Chapter 1
Introduction

As an alternative to the application of the standard coherent modulation techniques like ASK, FSK, PSK and DPSK to coherent optical communications, modulation methods exploiting the vector characteristics of the propagating light radiation have been recently proposed and/or experimentally demonstrated in laboratory [1-3]. They use the state of polarization (SOP) of a polarized lightwave as the information-bearing parameter. Demodulation and detection is accomplished through the analysis of the SOP. A SOP is fully described by the knowledge of the Stokes parameters [4-6]. Among these techniques, Polarization-Shift-Keying (PolSK) is the most attractive technique in the digital optical communication system because of its high insensitivity to laser phase noise [7]. Therefore, we will introduce the PolSK in the first section. Then we will introduce the polarization state and the Stokes parameters on the Poincaré sphere in the next section. Then will give a conclusion and our motivations in the last section.

1-1 Introduction of PolSK Transmission

Polarization modulation transmission schemes have long been of interest to the communications community. PolSK transmission encodes information on a constellation of signal points in the space of the Stokes parameters. In general, each signal point corresponds to a given state of polarization and a given optical power. If only the polarization of the lightwave, and not its power, is modulated, all the signal points lie on the Poincaré sphere. When a polarized lightwave is sent through a single-mode optical fiber, it is well-known that the state of polarization of the lightwave is altered due to the birefringence of the channel. However, if we look at a whole PolSK signal constellation, fiber birefringence only causes a rigid rotation of the constellation over the Poincaré sphere. In other words, each of the signal points is displaced, but the spatial relationship between the points is preserved. As a result, information is not corrupted.

All so far proposed PolSK systems make use of a binary modulation scheme (2-PolSK) which information is sent by switching the polarization of the transmitted lightwave between two linear orthogonal SOPs. For binary systems, polarization modulation offers a 3 dB better power sensitivity than intensity modulation and a reduced sensitivity to self- and cross-phase modulation. Modulations based on the SOP are made possible by the fact that depolarization phenomenon are of little importance even after relatively long fiber spans [8]. Moreover, previous measurements [9] have shown that the rate of polarization changes due to the transit along the fiber is very low, and no significant variation can take place within a time span comparable with the symbol time. In the three-dimensional space defined by the Stokes parameters, two orthogonal SOPs map onto opposite points with respect to the origin. Thus, detection of binary modulation schemes is simply accomplished by looking at the sign of the scalar product of the received SOP vector in the Stokes space with a reference vector representing one of the received SOPs in the absence of noise. This reference vector depends on the fiber induced changes on the transmitted SOPs, and for this reason, all 2-PolSK systems must somehow keep track of it. As to the effect of the laser phase noise, a general analytical treatment in coherent optical heterodyne receivers is not available. However, numerical analyses and experimental results have proved the considerable insensitivity to phase noise of receivers based on non-linear memory less processing of the signal, provided that the IF filter bandwidth is large enough to avoid phase-to-amplitude noise conversion [10].

Initially PolSK was both theoretically analyzed and experimentally demonstrated only in conjunction with coherent detection [11-12]. This early work on coherent detection PolSK has established some important facts: fiber birefringence does not corrupt polarization-encoded information and in particular the bit error probability is ideally unaffected; birefringence compensation at the receiver is necessary but can be performed at the decision stage after photodetection; binary PolSK has a 40 photons/b quantum-limited sensitivity, whereas coherent ASK requires 80 photons/b (peak); binary and multilevel PolSK systems are largely insensitive to phase noise; multilevel PolSK quantum limited performance is better than DPSK if 3 b/symbol or more are transmitted. In the last few years, the advances in erbium-doped fiber amplifier (EDFA) technology have made it possible for direct-detection systems to approach the sensitivity performance of coherent systems. As a consequence, there has been a considerable shift of interest from coherent detection to direct detection on the part of both research organizations and industry, and a general agreement on the central role direct detection will play for long-haul, high-speed transmission.

1-2 Definition of Polarization and Stokes Parameters

As described in last section, the most important issue of PolSK is the SOP of the modulated lightwave. It is commonly knows that the SOP can be denoted by Stokes parameters on the Poincaré sphere. Therefore, we will simply discuss the definitions of polarization, Stokes parameters and Poincaré sphere.

1-2-1 Polarization and the State of Polarization (SOP)

The state of polarization (SOP) refers to distribution of light energy between the two-polarization modes. The reason of that the fiber is still termed single mode, which means these two-polarization modes have the same propagation constant, is that ideally the fiber is a perfectly circularly symmetric fiber [13]. Thus, though the energy of a pulse is divided between these two-polarization modes, since they have the same propagation constant, it does not give rise to pulse spreading by the phenomenon of dispersion.

Polarization is a distinguishing feature of electromagnetic radiation describing the shape and the orientation of the locus of the electric field vector extremity as a function of time. The polarization state is transformed when a lightwave passes through a medium or is reflected by an object. The variations in the SOP of a lightwave enable one to characterize the system under consideration. The classical concept of polarized light represents the SOP of a lightwave as a function of evolution of its electric field vector E. If the vector describes a stationary curve during the observation or measurement time, the lightwave is called polarized lightwave, sometimes the polarized light has a systematic change and the track of the electric field is predictable. It is called non-polarized if the extremity of vector E has a random position, and the track of the electric field is unpredictable. The electric field vector of an electromagnetic monochromatic plane wave can be expressed in terms of three orthogonal components in the right-handed Cartesian coordinate system [14]. If light is assumed to progress in the z direction, the real instantaneous electric field vector can be written as:

$$\vec{E}(z,t) = \begin{bmatrix} E_x(z,t) \\ E_y(z,t) \\ E_z(z,t) \end{bmatrix} = \begin{bmatrix} E_{ox}\cos(\omega t - k_x z + P_x) \\ E_{oy}\cos(\omega t - k_y z + P_y) \\ 0 \end{bmatrix} \tag{1-1}$$

P_x and P_y are the instantaneous phases, and the ω means angular frequency.

While z = 0, Eq. 1-1 can be shortened as Eq. 1-2:

$$\vec{E}(t) = \begin{bmatrix} E_x(t) \\ E_y(t) \end{bmatrix} = \begin{bmatrix} E_{ox}\cos(\omega t + P_x) \\ E_{oy}\cos(\omega t + P_y) \end{bmatrix} \tag{1-2}$$

We define the electric field phase difference between x-axis and y-axis as Delta δ as Eq. 1-3 below

$$\delta \overset{def}{=} P_y - P_x \tag{1-3}$$

Where $-180^o < \delta \le 180^o$. The orientation of the electric field vector E depends on the sign of the relative phase δ. Usually, if $\sin\delta < 0$, the ellipse is termed right-hand i.e. the rotation is clockwise to an observer looking toward the light source. Then

$$\begin{cases} -\pi < \delta < 0 & \text{Left - Circle Polarization} \\ 0 < \delta < \pi & \text{Right-Circle Polarization} \end{cases}$$

1-2-2 Stokes Parameters

As decribed in section 1-2-1, the polarization of a uniform plane wave describes the time-varying behavior of the electric intensity vector at a given point in space.

In 1852, Mr. Stokes used four parameters (S_0, S_1, S_2 and S_3) to completely describe the polarization state of the lightwave in vector form. That is so called Stokes vector. While the E vector of the plane wave is fixed in the x direction, the Stokes vector is (S_0, S_1, S_2, S_3) = (1,1,0,0). The wave is said to be linearly polarized in the x-direction. While the E vector of the plane wave is fixed in the y direction, the Stokes vector is (S_0, S_1, S_2, S_3) = (1, -1, 0, 0), the wave is said to be linearly polarized in the y-direction. While the E vector of the plane wave is fixed in the composed of x and y direction with phase difference 0^o and 180^o, the Stokes vector is (S_0, S_1, S_2, S_3) = (1, 0, 1, 0) and (1, 0, -1, 0). The wave is said to be 45^o and 135^o (-45^o) linearly polarized in the x-y plane. While the E vector of the plane wave is fixed in the composed of x and y direction with phase difference 90^o and -90^o, the Stokes vector is (S_0, S_1, S_2, S_3) = (1, 0, 0, 1) and (1, 0, 0, -1). The wave is said to be right circular and left circular polarized in the x-y plane.

Adopting the widely used definitions, we define the Stokes Parameters as following:

$$S_0 \overset{def}{=} E_{ox}^2 + E_{oy}^2 \tag{1-4}$$

$$S_1 \overset{def}{=} E_{ox}{}^2 - E_{oy}{}^2 \tag{1-5}$$

$$S_2 \overset{def}{=} 2E_{ox}E_{oy}\cos\delta \tag{1-6}$$

$$S_3 \overset{def}{=} 2E_{ox}E_{oy}\sin\delta \tag{1-7}$$

Since there are only three independent variables, the four Stokes parameters are verified as:

$$S_0{}^2 = S_1{}^2 + S_2{}^2 + S_3{}^2 \tag{1-8}$$

And we can get the phase difference when we use Eq. 1-7 divided by Eq. 1-6:

$$\delta = \tan^{-1}\left(\frac{S_3}{S_2}\right) \tag{1-9}$$

Normalize the Stokes parameters by the total optical intensity (including polarized and unpolarized light), we can write

$$s_1 = \frac{E_{ox}^2 - E_{oy}^2}{S_0}, \quad s_2 = \frac{2E_{ox}E_{oy}\cos\delta}{S_0}, \quad s_3 = \frac{2E_{ox}E_{oy}\sin\delta}{S_0} \tag{1-10}$$

The range of the normalized Stokes parameters is –1 to +1. By gathering the formula we mentioned above, we can get the full meanings of Stokes parameters in Eq. 1-11:

$$\begin{bmatrix} S_0 \\ S_1 \\ S_2 \\ S_3 \end{bmatrix} = \begin{bmatrix} I \\ I_0 - I_{90} \\ I_{45} - I_{-45} \\ I_{RCP} - I_{LCP} \end{bmatrix} = \begin{bmatrix} E_{ox}{}^2 + E_{oy}{}^2 \\ E_{ox}{}^2 - E_{oy}{}^2 \\ 2E_{ox}E_{oy}\cos\delta \\ 2E_{ox}E_{oy}\sin\delta \end{bmatrix} = \begin{bmatrix} 1 \\ \cos 2\varepsilon \cos 2\theta \\ \cos 2\varepsilon \sin 2\theta \\ \sin 2\varepsilon \end{bmatrix} \tag{1-11}$$

Where ε is the ellipticity and θ is azimuth. The meanings of Stokes parameters are list below:

$$\mathbf{S}=\begin{pmatrix} s_0 \\ s_1 \\ s_2 \\ s_3 \end{pmatrix}=\begin{pmatrix} s_0 = \text{Total Intensity (in polarised and unpolarised states)} \\ s_1 = \text{Intensity difference between Vertical \& Horizontal SOP} \\ s_2 = \text{Intensity difference between Linear} \pm 45^0 \text{ SOP} \\ s_3 = \text{Intensity difference between (RHC) \& (LHC) SOP} \end{pmatrix}$$

From Eq. 1-11, we can derive some relationship between the polarization parameters and list below:

Phase Angle	$-180^{o} < \delta < 180^{o}$	$\frac{S_3}{S_2} = \tan\delta$
Ellipticity	$-45^{o} < \varepsilon < +45^{o}$	$\frac{S_3}{S_0} = \sin 2\varepsilon$
Azimuth	$0^{o} < \theta < 180^{o}$	$\frac{S_2}{S_1} = \tan 2\theta$
Direction	$90^{o} < \beta < -90^{o}$	$\frac{E_{oy}}{E_{ox}} = \tan\beta$
DOP	$DOP = \frac{\sqrt{S_1^2 + S_2^2 + S_3^2}}{S_0^2}$	
Orientation	$\text{Orientation} = \sqrt{\frac{S_0 - S_1}{S_0 + S_1}}$	

1-3 Summary

In this chapter, we have introduced the definitions of polarization and Stokes parameters on the Poincaré sphere. We derive some useful equations for the application in the later study. As described in section 1-1, the PolSK will play an important role for long-haul, high-speed transmission in the future. But the most difficult problem for PolSK transmission to solve is how to track the SOP, compensate the SOP and manufacture a practical PolSK light source and receiver. Therefore, we set up a WDM/PolSK communication system and provide simple but novel scheme to provide the WDM/PolSK signal source and receiver.

In this thesis, we provide a simple but novel solution for WDM/PolSK communication. In the first chapter, we use a 1.3 μm SOA, 1×4 channel WDM, 90:10 2×2 fiber couplers, and 50:50 1×2 fiber couplers to form a WDM symmetric resonator laser. By combining the resonator laser, WDM MUX and phase modulators together, we can provide a well performance WDM/PolSK light source. To track the changes of the SOPs of the WDM/PolSk lightwave, we design a multi-channel Stokes receiver as the polarization-state measured PolSK receiver in chapter 3. By using the Stokes receiver, we can easily find the changes of the SOPs and provide a reference value for SOPs compensation. Moreover, in chapter 4, we use the WDM/PolSK light source, our Stokes receiver and homemade dynamic polarization compensator, to proceed a 10 km WDM/PolSK transmission. In this experiment, we will track the SOP variation by using our Stokes receiver. Moreover, we will compare the received signal with the initial signal to see the performance of our WDM/PolSK fiber-optic communication system and check the practicalities of our homemade components in the WDM/PolSK fiber-optic communication system. We give brief conclusions of our research in the last chapter.