CHAPTER 1

INTRODUCTION

1.1. General background

One of the most impressive engineering achievements of the past decade has been the explosive advance of optical fiber communication [1-4]. Optical fibers, which even as recently as 1970 were primarily objects for laboratory research, are now being manufactured and in regular commercial service in both terrestrial and undersea systems. Low transmission loss and large bandwidth are particularly important characteristics which make optical fiber so attractive for telecommunications applications. The other advantages include immunity to electromagnetic interference, small size, light weight, no need for electrical transmission, and excellent security against unauthorized "tapping".

Figure 1(a) illustrates a simple lightwave transmission consisting of a laser transmitter, fiber transmission line and optical receiver. Using simple intensity modulation (IM), the modulating binary signal converts the transmitter output light to on-off light pulses which are launched into the fiber. At the receiver, the modulated optical signal power is detected directly and converted back into electrical signal using avalanche photodetector (APD) or p-i-n photodiode. Before 1970, such a link could not have been used for transmission over distances greater than a few hundred meters, because of rapid signal attenuation in the fiber. In the same year, however, Corning Glass achieved a breakthrough by producing a fused silica fiber with loss low enough (20 dB/km) to make transmission lengths of a few kilometers commercially practical [5]. This event, coupled with the development of efficient semiconductor light sources, stimulated a worldwide build-up of lightwave research and development which actively continues today.

Such scheme is now being employed in the present standard optical fiber communication systems which already surpass conventional coaxial cable microwave transmission systems in terms of transmission performance. These systems are primarily due to advances in optical source and fiber technologies. However the optical receiver sensitivity has not significantly been improved.

The most demanding requirement for the next level of sophistication in optical communication systems is the significant improvement in receiver sensitivity and this can be accomplished through heterodyne or homodyne detection scheme. Note that optical communication systems which use heterodyne or homodyne detection scheme are commonly referred to in the literature as coherent optical communication systems[6].

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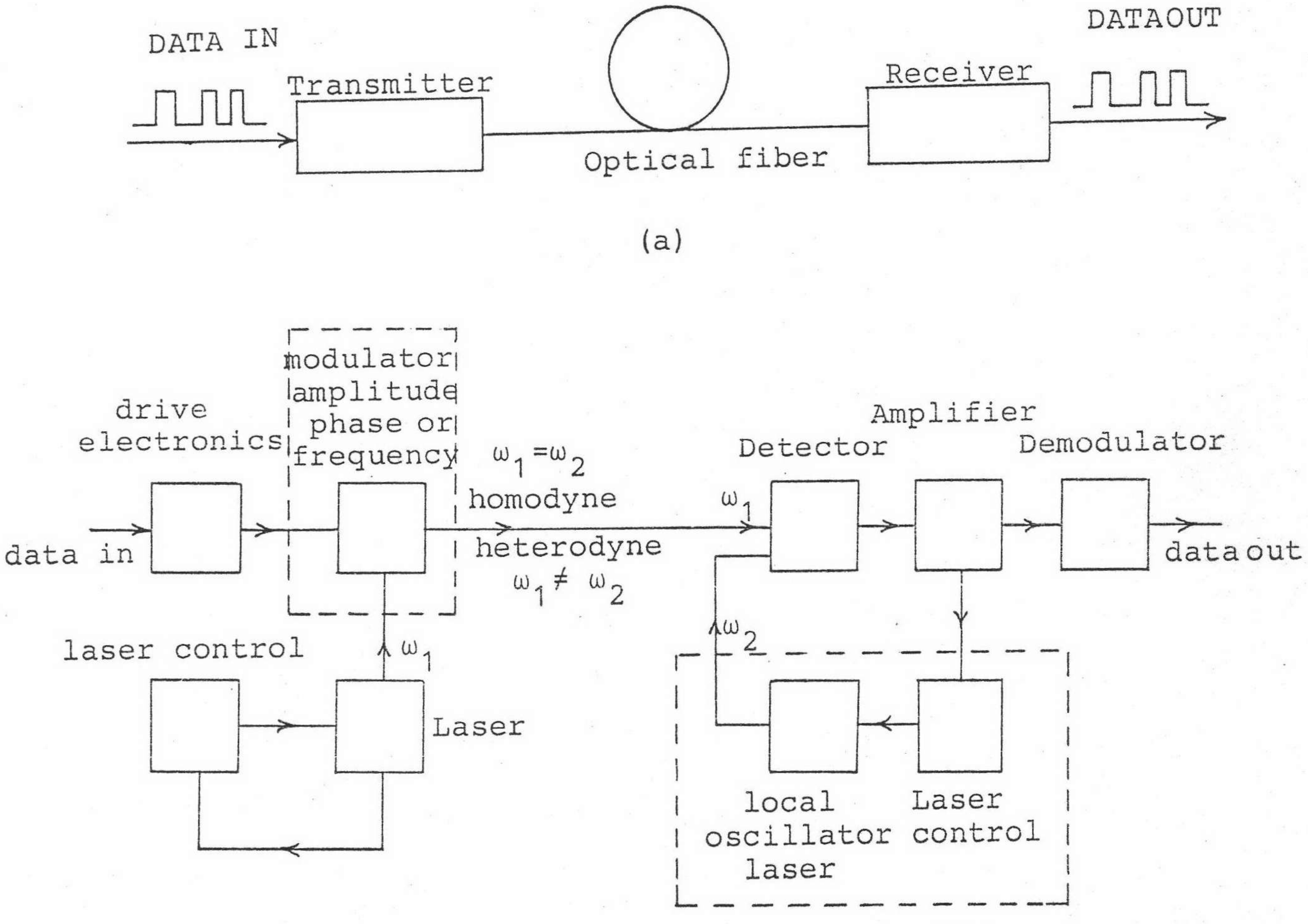

(a)

(b)

Fig. 1. Principle idea of optical fiber communication. (a) Simple intensity modulation/direct-detection transmission link. (b) Schematic diagram of coherent (heterodyne/homodyne) optical system (receiver), (ω = laser optical frequency).

results. To achieve shot noise limited receiver sensitivity 4-11 dB improvement in performance is necessary.

The techniques determining the performance of coherent optical fiber communications [12-13] are : (1) laser linewidth narrowing, e.g., DFB/DBR laser, external cavity; (2) compensation of laser modulation characteristics, e.g., electrical compensator, phase tunable laser diode; (3) polarization compensation, e.g., fiber type controller, polarization diversity; (4) demodulation, e.g., frequency discriminator, single filter;(5) optical detection, e.g., broadband detector dual detector, phase diversity;(6) external modulator, etc.

The major problems that limit the ultimate transmission performance of coherent optical fiber communications are laser linewidth broadening and polarization fluctuation of the received signal.

The above expectation on the increased receiver sensitivity and improved channel selectivity are the motivating factors underlying the present effort toward coherent optical fiber communication research [12-14]. However, several technical problems must be overcome before a practical coherent system is realized in the future.

1.2. Technical problems

In coherent optical fiber system experiments, laser linewidths ranging from a few KHz to a few MHz are needed, depending on the modulation format and receiver type [15]. Unfortunately, the linewidths of current single-frequency lasers are at least ten times this value. The main types of digital modulation, amplitude shift keying (ASK), frequency shift keying (FSK), and phase shift keying (PSK), differ widely in the demand they place on laser linewidth. ASK and FSK can, in principle, be used with lasers having linewidths comparable to the signal bitrate [16-17] while PSK requires laser linewidths of order 0.01% of the bitrate [18]. Requirements and performance for continuous-phase FSK (CPFSK) and differential phase shift keying (DPSK) are very similar. The linewidths for both techniques are within 0.2-0.5% of the bitrate [19].

In most cases the solution of this linewidth problem has been accomplished by using an external cavity laser, either as a source laser or as a local oscillator [20-22]. The external cavity can produce linewidths as narrow as 1 KHz [20], and proper adjustments can allow the frequency to be tuned over a continuous range of 1.5 nm [23].

More complicated devices are also being reported; linewidths of 1.5 MHz have been achieved by monolithically integrating a waveguide with a DFB laser [24], and a flat FM response for FSK systems was achieved by modulating the wave guide region [25].

In the future, high bit rate coherent optical transmission over 1 Gbit/s will become the target of research. For heterodyne scheme, the difficulty of using the wideband IF amplifier (at least 3-4 times bitrate) arises. A solution which eliminates the high-frequency requirements of heterodyne detection is the use of homodyne detection. However, synchronous homodyne formats require the local oscillator phase to be locked to the phase of the received signal, and this is difficult to achieve in practice because it places unrealistic demands on the laser linewidth [16,18]. An alternative approach for homodyne systems is to use phase diversity receivers, such as the triple-branch [26] and double-branch [27] multiport techniques. With multiport techniques, it is possible to accomplish homodyne reception while simultaneously relaxing laser linewidth requirements.

Another major problem that limits the ultimate performance of coherent optical fiber communications is the fluctuation of the state-of-polarization (hereafter, SOP) at the receiving end of the fiber lightguide. In this thesis, the emphasis will be placed upon the polarization state control of the fiber output signal. Overview of the polarization problems is discussed in the following section.

1.3. Polarization problem

The conventional circular symmetric single-mode fibers allow two mutually-independent orthogonally polarized fundamental modes to propagate. In the framework of Cartesian coordinates, these are the HE_{11x}-mode which has the principal electric field component in the x-direction, and the HE_{11y}- mode which has principally the y-component of the electric field. In a perfectly formed fiber, both modes would propagate together and are degenerated under ideal conditions; i.e. the propagation constants of the two modes are the same.

When no coupling occurs between the polarization modes; i.e. if the fiber is completely straight, any polarization state injected into the fiber would propagate unchanged. In practice, the fiber contains random manufacturing irregularities such as asymmetrical lateral stress, non circular core; etc., which break the circular symmetry of the ideal fiber and lift the degeneracy of the two modes. They propagate with different phase velocities and the difference between their effective refractive indexes is the fiber birefringence $\delta\beta$ (= $k_0(n_y-n_x)$, n = refractive index, k_0 = wave number). Generally, the HE_{11x}-mode is taken to be the fast mode and the slow mode is the HE_{11y}-mode. If the light is launched into the fiber so that both modes are excited, phase of one mode will lag or lead the other as they propagate.

When this phase difference is an integral number of 2π, the two modes will beat and at this point, the input polarization state will be reproduced. Thus the effect of a uniform birefringence is to cause a general polarization state to evolve through a periodic sequence of states as it propagates.

At any given point in the fiber, the polarization state can therefore be linear, elliptical or circular. The length over which the beating occurs is the fiber beat length L_p ($= 2\pi/\delta\beta$), an important parameter expressing the degree of birefringence. Commonly available single-mode fibers have beat lengths in the range 10 cm $< Lp <$ 1 m, corresponding to effective refractive index differences in the range $10^{-7} < n_y - n_x < 10^{-4}$.

For an optical fiber communication system utilizing long single-mode fibers, the state of polarization (SOP) at the output end of the optical fiber is unstable and randomly fluctuates due to changes in ambient conditions such as mechanical vibration, temperature fluctuations and pressure changes. Such polarization fluctuations would lead to fading in the receiver and thus presents a serious problem for connection of single-mode optical fibers to integrated optical circuits, optical multiplexers, some kinds of optical switches, and optical heterodyne/homodyne system. In optical fiber sensor system, such as laser gyroscope, the measurement accuracy is also effected. In these cases, therefore, a polarization-state control scheme is indispensable.

Three methods have been devised to overcome this difficulty :

(1) Use of a polarization-maintaining fiber [28],

(2) Use of active SOP-control device at the receiving end [29],

(3)Polarization insensitive (or polarization diversity) receiver [30].

The first method would be a complete solution to the problem. However, the polarization-maintaining fiber is still technologically at a prematured stage. Currently, such fibers have only been made with significant attenuation penalties over the conventional single-mode fiber, and are more difficult and expensive to make.

This problem may be solved in the future. However, it is clear that a polarization matching method compatible with standard single-mode fiber would have significant advantages, since it would allow the use of coherent optical systems in upgrading existing single-mode systems to higher bit rates or longer repeater spacings. Measurements of the polarization state on long cable links have shown that the polarization state drifts slowly [31]. This result suggests that it would be attractive to use conventional single-mode fiber in conjunction with a SOP control device which could provide correction with adequate response time. In a polarization tracking receiver using SOP control devices, the polarization state of the incoming signal is actively modified to match this of the local oscillator (LO) or vice versa. Currently, this second method is the most widely researched technique.

The other alternative method would be the use of a polarization insensitive receiver [30], as has been used in the past for microwave communication. Such an approach normally employs separate heterodyne detection for the two polarizations and recombines them in the receiver electronics.

Presently, various versions and combinations of the last two schemes are being intensively investigated.

1.4. Purpose of the thesis

The purpose of this thesis is to study the polarization-state control in coherent optical fiber communication systems. A new automatic SOP control scheme called "polarization recombining" is proposed and tested. The system consists of a vertical/horizontal linear polarization beam splitter (a Wallaston prism), a 90° linear polarization rotator, an endless phase shifter, and a beam combiner. This scheme features a very simple (probably the simplest) principle for the SOP control and endlessness (resetting-free) in control. In addition, the SOP of the output light is always linear with a fixed inclination angle regardless of changes in SOP of the incoming light.

Such a characteristic is particularly useful in a phase diversity [27]. The experiment simulating actual phase diversity receiver using the new scheme for compensating the polarization-state fluctuation is also presented.

1.5. Synopsis of the thesis

This thesis is composed of seven chapters; each of which begins with an introduction section which gives a brief explanation of topics to be discussed in that chapter. A short summary which concludes the concepts and work described in that chapter is also included.

The present chapter is an introduction to the study in which general background and technical problems, particularly in polarization-state control of coherent optical fiber communications, are presented.

In chapter 2, the mathematical expressions describing different SOP's (i.e. elliptical, linear and circular polarization of a completely polarized light) are given. Next, a partially polarized light, which is generally encountered in the real situation, is considered. The expression for the degree of polarization (hereafter, DOP) of the light is then derived. Finally, recent theoretical treatments of the DOP and measurements of the polarization-state fluctuation in single-mode optical fiber are reviewed and discussed.

Chapter 3 reviews and compares various countermeasures against polarization-state fluctuation which have been reported in the past years.

Chapter 4 describes the principle of the polarization recombining scheme which is proposed as an alternative approach for compensating the polarization-state fluctuation. The visibility and polarization characteristics of the polarization recombined light have been measured for different length of single-mode optical fiber (300 m, 1.5 km, 15.4 km, and 27 km). The results are presented in this chapter.

The endless phase shifter based on a simple polarization rotating technique is the key component in this scheme. Chapter 5 describes the principle of the device in detail. In order to investigate the performance, two types of phase shifters have been constructed and tested. Error analysis is also included.

The feasibility of the polarization recombining scheme in a SOP control system is studied in Chapter 6. The demonstrating SOP control experiments are presented. The implementation of the scheme for compensating the polarization-state fluctuation in a simulating phase diversity homodyne optical receiver is also demonstrated. The effect of polarization misalignment on the signal-to-noise ratio in such receiver is also discussed.

Chapter 7 concludes the work, discussing the features of the proposed SOP control scheme as compared with the previous ones together with comments on technical improvements of the scheme.