Balanced Phase and Polarization Diversity Coherent Optical Receiver

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***Abstract*—A balanced phase and polarization diversity coherent optical receiver employing two novel components is tested in a 565 Mbit/s DPSK transmission system. The two novel components are, firstly, a compact bulk optical 90° hybrid which provides all eight optical signals required for balanced phase and polarization diversity operation and, secondly, a silicon bipolar multiplier IC which has a dynamic range of at least 15 dB guaranteeing negligible degradation in both diversity operations.**

INTRODUCTION

A balanced phase and polarization diversity receiver is appropriate to overcome many problems appearing in coherent optical communications. This receiver reduces the impact of transmitter and local oscillator phase noise, of polarization fluctuations of the received signal, of intensity noise of the local oscillator laser, and of channel-cross-channel interference in multichannel systems [1]. Because this receiver enables baseband reception, less receiver bandwidth is required and, in multichannel systems, smaller channel spacings are allowed, than with the corresponding heterodyne receiver [1]. However, phase and polarization diversity operation in conjunction with balanced detection require a complex structure of the receiver. To our knowledge no complete but only partial implementations of the balanced phase and polarization diversity receiver were reported up to now (see [1], [2] and references given therein).

In this letter we describe a balanced phase and polarization diversity receiver employing a compact bulk optical hybrid and a silicon bipolar multiplier IC. The compact bulk optical hybrid provides all required optical signals with well defined phase relations in a single unit and is therefore a good solution of the problems associated with the complex structure of the optical part of the receiver. The multiplier IC has a dynamic range of at least 15 dB. It guarantees that variations of the signal power in the different detection branches of the receiver cause negligible degradation in both diversity operations. The balanced phase and polarization diversity receiver is tested in a 565 Mb/s DPSK transmission system.

EXPERIMENTAL SYSTEM

Fig. 1 shows a block diagram of the receiver. A DPSK-signal is generated by an external cavity laser (ECL) operating at 1300 nm (linewidth ≤ 100 kHz) and by a $\mathrm{LiNbO_3}$ phase modulator which is driven by a pulse pattern generator. A similar ECL is used as local oscillator laser. An automatic frequency control (AFC) stabilizes the beat frequency of the two lasers to 15 MHz. The key component of the receiver is the compact bulk optical hybrid, which is shown in detail in Fig. 2 and which is described below. It has eight output ports, which provide the required optical signals for phase and polarization diversity in conjunction with balanced detection. The detectors are InGaAs p-i-n-photodiodes and transimpedance preamplifiers in bipolar technology (3 dB cutoff at 2 GHz). The resulting electrical IF signals are lowpass filtered (3 dB cutoff at 570 MHz) and subsequently demodulated by DPSK delay line demodulators. The most important part of the demodulator is a bipolar multiplier IC. Finally the signals of the four electronic branches are combined by an active adding stage and passed to an error detector.

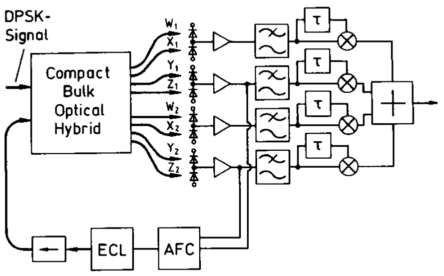

Fig. 1. Schematic diagram of the balanced phase and polarization diversity.

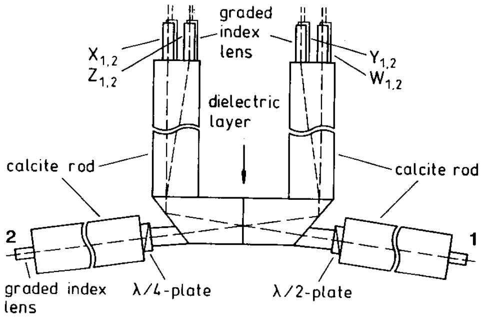

Fig. 2. Schematic drawing of the bulk optical hybrid for balanced phase and polarization diversity receiver.

The optical hybrid is an extended version of a previously reported hybrid, which was developed for balanced phase diversity operation only [3]. The extension consists in the addition of two calcite rods and two retardation plates at the inputs 1 and 2 (for the DPSK-signal and for the local oscillator wave). In each calcite rod the injected light beam is spatially separated (in vertical direction in Fig. 2) into two linearly and orthogonally polarized light beams. The λ/4 plate at input 2 transforms the two linear SOP's into two circular SOP's and the λ/2 plate at input 1 rotates the two linear SOP's by 45°. The remaining part of the hybrid is identical with the optical hybrid described in [3]. However, in the present setup the hybrid is used in two sepa-

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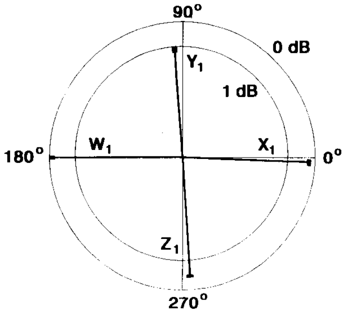

Fig. 3. Vector diagram depicting measured phase and loss characteristics of the upper outputs of the optical hybrid.

rated horizontal planes, the upper plane with the outputs X_1, Y_1, Z_1, and W_1 for one branch and the lower plane with the outputs X_2, Y_2, Z_2, and W_2 for the other branch of the polarization diversity receiver. The characteristics of the hybrid were measured within the wavelength range from 1280 to 1310 nm. As an example the vector diagram in Fig. 3 shows the results for the outputs X_1, Y_1, Z_1, and W_1. The phase relations (with output W_1 as reference) are represented as angles. They were measured by a vector voltmeter and a selfheterodyne setup using an acoustooptical modulator to generate the two input signals of the optical hybrid (for details see [4]). The length of each vector is proportional to the IF signal amplitude generated in a detector taking into account the measured coupling efficiencies from the inputs to the corresponding output fibre. As a reference the circles represent the signal current amplitudes for hybrid losses of 0 and 1 dB, respectively. The area at the tip of the vector represents the small wavelength dependence of the results. The average insertion loss is 0.6 dB and the maximum deviation of the phases from the ideal values 0°, 90°, 180°, and 270° is only 5°. Similar results were obtained for the outputs X_2, Y_2, Z_2, and W_2 in the lower plane. The maximum deviation from the average signal amplitude appears at the output Y_1 with -13%. The deviations in amplitude and phase do not cause any significant receiver degradation [5].

Due to polarization fluctuations the IF signal levels vary strongly in the four electronic branches of the diversity receiver. If conventional double balanced mixers are used in the DPSK-demodulators, they may cause a sensitivity degradation due to their small dynamic range and bandpass limitations. The monolithically integrated bipolar multiplier IC's in our experiments avoid these problems. This device, is an improved version of the previously described multiplier IC [6] with better suppression of spurious harmonic components, a larger bandwidth and approximately the same dynamic range. This component is used here for the first time in a polarization diversity receiver.

Transmission Experiments

To verify the polarization insensitivity of the receiver we adjust the signal power P_s to a bit error rate BER = 10^{-8} and vary the signal polarization via a fibre polarization controller. By this we change the signal power splitting ratio α which defines the signal powers αP_s and $(1-\alpha)P_s$ in the two polarization diversity branches. P_s is the sum of the received power at all 8 photodiodes. α is measured with use of RF-power detectors which are connected to each receiver branch (not shown in Fig. 1). Fig. 4 shows the signal power P_s needed for BER = 10^{-8} and BER = 10^{-6} versus the power splitting ratio α. There is a negligible dependence of the receiver sensitivity on the signal polarization only.

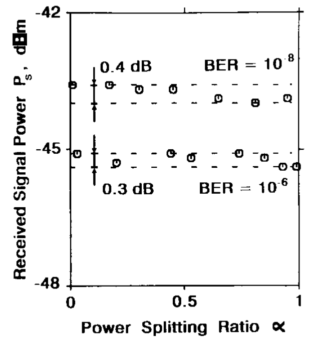

Fig. 4. Receiver sensitivity at BER = 10^{-8} and BER = 10^{-6} versus the power splitting ratio α between the two polarization diversity branches.

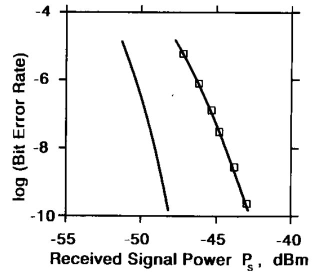

Fig. 5. Experimental and theoretical results of BER versus received signal power P_s; system parameters: $i_{\text{th}} = 9\ \text{pA}/\sqrt{\text{Hz}}$, $P_{\text{LO}} = -6.8$ dBm, $R = 0.9$ A/W.

Fig. 5 depicts experimental and theoretical results of the BER versus the received signal power P_s. The theoretical result (solid line) was calculated following [7]. However, with respect to [7], the signal to noise ratio was modified in order to take into account the thermal noise of the receiver i_{th}, the limited local oscillator power P_{LO} and the photodiode responsivity R. The theoretical result predicts a sensitivity degradation of 8.7 dB compared to the shot noise limit (-57.2 dBm). 8.0 dB of this degradation are due to the thermal noise of 9 $\text{pA}/\sqrt{\text{Hz}}$ of each receiver in conjunction with the LO-power of only -6.8 dBm, which is divided among four receiver ports. To reduce the effect of thermal noise to a penalty of 1.0 dB a local oscillator power of $+6.5$ dBm would be required. The experimental results show a receiver sensitivity of -43.4 dBm at a BER = 10^{-9}, which is about 5 dB worse than the theoretical prediction. With use of the system simulation program BOSS a sensitivity degradation of 3.5 dB could be attributed to the nonzero intermediate frequency, and the nonoptimized filter characteristics. The remaining 1.5 dB are probably caused by the phase modulator. The measurements in Fig. 5 were performed with a pseudorandom word pattern of length $2^{23}-1$. Measurements with shorter word lengths received nearly the same receiver sensitivities.

Conclusion

A balanced phase and polarization diversity receiver was successfully operated. Two components give this receiver its good performance. A compact bulk optical hybrid provides all optical signals for both diversity operations and for balanced detection in a single unit and for a large wavelength range of more than 30 nm. A multiplier IC in the demodulator stage gives the required dynamic range for both diversity operations. The receiver is almost insensitive to polarization variations.

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