Polarization of optical wave in optical fiber communication system

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Abstract : Here, in this paper we have discussed the polarized optical wave and modes aiming to maintain state of polarization. An optical wave being composed of two orthogonal electromagnetic field components varying with amplitude and frequency. A polarized light occurs when these two components differ in phase or amplitude. Polarization in optical fiber (polarization maintaining optical-fibers : maintaining low PMD) has been extensively studied and methods are available to minimize the phenomenon. Lower the PMD higher will be the information carrying capacity of the optical fiber, hence low PMD should be maintained". Here, basic principles and technical background are introduced in explaining how the polarization in fiber optics works.

Keywords : Electric field E, Magnetic field H, Amplitude (A_0), Frequency ν, wave vector k, Phase difference δ, SOP (State of Polarization), Polarized optical wave, PMD (Polarization mode dispersion).

I. Introduction

A fundamental property of an optical wave signal is its prolarization states. Polarization refers to the electric-field orientation of an optical wave signal, which can vary significantly along the length of a fiber. Signal energy at a given wavelength occupies two orthogonal polarization modes. A varying briefringence along its length will cause each polarization mode to travel at a slightly different velocity. The resulting difference in propagation times $\Delta\tau_{PMD}$ between the two orthogonal polarization modes will result in pulse spreading. This is the polarization-mode dispersion (PMD). Here, we are interested to those optical waves which are polarized, maintaining state of polarization (SOP). For this purpose we have discussed polarizer, Faraday rotators and Birefringent crystals. These are used as optical signal modulators, beam splitters and beam displacers in the optical fiber communication system. Since we need no change in the state of polarization of the optical wave, since change in state of polarization causes attenuation of optical signal. Here, in this paper we have discussed the polarized optical wave and modes aiming to maintain state of polarization. Hence polarization maining optical fibers are used widely to overcome the above discrepancies. In this paper we have discussed polarisation components of the optical wave, methods of maintaining polarization in optical fiber and PMD.

II. Development

Polarization components of optical wave

The electric or magnetic field of a train of plane linearly polarized waves travelling in direction **k** can be represented in the general form

$$\mathbf{A}(\mathbf{x},t) = \mathbf{e}_i A_0 \exp[j(\omega t - \mathbf{k}\cdot\mathbf{x})] \quad \text{......................(1)}$$

with $\mathbf{x} = x\mathbf{e}_x + y\mathbf{e}_y + z\mathbf{e}_z$ representing a general position vector and $\mathbf{k} = k_x\mathbf{e}_x + k_y\mathbf{e}_y + k_z\mathbf{e}_z$ representing the wave propagation vector.

Here, A_0 is the maximum amplitude of the wave, $\omega = 2\pi\nu$, where ν is the frequency of the optical wave; the magnitude of the wave vector **k** is $k = 2\pi/\lambda$, which is known as the wave propagation constant, with λ being the wavelength of the optical wave; and $\mathbf{e}_i$ is a unit vector lying parallel to an axis designated by *i*.

The components of the actual (measurable) electromagnetic field represented by equation (1) is obtained by taking the real part of this equation. For example, if $\mathbf{k} = k\mathbf{e}_z$, and if $\mathbf{A}$ denotes the electric field $\mathbf{E}$ with the coordinates axes chosen such that $\mathbf{e}_i = \mathbf{e}_x$, then the real measurable electric field is given by

$$\mathbf{E}_x(z,t) = \mathrm{Re}(\mathbf{E}) = \mathbf{e}_x E_{0x} \cos(\omega t - kz) \quad \text{....................(2)}$$

which represents a plane wave that varies harmonically as it travels in the z-direction. The reason for using the exponential form is that it is more easily handled mathematically than equivalent expressions given in terms of sine and cosine.

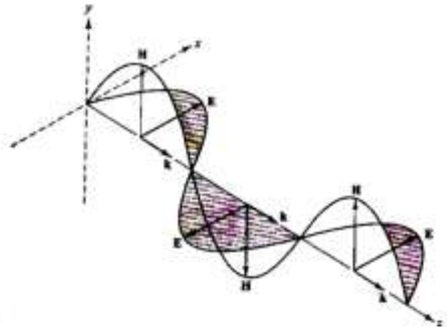

Fig.-1. : Electric and magnetic fields distributions in a train of plane electromagnetic waves at a given instant in time

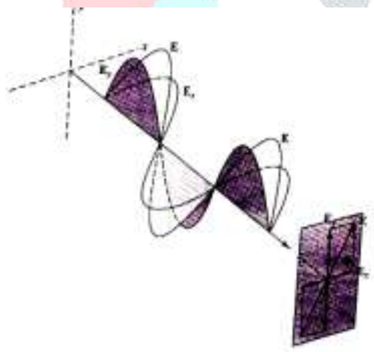

Fig.-2. : Addition of two linearly polarized waves having a zero relative phase between them.

The electric and magnetic field distributions in a train of plane electromagnetic waves at a given instant in time are shown in Fig.-1. The waves are moving in the direction indicated by the vector **k**. Based on Maxwell's equations, it can be shown that **E** and **H** are both perpendicular to the direction of propagation of optical wave. This condition defines a plane wave, that is, the vibrations in the electric field are parallel to each other at all points in the wave. Thus, the electric field forms a plane called the plane of vibration. Likewise all points in the magnetic field component of the wave lie in another plane of vibration. Furthermore, **E** and **H** are mutually perpendicular, so that **E**, **H**, and **k** form a set of orthogonal vectors. The plane wave example given by equation (2) has its electric field vector always pointing in the $\boldsymbol{e}_x$ direction. Such a wave is linearly polarized with polarization vector $\boldsymbol{e}_x$. A general state of polarization is described by considering another linearly polarized wave which is independent of the first wave and orthogonal to it. Let this wave be

$$\mathbf{E}_y(z,t) = \mathbf{e}_y E_{0y} \cos(\omega t - kz + \delta) \quad \text{......................(3)}$$

where, δ is the relative phase difference between the waves. The resultant wave is

$$\mathbf{E}(z,t) = \mathbf{E}_x(z,t) + \mathbf{E}_y(z,t) \quad \text{.......................(4)}$$

If δ is zero or an integer multiple of 2π, the waves are in phase. Equation (4) is then also a linearly polarized wave with a polarization vector making an angle

$$\theta = \arctan\frac{E_{0y}}{E_{0x}} \quad \text{.......................(5)}$$

with respect to $\mathbf{e}_x$ and having a magnitude

$$E = \left(E_{0x}^2 + E_{0y}^2\right)^{1/2} \quad \text{.......................(6)}$$

This case is shown schematically in Fig.-2. Conversely, just as any two orthogonal plane waves can be combined into a linearly polarized wave, an arbitrary linearly polarized wave can be resolved into two independent orthogonal plane waves that are in phase. An ordinary light wave consists of many transverse electromagnetic waves that vibrate in a variety of directions (i.e., in more than one plane) and is called unpolarized light. However, we can represent any arbitrary direction of vibration as a combination of a parallel vibration and a perpendicular vibration, as shown in Fig.-3. Therefore, we may consider unpolarized optical wave as consisting of two orthogonal plane polarization components, one that lies in the plane of incidence (the plane containing the incident and reflected rays) and the other of which lies in a plane perpendicular to the plane of incidence. These are parallel polarization and the perpendicular polarization components respectively. In the case when all the electric field planes of the different transverse waves are aligned parallel to each other, then the light wave is linearly polarized. This is the simplest type of polarization.

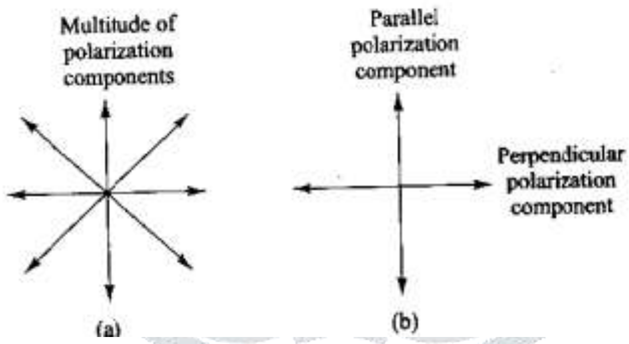

Fig.-3: Polarization represented as a combination of a parallel vibration and a perpendicular vibration.

Unpolarized light can be split into separate polarization components either by reflection off of a nonmetallic surface or by refraction when the light passes from one material to another. A circled dot and an arrow designate the parallel and perpendicular polarization components, respectively, in Fig.-4. The reflected beam is partially polarized and at a specific angle (known as Brewster's angle) the reflected light is completely perpendicularly polarized. The parallel component of the refracted beam is transmitted entirely into the glass, where as the perpendicular component is only partially refracted. How much of the refracted light is polarized depends on the angle at which the light approaches the surface and on the material composition.

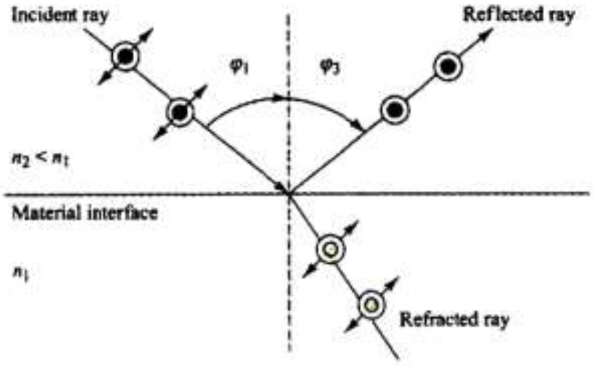

Fig.-4 : Behavior of an unpolarized optical beam at the interface between air and a nonmetallic surface

The polarization characteristics of optical wave are important when examining the behavior of components such as optical isolators and light filters. Here we look at three polarization sensitive materials or devices that are used in such components. These are polarizers, Faraday rotators, and Birefringent crystals. A polarizer is a material or device that transmits only one polarization components and blocks the other. For example, in the case when unpolarized optical wave enters a polarizer that has a vertical transmission axis as shown in Fig.-5, only the vertical polarization component passes through the device. A familiar example of this concept is the use of polarizing sunglasses to reduce the glare of partially polarized sunlight reflections from road or water surfaces. To see the polarization property of the sunglasses, a number of glare spots will appear when users tilt their head sideway. The polarization filters in the sunglasses block out the polarized light coming from these glare spots when the head is held normally.

A Faraday rotator is a device that rotates the **state of polarization** of optical wave passing through it by a specific amount. For a example a popular device rotates the SOP clockwise by 45° or a quarter of a wavelength, as shown in Fig.-6.

This rotation is independent of the SOP of input light, but the rotation angle is different depending on the direction in which the light passes through the device. i.e., rotation process is not reciprocal. In this process, the SOP of the input light is maintained after the rotation. For example, if the input light to a 45° Faraday rotator is linearly polarized in a vertical direction, then the rotated light exiting the crystal also is linearly polarized at a 45°. The Faraday rotator material usually is an asymmetric crystal such as yttrium iron garnet (YIG) and the degree of angular rotation is proportional to the thickness of the device.

Birefringent or double refractive crystals have a property called double refraction. This means that the indices of refraction are slightly different along two perpendicular axes of the crystal as shown in Fig.-7.

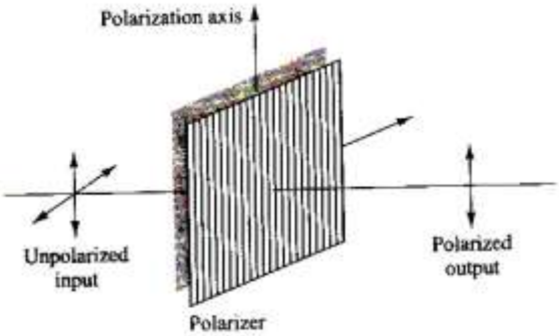

Fig.-5 : Only the vertical polarization component passes through a vertically oriented polarizer.

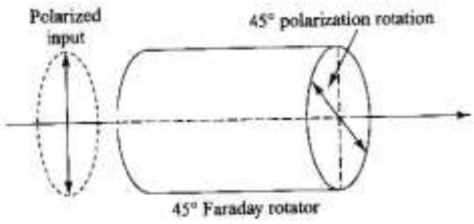

Fig.-6 : A Faraday rotator is a device that rotates the state of polarization clockwise by 45° or a quarter of a wavelength.

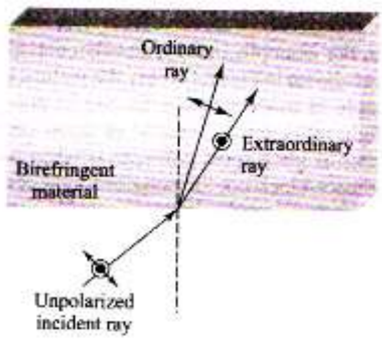

Fig.-7 : A Birefringent crystal splits the light signal entering it into two perpendicularly polarized beams.

A device made from such materials is known as a spatial walk-off polarizer (SWP). The SWP splits the light signal entering it into two orthogonally polarized beams. One of the beams is called an ordinary ray or O-ray, since it obeys snell's law of refraction at the crystal surface. The second beam is called the extraordinary ray or E-ray, since it refracts at an angle that deviates from the prediction of the standard form of snell's law. Each of the two orthogonal polarization components thus is refracted at a different angle as shown in Fig.-7. for example if the incident unpolarized light arises at an angle perpendicular to the surface of the device, the O-ray can pass straight through the device whereas the E-ray component is deflected at a slight angle show it follows a different path through the material.

Table-1; Lists the ordinary index n_0 and the extraordinary index n_e of some common Birefringent crystals that are used in optical communication components and gives some of their applications.

Table-1 : *Common Birefringent crystals and some applications*

Crystal name	*Symbol*	n_0	n_e	*Applications*
Calcite	$CaCo_3$	1.658	1.486	Polarization controllers and beam splitters
Lithium niobate	$LiNbO_3$	2.286	2.200	Light signal modulators
Rutile	TiO_2	2.616	2.903	Optical isolators and circulators
Yttrium vanadate	YVO_4	1.945	2.149	Optical isolators, circulators, and beam displacers

III. Methods of Maintaining Polarization

Controlling the polarization state in optical fiber is similar to the free space control using waveplates via phase changes in the two orthogonal state of polarization. In general three configurations are commonly used. In the first configuration, a half-wave plate (HWP) is sandwiched between the two quarter-wave plates (QWP) and the retardation plates are free to rotate around the optical beam with respect to each other. The first QWP converts any arbitrary input polarization into a linear polarization. The HWP then rotates the linear polarization to a desired angle so that the second QWP can translate the linear polarization to any desired polarization state. An all fiber controller based on this mechanism can be constructed, with several desirable properties such as the low insertion loss and cost as shown in the figure -8. In this device, three fiber coils replace the three free-space retardation plates. Coiling the fiber induces stress, producing birefringence (discussed in polarization component of optical wave) inversely proportional to the square of the coils diameter. Adjusting the diameters and number of turns we create any desired fiber wave plate. Because bending the fiber generally induces insertion loss, the fiber coils must remain relatively large.

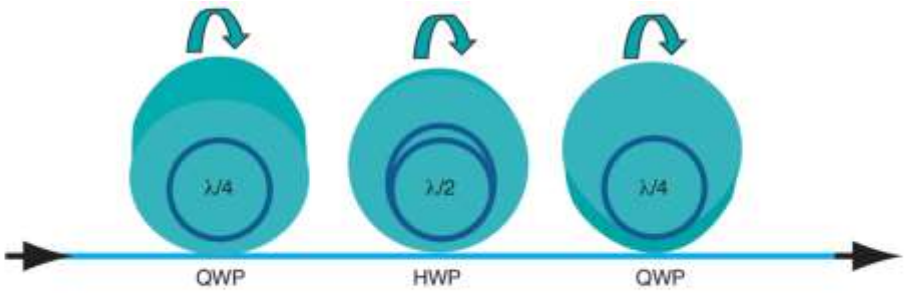

Figure -8 : Polarization control using multiple coiled fiber

The second approach is based on the Babinet-Soleil Compensator. An all-fiber polarization controller based on this technique is shown in Figure-9. The device comprises a fiber squeezer that rotates around the optical fiber. Applying a pressure to the fiber produces a linear birefringence, effectively creating a fiber wave plate whose retardation varies with the pressure. Simple squeeze-and-turn operations can generate any desired polarization state from any arbitrary input polarization

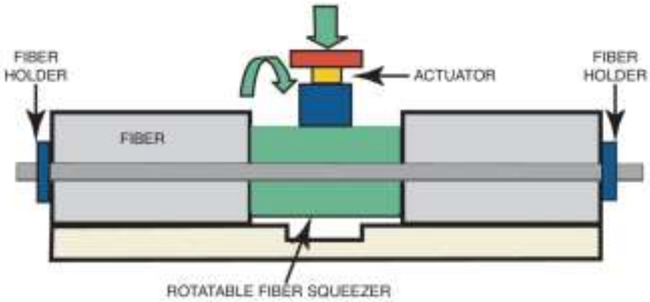

Figure -9: Polarization control using Babinet-Soleil compensator principle.

Polarization controllers also can be made with multiple free-space wave plates oriented 45° from each other. An all-fiber device based on the same operation principle would reduce the insertion loss and cost. The retardation of each wave plate components varies with the pressure of each fiber squeezer. The challenge is making the device reliable, compact and cost-effective.

Piezoelectric actuators drive the fiber squeezers for high speed. Because it is an all-fiber device, it has no back reflection and has extremely low insertion loss and polarization-dependent loss. All new **25xxP Series** Polarization Control instruments employ the fiber squeeze technique.

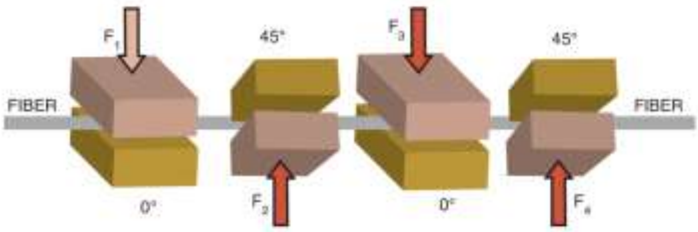

Figure -10: Polarization control by squeezing fiber from various directions.

Polarization Mode Dispersion (PMD)

Polarization mode dispersion (PMD) results from the fact that light-signal energy as a given wavelength in a single mode fiber actually occupies two orthogonal polarization states or modes. PMD arises because the two fundamental orthogonal polarization modes travel at slightly different speeds owing to fiber birefringence. The resulting difference in propagation times between the two orthogonal polarization modes will result in pulse spreading. This PMD effect cannot be mitigated easily and can be a very serious impediment for links operating at 10 Gb/s and higher.

To have a power penalty of less than 1.0 dB, the pulse spreading $\Delta\tau_{PMD}$ resulting from polarization mode dispersion must on the average be less than 10 percent of a bit period T_b. A useful means of characterizing PMD for long fiber lengths is in terms of the mean value of the differential group delay. This can be calculated according to the relationship.

$$\Delta\tau_{PMD} = D_{PMD}\sqrt{L} \qquad ....(7)$$

Using this relation, we have the condition $\Delta\tau_{PMD} = D_{PMD}\sqrt{L} < 0.1T_b$. For an example, if we consider a 100-km long fiber for which DPMD = 0.5 ps/$\sqrt{km}$. Then the pulse spread over this distance is $\Delta\tau_{PMD}$ =5.0 ps, to send an NRZ-enclosed signal over this distance and the lower -penalty requirement is that the pulse spread can be no more than 10 percent of a pulse width T_b. In this case the maximum possible data rate is $1/T_b$ = 20 Gb/s.

IV. Conclusion

The resulting difference in propagation times $\Delta\tau_{PMD}$ between the two orthogonal polarization modes will result in pulse spreading. This is the polarization-mode dispersion (PMD). Thus $\Delta\tau_{PMD}$ should be no more than 10 to 20 ps for 10-Gb/s data rates and 3 ps at 40 Gb/s. Taking the lower tolerance limit, this means that for a 10-Gb/s link which has 20 spans of 80 km each, the PMD of the transmission fiber must be less than 0.2 ps / $\sqrt{km}$. Various optical and electronic means to monitor and mitigate PMD in a fiber have been investigated. Fibers with low polarization-mode dispersion should be developed and characterized.

References

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