Comparison of Polarization Handling Methods in Coherent Optical Systems

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***Abstract*—Coherent optical transmission systems require that the polarization of the received signal and the local oscillator are matched. Endless polarization control, polarization diversity, and data-induced polarization switching are the most promising solutions for this problem. However, in spite of a host of publications, no clear favorite has emerged, maybe because few laboratories have implemented more than one method and no direct comparison was ever made.**

In this paper we directly compare these three methods, and active, data-synchronous polarization switching, for the first time to our knowledge. We will see that endless polarization control is potentially the most powerful candidate, however, the choice of polarization control devices remains questionable. Polarization diversity is as versatile as polarization control and is potentially the fastest method; however, it yields lower receiver sensitivity. Endless control or a well-designed diversity receiver should be used for coherent trunk systems. Data-induced polarization switching is restricted to FSK systems. It promises a loss span similar to that of diversity but is far simpler which makes it recommendable for FSK distribution systems.

I. Introduction

Coherent optical transmission systems are rapidly moving toward commercialization. The phase-noise problem has become less important as bit rates continue to rise and low-linewidth lasers have become available. The other fundamental problem of coherent systems is the polarization dependence for which several solutions have been proposed.

Polarization-maintaining fibers [1] are the simplest solution, however, certain requirements have still to be met: If coherent trunk systems are to be favored over direct detection systems, the loss of polarization-maintaining fibers must be virtually identical to that of the best available standard fiber. For multisubscriber systems polarization-maintaining 3-dB couplers of high extinction ratio are required, in order to allow for a reasonable polarization extinction ratio to be maintained even if ten or more couplers and a similar number of splices are cascaded.

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It has been argued that at the end of a standard fiber "endless" changes in the state of polarization (SOP) of the received signal have to be accomodated, e.g., linear polarization that rotates steadily over many full cycles. The polarization handling methods that are discussed subsequently all meet this requirement.

Section II is devoted to endless polarization control [2]–[25], which tracks the SOP of the received signal in a feedback loop (Fig. 1(a)). If resets of the control devices occur they have to be perfomed without signal loss.

Section III deals with polarization diversity receivers [28]–[51]. The incoming signal is split into two orthogonal polarization components that are being processed in two receiver branches (Fig. 1(b)). The respective signals are added in the baseband.

In Section IV we discuss data-induced polarization switching (DIPS) [52]–[55]. Half of the signal power is transmitted in either of two orthogonal SOP's (Fig. 1(c)). DIPS has an intrinsic loss of 3 dB and is only applicable for FSK systems with a modulation index $m > 2.5$. Switching is achieved synchronously to the data pattern by a passive birefringent component.

Very similar to DIPS, Section V presents active data-synchronous polarization switching by means of an integrated optical polarization modulator [53] (Fig. 1(d)).

Active, clock-synchronous polarization switching, scrambling, modulation, or spreading [56]–[62] works in a similar manner for ASK, FSK, and DPSK. (If the modulation frequency is high compared to the data rate, it need not even be clock-synchronous.) Any type of active, data- or clock-synchronous polarization switching in conjunction with a standard receiver brings along an intrinsic 3-dB penalty. In most cases the insertion loss of an integrated optical component has to be added to this figure.

Concerning spectral broadening due to polarization modulation, DIPS and active, data-synchronous polarization switching feature one polarization transition, not even each time slot, but only each time the modulating signal changes polarity. Clock-synchronous polarization switching, which has the advantage of being applicable to all modulation formats, requires at least two transitions per time slot which, however, need not be rectangular [56] but can be smooth [57]–[62] in order to minimize band-

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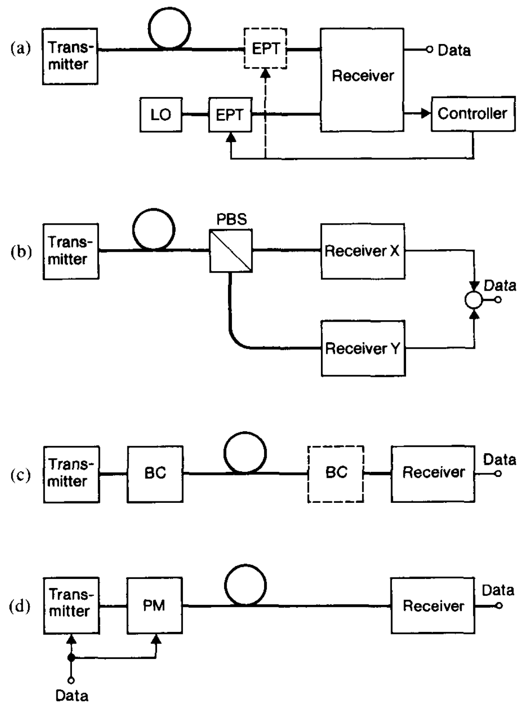

Fig. 1. Coherent transmission system using (a) polarization control, (b) polarization diversity, (c) data-induced polarization switching, (d) active, data-synchronous polarization switching. EPT = endless polarization transformer, PBS = polarization beam splitter, BC = birefringent component, PM = polarization modulator. Dashed lines specify alternative component placements.

width. In particular, [60]–[62] compare a family of different polarization spreading waveforms in simulation, theory, and experiment. It is shown that sinusoidal polarization spreading is advantageous over rectangular switching. In [59] the polarization modulation is brought about by combining two lasers having different frequencies and orthogonal polarizations. This exchanges the insertion loss of a polarization modulator against the (generally lower) insertion loss of a polarization combiner. At the same time the laser power is effectively doubled which partly or fully compensates the intrinsic 3-dB loss, depending on whether the two orthogonally polarized lasers are local oscillators [59] or transmitters.

Polarization shift keying in conjunction with a polarization diversity receiver has also been demonstrated [63]–[65]. The key to the competitiveness of these techniques is the insertion loss of the required integrated optical component. Interest for these methods should rise as soon as integrated optical chips containing a laser, a polarization modulator and a semiconductor booster amplifier become available. We will not discuss these methods here in detail but rather refer the reader to the references.

In Section VI we will conclude this paper with a comparison of the polarization handling methods that we have implemented and will try to give recommendations for the right choice [70].

II. Endless Polarization Control

A. *Choice of Control Algorithm*

A large number of publications has recently addressed endless polarization control. The state of polarization (SOP) is changed by an endless SOP transformer that consists of one or more birefringent devices, i.e., retarders. Commonly a controller dithers the driving signals of the devices. It detects the corresponding changes in the IF or baseband signal power of the receiver in order to gather information about the degree of SOP matching. The operation points of the devices are accordingly modified such that 1) nearly perfect SOP matching is achieved at all times, and 2) the driving signals of the devices stay within the technically allowable limits.

The algorithms for endless polarization control can be subdivided into two groups. In one group the retardation range limits of the birefringent devices are specified in absolute terms [2]–[4], [6]–[8], [10], [16], [19]. It is therefore necessary to know which driving voltages generate these retardations. The other group specifies the minimally required range widths rather than fixed range limits [5], [9], [12]–[15], [17], [18]. The retardations must only be known relative to the current operation point. This simplifies not only the algorithm, but also the choice of devices. We will refer to the two algorithm types as A (absolute) and R (relative), respectively. The advantages of both algorithm types can be combined [11] if the device characteristics are measured by the controller 'on line.' This will, however, decrease the tracking speed.

The SOP transformers can be located either in the local oscillator (LO) path if the coupler is polarization independent, or in reversed order in the signal path. This is possible because the Jones-matrices that describe these devices are unitary. Generally it is advantageous to place the retarders in the LO path: 1) Attenuation of the LO does not decrease the receiver sensitivity as much as attenuation of the signal. 2) If bulk or integrated-optical retarders are used in conjunction with a fiber coupler, they can be placed between LO and fiber, thereby minimizing the coupling loss. 3) Even if the SOP transformer can deal with only one unknown SOP the coupler need not maintain polarization.

A- and R-algorithms have been implemented that can handle unknown or varying input or output SOP's [2], [5], [9] [12]–[15], [17], [18], [20]–[22]. However, in a coherent receiver either the input SOP to or the SOP to be generated by the transformer can be chosen fixed. We therefore limit our considerations to systems where one polarization is fixed.

We have simulated the tracking behavior of both A- and R-algorithms. As A-algorithm we have chosen a system with four linearly birefringent elements similar to [4]. The eigenmodes of neighboring retarders are staggered by $\pm 45°$. In addition, the unwinding procedures have been speeded up by incorporation of the nonlinear functions given in [3]. This system is error-tolerant or redundant, i.e., residual intensity losses that might arise due to device imperfections or nonideal input SOP will be corrected thanks to the presence of one additional retarder.

The same four-retarder configuration is needed for the orignal R-algorithm [5]. It is designed for both varying input and output SOP's. Since it is possible that the LO SOP meets an eigenmode of the first retarder at all times this is equivalent to three retarders with fixed but optimally chosen input SOP. (One additional retarder is generally needed if two instead of one variable SOP are to be tracked.) In order to obtain better performance we have chosen four or five retarders [13] in conjunction with fixed optimum input SOP.

The simulation program takes into account 12-bit quantizations of the IF or baseband signal intensity and of the retarder driving signals. We further assume electrical noise with a standard deviation of 0.001.

Ideally the input SOP would be horizontal or vertical, assuming the eigenmodes of the first linearly birefringent retarder are at $\pm 45°$. An A-algorithm that is not error-tolerant relies on ideal input SOP and perfect devices. In order to verify the error-tolerance of our A-algorithm we used a nonideal input SOP given by the Stokes parameters (0.977, 0.15, 0.15), rather than horizontal SOP (1, 0, 0). Nonideal input SOP has the same effects as imperfect retarders or insufficiently well known retardations.

The program simulates the behavior of the control algorithm while a changing polarization is being tracked. The SOP to be generated is represented by a point on the surface of the Poincaré sphere. After a few iterations to reach maximum intensity it is moved by a rotation of constant angular speed (0.01 rad/iteration) around an axis that is either fixed, or is allowed to vary up to 0.04 rad/iteration in an arbitrary direction, similar to a Brownian motion. The speed of SOP change has to be relatively slow because of the restricted tracking capability during the resets. (In contrast, the response time needed to recover maximum intensity after a sudden SOP change is only about 10 iterations, as will be shown experimentally in Section II-C.) We calculate and monitor the intensity in all steps of the gradient algorithm that is used to maximize the intensity.

The results for the A-algorithm are given in Fig. 2. The normalized intensity I of the *IF* signal is drawn on the abscissa. The ordinate gives the cumulative density function $F(I)$ of the intensity, i.e., the time-averaged probability of the case that the intensity drops below the value given on the abcissa. Curve (a) refers to SOP rotations around a slowly varying axis. We also investigated the intensity statistics for those SOP movements that are likely to cause the highest penalties. The most difficult cases are rotations that follow great circles on the Poincaré sphere around the coordinate axes S_1 (0°/90° linear), S_2 ($\pm 45°$ linear), and S_3 (right/left circular). Curves (b) correspond to these cases. It is seen that the A-algorithm guarantees an intensity >0.95 at all times. In other words, the penalty we have to cope with is <0.2 dB.

Curve (a) in Fig. 3 shows the R-algorithm with four elements tracking arbitrary polarization. During most of the time it behaves as well as the A-algorithm. However, with a probability of 10^{-5} the intensity drops below 0.75. For SOP rotations on the worst-case great circles there is a considerable difference with respect to the A-algorithm (Fig. 3, curves (b)). The R-Algorithm is not able to reset the elements properly. After a few rotations of the SOP on the Poincaré sphere the retardations of two control elements will not only assume values outside the specified minimum range (± 5 rad in our simulation), but touch an absolute range limit (± 10 rad). Typically, 'unwinding' of a retarder that has to transform the SOP on a great circle of the Poincaré sphere winds up the next but one retarder at the same time because an R-algorithm is not always able to recognize the necessity to change the retarder between these two by π during the reset. As a consequence the intensity may drop to values below 0.1!

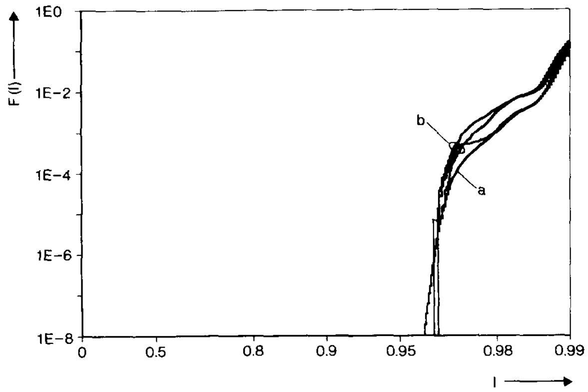

Fig. 2. Simulated intensity distribution function for endless polarization control using A-algorithm. Tracked SOP changes are arbitrary (a, 2.7 * 10^8 iterations) or follow three orthogonal worst-case great circles on the Poincaré sphere (b, 5 * 10^4 iterations each).

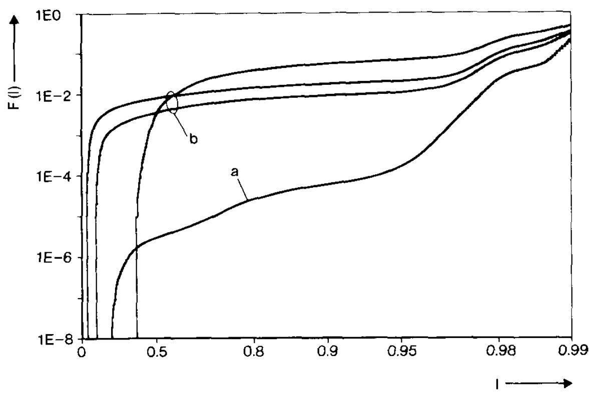

Fig. 3. Simulated intensity distribution function for endless polarization control using four-element R-algorithm. Tracked SOP changes are arbitrary (a, 6.5 * 10^7 iterations) or follow three orthogonal worst-case great circles on the Poincaré sphere (b, 3 * 10^4 iterations each).

Turns around the S_1, S_2, S_3 axes are the worst cases for *R*-algorithms with ideal input SOP (1, 0, 0). Nonideal input SOP (0.977, 0.15, 0.15) will work out better for these turns unless the corresponding worst cases are found and applied. But one should not try to make the input SOP as nonideal as possible. In that case one would choose an eigenmode of the first device which equals a reduction of the number of elements by one. Since intensity drops are undesirable we have simulated a more redundant R-algorithm with five elements [13], [14]. The input SOP is chosen ideal. However, control is largely eased by reductions of SOP turning speed and axis variation to 0.001 and 0.012 rad/iteration, respectively. Also the reset speed is reduced by a factor of 5. In curves (b) of Fig. 4 it is seen that two of the formerly three worst cases are well controlled now and only one persists. The differences between the R-algorithms tracking arbitrary SOP (Figs. 3 and 4, curves (a)) are not believed to be statistically significant. This is because a large number of iterations corresponds to a much lower number of turns on the Poincaré sphere, and only several successive 'bad' turns will cause intensity losses. The tracking capability is also largely influenced by the reset speed and by the range widths and limits. The wider the ranges and the slower the SOP changes, the lower is the probability that each of the repeated unwinding attempts causes unwanted winding up of another element.

The intensity losses of the R-algorithms are undesirable in a commercial system. But they occur only with a small probability. The crucial question is whether several turns around one of the axes S_1, S_2, S_3 will occur in practice or not. Although curves (a) in Figs. 3 and 4 suggest only a small degradation of the average bit error ratio compared to Fig. 2 we think it is generally safer to use an A-algorithm.

It should also be taken into account that low range widths ease the fabrication of certain types of polarization transformers. For our A-algorithm none of the range widths exceeds 3π and the sum of range widths of all four retarders is 8π. In contrast, the original R-algorithm [5] requires ranges of at least 4π, but perferably 12π for each of the four retarders. (Our simulation of R-algorithm assumes ± 10 rad $= 6.4\pi$.)

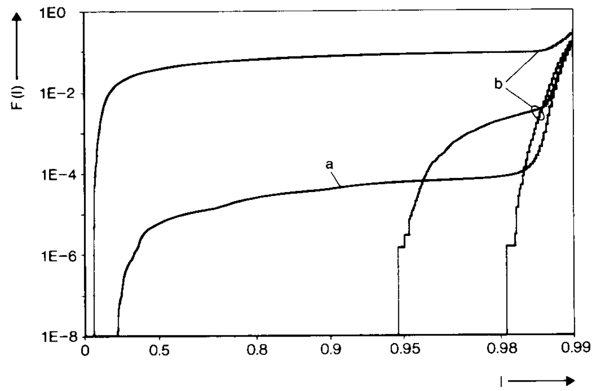

Fig. 4. Simulated intensity distribution function for endless polarization control using five-element R-algorithm. Speed of polarization fluctuations is reduced to 1/10 with respect to Fig. 3. Tracked SOP changes are arbitrary (a, $3 * 10^8$ iterations) or follow three orthogonal worst-case great circles on the Poincaré sphere (b, $2 * 10^5$ iterations each).

B. Choice of Polarization Transformers

Early polarization control experiments were carried out with fiber squeezers [26]. Lateral force on the fiber makes the waveguide linearly birefringent. The SOP eigenmodes are oriented parallel and perpendicular to the direction of the force. A force of about 20 N corresponds to about 2π retardation at 1.5-μm wavelength. If magnets are used to apply the force, the retardation value is well defined. If piezoelectric transducers are used, the absolute retardation value is likely to be altered by mechanical drift. Hence, piezoelectric fiber squeezers are temperature-dependent and likely to age, which precludes application of A-algorithms. Plastic [13] or metal [14] coatings on the fiber have been used to solve the problem of occasional fiber breaks. It remains to be seen whether metal-coated fiber remains stable over the required time.

Another type of fiber-based device uses polarization-maintaining fiber [27]. It is very practical to wind it onto a piezoceramic cylinder [5]. A voltage applied to the ceramic stretches the fiber and changes the retardation. However, the absolute retardation values change strongly with temperature and make these devices unsuitable for A-algorithms.

Liquid crystals have recently been used as linearly birefringent elements [17]–[19]. Insertion loss is as low as 0.75 dB [18] for a stack of four retarders. The retardation is time-invariant as required for an A-algorithm. One drawback seems to lie in the response speed that restricts the time to acquire maximum intensity to about 1 s [18]. This corresponds to a safe tracking speed of about 0.1 rad/s. The speed may be sufficient for undersea cables, but not for fiber that is being moved in an exchange or in subscriber premises.

Another alternative are integrated-optical components. Devices that can turn around 2 [4], [5], [7], [20], [21] or even all three axes [22] of the Poincaré sphere have been fabricated. A possible drawback is the insertion loss. A 3-dB loss in the LO path alone should be tolerable. Furthermore, reflections and dc drift have to be fully eliminated, at least if A-algorithms are to be employed.

The ideal SOP transformer has no moving parts, stable retardation characteristic, low insertion loss, and submillisecond speed. To our knowledge, no such device is available commercially.

C. Experiment

Our experiments with A-Algorithms have been described earlier [2], [4], [23]. We present here a coherent transmission experiment using the R-algorithm with five linearly birefringent retarders. The experiments in this paper have been conducted at 1.5-μm wavelength using a

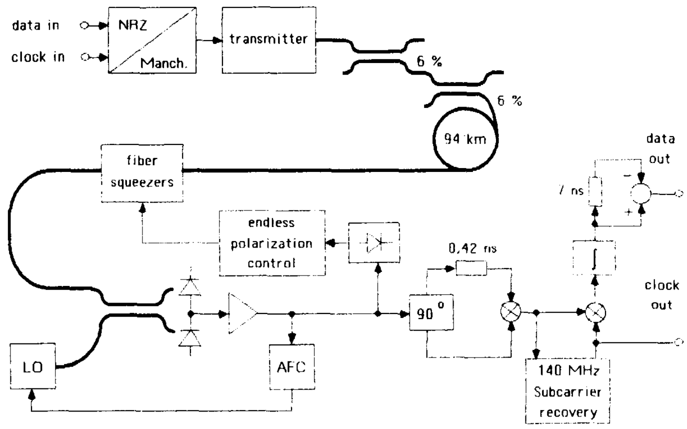

Fig. 5. FSK heterodyne system with Manchester coding and endless polarization control.

140-Mb/s FSK heterodyne system [13]. Improved DFB lasers and front ends have been incorporated as available and the frequency deviation has been changed. While making these changes we have taken care to keep the system comparable to earlier stages. All lasers, single and integrated dual-p-i-n photodiodes, and the polarization modulator are fabricated by Siemens.

The transmission system is shown in Fig. 5. Manchester (biphase) coding was used to overcome the nonuniform frequency response of the transmitter laser. In the first experiment the launched power was > -1.7 dBm. Two concatenated 6% couplers simulated the splitting loss of a distribution star for 256 subscribers. This signal was transmitted over 94 km of fiber. The received and LO signals were heterodyned in a balanced 2 GHz front end. An automatic frequency control (AFC) locked the center IF (45-MHz linewidth) to 1.1 GHz. A delay-line discriminator demodulated the signal. The Manchester code was removed by multiplying the discriminator output signal with the recovered 140-MHz square-wave subcarrier or clock. A low-pass filter removed noise from the data signal. For best performance we chose a Nyquist filter with rectangular impulse response. It was made of an integrator, a one bit delay line and a subtractor. This filter type had already successfully been used in [66].

The polarization transformer consisted of five magnets used as fiber squeezers. The fiber coating was stripped and a thinner plastic coating was applied to protect the fiber against breakage. However, one fiber break occurred after 6 mo of occasional use. Since the insertion loss was only 0.3 dB we did not bother to put the SOP transformer into the LO branch. In our experiment it was more convenient to insert it into the signal path.

A rectifier detected the IF level of the heterodyne receiver and fed it to the electrical SOP controller for which we used a personal computer. The fiber squeezers were dithered (<0.05-dB loss) to derive control signals and achieve maximum IF signal. The eye pattern at 140 Mb/s is shown in Fig. 6. The diamond shape is due to the rectangular low-pass filter impulse response. The eye patterns obtained in the other experiments (Sections III–V) were indistinguishable from the pattern given in Fig. 6. Fig. 7 shows bit error ratios measured with polarization control. The sensitivites of a 1010 and $2^{15} - 1$ pattern almost coincided. With the long pattern -56.7 dBm or 119 photoelectrons/bit were needed for a BER of 10^{-9}. The power at the polarization transformer input was -55.2 dBm, which included -0.7 dB for quantum efficiency and photodiode coupling, 0.3-dB loss of the polarization transformer and an estimated 0.5-dB coupler and splice loss. The usable loss span was 53.5 dBm thanks to the low-loss polarization transformer. The endless polarization control system operated continuously. There was insignificant, if any, degradation during the resets, an no improvement if the system was switched off and polarization was controlled manually. The observed behavior was similar to the top right portion of Fig. 3, curve (a). Since the operation time was in the order of hours and the temperature of the 94-km-long fiber did not change much we did not

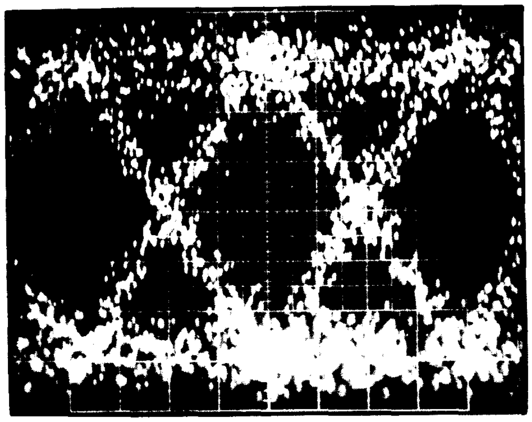

Fig. 6. 140-Mb/s eye pattern. The diamond shape is due to the rectangular impulse response of the low-pass filter.

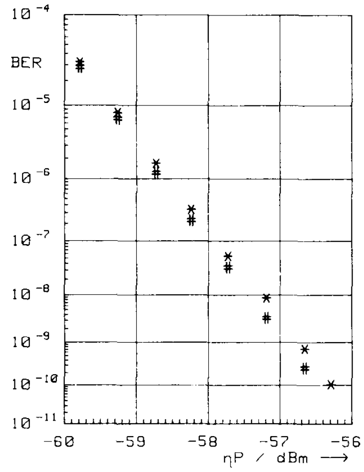

Fig. 7. Bit error ratio for receiver with endless polarization control against received power ηP for $2^{15} - 1$ (*) and 1010 (#) data patterns.

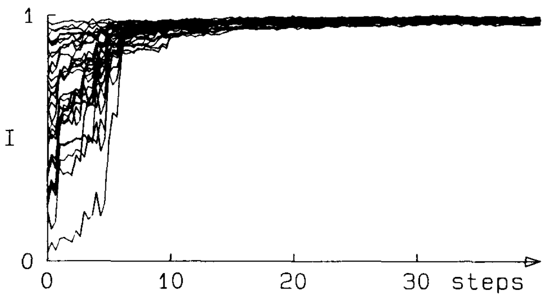

Fig. 8. Measured transient responses of endless polarization control system from random starting points; IF intensity I versus number of maximization steps.

observe strong intensity losses like the ones shown in the bottom left portion of curve (a) in Fig. 3. We believe the SOP mismatch penalty was within 0.1 dB in our experiment which gives a total experimental penalty of 0.4 dB for endless polarization control.

Later the algorithm was implemented on an 8-bit microprocessor [25]. The time needed for one iteration dropped from about 100 to 1 ms. The acquisition speed of the control system was assessed with this fast controller. Fig. 8 shows transient responses from 32 random starting points. The maximum intensity is reached after about 10 iterations or 10 ms. Other authors have reported similar or even somewhat higher speeds [11], [12], [16].

In our case the control speed was limited by both the microprocessor and the retarders. Of course there is also a fundamental speed limit: A polarization control algorithm needs roughly the same signal-to-noise ratio as the decision circuit of the receiver. If $\delta = 1\%$ intensity loss due to modulation is permitted, the bandwidth of the lowpass filter following the rectifier has to be $\delta^{-2} = 10^4$ times lower than the bandwidth of the data. One modulation step must therefore last at least $\delta^{-2} = 10^4$ bit periods.

III. Polarization Diversity

A. Theory

A first experiment pointed out the possibility of polarization diversity [28], but the proposed signal combining would have caused a 3-dB loss in sensitivity. Subsequently other researchers seem to have become aware quite early of the 'correct' combing method [29], [30]. It was then quite astonishing to observe how many authors found the same baseband combining method within a short time, many of them independently [31]–[49]. Let us quickly review the function with our experimental polarization diversity receiver serving as example (Fig. 9). The LO polarization is chosen linear with 45° azimuth. Signal and local oscillator light are added in a polarization-maintaining coupler (PMC). The TE- and TM-components of either output are separated in a polarization beam splitter (PBS). For each component there is a complete IF branch including the demodulator. If we assume linear signal polarization with an azimuth angle ϑ at the receiver input, the heterodyne signal currents in the two IF branches are porportional to cos (ϑ) and sin (ϑ), respectively.

The two branch signals can not be combined directly because their phases are different in general. Each IF branch is terminated by an asynchronous demodulator. Squarers are used in the case of ASK and dual-filter FSK systems, whereas delay-and-multiply demodulators are chosen for discriminator-FSK and DPSK systems. In all cases the demodulated signal will be proportional to the square of the demodulator input signal. The demodulated signals having amplitudes $\cos^2(\vartheta)$ and $\sin^2(\vartheta)$, respectively, are now added and form a polarization-independent baseband signal.

The sensitivity of polarization diversity receivers has been calculated in [33], [36], [50], [51]. There is no intrinsic penalty for synchronous receivers that are equipped with a ratio combineer (see below). In [51] it is shown that a diversity receiver with asynchronous squaring demodulators behaves just like a corresponding single polarization receiver having twice the IF bandwidth. In Fig. 10[1] the sensitivity penalties of heterodyne receivers versus standard receivers are shown for different normalized IF filter bandwidths $n = B/f_B$, the ratio of actual IF filter bandwidth B to bit rate f_B. The penalty for ASK diversity receivers is 0.26 dB if the bandwidth is chosen equal to the bit rate ($n = 1$), but increases with increasing bandwidth. For dual-filter FSK and for DPSK the penalty is slightly higher. We find 0.39 dB in the case of minimum IF bandwidth ($n = 1$), and about 0.7 dB for $n = 8$. The calculations are, strictly speaking, not applicable for FSK receivers using discriminators as demodulators. Nevertheless we expect Fig. 10 to give a useful estimate of the penalty for this case.

The foregoing applies to squaring demodulators. However, the double balanced mixers that are widely used as

[1]The work for Fig. 10 was carried out by R. Noé in 1988 while he was with Bellcore, NJ.

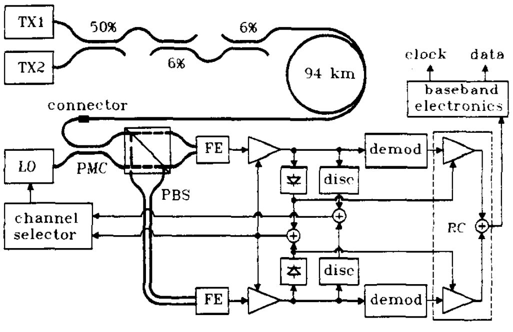

Fig. 9. Experimental setup for polarization diversity: PMC = polarization-maintaining coupler, PBS = polarization beam splitter, FE = front end, demod = demodulator, RC = ratio combiner.

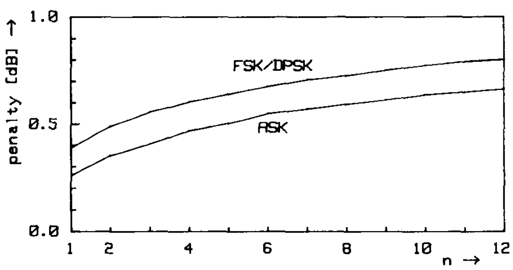

Fig. 10. Sensitivity penalty of polarization diversity versus standard heterodyne for asynchronous detection as a function of n, the ratio of IF filter bandwidth to bitrate.

demodulators in heterodyne receivers have only a very limited range or square law response [36]. It starts only above the diode threshold and soon approaches linear response for high input signal levels. Likewise, synchronous receivers that are used for optical PSK transmission do not have a squaring device.

In these cases the excess penalty [32], [36], [37], [39], [41], [47] can be avoided by employing a ratio combiner [31], [34], [36], [40], [45]. Assuming ideal linear synchronous demodulators, each demodulated branch signal is amplified before the summation by a factor that is proportional to the signal amplitude and inversely proportional to the noise power. The SNR of the sum signals is equal to the sum of the SNR's in the branches. In practice it has proved sufficient to vary the gains more or less proportional to the demodulated signal amplitude.

Other authors have successfully used transistor multipliers or biased diodes as detectors [44], [46]. These devices operate at low power levels and offer a highly quadratic demodulator characteristic.

Polarization diversity normally results in yet another sensitivity reduction. Due to splitting and possibly attenuation of the LO signal there is less LO power per receiver. High LO power and low noise front ends can keep this penalty small. Alternatively, each of the two receiver branches can be equipped with a separate local oscillator.

The use of two LO's is mandatory in PSK homodyne polarization diversity receivers since the phase of the optical signal is transferred directly to the baseband signal. (It should be noted that one LO plus an endless phase shifter would also be sufficient. However, it seems more reasonable to use endless polarization control instead, since endless phase shifters and endless SOP transformers can be implemented using the same components, and present roughly the same technical difficulties.)

Remarkable progress has recently been achieved concerning the insertion loss of optical diversity circuits. Both fiber-based and bulk-optic hybrids with low insertion losses, partly below 1 dB, have been reported (see, e.g., [43], [46]–[49]).

B. Experiment

A polarization diversity receiver with microprocessor-controlled channel selection was incorporated into a two-channel heterodyne system [45] (Fig. 9). Compared to the previous configuration, a 3-dB coupler was inserted to add the two transmitter signals. This system had the capability of serving 512 subscribers through 94 km of fiber. The fiber launch powers were >2 dBm and the frequency deviation was increased to 1.2 GHz.

The received and LO signals were added in a polarization-maintaining 50% coupler (PMC). The polarization components were separated as they passed through a polarization beam splitter (PBS). For each polarization there was a balanced front end (FE), an IF-amplifier, level detector, demodulator, and a discriminator for the automatic frequency control. The front ends had 7 pA $Hz^{-1/2}$ noise current over a 2-GHz bandwidth. The sum of the two level detector signals, being fairly independent of the signal polarization, was used for automatic again control and channel selection. The demodulated signals were added in a ratio combiner (RC). The two combiner branches had a signal-dependent attenuation such that the output signal was proportional to the sum of roughly the squares of the IF signal amplitudes, in spite of nearly linear demodulators.

For the sensitivity measurements most of the fiber was removed in order to maintain stable polarization. We define $\alpha = P_{TE}/(P_{TE} + P_{TM}) = \cos^2(\theta)$, the normalized TE component of the signal power, as measure of the signal polarization. Fig. 11 shows bit error ratios for a $2^{15} - 1$ pattern as a function of the optical power at the receiver input connector. The sensitivity was −51.9 dBm for $\alpha = 0.5$, and was slightly better for $\alpha = 0$ and $\alpha = 1$.

This corresponded to a detected power of $\eta P = -55.7$ dBm. The difference between these values is explained by the losses of connector (1.0 dB), coupler (0.3 dB), splitter module (1.8 dB), a splice of (0.2 dB), and the quantum efficiency of the photodiodes (0.5 dB).

We also tried single-branch operation, without diversity. The LO and signal polarizations were chosen such that all signal power was detected in one receiver branch while the other branch was disconnected from the ratio combiner. For either branch we measured a sensitivity of

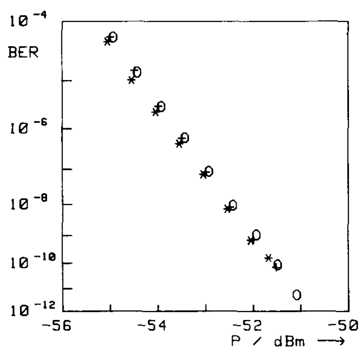

Fig. 11. Bit error ratio versus power at input connector of polarization diversity receiver ($\alpha = P_{TE}/(P_{TE} + P_{TM})$; $\alpha = 0 \leftrightarrow *$; $\alpha = 0.5 \leftrightarrow 0$; $\alpha = 1 \leftrightarrow +$).

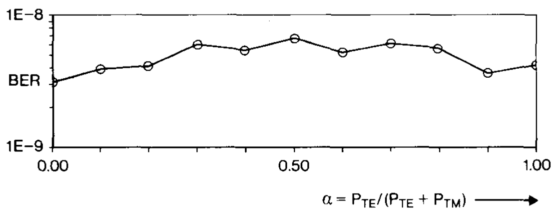

Fig. 12. Bit error ratio versus signal polarization for polarization diversity.

$\eta P = -57.3$ dBm. The 1.6-dB sensitivity degradation of polarization diversity is explained by the LO power being halved **(0.9 dB)** and the intrinsic penalty **(0.7 dB,** assuming dual-filter detection). We estimate that the single-branch sensitivities would have been another **0.3 dB** better if the LO signal had not been attenuated by the polarization beam splitter. Adding the numbers in bold letters gives 3.9 dB as total penalty of polarization diversity. The bit error ratio of the diversity receiver was measured in detail for a signal power of -52.4 dBm, as a function of signal polarization (Fig. 12). For low and high α values the performance was slightly better than for $\alpha = 0.5$, due to the beneficial action of the ratio combiner. The error ratios for $\alpha = 0$ and for $\alpha = 1$ were more than an order of magnitude better than measured previously without ratio combiner.

For system applications it is necessary to know the maximum speed of polarization changes the receiver can deal with. To determine this we inserted a Siemens $LiNbO_3$ polarization modulator into the signal path. The polarization was sinusoidally modulated between $\alpha = 0$ and $\alpha = 1$. Fig. 13 (° symbols) shows bit error ratios versus modulation frequency for a signal power of -52.5 dBm. The error ratio stayed practically constant for frequencies up to 10 kHz. This was the bandwidth of the level detectors that fed the ratio combiner. At 100 kHz the driving signals of the ratio combiner still followed the signal polarization to a reasonable degree, but with a phase delay. This resulted in a relatively high error ratio. At 300 kHz the ratio combiner had become inefficient and the receiver behaved as if it had no ratio combiner. Further degradation was only observed at 30 MHz and above, as the polarization modulation frequncy approached the data rate.

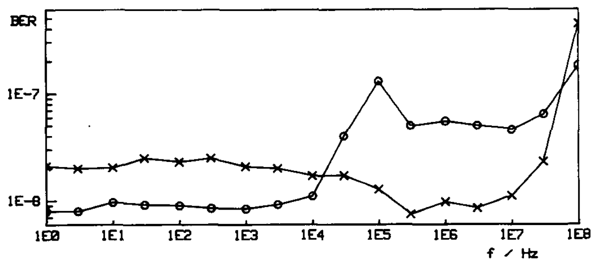

Fig. 13. Bit error ratio versus polarization modulation frequency for polarization diversity (*o*) and data-induced polarization switching (*x*).

The system performance was assessed with all fiber in place. For either channel we have recorded no error in 10^{12} transmitted bits. The loss span was 54 dB. Thanks to the polarization-independent AGC the receiver maintained an error ratio of $< 10^{-9}$ over an input power range of more than 25 dB.

IV. Data-Induced Polarization Switching

A. Theory

Data-induced polarization switching (DIPS) is a simple yet powerful technique to solve the polarization problem in optical FSK heterodyne systems [52], [53]. A birefringent component is placed in the signal path right after the transmitter. It is advantageous to choose a piece of polarization maintaining fiber as a birefringent component because of its low insertion loss. Linearly polarized light is launched at 45° with respect to the principal axes of the fiber. (In fact any SOP corresponding to equal powers in the two principal modes of the birefringent component can be used.) The time delay τ between the two principal states (0° and 90° linear SOP's) causes a phase difference. The SOP at the output of the birefringent component will therefore generally differ from the input SOP. If the product of time delay and frequency deviation is chosen $1/2$ the phase difference will be changed by π as the frequency is switched. Hence, the FSK modulation adds simultaneous polarization modulation between orthogonal states onto the signal. The passive birefringent device is the only optical component required to solve the polarization problem. The signal is transmitted through standard fiber to a standard heterodyne receiver. The polarization orthogonality of mark and space is preserved in nondichroic transmission media such as standard fiber. Due to DIPS there is an SOP mismatch between signal and LO that results in a 3-dB penalty.

The first DIPS received [52], [53] had two IF filters, two demodulators, and two frequency discriminators for AFC. In later experiments [54], [55] the two filters were eliminated. One delay-line discriminator was employed for data-demodulation and one more for AFC.

Two factors limit the permissible FSK modulation index m, the ratio of frequency deviation to bit rate: 1) A strong polarization mode dispersion occurs in the birefringent device; complete polarization switching is smeared over a time τ. 2) The transfer of the two orthogonally polarized signal components may result in an IF signal that has discontinuous phase transitions from bit to bit. These two factors cause intersymbol interference and hence a sensitivity penalty. One experiment with $m = 2.6$ resulted in a total penalty of 5 dB [54]. It is not recommended to go substantially below $m = 2.6$ since the penalty will rise sharply.

Azimuthal fiber misalignment and inappropriate fiber length (time delay τ) will of course cause extra penalties. For different SOP transfer conditions either mark or space component of the IF signal vanishes completely. The spectrum is then similar to that of an ASK receiver. Consequently the somewhat larger vulnerability of ASK receivers to phase noise [67] should as well apply for DIPS receivers. An experimental result will be given below. This effect has also been confirmed through computer calculations by F. Libbrecht (IMEC) [68]. Generally, an ASK-like IF spectrum will also result in vertical eye pattern distortion, like in an ASK heterodyne receiver that has a squarer as demodulator. Since the optimum threshold of such eye patterns is shifted from the center of the eye opening, it is useful to implement some form of automatic threshold adjustment to minimize the penalty. This is easily accomplished by adding a portion of the dc-output of the demodulator to the data signal at the input of the decision circuit.

In an FSK subscriber system one single birefringent component at each transmitter output is sufficient to make hundreds or thousands of subscriber receivers polarization independent. This way the added polarization handling costs per subscriber are reduced to a negligible amount.

As an alternative the birefringent component can be placed at the receiver input (see BC alternative in Fig. 1(c) and PMF (PANDA fiber) in Fig. 14). The LO SOP is chosen such that there is a 3-dB penalty if the received signal is a principal state of the birefringent component. To achieve this the LO is for instance launched with 45° linear polarization into a polarization maintaining coupler while the birefringent device is aligned to the principal axes of the coupler. This configuration makes it possible to incorporate DIPS into an existing network that has standard heterodyne transmitters (no polarization switching).

B. Experiment

In the RACE project R1010, Coherent Multichannel Communications, DIPS receivers will be incorporated besides polarization diversity receivers into an FSK distribution system that has standard transmitters. We describe here data-induced polarization switching in the receiver (Fig. 14). The standard 3-dB coupler in our receiver will later be replaced by a polarization maintaining coupler.

In our case 240 m of PANDA fiber were necessary to realize a time delay $\tau = 0.42$ ns between the two principal states, corresponding to our chosen frequency deviation of 1.2 GHz. The insertion loss of the PANDA fiber was only 0.5 dB, including one splice between PANDA and standard fiber. A low splice loss is possible because the near fields of PANDA and SIECOR fiber are particularly well matched. We used a front end with 5 pA $Hz^{-1/2}$ noise current and ± 0.75 dB passband ripple [69]. The thermal noise penalty was reduced to <0.4 dB. The IF amplifiers and the demodulator of the DIPS receiver were the same as for conventional operation. After the delay-line demodulator a high-pass filer cut off the dc part. For Manchester-coded signals each decoded NRZ symbol was a true average of high and low IF components, and the eye pattern did not change shape or threshold as function of received polarization. Automatic threshold adjustment would not have yielded further receiver sensitivity improvement.

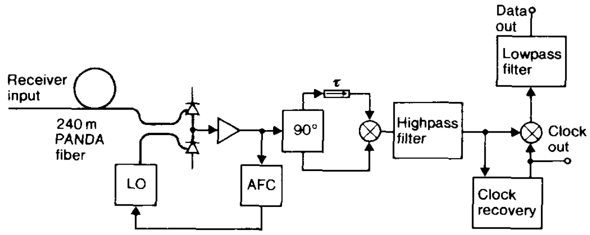

Fig. 14. Experimental setup for data-induced polarization switching in the receiver.

Under modulation the IF was switched between 0.65 and 1.85 GHz. Depending upon the received signal- and LO-polarizations, these two spectral components faded in antiphase. In order to avoid polarization-dependent IF shifts the automatic frequency control (AFC) used another frequency discriminator with zero crossings of equal slope polarities at these two frequencies. One might think that his condition restricts the IF choice, however, this is not true. There are many degrees of freedom to influence the discriminator characteristic: Variations in delay time, selection of either a 0° or a 90° power splitter, insertion of low-pass or high-pass filters in the delayed or undelayed branch, etc. allow virtually any choice of zero crossings.

Fig. 15 shows IF spectra for two different polarization conditions. In both cases the spectrum is locked in place even though one spectral IF component has disappeared completely. The basic receiver sensitivity for a $2^{15} - 1$ pattern was -59.0 dBm or 71 photoelectrons/bit. This is only 2.5 dB from the shot noise limit and is, to our knowledge, the best reported value for wide deviation FSK, even though the signals were Manchester-coded. In DIPS operation the worst-case penalty originally occurred if all energy was concentrated around 1.85 GHz. The IF response was therefore slightly raised for high frequencies which reduced the basic sensitivity to -58.8 dBm, as seen in Fig. 16 (* symbols). For DIPS operation the BER depended on the receiver input polarization. The best (+)

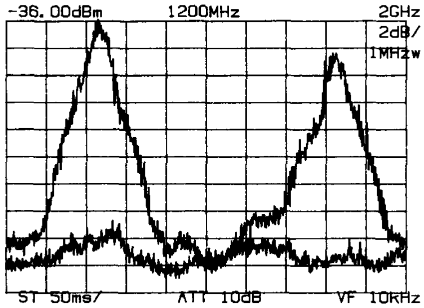

Fig. 15. IF spectra for two different polarization conditions.

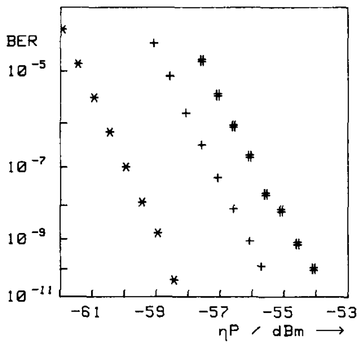

Fig. 16. Bit error ratios versus received power ηP; (*) standard heterodyne, (+) best and (#) worst cases of data-induced polarization switching.

and worst-case (#) sensitivities were -56.1 and -54.6 dBm, respectively. The latter value equals 194 photoelectrons/bit and corresponded to an optical power of -52.6 dBm at the input of the polarization maintaining fiber. The worst-case penalty of DIPS was 4.4 dB, including the initial circuit changes in the receiver. Together with the fiber insertion loss the total penalty of DIPS was 4.9 dB. The measured receiver sensitivity compares favorably with the figures published previously. The near shot-noise limited performance proves that only small sensitivity-impairing compromises were adopted in the receiver design.

We have transmitted the signal over the coupler network simulating 512 subscribers plus 94 km of standard fiber. No error was recorded in $4 * 10^{11}$ transmitted bits.

The IF linewidth was 47 MHz in this experiment. We have also assessed the sensitivity degradation caused by a linewidth increase to 62 MHz. For standard operation (no DIPS) the penalty was <0.1 dB at a BER of 10^{-9}. With DIPS the worst-case sensitivity was degraded by 0.3 to 0.5 dB, the uncertainty stemming from the difficulty to maintain worst-case SOP over a time long enough to record a significant number of errors. This shows that DIPS has a somewhat lower laser linewidth tolerance than polarization control or diversity.

The permissible speed of polarization changes (Fig. 13, x symbols) was assessed in the same way as for diversity. The BER decrease for polarization modulation frequencies above 30 kHz is believed to have been caused by a transmitter frequency change or by a temperature change in the polarization maintaining fiber that in turn altered the received SOP's. The BER stayed well within the window given in Fig. 16. In subsequent measurements it was confirmed that switching the modulation frequency between 1 Hz and 10 MHz did not or at least not significantly change the BER. Real degradation occurred only for frequencies of 30 MHz and above. The behavior is explained by the fact that both the high-pass filter after the demodulator and the Manchester decoder eliminated low-frequency signals stemming from the SOP modulation. Our measurements prove that the DIPS receiver can handle exceptionally fast SOP fluctuations. It should be noted, however, that NRZ signal format would result in a lower permissible speed because the low frequency components of the demodulated signal may not be cut off as for Manchester signals.

V. Active, Data-Synchronous Polarization Switching

While data-induced polarization switching is highly practical and competitive, it does not lend itself readily to optical integration because the necessary polarization dispersion would require a physically large device. As an alternative, however, an integrated optical polarization modulator can switch actively between orthogonal SOP's at the transmitter [53] (Fig. 1(d)). If the switching time is faster than the above-mentioned switching time τ of the DIPS fiber, it should at the same time be possible to employ somewhat lower FSK modulation indexes m. We have implemented this method using an integrated-optical $LiNbO_3$ phase shifter as polarization modulator. The Manchester-coded data signal not only modulated the transmitter frequency, but was also amplified to 26 dBm (± 4.5 V) in order to drive the polarization modulator. A permanently attached plano-convex silicon lens focused the parallel light beam from behind the isolators into the modulator. The system fiber was butt-coupled to the modulator output and carried 5.5-dB less power than the parallel beam. For comparison, typical coupling efficiencies without modulator did not exceed -3 dB. The applicable modulator insertion loss (loss span degradation) was therefore about 2.5 dB. The modulator bandwidth was 2 GHz.

In the receiver the DIPS fiber was of course removed. The IF response was only slightly modified which degraded the basic receiver sensitivity (ηP) from -59 to -58.9 dBm (Fig. 17, * symbols). With active polarization switching the best (+) and worst case (#) sensitivities were -55.9 and -54.9 dBm, respectively. The worst-case sensitivity was 0.3 dB better than for DIPS, part of which is attributed to the switching time in the modulator that was low compared to the 0.42-ns switching time of the DIPS fiber.

The measured receiver sensitivity degradation of 4.1 dB plus the modulator insertion loss resulted in a total system penalty of about 6.6 dB.

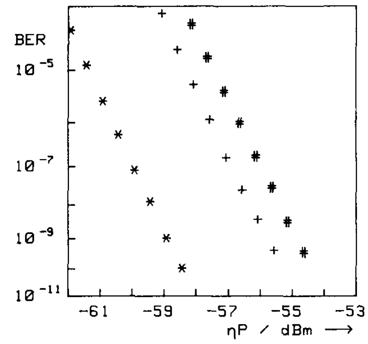

Fig. 17. Bit error ratios versus received power ηP; (*) standard heterodyne, (+) best and (#) worst cases of active, data-synchronous polarization switching.

TABLE I
PROPERTIES AND PENALTIES OF POLARIZATION HANDLING METHODS (SEE TEXT).

Comparison	Control	Diversity	Switching
Components needed	Polarization control elements: feedback controller	2nd IF branch, polarization splitter(s), polarization maintaining coupler(s), (ratio combiner, 2nd LO)	100 · · · 300 meters of polarization maintaining fiber
Modulation	PSK, DPSK, FSK, ASK		FSK, $m > 2.5$
Sharing possible?	no (yes)	no	yes
Response time	1 ms · · · 1 s	some bits · · · 10 μs	
LO loss [dB]	0.3 · · · 3	0.3 · · · 6	—
LO penalty [dB] 0.1 · · · 0.7 * LO loss	0.03 · · · 2.1	0.03 · · · 4.2	—
Signal loss [dB]	—	0.3 · · · 3	0.5
Polarization mismatch [dB]	<0.2	0 · · · 1	4 · · · 5
Electrical penalty [dB]	—	0 · · · 1.7	
Estimated total penalty [dB]	0.2 · · · 2.3	1 · · · 9	4.5 · · · 5.5

As mentioned in the introduction, the polarization modulator would also support clock-synchronous polarization switching, scrambling, or spreading for use with ASK, DPSK, or FSK modulation.

VI. COMPARISON

We will now try to compare the polarization handling methods which we have implemented. At the present time, active data-synchronous polarization switching is not competitive because it has higher system penalty and component count than DIPS, although we expect it can be used down to lower FSK modulation indexes. However, as already mentioned, the situation may change with the availability of integrated optical chips that contain a transmitter laser, the polarization modulator and possibly a semiconductor booster amplifier.

One important issue for designers of multichannel systems is the spectral occupation because the required local oscillator tuning range is proportional to the optical channel bandwidth. A broad spectrum also tends to decrease the receiver sensitivity since wide-band receivers normally have higher thermal noise and gain ripple than narrow-band receivers. While polarization control and diversity need minimum bandwidth and channel spacing, there is, in general, an optical bandwidth enhancement for all polarization handling techniques that have an intrinsic 3-dB penalty stemming from polarization mismatch [52]–[62]. In our experiments the frequency deviation was mainly determined by the desired amount of phase-noise tolerance (up to about 60 MHz IF linewidth). The larger bandwidth requirements of DIPS and active, data-synchronous polarization switching were therefore masked. However, for low linewidth-to-bit-rate ratios the spectral occupation should be carefully considered.

Table I compares those polarization handling methods that are most competitive today. The top lists the additional components that are needed to realize a specific scheme. It is interesting to note that diversity receivers require two matched IF chains whereas DIPS receivers need equal magnitudes of the mark and space IF reponses.

A second LO and a ratio combiner must be provided for synchronous (PSK, ASK) homodyne polarization diversity receivers. Polarization control equipment can be shared among several subscribers with restriction that polarization maintaining fibers have to be used between the common SOP transformer and each of the receivers [15]. Diversity with ratio combiner and DIPS using NRZ signal format have response times somewhere in the μs range. The response time is decreased down to a few bit periods for diversity without ratio combiner and for Manchester-coded DIPS.

In polarization control receivers the LO is attenuated by the insertion loss of the retarders, typically 0.3 dB for fiber devices or 3 dB for an integrated optical device. Roughly these numbers also apply for LO and signal attenuations of diversity receivers, the figures depending on the technology used. Diversity looses an extra 3 dB of LO power due to the presence of two receivers unless two LO's are used. Since coherent receivers generally operate somewhere near the shot noise limit we assume that the sensitivity degradation is the 0.1 to 0.7 fold of the LO attenuation; both quantities measured in dB. In DIPS systems the birefringent component attenuates the signal by about 0.5 dB. An additional 4- to 5-dB loss represents the intrinsic and excess penalties of DIPS. Endless polarization control with an A-algorithm keeps the SOP mismatch penalty at ≤ 0.2 dB. R-algorithms cause roughly the same losses, but it is difficult to give an upper limit for the maximum penalty that may arise for short periods of time. The safe continuous tracking speed is only about 0.01 rad/iteration, a fraction of the instantaneous response speed. The polarization mismatch penalty of diversity can be zero. However, assuming $\pm 1°$ LO misalignment, 20- and 15-dB extinction ratios for fiber-based polarization-maintaining coupler and polarization beam splitters, respectively, and front ends with 1.8-dB thermal noise penalty in diversity operation, a worst-case 0.9-dB misalignment penalty may occur. Diversity receivers with asynchronous demodulation finally have an electrical penalty that is between 0.3 and about 0.7 dB, depending on modulation format and the ratio of IF bandwidth to data rate. Researchers who employed commercial double balanced diode mixers as demodulators have observed an excess penalty of about 1 dB if no ratio combiner was used [32], [36], [37], [39], [41], [47]. Fortunately, the polarization for which the excess penalty occurs will in general not be the same for which the worst-case misalignment penalty occurs. The total penalty (last line of Table I) is the sum of all applicable penalties. It should be noted that diversity with low-loss fiber components may result in a SOP mismatch due to the finite extinction ratios of polarization maintaining fiber devices.

The total penalties of control and of DIPS are in the order of 1 and 5 dB, respectively. While these penalties are relatively well defined, there is a wide range for diversity, from about 1 to 9 dB. Low penalties can only be reached with low-loss optical components and possibly a separate local oscillator for each of the diversity branches.

We think that endless control or a well-designed diversity receiver should be used for coherent trunk systems, which aim for ultimate sensitivity. Data-induced polarization switching promises a sensitivity similar to that of a medium quality polarization diversity receiver. The tremendous cost saving potential of DIPS makes it recommendable for FSK distribution systems as long as one can live with the permissible modulation index $m > 2.5$. Subscriber services for instance will probably not require extremely high data rates, which means that DIPS can be used.

If ultimate signal acquisition speed is needed, e.g., for packet switching, diversity without ratio combiner or DIPS in conjunction with Manchester-coding are good solutions.

Or course, if polarization maintaining fiber and couplers with low losses and high polarization extinction ratios become available, other polarization handling schemes may well become obsolete.

VII. Conclusion

In a computer simulation we have compared endless polarization control algorithms. The algorithm which specifies fixed retardation range limits and needs to know the absolute magnitudes of retardation performed better than algorithms that have soft retardation range limits and need to know the retardations only relative to the current operation points. Theory and possible deteriorations were also discussed for polarization diversity, and data-induced polarization switching.

A pattern-independent 140-Mb/s FSK heterodyne system was operated using endless polarization control, polarization diversity, data-induced polarization switching, and active data-synchronous polarization switching. The corresponding system penalties were about 0.4, 3.9, 4.9, and 6.6 dB, respectively.

Finally, we have compared the potential of these polarization handling methods and have suggested preferred candidates for some applications.

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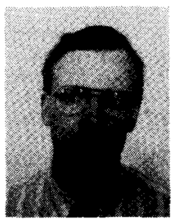

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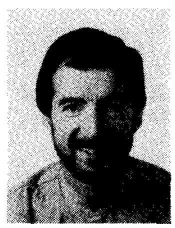

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Franz Auracher, photograph and biography not available at the time of publication.