Polarization Mode Dispersion - Characterization and Compensation Techniques

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Abstract: - We discuss polarization mode dispersion (PMD) in optical fibers and review its basic properties. Special emphasis is put on measurement methods and compensation methods, in particular the use of solitons.

Key-Words: - optical fiber communication, dispersion, pulse broadening, measurement technques, polarization, polarization mode dispersion

1 Introduction

Polarization mode dispersion (PMD) is by many regarded as a severe, ultimate limitation in fiber-optical communication systems. For example, two recent field trial transmission experiment [1,2] on 40 Gbits/s was found to be essentially limited by PMD for transmission distances over a few hundred kilometers.

Chromatic dispersion is well-known to limit the transmission capacity in fibers by the fact that different frequency components have different group velocities. As a result, the pulses that correspond to the bits in the data sequence will broaden and overlap. This will decrease the density with which we can pack the pulses, or in other words, limit the bit-rate of the system.

Polarization mode dispersion can be discussed in analogous terms. In this case it is the different polarization states of the light that has different group velocities. A short pulse in a given state of polarization will therefore split between the fastest and slowest polarization states, with a bit-rate-limiting broadening of the pulses as the result. Contrary to conventional chromatic dispersion, PMD is a particularly troublesome effect since it varies statistically with carrier wavelength and fiber propagation distance, and also drifts slowly with time. Therefore most PMD compensation schemes will have to dynamically adapt to changes while the system is running.

In this paper we will briefly review the properties of PMD in the time- and frequency domains, together with some measurement and compensation methods.

1.1 Origins of fiber birefringence

Single-mode fibers are not strictly single-mode, since they allow for two polarization modes. One might wonder what defines these polarization modes, if the fiber is circular and isotropic. The fact is that the fiber will never be circular and isotropic. Note that for one meter of fiber the light travels around one million wavelengths, and it will therefore take only an index difference between the polarization components of the order of 10^{-6} to induce a polarization change over that meter.

During the manufacture, the fiber is heated to the melting point of glass, and during the cooling, stresses will be introduced in the fiber core in a random manner. Such stresses, along with unwanted ellipticities of the core and microbends are well-known examples of manufacturing imperfections that give rise to birefringence.

When the fiber is cabled and installed there might be additional stresses and mechanical perturbations acting on the cable, and this will also contribute to birefringence. As a result, the polarization state of light traversing the telecom fibers evolves in a random manner through the fiber. Moreover, the polarization state will also change with wavelength and drift with time, due to external perturbations such as temperature and mechanical movements.

The fact that the absolute polarization state varies randomly need not necessarily be a problem, since most components in a communication system can be made polarization independent. However, the wavelength fluctuation might be troublesome if the polarization state changes over the wavelength range corresponding to the signal bandwidth. Then one must evaluate the details of how (and if) this fluctuation in wavelength deteriorates the signal.

1.2 PMD in the frequency domain

Assume that completely polarized, broadband light is launched in to a fiber. During propagation through the fiber one will find that the various frequency components have deviated in polarization relative to each other, see Fig 1.

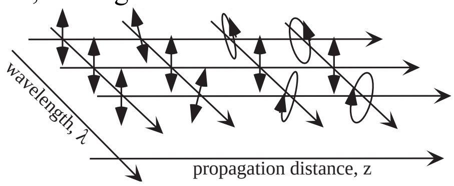

Figure 1: In the frequency domain PMD manidfersts as a wavelength dependent polarization change.

The amopunt of deviation in the polarization is then a measure of the PMD. Mathematically, the polarization change can be modelled via the Stokes vector $\mathbf{s}(\omega)$ in the fiber, which is a function of the optical frequency ω. Here we assume that the light is completely polarized, which means that the it sufficies to consider only three components of the Stokes vector, and those are related to the electric field components of the wave in the standard way[3]: $\mathbf{s}=[|E_x^2|-|E_y^2|,\ 2\mathrm{Re}(E_xE_y^*),\ 2\mathrm{Im}(E_xE_y^*)]$. Note that the modulus of **s** is proportional to the optical power, $|E_x^2|+|E_y^2|$. If the fiber has a Mueller matrix M, then the input and output Stokes vectors are related via $\mathbf{s}_{out}=M\mathbf{s}_{in}$,. In presence of PMD, M is frequency dependent, so that $\mathbf{s}_{out}(\omega)=M(\omega)\mathbf{s}_{in}$. Furthermore, optical fibers have almost no polarization dependent losses, which means that the modulus of **s** is constant, and s moves around on the surface of a sphere known as the Poincaré sphere. Moreover, the Mueller matrices are *orthogonal*, i.e. their inverse equals the transpose: $M^{-1}=M^t$. The properties of 3x3 orthoghonal matrices are well known [4], since they describe rotations in 3-space. Thus we have the geometrical picture of the polarization change clear; the Stokes vector rotates around some vector as the frequency change. Mathematically we describe this as $d\mathbf{s}/d\omega=\Omega\times\mathbf{s}$, where the rotation vector Ω is called the *PMD-vector*. From the definitions, it is straightforward to show that the PMD vector is related to the Mueller matrix via $\Omega\times = dM/d\omega\ M^{-1}$, where Ωx is the 3x3 skew-symmetric matrix corresponding to the cross-product operator. Note that Ω has the dimension time, which, as we will see below, will have a clear interpretation.

1.3 PMD in the time domain

In order move to the time domain one needs to Fourier transform the electric field vector from the frequency domain. We saw in the previous paragraph that the change of polarization could be neatly interpreted as a rotation of the Stokes vector. However, if the electric field is to be considered we must model the polarization and its change with Jones vectors and Jones matrices instead. There are no formal problems in doing this, but the Jones formalism lacks the geometrical interpretation of the Stokes formalism, so we omit the details (see e.g. [5-6]). The main result is simple enough; if a wave with a polarization state with stokes vector **j** is launched into the fiber, it will be *delayed in time* an amount $(\mathbf{j}\cdot\Omega)/2$ during propagation. Note that the maximum and minimum values of this scalar product is $\pm|\Omega|/2$, so the difference in group-velocity delay between the two orthogonal polarization states aligned with the PMD vector equals $|\Omega|$, see Fig. 2.

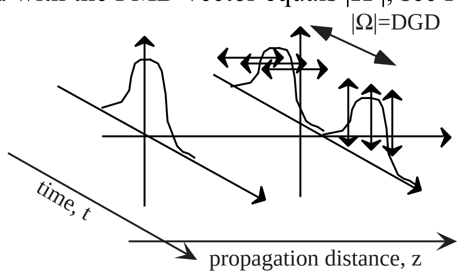

Figure 2: A short pulse in the time domain will break up due to the PMD.

The modulus of the PMD vector is therefore called the *Differential Group Delay* (DGD). The polarization states aligned with Ω are called the *Principle States of Polarization*, (PSP). Hence, if a short pulse is polarized in a state not equal to the PSP, it will be broken up in to the PSP:s by PMD. If, on the other hand, the pulse is polarized along a PSP, it will exhibit no broadening, but merely a constant time shift. Since this shift applies to the entire pulse train in a communication system, it will not degrade the system. Therefore it is advantageous to launch the signal along the principal states, and as we shall see below, this has been suggested as a way of overcoming PMD. Finally we might add that, the PSP:s are the states of polarization that does not change with wavelength (to first order in . In fact, this was the way the PSP:s were originally defined [7].

The above model of pulse breakup arises when one assumes that the PMD-vector is constant over all wavelengths, and it is called *first-order PMD*. In fact, as we shall see shortly, the PMD vector itself will almost always vary with wavelength. This is known as *second-* or *higher-order PMD*. For such cases, obviously, the principle states will lose their meaning. However, it is still possible to exactly calculate the RMS-width broadening τ of an optical puse, polarized along $\mathbf{j}$. The result is $\tau^2 = (<\Omega^2> - <\mathbf{j}\cdot\Omega>^2)/4 + \tau^2_0$, where <> denotes integration over the (normalized) pulse spectrum and τ_0 is the intial pulse width [5].

2 Properties of the PMD vector

The PMD vector contains all the essential information about the polarization properties of the fiber. In accordance with the above discussion, it should be clear that it is a three-component vector, the components of which is random functions of wavelength (or optical frequency ω), time t (due to the drift) an fiber distance z. Hence we can write it as $\Omega(\omega,t,z)$. Since the PMD vector fluctuates in a random fashion in all those parameters it must be treated by statistical means. Before we do this, however, we will discuss the concatenation problem. This is as follows: What is the PMD vector of a concatenation of birefringent elements? The answer is very simple, yet so far unpublished in its general form: *The PMD vector of a concatenation of birefringent elements is the vectror sum of the individual PMD vectors, provided each individual PMD vector is transformed by the Mueller matrices to a common position.*

The consequences of this theorem is that if a fiber is viewed as a concatenation of many small, say N, birefringent elements with the same amount of DGD, then the total PMD vector is a vector sum of N small, randomly oriented vectors. Hence each component of Ω will be a sum of many random variables, and according to the central limit theorem this sum will be a Gaussian random variable. The three components of the PMD vector are therefore identically, Gaussian distributed independent random variables [8-10]. This causes the DGD to have a Maxwellian distribution function. Note also that the average of the PMD vector is zero, i.e. $E[\Omega]=0$, since there is no preferred direction. The concatenation picture outlined above will also be useful in estimating how the average DGD grows with fiber length. We just note that the fiber length is proportional to N, and that Ω performs a random walk in three-space that is superposed by N random vectors. It is then straighforward to prove that $E[\Omega^2]$ will grow in proprtion to N, or that $E[|\Omega|]$ will grow in proportion to the square root of fiber length. The proportionality coefficient, which gives the DGD in picoseconds per square-root-kilometer is known as *PMD-coefficient* of the fiber. Common values of the PMD coefficient in installed fiber are 0.05-0.5 ps/√km. Spooled fiber in the lab have in general a much lower PMD-coefficient (over ten times), and this often makes it difficult to perform system experiments on PMD in the lab.

It should be observed that the square-root deoendence of the DGD for standard transmission fiber is in sharp contrast to the delay in polarization maintaing (PM) fiber. In that case the birefringence and its axes are constant throughout the fiber (not random) so that the DGD grows linearly with fiber length. In PM-fibers the birefringence is usually induced by artificially incorporated stresses, or elliptical core shapes. Typical amounts of the birefringences in such fibers are of the orders of ps/m.

We end this section with a few additional words on the statistics of the random PMD vector in transmission fibers. When it comes to the statistics of frequency derivative of Ω, i.e. $d\Omega/d\omega$, this quantity is important in estimating the contributions of higher-order PMD. The probability density function of this quantity is quite cumbersome things are getting more complicated, but an involved analysis [8] give that those have hyperbolic secant-shaped probability distribution functions. More recently [11], we have also computed the autocorrelation function of the PMD-vector, i.e. $g(\Delta)=E[\Omega(\omega+\Delta)\cdot\Omega(\omega)]$. We found $g(\Delta)=3(1-\exp(-2E[\Omega^2]\Delta^2/3))/2\Delta^2$. This is in agreement with simulation work that have been carried out previously [12-13], stating that the PSP:s vary over a frequency range of the order of an inverse DGD.

3 Measurement methods for PMD

There are many methods for measuring PMD, and the amount of commercial PMD measurement equipment grows at a steady rate. PMD can be characterized in either the time domain, or (which is usually more accurate) in the frequency domain. We will review the most common measurement methods below. We omit the time-domain pulse broadening methods due to limited space.

3.1 The fixed-analyzer method

The fixed-analyzer method is probably the most simple and straightforward method to measure fiber PMD. It consists of a polarized broadband source that is launched through the fiber under test (FUT), and the output is monitored on a spectrum analyzer (see Fig. 3). The method was pioneered by Poole and co-workers [17-18], and some later modifications of the theory have been suggested [19]. In this method, the DGD of the fiber under test is proportional to the number of oscillations of the transmission spectrum.

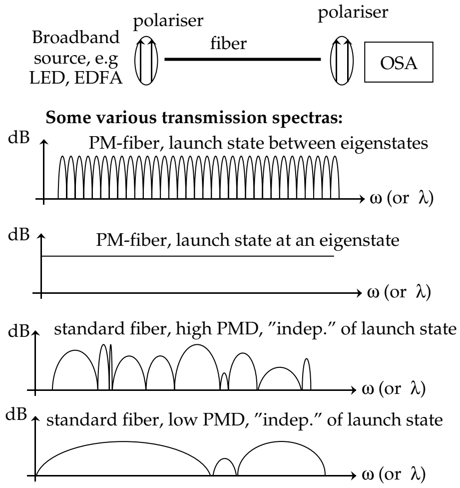

Figure 3: The fixed analyzer method.

The pros of this method are that it is simple, intuitive and uses fairly cheap optics. On the negative side is that it is limited to wavelength intervals and wavelength resolved measurements are difficult to obtain with high accuracy. A similar method in principle, but with a very different set-up (actually simpler, no polarizers are needed!), is the Sagnac interferometer method [20-21] which sends broadband, unpolarized light through a 3-dB-coupler, whose two output ports are closed by the fiber under test (i.e. a loop mirror). The transmission spectrum will then show the characteristic variations of a Fixed-analyzer trace.

3.2 Interferometric methods

There is a set of methods using interferometry for the determination of the PMD-properties (se e.g. [22-23] and references therein. Many of those use a homodyne detection scheme with lock-in amplifiers that are expensive and cumbersome to use, and they are seldom used for this reason. We will instead focus on the simple, polarizer-free scheme proposed by Thévenaz and co-workers [23-24]. This is shown in Fig. 4. The interferometric method is attractive in that it use cheap optics, i.e. broadband source, slow detector and no inlining of fibers. It has therefore got a lot of attention commercially. The drawback is that wavelength resolution is not possible, and that the accuracy is not excellent. In addition the source characteristics might affect the results [24-25].

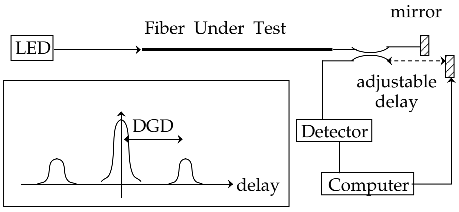

Figure 4: The interferometric method

3.3 Polarimeter methods

The most straightforward and accurate way of measuring the PMD is to directly measure the Jones or Mueller matrices of the FUT for a set of wavelengths, and then to use the definition to compute the PMD-vector [26-27]. Note that the PMD-vector is well-defined on every wavelength, but since it depends on the wavelength derivative of the Mueller matrix, at least to Mueller matrixes on different wavelength must be used for each measurement. A typical set-up is shown in Fig. 5

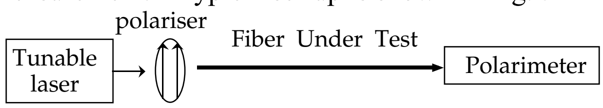

Figure 5: The basic set-up for the polarimeter methods.

In order to determine the Mueller (or Jones) matrix of the FUT one need three independent in-polarization states, and then the corresponding output states are measured. Therefore the method can be quite time consuming, and it also demands expensive equipment. On the pro-side is the excellent accuracy and the wavelength resolution.

4 Combating PMD

Several methods have been suggested to compensate or reduce the influence of PMD in a system. The main problem is the drift which forces all methods (except the use of solitons) to dynamically adapt to changes while the system is running. There is currently a lot of work under way in this area, and within a year we will probably see the first commercial PMD compensator.

4.1 Electrical and opto-electronical compensation

The signal distortion induced by PMD can to some extent be equalized electrically [28]. Opto-electronical compensators are another method, based on polarization diversity detection so that two or several electrical signals can be combined to yield a compensated signal, see e.g. [29].

4.2 PSP methods

The first demonstrated way of combating PMD optically was presented in [30]. The idea is based on the PSP:s, and the fact that the signal is least distorted by PMD when it is launched in a PSP. This is done by dynamically controlling a polarization controller before the signal is launched in to the transmission line. There are two main drawbacks of this method. Firstly, higher orders of PMD will not be compensated for. However, simulations show that the DGD as high as 30 % of the bit slot can be tolerated, as compared with 10% without compensation [31]. Secondly, the feedback must be all the way from the receiver to the transmitter.

4.3 Optical post-compensation

The most intense research on PMD compensation is for the moment on post-transmission compensation. In this case two problems face the engineer. Firstly, how shall we detect that PMD have distorted the signal? Secondly, how should we compensate the PMD-induced distortion? To answer the second question first, this is done by introducing a birefringent element with x degrees of freedom, so that it can be tailored to have the same PMD characteristics as the fiber, but in the reverse axes. The higher x is, the better the compensation, but then a more complex control system is required. It is trickier to answer the first question. In the first demonstration of this compensation technique, [32] the control system sought to minimize the signal at half the pulse repetition frequency. In more recent approaches control signals at not only half the baseband frequency but also at a fourth and an eight of the baseband were used[33]. This method used a compensator comprising 64 step motors for the change of polarization and DGD. Another idea recently proposed is to use the degree of polarization as an error signal [34].

4.4 Solitons

Soliton pulses arise due to the fiber nonlinearity, i.e. that the refractive index of the fiber increases weakly with intensity. This effect will prevent broadening due to chromatic dispersion [35]. Also in birefringent media, such as PM-fibers, the nonlinearity can prevent the birefringence-induced break-up of the pulses [36], due to the nonlinear attraction between the two polarization components. In randomly birefringent media the picture is more complex. The solitons are robust to constant birefringence, but when the birefringence axes are randomly rotated, the solitons are unstable and found to emit radiation and lose power to dispersive waves [37-38]. This power loss causes an adiabatic broadening, which, remarkably enough, is of the same $\sqrt{z}$-dependence [38] as linear pulse under the corresponding amount of PMD! From this one might expect that solitons are no improvement over linear pulses. However, this is not the case for two reasons. First, the dispersive radiation can be cancelled by various ways of soliton control [37]. Secondly, the amount of radiation is likely to be overestimated, since real fibers do not have the perfectly periodic random variation that is assumed in the simulations. Indeed, in the first experimental comparison between solitons and linear pulses, the solitons were found to be more robust [39]. As the polarization state of the pulses launched in to the transmission line was varied, the output pulse width was monitored. The linear pulses were found to broaden between 10.5-15 ps, whereas the solitons broadened only 10-11.5 ps (see Fig. 6).

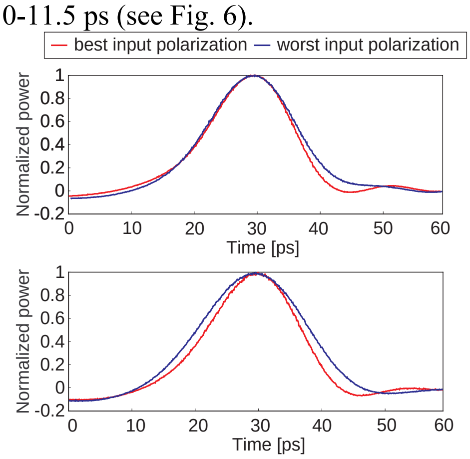

Figure 6: Output pulse widths for solitons (upper) and linear pulses (lower).

5 Conclusions

In conclusion, we have reviewed the basic properties of polarization mode dispersion in optical fiber communication systems. In particular, we focused on measurement methods and ways of reducing the influence of PMD in communication systems.

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