Polarization of optical wave in fiber optics

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Abstract -

An optical wave made up of two perpendicular electromagnetic field constituents changing with amplitude and frequency. A polarization of light occurs when these two constituents change in phase or amplitude. Polarization in optical fiber (polarization maintaining optical-fibers : maintaining low PMD) has been widely studied and approaches are possible to minimize the phenomenon. Lower PMD provides higher the information conveying efficiency of the optical fiber, so low PMD should be maintained". Here, basic theories and technical background are established in explaining how the polarization in fiber optics works.

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

Introduction :

A basic property of an optical wave signal is its dissipation states. Polarization pertains to the electric-field orientation of an optical wave signal, which can vary importantly along the length of a fiber. Signal energy at a given wavelength engages two perpendicular polarization modes. A changing briefringence along its length will effect each polarization mode to travel at a slightly dissimilar velocity. The resulting dissimilarity in propagation times $\Delta\tau_{PMD}$ between the two perpendicular polarization modes will affect in pulse increasing. 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.

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 introduced in the general form

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

with $\mathbf{x} = x\mathbf{e}_x + y\mathbf{e}_y + z\mathbf{e}_z$ constituting 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 conveying vector.

Here, A_0 is the highest 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 conveying 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 constituents of the actual (measurable) electromagnetic field represented by equation (1) is obtained by accounting the real part of this equation. For example, if $\mathbf{k} = k\mathbf{e}_z$, and if $\mathbf{A}$ represents the electric field **E** with the coordinates axes taken such that $\mathbf{e}_i = \mathbf{e}_x$, then the actual countable 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 denotes a plane wave that changes harmonically as it goes in the z-direction. The cause for applying the exponential form is that it is more simply operated arithmetically than identical expressions given in forms of sine and cosine.

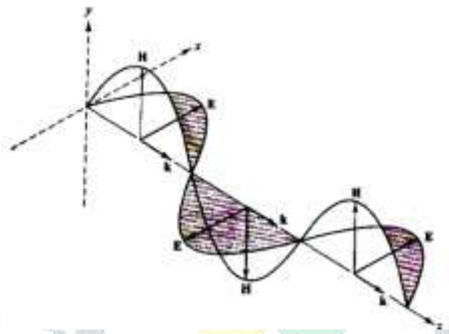

Fig.-1. : Electric and magnetic fields allocations in a train of smooth (flat) electromagnetic waves at a given instant in time

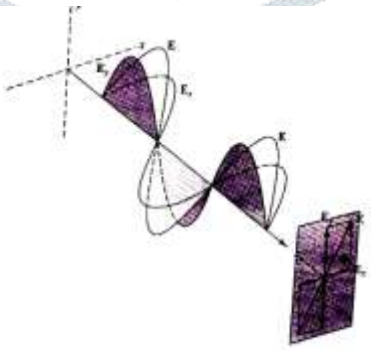

Fig.-2. : Inclusion of two linearly polarized waves possessing a zero relative phase between them.

The electric and magnetic field diffusion in a train of smooth electromagnetic waves at a certain instant in time are shown in Fig.-1. The waves are travelling in the direction indicated by the vector **k**. Assumed from Maxwell's equations, it can be shown that **E** and **H** are both perpendicular to the direction of propagation of optical wave. This situation explains 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 constituent 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 perpendicular 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

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

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

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

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

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

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

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

This situation is shown schematically in Fig.-2. Contradictorily, just as any two perpendicular plane waves may be integrated into a rectilinearly polarized wave, an arbitrary rectilinearly polarized wave can be resolved into two independent perpendicular plane waves that are in phase. An simple 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 unpredictable 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 be made up two orthogonal plane polarization constituents, one that lies in the plane of incidence (the plane accommodating the incident and reflected rays) and the other of which lies in a plane orthogonal to the plane of occurrence. These are equidistance polarization and the orthogonal polarization constituents 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 rectilinearly polarized. This is the simplest type of polarization of light wave.

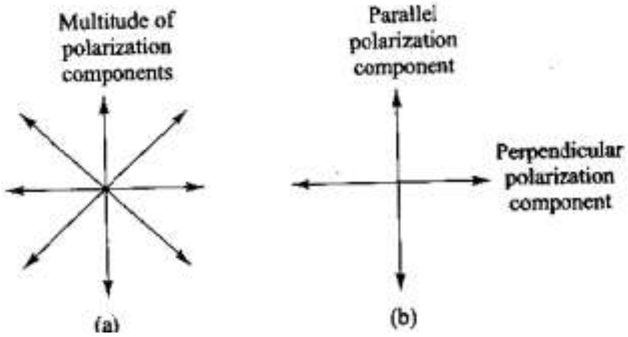

Fig.-3: Polarization considered as a combination of a parallel vibration and a orthogonal vibration.

Unpolarized light can be disintegrate into separate polarization constituents either by reflection off of a nonmetallic surface or by refraction when the light passes from one medium 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 particular angle (known as Brewster's angle) the reflected light is totally perpendicularly polarized. The parallel component of the refracted beam is transmitted entirely into the glass, where as the orthogonal component is only partly refracted. How much of the refracted light is polarized depends on the angle at which the light approaches the surface and on the structure.

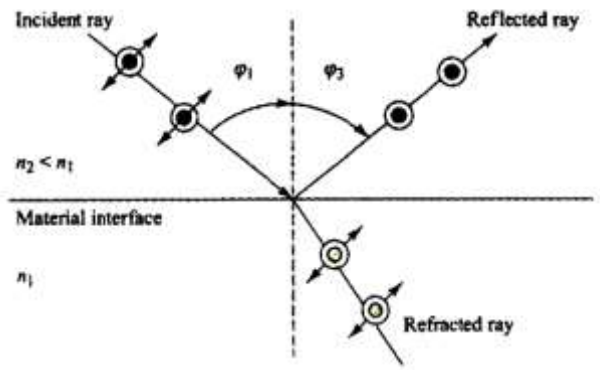

Fig.-4 : Action of an unpolarized optical wave at the junction between air and a nonmetallic surface

The polarization character of optical wave are principal when examining the behavior of constituents such as optical isolators and light filters. Here we look at three polarization sensitive materials or tools that are applied in such constituents. 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 perpendicular 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 characteristics of the sunglasses, a number of glare spots appear when users tilt their head sideway. The polarization purifies in the sunglasses block out the polarized light coming from these glare spots when the head is held normally.

A Faraday rotator is a tool that revolves 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 does not depend 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 supported after the rotation. For example, if the input light to a 45° Faraday rotator is rectilinearly polarized in a perpendicular direction, then the rotated light exiting the crystal also is rectilinearly polarized at a 45°. The Faraday rotator material generally 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 characteristics called double refraction. This means that the indices of refraction are somewhat different along two orthogonal axes of the crystal as shown in Fig. -7.

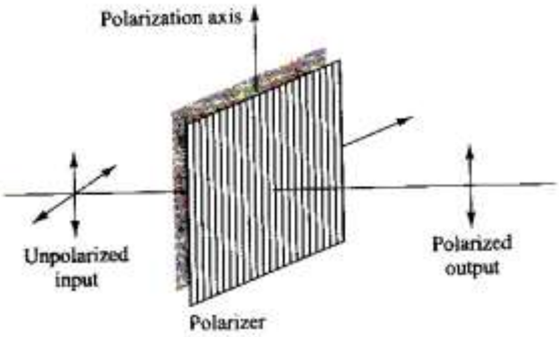

Fig.-5 : Only the perpendicular polarization constituents passes through a perpendicularly oriented polarizer.

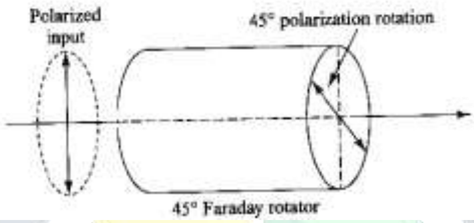

Fig.-6 : A Faraday rotator is a tool that rotates the state of polarization clockwise by 45° or a quarter of a wavelength.

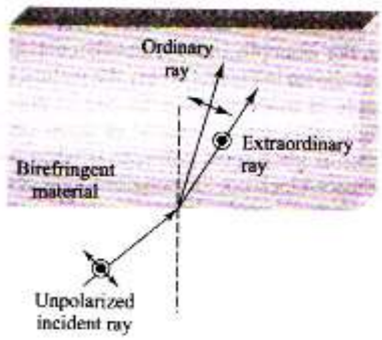

Fig.-7 : A Birefringent crystal bricks up the light signal entering it into two orthogonally polarized beams.

A tool made from such materials is known as a spatial walk-off polarizer (SWP). The SWP bricks up the light signal entering it into two perpendicularly 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 bends at an angle that deviates from the forecast of the standard form of snell's law. Each of the two perpendicular polarization constituents thus is refracted at a different angle as shown in Fig.-7. for example if the incident unpolarized light arises at an angle orthogonal to the surface of the tool, the O-ray can pass straight through the tool 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

Methods of maintaining polarization :

Maintaining the polarization state in optical fiber is alike to the free space control using waveplates via phase changes in the two perpendicular state of polarization. In general three structures are generally used. In the first structure, 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 changes any arbitrary input polarization into a linear polarization. The HWP then revolves the linear polarization to a certain angle so that the second QWP can translate the linear polarization to any certain polarization state. An all fiber controller based on this mechanism can be constructed, with many desirable characteristics such as the low insertion loss and cost as shown in the figure -8. In this tool, 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. Maintaining the diameters and number of turns we create any desired fiber wave plate. Because bending the fiber commonly induces insertion loss, the fiber coils must remain relatively large.

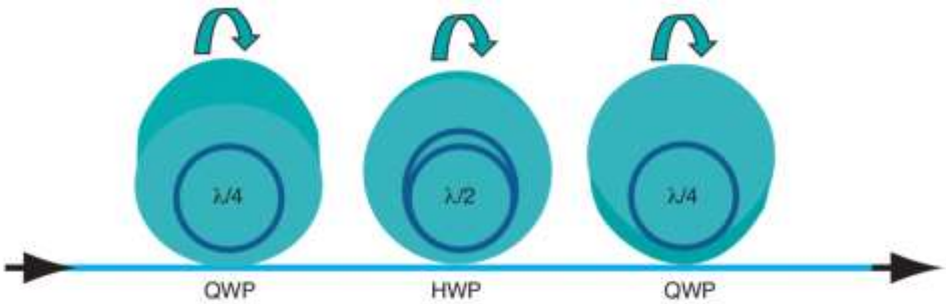

Figure -8 : Polarization control using multiple coiled fiber

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

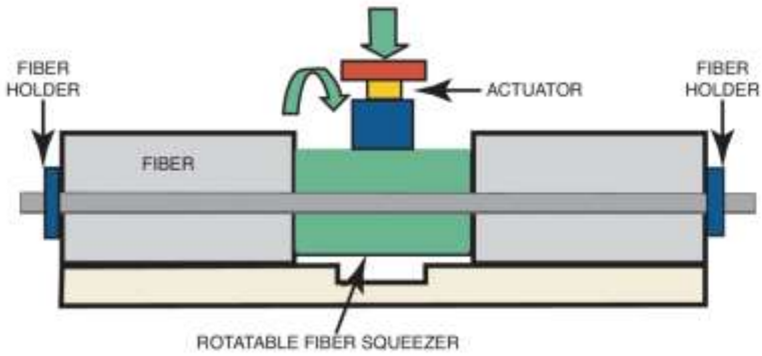

Figure -9: Polarization control using Babinet-Soleil compensator principle.

Polarization maintainers also can be composed with complicated free-space wave plates positioned 45° from each other. An all-fiber tool based on the same working principle would reduce the insertion loss and cost. The decelaration of each wave plate components changes with the pressure of each fiber squeezer. The challenge is making the tool reliable, compact and cost-effective.

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

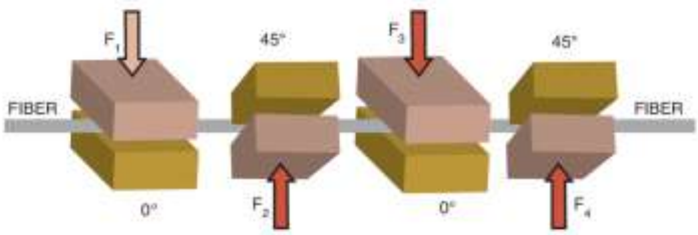

Figure -10: Polarization controller by squeezing fiber from vmany directions.

Polarization Mode Dispersion (PMD)

Polarization mode dispersion (PMD) causes from the fact that light-signal energy as a given wavelength in a single mode fiber actually occupies two perpendicular polarization positions or modes. PMD is due to the two basic perpendicular polarization modes travel at slightly different speeds owing to fiber birefringence. The resulting difference in travelling times between the two perpendicular 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 punishment of less than 1.0 dB, the pulse spreading $\Delta\tau_{PMD}$ following from polarization mode dispersion must on the average be less than 10 percent of a bit period T_b. A useful ways 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.

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

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 increase over this distance is $\Delta\tau_{PMD}$ =5.0 ps, to send an NRZ-enclosed signal over this gap and the lower -punishment requirement is that the pulse increase can be no more than 10 percent of a pulse width T_b. In this case the maximum attainable data rate is $1/T_b$ = 20 Gb/s.

Conclusion

The resulting difference in propagation times $\Delta\tau_{PMD}$ between the two perpedicular polarization modes will result in pulse increasing. 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 says that for a 10-Gb/s link which has 20 spans of 80 km each, the PMD of the transmission fiber should be less than 0.2 ps / $\sqrt{km}$. Thus fibers with low polarization-mode dispersion should be developed and characterized.

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