CHAPTER 3

COUNTERMEASURES AGAINST THE FLUCTUATION OF THE STATE-OF-POLARIZATION IN A SINGLE-MODE OPTICAL FIBER

3.1. Introduction

To realize highly efficient coherent optical fiber communication systems, polarization matching between signal lights and local oscillator light is required. Several methods exist which have the potential to provide the required polarization matching at the receiver. Possible countermeasures are :(1) the use of a polarization-maintaining fiber over the entire length of the communication channel, (2) the use of polarization insensitive receivers and, (3) the use of a polarization-state control device at the receiving end which matches the polarization state of LO with that of the signal, or vice versa.

This chapter reviews recent activities on these methods.

3.2. Polarization-maintaining fiber

With respect to the first countermeasure against the polarization fluctuation, an optical fiber having axial asymmetry in its cross section is used. When the cross section of a conventional single-mode fiber is intentionally deformed away from axial symmetry, degeneracy of two possible polarization modes is removed. According to Sakai [53], two eigenpolarization modes, independent and orthogonal to each other, can propagate through such deformed fibers. In order to transmit one of the two eigenpolarization modes, only the polarization mode should be launched into the fiber, while mode conversion to another eigenmode must be suppressed during propagation

An important parameter describing the performance of a polarization-maintaining fiber is the extinction ratio at fiber output, which is defined by the power ratio of the unwanted mode to the launched mode [54]. The extinction ratio is given as a function of the mode coupling coefficient, which is determined by the modal birefringence $\delta\beta$ should be made large or, on the other hand, the beat length L_p ($= 2\pi/\delta\beta$) should be made small.

Several types of polarization-maintaining optical fibers have been proposed to increase modal birefringence. Early proposals included fibers having geometrically asymmetric refractive-index profiles, such as elliptical-core fibers [55]. The thermally induced modal birefringence has been theoretically treated for specific profile [56]. Thermally-stressed polarization-maintaining fibers, such as elliptical jacket [57], PANDA [58] and bow-tie [59] fibers have been fabricated. Among these, the shortest beat length thus far achieved has been $L_p = 0.8$ mm [57].

These polarization-maintaining fibers can actually convey either of the two eigenpolarization modes. In order to permit only one polarization mode to propagate through such fibers, an attempt to impose a cutoff condition on the other mode has been made by introducing a loss difference between the two eigenpolarization modes [60].

It is essential that polarization-maintaining fibers have a small loss comparable to that of conventional single-mode fibers. Suppression of the extinction ratio, as well as reduction of fiber loss is also indispensable. Significantly, a 26 km-long PANDA fiber whose loss approached that of the single-mode has recently been developed [61]. The loss characteristic of this fiber is shown in Fig. 7, with a minimal fiber loss of 0.3 dB/km being achieved for a 26 km-long fiber, which corresponds to a mode coupling coefficient of 2.4×10^{-7} m^{-1}. These results indicate the possibility that polarization-maintaining fiber can be practically utilized in future high-speed and medium span coherent optical fiber communications.

The extinction ratio is shown in Fig. 8 as a function of the mode coupling coefficient for cases with and without a loss difference occurring between the two polarization modes [62]. The mode coupling coefficient can be suppressed by increasing the modal birefringence and by decreasing the fiber

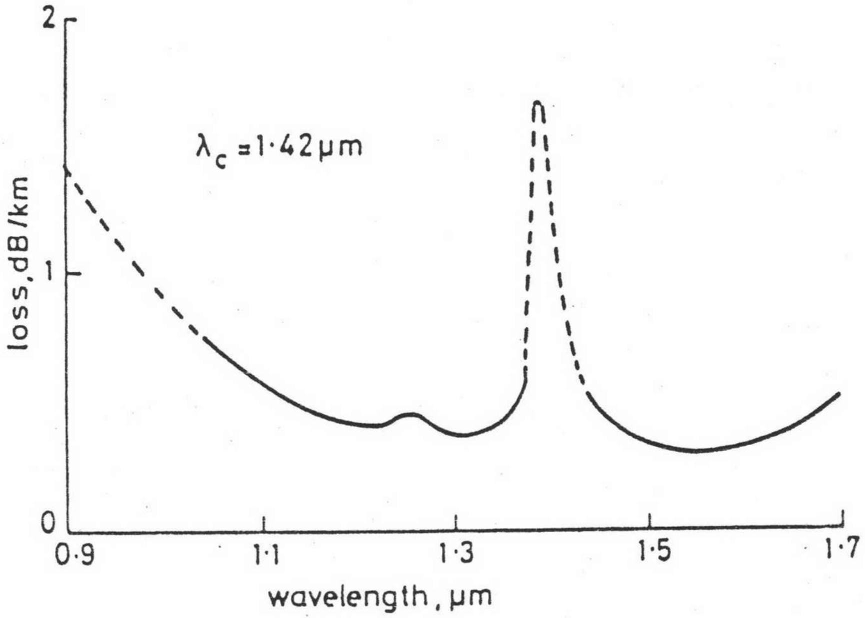


Fig. 7. Loss spectrum for a 26-km-long polarization-maintaining (PANDA) fiber. Cut-off wavelength λ_c is 1.42 µm (after Sasaki et al.[61]).

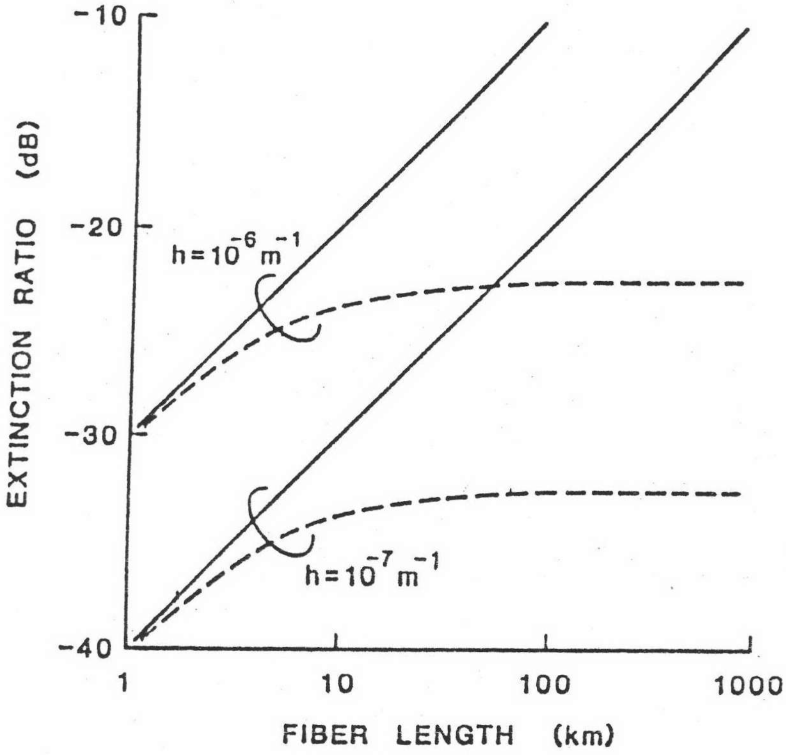


Fig. 8. Extinction ratio as a function of mode coupling coefficient h. Solid lines indicates no loss difference between two polarization modes. Broken lines indicate loss difference (0.2 dB/km: 1 dB/km) (after Marrone [62]).

perturbations. Introduction of the loss difference which leads to saturation in the extinction ratio for a long fiber, is effective for achieving a small extinction ratio although it may cause an increase in propagation mode loss. Thus, it is important to develop thermally stressed polarization-maintaining fibers having properties of both low loss and a small extinction ratio.

Mode coupling between the two orthogonal polarization modes occur because of internal and external perturbation existing along the fiber. Internal perturbations such as core-cladding irregularity, depend on the fiber fabrication technology employed. In order to simultaneously suppress mode conversion and decrease fiber loss, it is necessary to improve the uniformity along the fiber axis. Direct measurement of the coupling coefficient under suppressed external fluctuation conditions can provide information about internal perturbations [63].

By introducing polarization-maintaining fibers instead of conventional single-mode fibers, polarization-state matching between signal and local oscillator light can be easily carried out without the necessity for any additional polarization control scheme. These fibers are the complete solution to the polarization-state fluctuation and offer great advantages in developing sophisticated coherent systems using optical amplifiers and optical integrated circuits, which are often sensitive to the polarization state of input signals. Moreover, polarization-maintaining fibers also offer the possibility of polarization-division multiplexing.

However, the polarization-maintaining fibers are still undergoing development and expensive, coherent optical transmission experiments have thus far mainly used only conventional single-mode fibers in conjunction with a polarization compensator or a polarization insensitive receiver.

3.3. Polarization insensitive (or polarization diversity) receiver

Recently, polarization insensitive or (polarization diversity) receivers, which allow construction of coherent optical receivers without polarization controllers were increasingly studied [64].

To date three techniques which achieve polarization diversity reception have been proposed and demonstrated : (1) those which independently detect two orthogonal polarization states of the received signal and then combine either the resulting IF signals [30] or the demodulated signals [65], (2) those involving polarization scrambling or switching [66] and (3) those which the received signal light is mixed with two orthogonally polarized (of arbitrary SOP) local oscillator LO states which have been separated in the optical frequency domain [67].

Polarization insensitive receivers which employ the three techniques mentioned above, are tabulated in Table I, in chronological order.

For reviewing purposes, these receivers are classified into three groups according to their detection principles as : (1) polarization diversity receiver, (2) polarization scrambling receiver and (3) polarization orthogonality receiver.

3.3.1. Two-branch polarization diversity receiver

The principle of polarization diversity has been used in the past for microwave communication. Polarization diversity receiver for heterodyne coherent optical fiber communication was first proposed by Okoshi et al. in 1983 [30].

Figure 9 shows the basic configuration of the polarization-diversity heterodyne optical receiver. In Fig. 9(b), the received signal light is separated into two orthogonal linear polarizations, with an assumed power ratio of $\alpha : (1-\alpha)$. Each of these are then heterodyne-detected separately with two linearly polarized LO beams having matched SOP with the signals. The two IF signals obtained in the two heterodyne detectors are amplified, and added together after phase

Table I. Polarization-Insensitive Receiver

Ref.	Authors	Laser	Wavelength	Bit-rate	IF	Modulation	Sensitivity	Technical significance
30 (1983)	Okoshi, Ryu Kikuchi	One:DFB	0.85 μm	-	40 MHz	-	-	First proposal of a polarization diversity
69 (1986)	Kuwahara et al.	-	-	-	-	-	-	First proposal of dual balanced polarization diversity
70 (1986)	Imai, Matsumoto, and Iwashita	Two:DFB	1.54 μm	400 Mb/s	250 MHz	FSK	< 0.4 dB S/N degradation	First FSK experiment (using maximal-ratio combining method)
71 (1987)	Kreit, Youngquist	One:DFB	unknown	40 Mb/s	49 MHz	FSK	17% fluctuation	Use square-law and variable ratio adder
65 (1987)	Glance	-	-	-	-	-	-	Theoretical analysis small penalty (0.4 dB) predicted
79 (1987)	Okoshi, Cheng	Two:DFB	1.3 μm	200 Mb/s	30 MHz	DPSK	-48.8 dBm	First receiver comprising phase and polarization diversity
66 (1987)	Hodgkinson, Harmon, Smith	Two: external cavity	unknown	20 Mb/s	560 MHz	ASK	4.5 dB penalty	First polarization scrambling receiver
67 (1987)	Kersey, et al.	Two: AlGaAs diode laser	0.8 μm	-	550 MHz and 1.31GHz	-	-	First polarization orthogonality receiver
73 (1987)	Tzen, Emkey, Jack	One:HeNe	1.523 μm	4 Mb/s	80 MHz	DPSK	0.8 dB variation in amplitude	First DPSK experiment with dual balanced receiver
74 (1987)	Darcie, et al.	Two: external cavity	1.5 μm	50 Mb/s	300 MHz	FSK	-55.5 dBm	First FSK experiment with LO excess noise cancelling
75 (1987)	Ryu, Yamamoto, Mochizuki	Two:DFB	1.56 μm	560 Mb/s	980 MHz	FSK	-44 dBm	Use square-law combining method
76 (1988)	Enning et al.	Two:BH	1.3 μm	560 Mb/s	1.5 Ghz	ASK	-35 dBm	Use envelope detectors
77 (1988)	Hodgkinson, Harmon and Smith	Two: external cavity	1.5 μm	70 Mb/s	280 MHz	ASK	-54 dBm	Use square-law combining method
72 (1988)	Okoshi, Ishida, Kikuchi	-	-	-	-	-	-	Theoretical analysis small penalty (0.4 dB) predicted

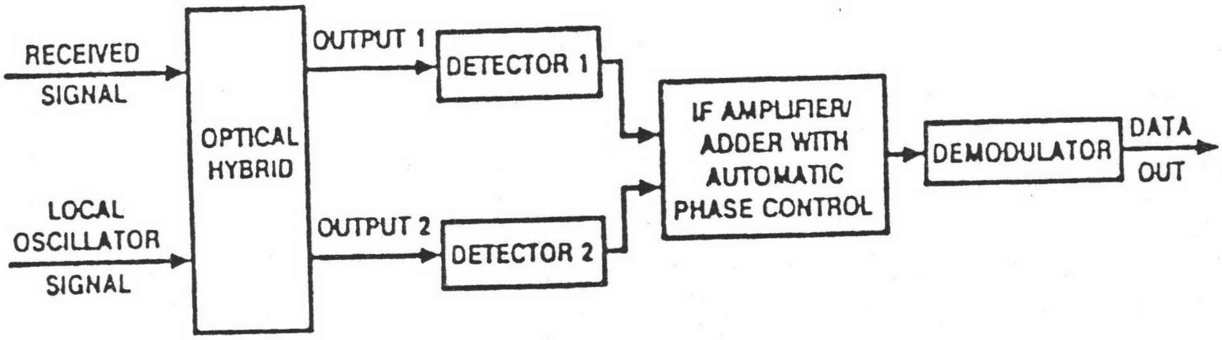
compensation. A phase shifter is needed because the two IF signals usually have an arbitrary phase difference.

The overall S/N of this system is calculated as

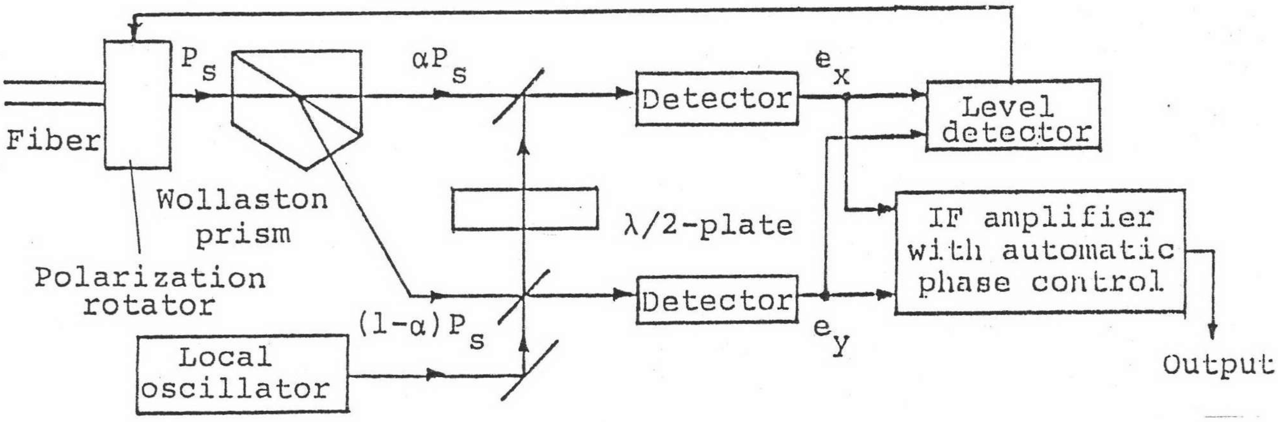
$$S/N = (RP_s/2eB)[1+2\sqrt{\alpha(1-\alpha)}]$$

where R = photodetector responsivity, P_s = received signal power, e = electron charge, B = receiver bandwidth

Figure 10 shows the S/N degradation γ value from the ideal heterodyne detection system as functions of α , for three basic signal combining methods [68]. The term "selection combining" means that one of the IF signals exhibiting a better S/N is always picked up, whereas the other If signal is discarded. The "maximal ratio combining" means that two signals are multiplied by the factors proportional to the respective signal levels, and added coherently afterwards. The "equal-gain combining" means that the IF signal (or baseband signals) are directly combined. The latter method's S/N degrades by 3 dB from its maximum value (α=0.5) with the worst case of polarization fluctuation i.e. α = 0 or 1. In this scheme (see Fig. 9(b)), therefore, the polarization inclination angle of the received signal is adjusted automatically by using a fiber-type Faraday so that the two IF signal levels are equal (α = 0.5). However, this system presents the complexity of the electronics especially the electronic phase compensator is difficult to design.



(a)



(b)

Fig. 9. (a) Principle idea of polarization diversity receiver employing IF signals combining. (b) First polarization diversity receiver proposed by Okoshi, Ryu, et al. [30].

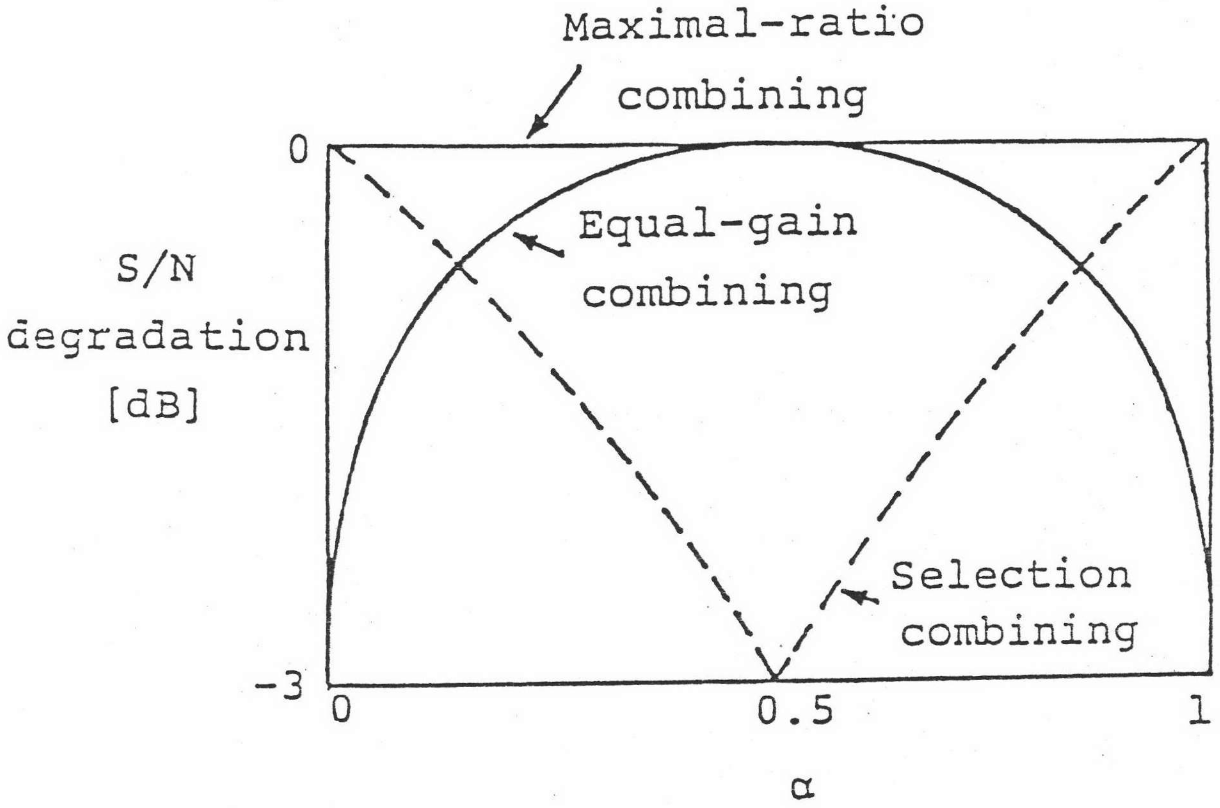


Fig. 10. S/N degradation as a function of power-splitting factor of polarization beam splitter α for three different combining methods (after Ryu [68]).

Such drawback together with the slow drift of SOP fluctuation in a single-mode fiber have made the diversity scheme less attractive than the SOP control schemes. Therefore, the polarization-state control has been performed mainly on the latter techniques.

Until 1986, the research and development of the polarization diversity receiver began to pick up. In that year, two papers proposed the use of polarization diversity receiver for coherent optical detection had been reported [69,70]. One paper was presented by Kawahara et al. [69] who proposed the first idea of a dual balanced polarization diversity receiver enabling the suppression of LO excess-intensity noise.

The other paper reported by NTT researchers [70] at OFS'86 presented a simple polarization diversity detection system employing the maximal ratio combining method. A 400 Mbit/s FSK transmission experiment was performed. The two IF signals were separately demodulated and the resulting baseband signals were then combined using two weighting networks and one combining network. A similar system using variable ratio adder [71] instead of weighting networks has also been reported, shortly after.

However, in the realization of the maximal-ratio combining method, special well-designed weighting circuits and fine adjustment of these circuits are required in order to take the advantage of this method that presents no S/N deterioration compared with the ideal polarization-state control schemes.

Recent theoretical studies have shown that for DPSK polarization diversity receiver in which two IF signals with orthogonal polarization are independently detected and demodulated as in a conventional DPSK heterodyne receiver and subsequently combined without a combination method (see Fig. 11), introduces a 0.4 dB penalty as compared with maximal-ratio combining [65,72].

This value is small and still apply for FSK systems, but as a result of the different noise conditions a larger value is expected for ASK systems. Such polarization diversity detection technique offers an overall reduction in system complexity as compared with those using a combination method [30,70,71], and is now employed in most of the currently reported polarization diversity detection experiments [73,74].

The first dual balanced polarization diversity experiment with a 40 Mbit/s DPSK self-heterodyne system has been demonstrated by AT&T researchers [73]. In this receiver set-up, the amplitude variation of the baseband signal is found to be less than 0.8 dB owing to the unbalanced local oscillator power at the dual receivers.

The second equivalent-dual balanced polarization

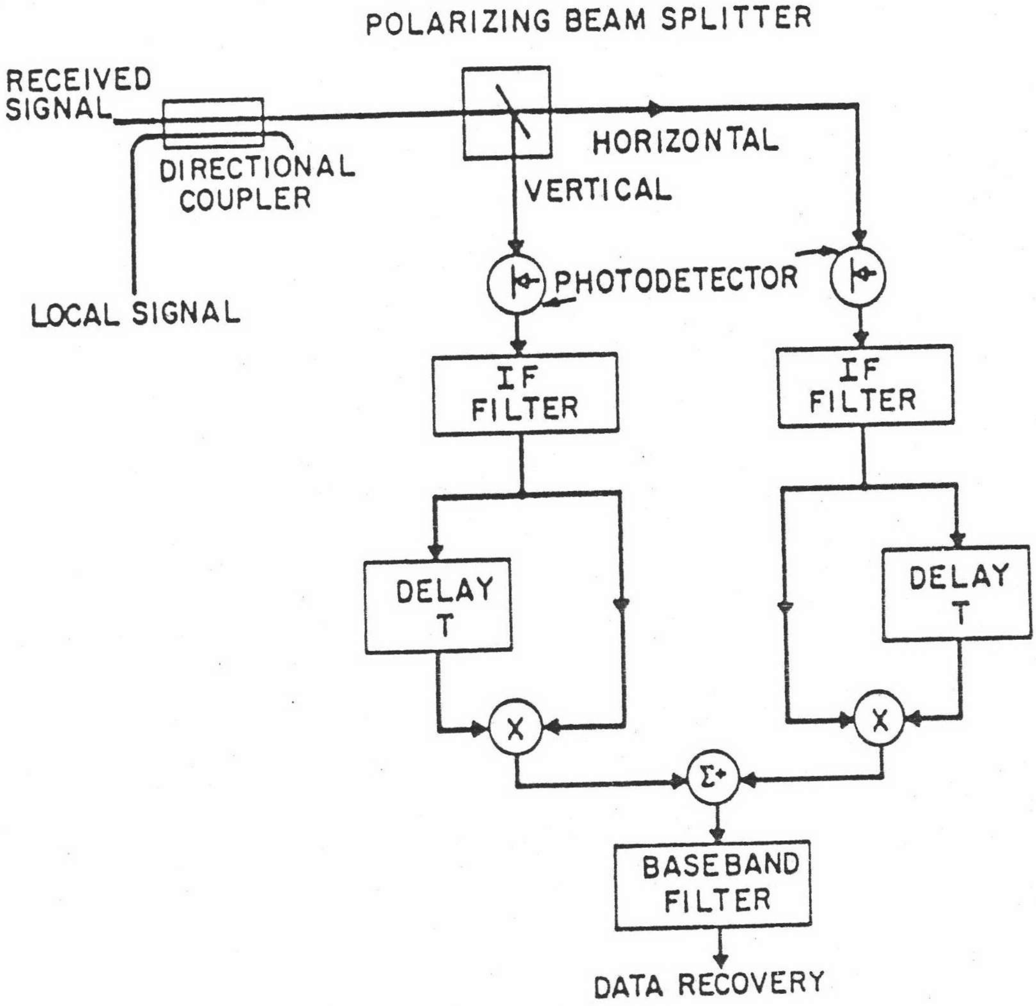


Fig. 11. Polarization diversity receiver employing baseband combining method (after Glance [65]).

diversity experiment [74] employed 50 Mbit/s FSK modulation with two independent grating-tuned external-cavity lasers. The receiver consisted of a 3 dB fiber coupler, a path length difference, a polarization beam splitter and two identical single photodiode PINFET detectors and demodulators (frequency discriminator for FSK). In this system, the variation in receiver sensitivity was found to be 2 dB resulted from variations in the sensitivity of the PINFET front ends. Because of path length dependent $\Delta L = 1/2B$, this technique is limited by the receiver bandwidth B. Thus, more LO power may required to overcome thermal noise which generally increases with increasing IF frequency for a given receiver bandwidth. With the view point of simplicity, the use of the conventional dual balanced receivers as in [73] is more attractive since the system performance is independent of the path length difference.

Feasibility of FSK system with a square-law baseband combining technique was demonstrated in a recent 560 Mbit/sec [75]. The receiver sensitivity penalty of 1.5 dB from the conventional single-detector receiver showed that the system operated near the optimum performance of the maximal-ratio combining method, taking into consideration of the receiver excess noise and non-ideal performance of the square-law circuits.

So far, two experimental systems with ASK modulation using envelope detection have been reported [76,77]. In one of the papers [76], theoretical and experimental results for non-ideal envelope detection showed that the effects of non-ideal processing were small, resulting in an additional 1.0 dB sensitivity penalty in the case of linear rectifiers as compared with the conventional heterodyne receiver. If automatic gain control was added in the IF signal processing, this additional penalty could be as small as 0.2 dB.

In the other paper [77] the system performance was 2 dB worse than the standard ASK heterodyne receiver. This result confirms that polarization diversity can be achieved without using envelope detection prior to the squaring process.

3.3.2. Polarization scrambling receiver

Polarization switching or scrambling [66] has been proposed as an alternative technique for achieving diversity. The polarization scrambler shown enclosed by broken line in Fig. 12 consists of a 1:1 fiber coupler, an phase modulator, a bulk optic polarization selective coupler and several manual polarization controllers (PC). Polarization scrambling between orthogonal states of the signal light is achieved by driving the phase modulator with a square wave such that a 180° modulation depth is satisfied. PC1 is

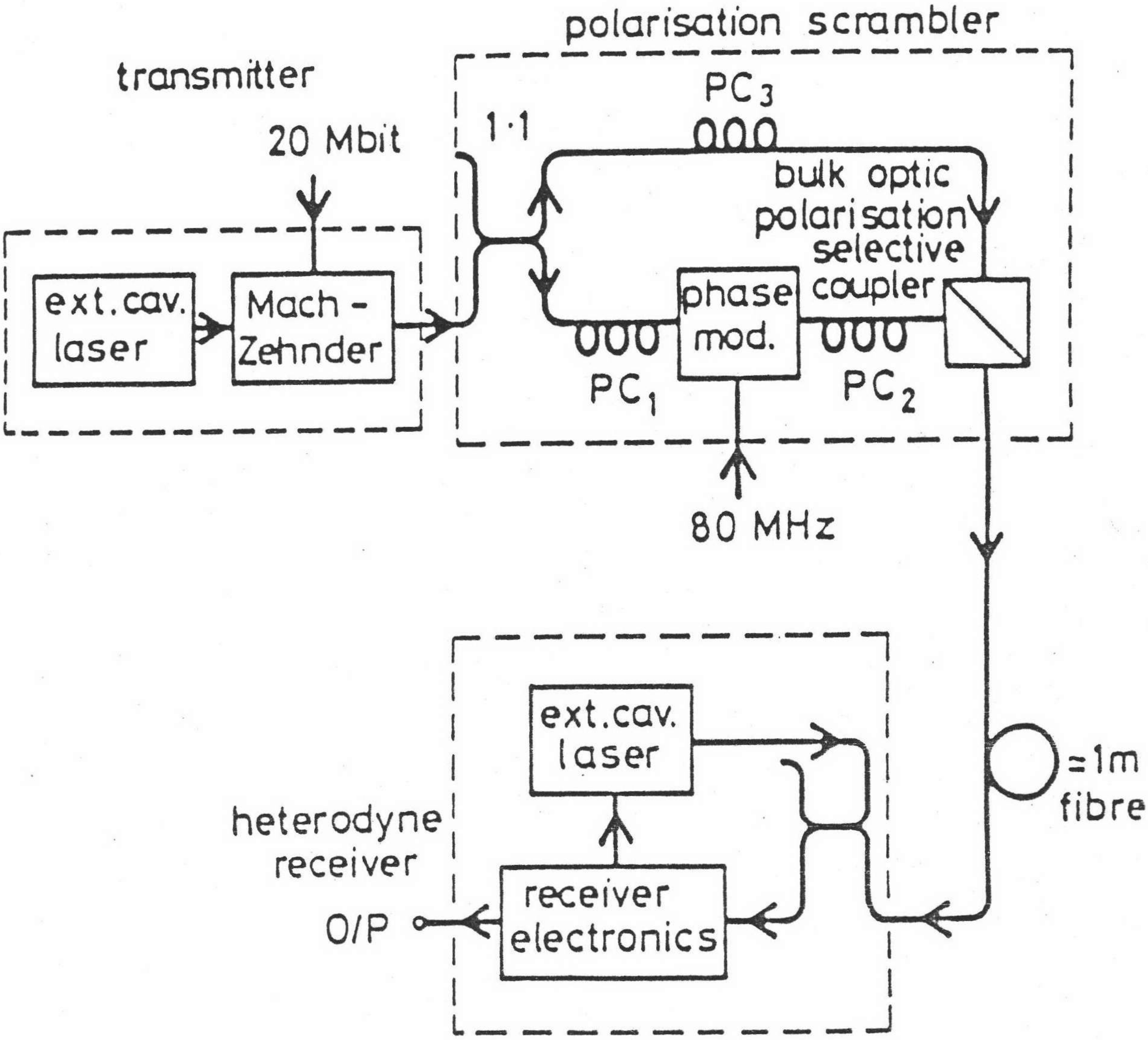


Fig. 12. Experimental setup of polarization scrambling receiver; PC: polarization controller (after Hodgkinson et al. [66]).

adjusted to ensure a collect linearly polarized light entering the phase modulator and equal power from each arm of the scrambler are launched into the polarization-selective coupler by appropriately adjusting the respective PC_2 and PC_3.

Consequently, the two orthogonal polarizations are detected at different time depending on the scrambling rate. In this system, thus, only single photodetector is needed and receiver electronics are considerably less complicated than that in two-branch polarization diversity receiver. However, these advantages are achieved at the expense of 3 dB power penalty relative to an ideal heterodyne receiver.

3.3.3 Polarization orthognality receiver (frequency shifted orthogonally polarized LO modes technique)

The most recent polarization diversity detection technique for coherent heterodyne optical fiber communications was proposed by Kersey et al. [67]. The technique is based on a scheme in which the received signal light is mixed with two orthogonally polarized (of arbitrary SOP) LO modes which have been separated in the optical frequency domain, as shown in Fig. 13. The signal light in mixing with both LO modes produces two IF signals at the detector at frequency $\omega_i + \omega_o$, where $\omega_i = \omega_L - \omega_S$. It is assumed that the two

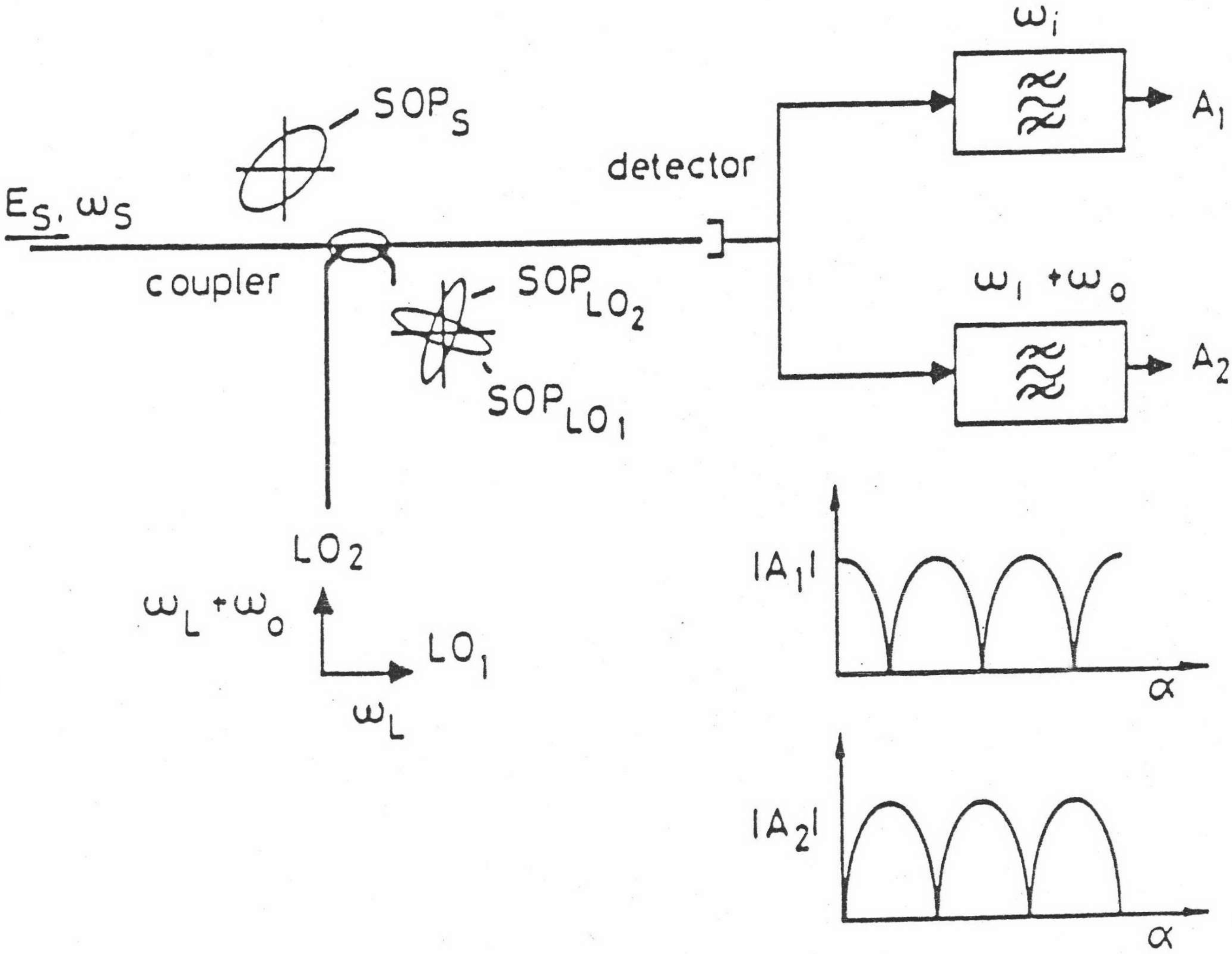


Fig. 13. System configuration of polarization insensitive receiver utilizing frequency shifted LO orthogonal modes technique (after Kersey et al. [67]).

polarization modes of the LO remain orthogonal at the coupler, although the input linear states may have changed states (i.e. elliptical states) many times as they propagate along the fiber. With this statement in mind, the two IF signals fade in antiphase with SOP variations in the signal light. A 0.4 dB power penalty as in the system proposed by Glance [65] is expected when decision circuits on each IF channel are used for data recovery.

The feasibility of this scheme and the polarization scrambling technique rely heavily on the preservation of polarization orthogonality through an optical single-mode fiber transmission line. A recent study on this matter was reported by Cimini et al. [78]. They derived a simple bound on the loss of orthogonality along the fiber transmission line and predicted that orthogonality is virtually preserved for long lengths of fiber and other common single-mode optical components. This result confirms the validity of the principles of both aforementioned polarization diversity detection techniques. One obvious disadvantage of using these two techniques as compared with two-branch polarization diversity receivers discussed in Subsection 3.3.1 is the requirement of wider receiver bandwidth for a given bit-rate.

In the frequency shifting orthogonally polarized LO modes scheme, receiver bandwidth B is determined by the offset frequency ω_0 of the two orthogonal LO polarization modes and bit rate (i.e. $B = 2\omega_0 + 2R_b$, $R_b \leqq \omega_0$). In the polarization scrambling scheme, B is determined by the scrambling frequency f_c (i.e. $B = 2f_c + 2R_b$, $R_b \leqq f_c$). Another disadvantage is that several bulk optic components are needed to realize appropriate modulations. On the other hand , such schemes have one great advantage over the conventional polarization diversity scheme for requiring only single photodetector. This reduces the complexity of the receiver electronics, particularly in the polarization scrambling scheme.

Table I summarizes recent developments in polarization insensitive receivers. An unique four-port homodyne receiver comprising phase and polarization diversities recently proposed by Okoshi and Cheng [79] is also included, as shown in Fig. 14. This receiver is particularly attractive in the future high bit rate (a few Gbits/s) coherent optical fiber communications since it combines passive countermeasures against both the phase noise fluctuation and the SOP fluctuation. From Table I, it can be seen that the research activities in polarization-insensitive receivers are rapidly increased in the past two years.

3.4. Polarization-state control schemes

So far, the most widely researched technique to

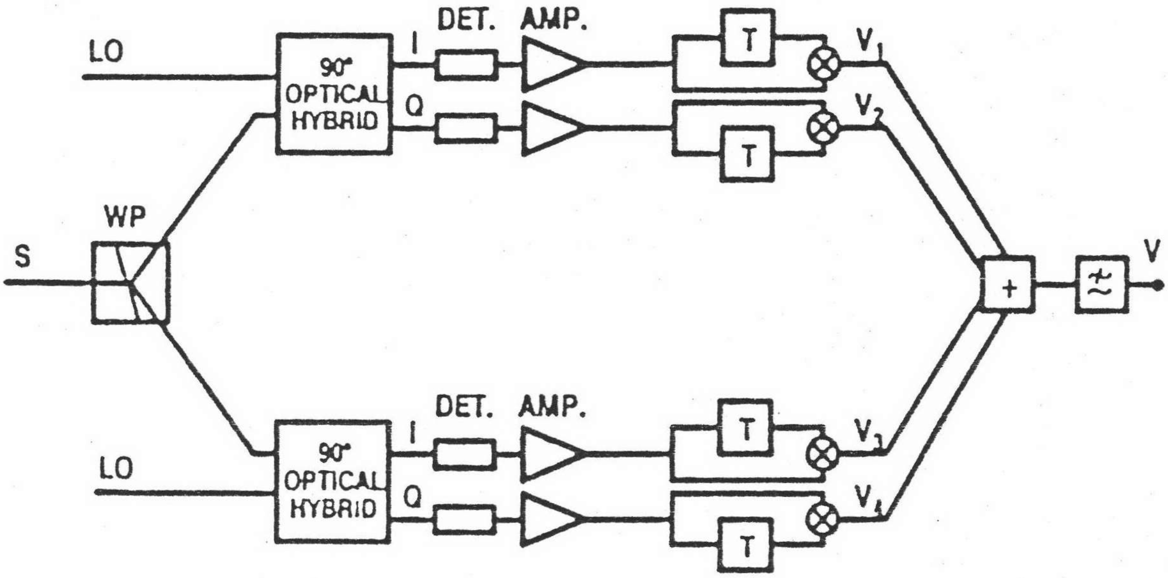


Fig. 14. First four-port homodyne receiver comprising phase and polarization diversities. S : signal light; LO : local oscillator light; WP :Wollaston prism; I : in-phase signal; Q : quadrature signal; T : delay line demodulator. (after Okoshi and Cheng [79])

overcome the polarization fluctuation in single-mode optical fibers is the use of SOP control devices.

In principle a SOP device should be able to convert any incident polarization state to any other state at the output. However, in almost all practical applications for coherent optic fiber communications, the requirement is to convert the fixed (in most cases, linear) SOP of the LO to an arbitrary state of the signal, or vice-versa.

As mentioned previously, measurements of the polarization on long-installed fiber cable have shown that the polarization state drifts slowly [48], and that to use conventional single-mode fiber in conjunction with SOP control devices should provide correction with adequate response time. Many SOP control schemes have been proposed using fiber optics [80-83,91], electrooptics [84-85] and conventional optical components [86]. The various schemes are summarized in Table II, in chronological order.

These schemes can be classified into five groups according to their SOP-conversion principles. The first three groups (Type I - Type III) follow those of Okoshi [29]. The last two groups [92-94] have been proposed very recently.

3.4.1. Type-I SOP control scheme

This Type is common in those schemes using

Table II. Polarization-State Control Schemes

Type of SOP control scheme	Insertion loss	Endlessness in control	Temporal response	Mechanical fatique	References
Type I :					
Fiber squeezer :					
(Ulrich, 1979)	Low	No	Medium	Yes	80
(Honmon et al., 1986)	Low	No	Medium	Yes	88
(Noe, 1986)	Low	Yes (with reset)	Medium	Yes	89,90
(Walker et al.,1987)	Low	Yes (with reset)	Medium	Yes	91
Electro-optic crytals :					
(Kubota, 1980)	High	No	Fast	No	84
(Kidoh, 1981)	High	No	Fast	No	85
(Heidrich, 1987): Integrated optical device	Medium	Yes	Fast	No	96
Type II :					
Rotatable fiber coils :					
(Lefevre, 1980)	Low	No	Slow	Yes	81
(Matsumoto, Kano, 1986)	Low	Yes	Slow	Yes	87
Rotatable phase plates :					
(Imai et al., 1985)	Medium	Yes	Slow	No	86
Rotatable fiber cranks :					
(Okoshi, Cheng et al., 1985)	Low	Yes	Slow	Yes	83
Type III :					
Faraday rotators :					
(Okoshi, Cheng et al., 1985)	Low	No	Fast	No	82
Type IV :					
Linearly birefreingent fiber :					
(Tatam, 1987)	Low	No	Slow	Yes	92
Type V :					Present work
Polarization recombining :					
(Mahon, Khoe, 1987)	Medium	Yes (with reset)	Medium	Yes	93
(Napasab, Okoshi, 1988)	Medium	Yes	Slow	Yes	94

electromagnetic fiber squeezers [80,88-91] and electrooptic crystals [84-85].

a) Electromagnetic fiber squeezers:

The SOP control scheme using the electromagnetic fiber squeezers was first proposed by Ulrich [80]. Figure 15(a) and (b) show the principle of operation of such scheme and its schematic diagram, respectively.

Note that for simplicity, we consider here only conversions from any SOP to the horizontal or vertical linear polarization.

Two electromagnets M45 and M0 transversely stress the fiber in the directions of 45° and 0°to the x-axis. Therefore, the fiber section squeezed by M45 acts like an optical retarder, converting an arbitrarily elliptical incident polarization state to a linear polarization state with an arbitrarily inclination angle. This linear polarization-state is converted to the horizontal or vertical linear polarization by M0.

The magnetic forces applied to both M45 and M0 are controlled by the four signals (D_1-D_4) obtained from the polarimeter. The signal D_1 and D_2 are used to determined the 90° phase shift between two eigenpolarization modes i.e. linear polarization state at the output of M45, $D_1 = D_2$ is maintained. The inclination angle of the linear polarization e.g. for horizontal or vertical polarization state at the exit of M0, is determined by D_3 and D_4, i.e. $D_3 = D_4$ is

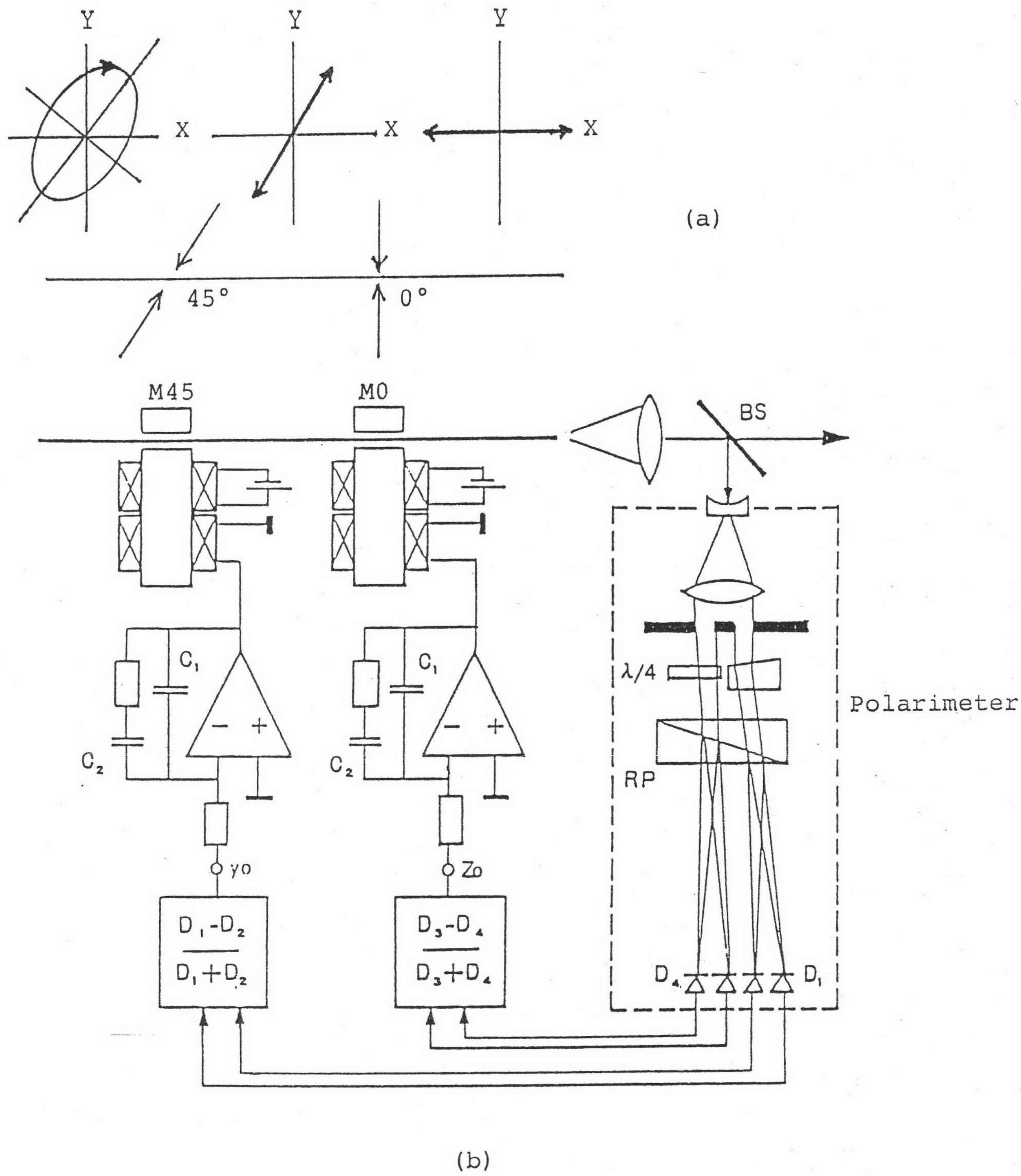


Fig. 15. Type-I SOP control scheme : polarization-state control experiment using fiber squeezers (after Ulrich [80]).

maintained.

Latter, Honmou et al. [88] demonstrated an automatic polarization control system using two fiber squeezers (multilayer piezoelectric actuators) with 280 Mbits/s FSK heterodyne, 141 km transmission system. They showed that the fluctuation of the receiver sensitivity was less than 0.4 dB at a bit error rate (BER) of 10^{-8}.

In these schemes, one problem arises, that is the finite control range of the squeezers which limits the endless operation of the control system. However, this problem can be overcome by adding more elements in series. The experimental systems using three [90] or four [91] squeezers with complicated reset procedures controlled through microprocessor have been reported.

b) <u>Electrooptic crystals</u>:

Kubota et al. [84] reported an alternative SOP control system using the eletrooptical crystals whose principle of operation was similar to the Ulrich's proposal. In the scheme, two Z-cut $LiNbO_3$ modulators M1 and M2 are tilted 45° relative to each other as shown in Fig. 16. The first modulator M1 transforms the principal axis of the elliptical polarization state of the incoming light into the x-axis of the second modulator M2. The modulator M2 transforms the elliptically polarized light with fixed inclination angle into linearly polarized light along the X (or Y)

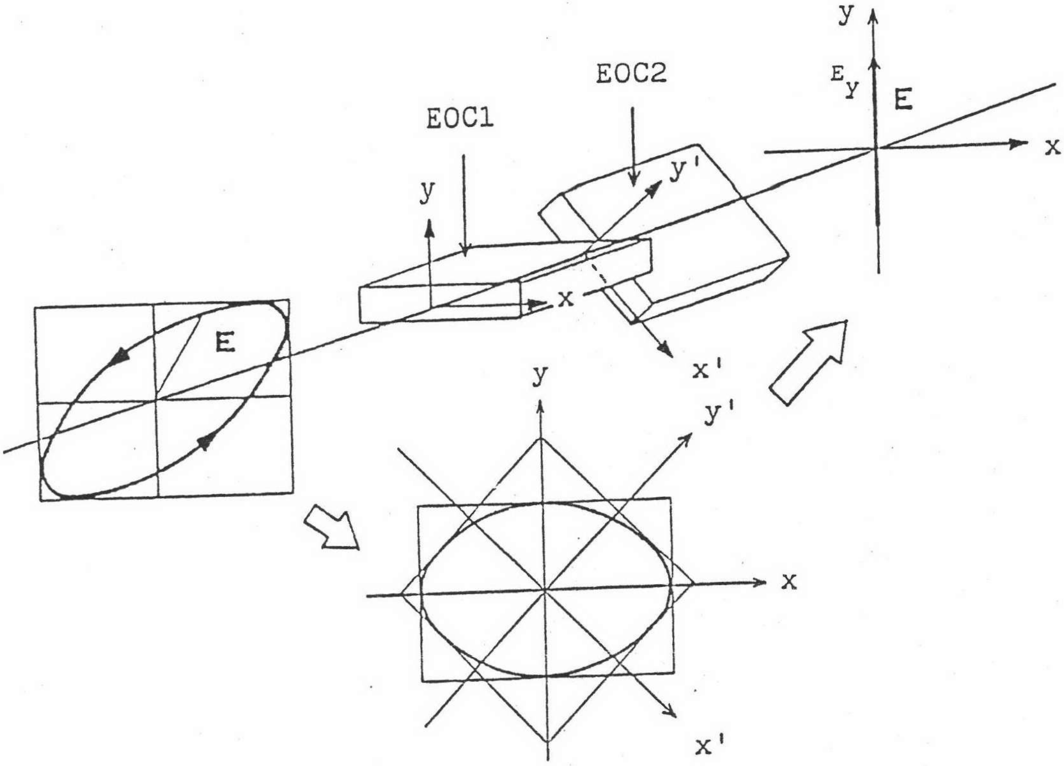


Fig. 16. Type-I SOP control scheme using electrooptic crystals (after Kubota et al. [84], and Kidoh et al. [85]).

axis.

The electro-optic crystals are also the finite range limited birefringent devices. To achieve endless operation with those devices, several elements arranged in series are required together with an optical reset [95]. Experimental results of a reset-free SOP control using an integrated-optical device on Ti : $LiNbO_3$ has also been presented [96]. This study suggests that the integration of the polarization transformer with polarization-insensitive directional couplers on one chip is possible (see Fig. 17).

3.4.2. Type-II SOP control scheme

The Type-II conversion is common in those schemes using rotatable fractional-wave devices [81,87], rotatable phase plates [86], and rotatable fiber crank [83].

a) Rotatable fractional-wave devices:

The device called rotatable fractional-wave (or fiber coils) has been invented by Lefevre [81]. The construction of such device is shown in Fig. 18(a). The first coil FC1 gives, by bend-induced birefringence, a 90° phase difference to two eigenpolarization modes, whereas the second coil FC2 gives a 180° phase difference. Hence, as illustrated in Fig. 18(c), any elliptical polarization can be first converted to by adjusting the tilt angle of FC1 (such

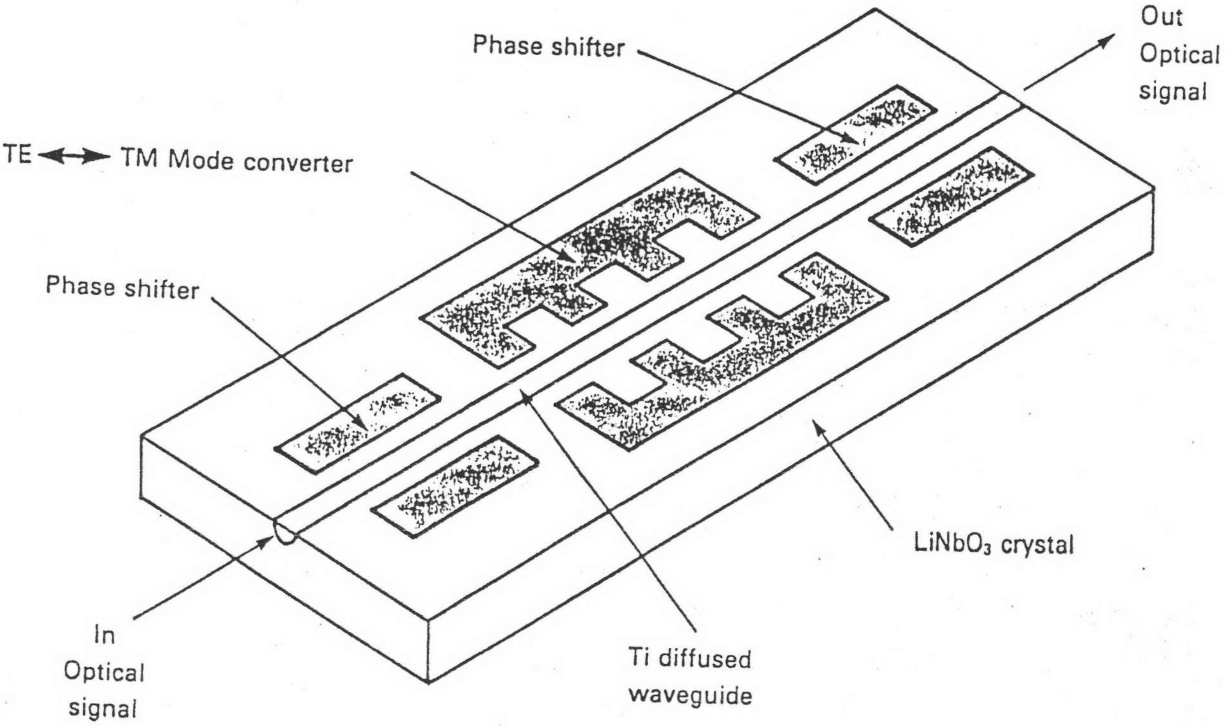


Fig. 17. Integrated Ti: $LiNbO_3$ polarization-state transformer (after Herdrich [96]).

that the principal axis of FC1 lies parallelly with the fast axis of the ellipse), to a tilted linear polarization. The inclination angle of the tilted linear polarization can then be rotated to an arbitrary angle by adjusting the tilt angle of FC2, so that for example, the horizontal or vertical linear polarization can be obtained.

However, these devices have a problem in that their birefringence principal axis cannot be endlessly rotated. This is because rotations may cause fiber to twist or require the increase of supplied voltage. Latter, Matsumoto et al. [87] constructed the endless rotatable fractional-wave devices based on the same principle as the fiber coils and demonstrated the use of their devices as a polarization controller in a 400 Mbit/s, 251-km-long FSK transmission experiment.

b) <u>rotatable phase-plates</u>:

After the invention of Lefevre's fractional wave devices, Imai et al. [86] reported a new scheme in which quarter-wave and half-wave plates are used in place of the FC1 and FC2 respectively. The principle of the operation, as shown in Fig. 18(b) and (c), is entirely identical to that of the Lefevre's device. This is due to the fact that the quarter-wave plate can be used as an optical retarder with 90° phase retardation, and the half-wave plate which gives 180° phase retardation also operates as a linear

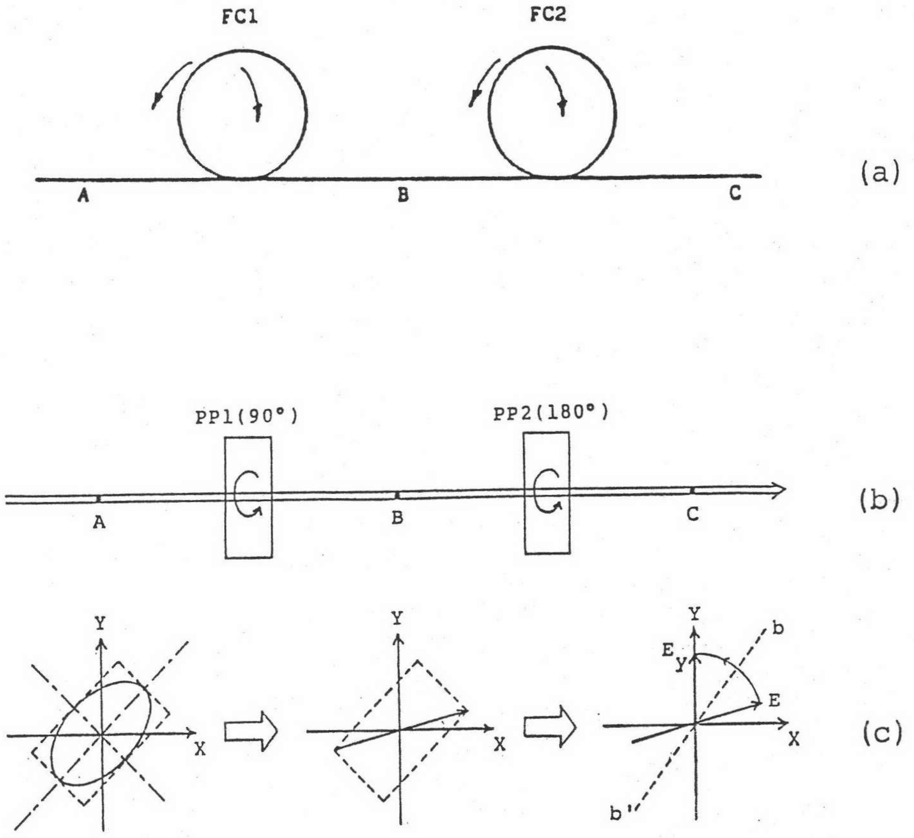


Fig. 18. Type-II SOP control schemes: (a) rotatable fiber coils (FC) (after Lefevre [81]), (b) rotatable phase plates (after Imai et al. [86]), (c) principle of SOP conversion.

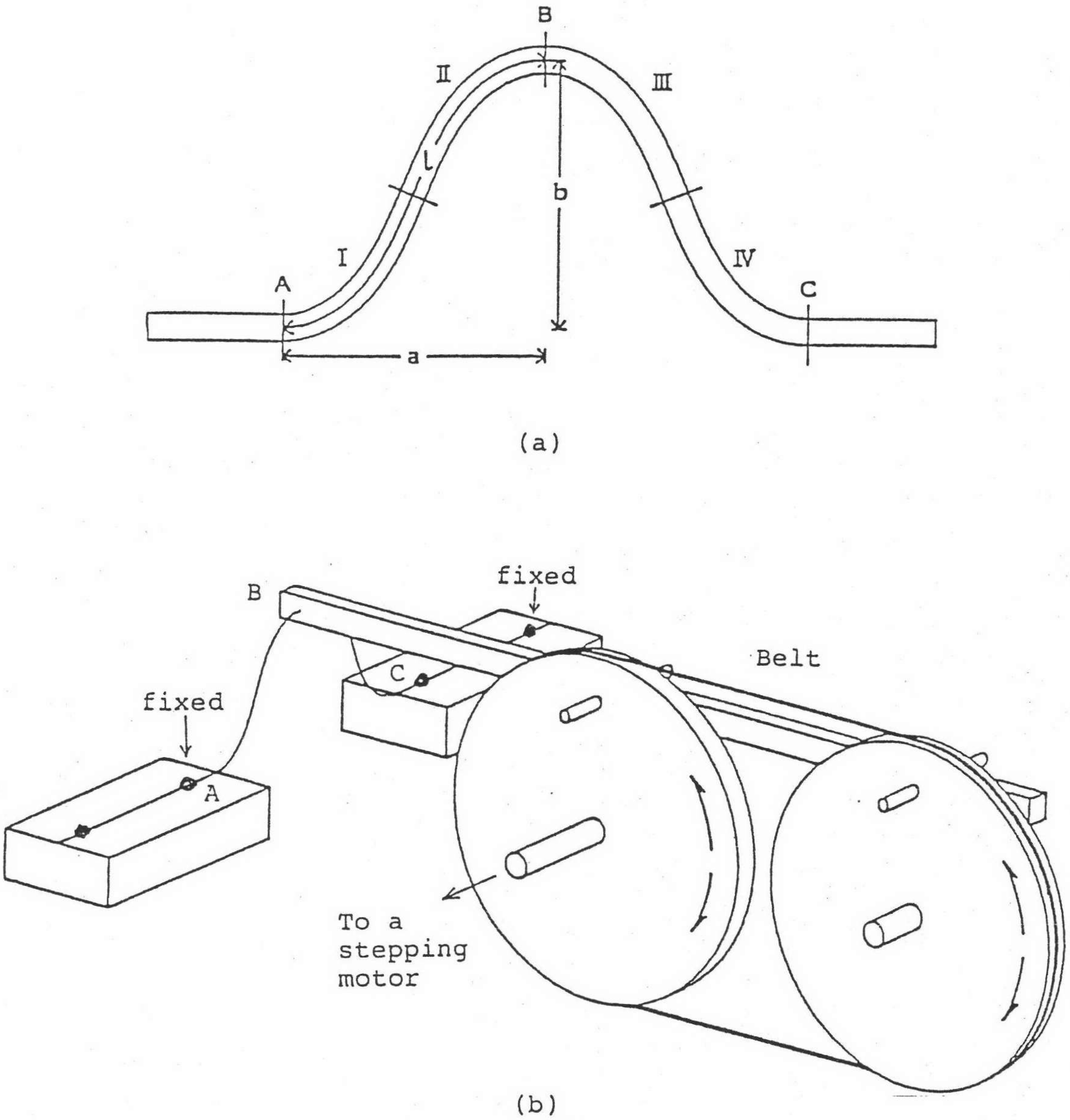
polarization rotator. In addition, these wave-plates work as an endless polarization controller as well.

c) <u>rotatable fiber crank</u>:

Shortly after Imai's proposal, Okoshi et al. [83] invented a new SOP control device consisting of two fiber elements called "rotatable fiber cranks" which are equivalent to rotatable quater-wave and half-wave plates. Figure 19(a) and (b) show the principal construction of a rotatable fiber crank. The linear birefringence is induced between x and y axis when a short fiber is bent in a crank form as shown in Fig. 19(a). The principal axis of bending birefringence can be rotated without changing its magnitude by rotating the crank element around the axis A-C (see Fig. 19(b)) giving only "translation" movement to the fiber at point. Hence, if an appropriate fiber length and shape are chosen so that the bending birefringence $\delta\beta = \pi/2$ (i.e. a = b = 25 mm, l = 37.5 mm) or π (a = b = 10 mm, l = 15 mm), a device equivalent to a quarter-wave plate or a half-wave plate, respectively can be obtained. Experimental set-up of this SOP control scheme is illustrated in Fig. 20 (for detailed discussion, see [83]).

3.4.3. Type-III SOP control scheme

The Type-III SOP conversion scheme shown in Fig. 21, is used in the Faraday ratator device proposed by



(a)

(b)

Fig. 19. Construction of a rotatable fiber crank (RFC): (a) shape and dimensions, (b) driving mechanism for "translation" movement, (after Okoshi and Fukuya et al. [83]).

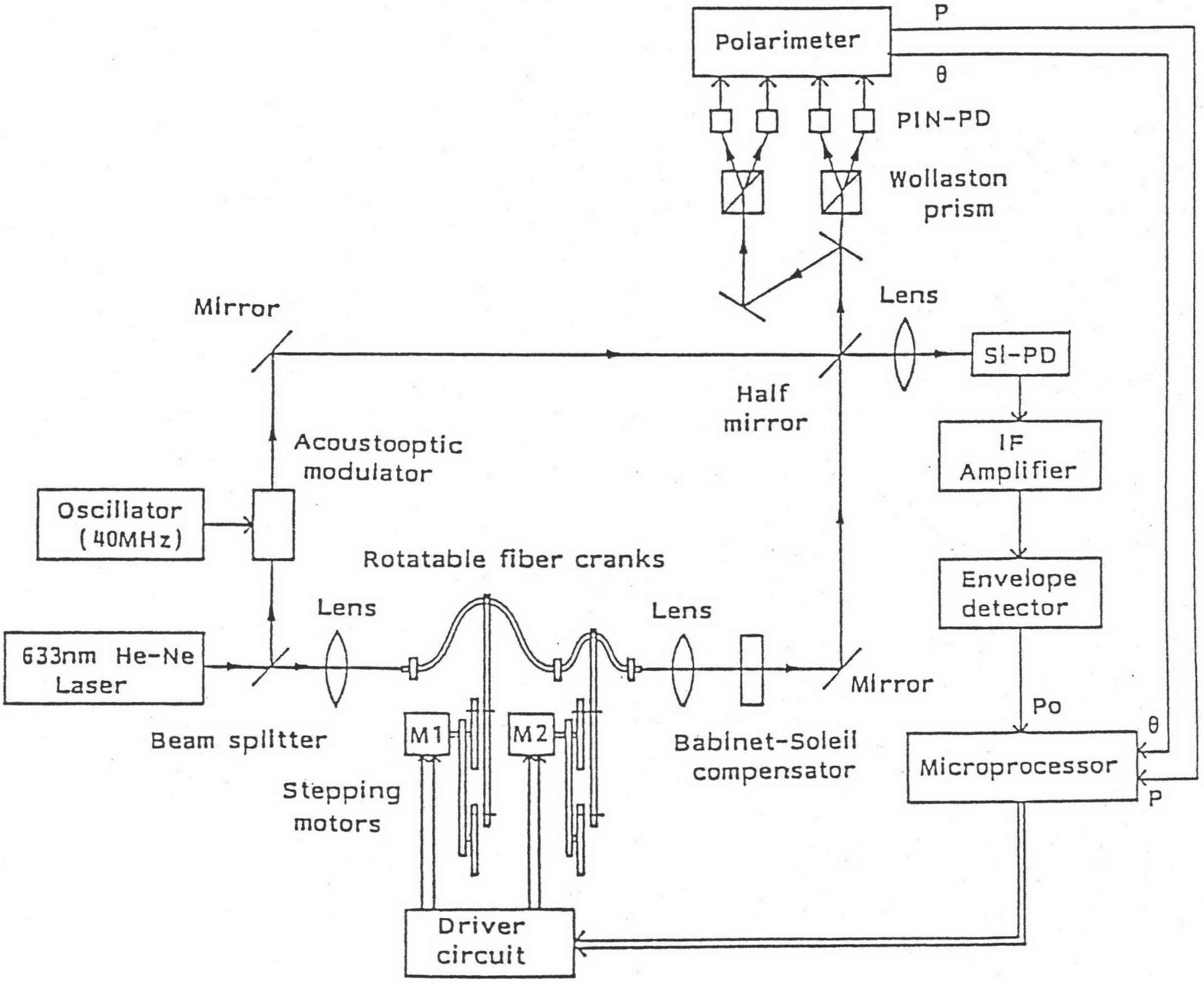


Fig. 20. An experimental setup for SOP control using two RFC elements, simulating an optical heterodyne receiver. IF signal is used for SOP tracking employing "maximum-research" method. (After Okoshi and Fukuya et al. [83]).

Okoshi et al. [82]. In this scheme, two fiber-type Faraday rotator are used as the polarization rotators connected in cascade between a fiber coil (FC) giving 90° phase retardation between the two orthogonal polarizations. An arbitrary SOP incident at A is converted to an upright elliptical polarization at B by controlling the current I_1, flowing in FR1. The SOP is then converted to a tilted linear polarization at C by FC. This linear polarization is finally rotated to a vertical (or horizontal) one at D by controlling current I_2 in FR2. As compared with the Type- II SOP conversion, the Faraday rotator scheme gives faster response since it is an electrooptic device, but the endlessness in control is lost due to the finite limitation of the current supply.

3.4.4. Type-IV SOP control scheme

The Type-IV SOP conversion scheme utilizes axial strain of a highly linearly birefringent fiber [92] and is shown in Fig. 22. Two elements of linearly birefringent fiber are required. The principle axis of the first fiber element (1) is oriented at 45° with respect to the x-y coordinate system, whereas that of the second fiber element (2) is oriented at 45° with respect to the first fiber, i.e., aligned with the coordinate system. Two piezoelectric transducers (PZ) are used to provide axial strain to both fiber elements

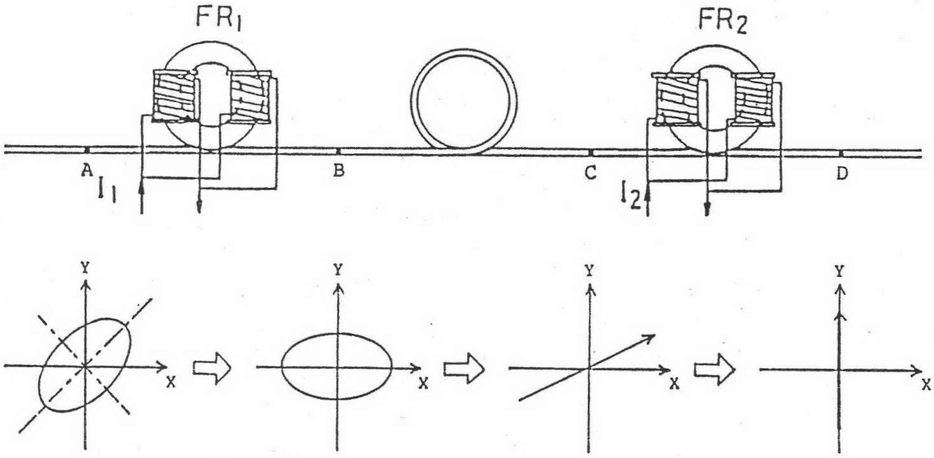


Fig. 21. Type-III SOP control scheme using two Faraday rotators (FR) a stationary fiber coils (after Okoshi and Cheng et al. [82]).

which is used to control the propagation constants of the two orthogonal modes. The first fiber element is thus used to adjust the inclination angle of the input SOP, and the phase retardation between the two orthogonal polarization modes is controlled by applying axial strain to the second fiber element. Figure 22(b) shows that a horizontally (or vertically) polarized light can be converted to an arbitrary SOP at the output. The use of highly linearly birefringent fiber for SOP controllers has two great advantages compared to SOP controllers based on normal low birefringence fiber : firstly, the SOP can be controlled without bending, twisting or subject the fiber to transverse pressure; and secondly, the stress-optic coefficient of this fiber is temperature independent, therefore, it overcomes the problems associated with limited temperature range of the normal low birefringence fiber.

In principle, a SOP control device should be able to convert any polarization state to any other. The device described here converts a horizontal or vertical linear polarization to an arbitrarily polarization. If the input were elliptical, then four sections of fiber would be needed, (from symmetry of the device). To achieve endlessness in control, the technique used in fiber squeezers [90] may be applied to this scheme.

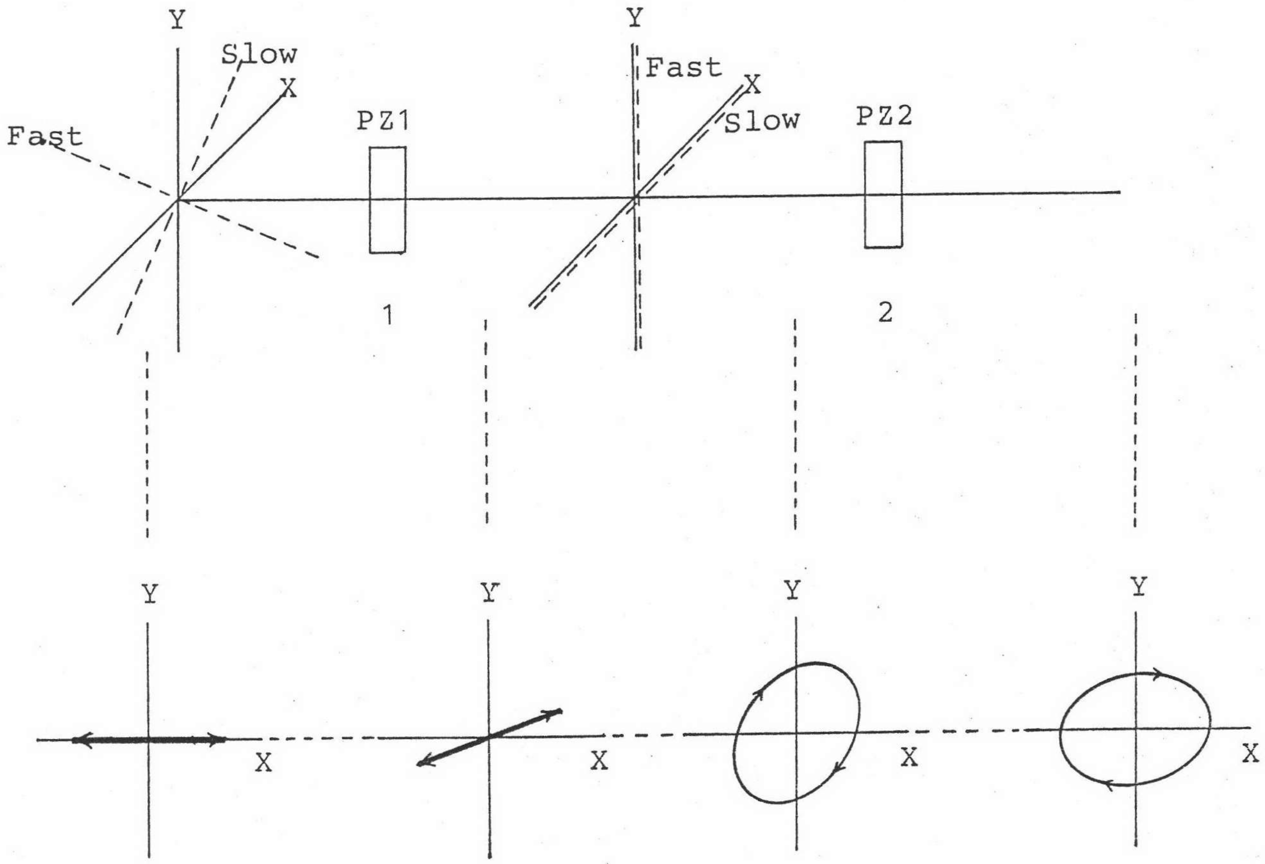


Fig. 22. Type-IV SOP control scheme using highly linearly birefringence fibers, 1 and 2 : highly linearly birefringence fiber; PZ : piezoelectric transducers, (after Tatam et al. [92]).

3.4.5. Type-V SOP control scheme

The Type-V SOP conversion is the most recent SOP control technique used in the polarization state matching control scheme [93] and polarization recombining scheme [94] both of which are based on the same principle. In the next chapter, we shall look at this scheme in details. The principle of operation and experimental results with polarization recombining scheme will be presented.

3.5. Features of various polarization-state control scheme

Various schemes (except the Type-V scheme) are compared with respect to four technical requirements : (a) insertion loss, (b) endlessness in control, (c) temporal response, and (d) presence or absence of mechanical fatique. These parameters follow those of Okoshi [29].

3.5.1. Insertion loss

At present, only all-fiber-type SOP control devices can satisfy this requirement, since control on the SOP of the signal (or LO) light is performed in a single-mode optical fiber. An all-fiber-type device can be spliced with much lower insertion loss (≃ 0.2 dB) compared with insertion of the conventional bulk optical elements.

3.5.2. Endlessness in control

This is an important requirement since the polarization state in a practical installed fiber cable fluctuates randomly with time due to variations in the ambient conditions. To avoid data loss by a reset of the device, SOP control devices should operate with unlimited control range, i.e. without an optical reset. So far, an endless (resetting-free) SOP control device can only be achieved with the devices used in the type III schemes. The use of three [89] or four [90] fiber squeezers to achieve endlessness in control have also been reported, but this is realized with expense of complicated reset procedures.

3.5.3. Temporal response

All the mechanical schemes have poor temporal response as compared with all-electronic ones, i.e. the electrooptic and Faraday devices.

3.5.4. Presence or absence of mechanical fatique

All the mechanical schemes have more or less the possibility of mechanical fatique.

The features of Type-V scheme are discussed later in Chapter 4 and 7.

3.6. Summary

The recent progress in countermeasures against polarization-state fluctuation in a single-mode fiber has been reviewed. At present, long length polarization-maintaining optical fiber with the transmission loss comparable to that of conventional single-mode fiber is being developed but its fabrication is still difficult and expensive.

As the existing optical fiber communication systems use single-mode fiber for data transmission, the use of a polarization diversity or a SOP control scheme to overcome the SOP fluctuation in the received signal would be more appropriate than the use of a polarization-maintaining optical fiber. Polarization diversity receivers are excellent both in terms of system response speed and endless tracking capability, as compared with the SOP control schemes. However, these advantages are achieved at the expense of more complicated signal processing, reduced sensitivity and other technical problems.