal transmitted in the link and varies between a maximum and a minimum value. The maximum value is equal to the summation of the PDL values of all the components in the link. It is the difference between two insertion loss measurements of the link: the first one is when SOP of the light before each component is aligned with the minimum loss axis of the component and the second one is when SOP of the light before each component is aligned with the maximum loss axis.

The minimum PDL value corresponds to the case that the SOPs of a light signal before all the PDL components are arranged such that the PDLs cancel one another out. The net residual PDL is the minimum PDL of the link.

The presence of PDL in a fiber link also complicates PMD compensation. When PDL is present in the fiber link, the link is no longer equivalent to a single retardation plate. It instead is equivalent to two retardation plates with a partial polarizer sandwiched in between. Any PMD compensation scheme therefore must take the effect of the partial polarizer into account, which may increase the complexity of the compensation arrangement significantly.

Like the PMD penalty, the PDL effect in a fiber link containing multiple PDL components separated by sections of single mode fiber is also time dependent. At any moment, the states of polarization in different sections of the link may be oriented favorably to allow a low link loss such that the detected optical power at the receiver is high enough to achieve acceptable bit-error rate (or signal-to-noise ratio). However at a different moment, the link loss may be too high to achieve quality transmission due to the external thermal or mechanical stress on the fiber that causes the states of polarization in different fiber sections to re-arrange.

To combat the time-varying PDL problem, dynamic polarization controllers may be used at selected locations in the fiber link, as shown in Fig. 3. Each polarization controller assures that the light passing through the PDL component following the controller has the lowest loss.
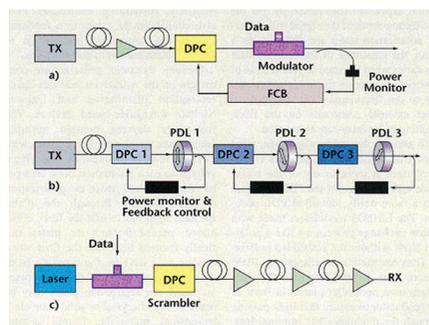
Fig. 3 Dynamic Polarization Controllers (DPC) for a) Polarization stabilization; b) PDL compensation; c) PDG mitigation.

Polarization Dependent Gain (PDG)

The gain of an optical amplifier for the stronger polarization component is less than that for the weaker component (because the stronger component saturates the gain more) and the gain difference is called polarization dependent gain (PDG). One cause for the PDG is that the cross sections of the stimulated emission for different polarization states are different. This polarization hole burning always gives more gain to the weaker polarization component and thus tends to cause the polarization state to change with time. In addition, when the input SOP changes, the signal gain may increase temporarily , then come down in a short period of time. Consequently, the polarization hole burning always encourages polarization fluctuations in a fiber laser system and thus causes mode-hopping and increases super-mode noise in a mode-locked laser.

An optical amplifier may at the same time exhibit PDL effect. For example, couplers and isolators are generally contained in an Er+ doped fiber amplifier (EDFA) and the presence of PDL in these components gives rise to the apparent PDL of the amplifier. Even in semiconductor optical amplifiers (SOA), the facets of the semiconductor chip are generally angle cleaved to prevent optical feedback into the amplifier. As discussed previously, these

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angled interfaces exhibit large PDL, which directly contributes to PDL of the SOA.

In a fiber optic link with many optical amplifiers and many components with PDL, the effect of PDG can be significant at some moments and negligible at other times. When a large number of optical amplifiers are cascaded in a long haul fiber link, the performance degradation caused by PDG is significant even though each amplifier may have a very small PDL (~0.1 dB). The performance degradation becomes even worse when PDG is combined with the PMD and PDL of the fiber and other components in the link. Polarization scrambling at a frequency above amplifier's response rate (inverse of amplifier's upper energy level life time, ~ 500 Hz for EDFA) has proven to be effective in mitigating PDG impairment in long haul systems, as shown in Fig. 3. A factor of 2 increase in system Q factor was demonstrated in an 8100-km link containing 181 EDFAs with such a scheme.

Polarization Dependent Modulation (PDM)

In addition to PDL, external modulators, such as $LiNbO_3$ based electro-optical modulators and semiconductor electro-absorption modulators, also exhibit polarization dependent modulation in that the modulation depth of signals with different polarization states are different. As a result, the amplitude of the received data bits varies when the state of polarization of light before entering the modulator varies due to the fluctuation of temperature or other external constraints on the fiber, resulting in bit-error-rate fluctuation.

To assist polarization alignment, most Ti-indiffused $LiNbO_3$ modulators embed a polarizer at input or out of the waveguide and thus convert the PDM problem into a more easily identified PDL problem. The $LiNbO_3$ modulators made with proton exchange process act like a polarizer themselves without the embedded polarizer. Thus one method of eliminating PDM effects uses a fast response dynamic polarization controller placed in front of the modulator to assure that light passing through the modulator has minimal loss, as illustrated in Fig. 3.

"Dynamic" is the Magic Word for Polarization Control

Because polarization-induced penalties are time dependent, polarization-impairment mitigation must be dynamic and adaptive to random time variations. A dynamic polarization controller is the single most important element for overcoming these impairments.

Fast speed, low PDL, low insertion loss, and low activation loss are all critical parameters in evaluating a dynamic polarization controller. Activation loss measures the additional insertion loss caused by activation of the device and is defined as the difference between the maximum and minimum insertion losses of the device considering all possible activation conditions. This specification is particularly important because all polarization-impairment compensation schemes utilize a feedback signal to activate the polarization controller. The activation-induced loss causes errors in the feedback signal and directly degrades the performance of the compensation apparatus. In addition, when an instrument for measuring the PDL of optical components includes a polarization controller, the activation-induced loss limits the resolution and accuracy of the measurement. Similarly, a polarization controller's PDL also contributes to errors in a feedback system and complicates the design of compensation hardware and software.

Present dynamic polarization controllers on the market include free-space retardation plate based and Lithium Niobate waveguide based devices. The free-space devices contain multiple (sometimes three) retardation plates with different relative orientations. Applying a voltage to each retardation plate changes its retardation and hence the polarization of light passing through the plate. Because light has to exit the fiber, be collimated, pass through the plates and finally be focused back into the fiber when making such devices, the resulting labor costs, material costs, and insertion losses are high. The retardation plates may be made of liquid crystal or solid state electro-optical materials. Liquid crystal devices also suffer from low speed (10 to 100 ms), narrow operating temperature ranges, and high PDL.

Lithium Niobate based dynamic polarization controllers contain multiple sections of waveguide with different electrode (or crystal) orientations. Similar to the liquid crystal based devices, each waveguide functions as an electrically variable retardation plate. By applying different voltages to different waveguide sections, any polarization states can be generated. However, typical of lithium niobate waveguides, such a controller has high insertion loss (~ 4 dB), high polarization dependent loss (~0.2 dB), low return loss (45 dB), high cost, and narrow temperature range (0 to 60°C). In addition, the maximum power of the device is limited to 50 mW, making it impractical to use after optical amplifiers.

Advantages of Fiber Squeezer Polarization Controllers

Polarization controllers based on fiber squeezers have been investigated by researchers for over a decade. However, reliability concerns associated with fiber squeezing and high activation loss prevented such devices from becoming commercially feasible. In 1996, General Photonics Corporation in Chino, CA successfully introduced the first commercial fiber-squeezer based polarization controller (PolaRITE). Subsequently, the same company also introduced the first fiber squeezer-based polarization scrambler. Over the years, the company has perfected the art of fiber squeezing and developed several proprietary technologies.

Based on the prior experiences with fiber squeezers, General Photonics recently introduced the first multi-axis fiber-squeezer based dynamic polarization controller/ scrambler shown in Fig. 4. Similar to the bulk-wave plate and Lithium Niobate based polarization controllers, the fiber-squeezer controller contains multiple retardation plates with different orientation angles. Each retardation plate is created by squeezing a section of fiber with a PZT actuator and the retardation of the plate can be easily changed by varying the voltage applied to the PZT actuator. It can be shown that this device can convert any polarization state to any desired polarization state on the Poincare Sphere by controlling the voltages on different fiber sections.
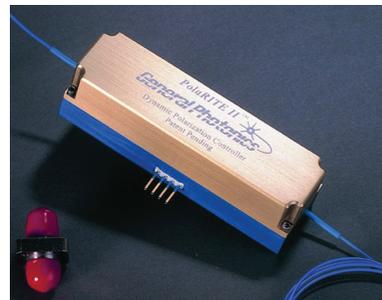
Fig. 4 Fiber squeezer dynamic polarization controllers have the advantages of no insertion loss, no backreflection, no wavelength dependence, extremely low PDL and activation loss, and high speed.

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Due to its all fiber nature, this device has practically no insertion loss, no back reflection, and no polarization dependent loss. In addition, it is has a response time of less than 35 µs, significantly faster than that of a liquid crystal based device. Such high speed operation is essential for tracking fast polarization variations which are caused either by passing locomotives as in fibers laid along railway tracks or by ocean waves as in the trans-oceanic fiber trunks.

Perhaps most impressively, General Photonics has succeeded in reducing activation-induced losses in its fiber squeezer controller to less than 0.003 dB. The low activation-induced loss makes these components ideal for use in high precision PDL instruments and in feedback loops for compensating for polarization induced penalties.

Another unique and attractive feature of General Photonics' device is that its performance is wavelength independent: the device functions equally well for signals ranging from 1280 nm to 1650 nm. This one-device-fit-all feature helps to simplify system design, lower implementation cost, and enables system's channel expandability.

Implementation of fiber squeezers is also cost effective. Half-wave voltage requirements of the fiber squeezer controllers have been reduced to less than 40 VDC. The low voltage requirements allow the use of readily available low cost electronics to drive and control the fiber squeezer controller. Reliability of the fiber squeezers has also proven to be very high. In testing, over 10 billion activation cycles at half wave voltages have been achieved without a single failure.

An additional application of the fiber squeezer controller is as a polarization scrambler to effectively randomize polarization states. With a built-in resonant enhanced circuit, the half wave voltages of the device at scrambling frequencies are reduced to only a few volts. Such low voltage requirement makes the driving electronics simple and low cost. With properly selected driving parameters, the scrambler has successfully achieved a polarization sensitivity of less than 0.05 dB and a degree of polarization less than 1%.

Applications

Due to its superior performance (low insertion loss, low PDL, low activation loss, low backreflection, high speed, and low cost), the fiber squeezer dynamic polarization controllers are ideal for PMD mitigation, PDL compensation, and PDG effect reduction, as illustrated in Figures 2 and 3.
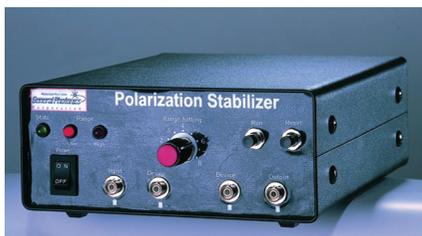
Fig. 5 The polarization stabilizer has an input port, an output port, and two device ports for accepting the two ends of a polarization sensitive device, such as a LiNbO3 modulator. The stabilizer automatically adjusts the SOP to the modulator and ensures a maximum light transmission. The heart of the stabilizer is a fiber squeezer polarization controller.

The fiber squeezer dynamic controllers can also be used for polarization stabilization, which is important for electro-optic and electro-absorption modulators, optical interferometers, and heterodyne optical receivers. We designed and buil a polarization

stabilizer (Fig. 5) using the fiber squeezer-dynamic controller and have achieved output power stability to within 0.05 dB against all possible polarization variations.

The polarization scrambling feature of the fiber squeezer based device can also be used to eliminate instrument's polarization sensitivity. Some optical instruments, such as diffraction grating based optical spectrum analyzers, are sensitive to the state of polarization of the input light. Scrambling the input polarization is an effective way of removing the measurement uncertainties caused by the polarization sensitivity. The fiber-squeezer based dynamic polarization controller/scrambler is ideal for such an application because of its low scrambling voltages and multiple resonant scrambling peaks. The scrambler has successfully achieved a polarization sensitivity of less than 0.05 dB and a degree of polarization less than 1%.

Fast and accurate PDL characterization of fiber optic devices in a manufacturing environment is important. The dynamic polarization controller can be readily included in an instrument to automatically search for the maximum and minimum insertion loss of a device under test and calculate the corresponding PDL. Fiber-squeezer based dynamic controllers are especially attractive for this application because of their low activation loss and low PDL, which ultimately limit the PDL measurement accuracy. Our test indicates that a PDL measurement with a resolution of 0.01 dB can be readily achieved in a fraction of a second using a dynamic controller manufactured by General Photonics Corporation.

Conclusion

In conclusion, polarization related penalties, including PMD, PDL, PDG, and PDM, in fiber optic systems are all time-varying and unpredictable. Fast dynamic polarization controllers must be employed to mitigate the relevant impairments. Fiber-squeezer based polarization controllers are superior to other approaches in terms of insertion loss, back return loss, PDL, activation loss, and speed, and can efficiently squeeze out these polarization related problems.

Suggested Readings:

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