Ultra Fabrication-Tolerant Fully Packaged Micro-Optical Polarization Diversity Hybrid

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***Abstract*— We report on a novel fully packaged micro-optical polarization diversity hybrid, which shows excellent performance in combination with large fabrication and assembly tolerances. Our novel design employs highly parallel glass plates, which results in parallel and equidistant input and output beams. Critical fabrication and alignment procedures are thus avoided. At the target wavelength of 1.55 μm, typical fiber-to-fiber insertion loss is 0.7 dB, balancing is 50 ±3%, polarization extinction ratios are better than 25 dB, and measured optical back reflection is smaller than -58 dB. Wavelength insensitive behavior has been observed, resulting in a wide usable spectral operating range in excess of 90 nm. The micro-optical hybrid has been successfully tested in a dual-balanced polarization-diversity coherent CPFSK transmission experiment at 2.5 Gbt/s.**

I. INTRODUCTION

POLARIZATION diversity hybrids are key components in coherent lightwave receivers, whose wavelength tunability can be used, for example, to enhance the flexibility and survivability of photonic networks based on optical frequency division multiplexing (OFDM) [1]. Whereas, in the past, polarization diversity hybrids were assembled using separate components, the drive for cost and size reduction has stimulated a trend toward either all-fiber [2], [3], monolithically integrated [4]–[9], or completely micro-optical [10]–[15] polarization diversity hybrids. All-fiber hybrids [2], [3] offer low losses (0.2–0.6 dB), but polarization extinction ratios are weak (typ. 15 dB) and reliability problems may be encountered. InP-based monolithic integration is promising, but shows higher losses (2–5 dB) [9] and may present reflection problems. Good results have been obtained by means of micro-optical assembly techniques, which are low-loss ($\leq$0.7 dB), show low reflection, and have excellent polarization extinction ratios (>25 dB) [10], [13]. The main disadvantages, so far, have been the fabrication and packaging of micro-optical hybrids, which require skillful and time-consuming polishing of highly accurate components, leading to increased costs.

In introducing lightwave communication systems to the market, it is crucial to have low-cost, small and reliable components. In [16], we presented the first experimental results of a novel micro-optical polarization diversity hybrid with large fabrication and assembly tolerances. In this paper, we report on the packaged polarization diversity hybrid, demonstrating that, in addition to increasing fabrication tolerances, our novel design also considerably simplifies packaging, thereby enhancing reliability and robustness.

II. DESIGN

A. Modular Approach

A central element in our micro-optical polarization diversity hybrid, as shown in Fig. 1, are Philips' lens ferrules [10], [17], which collimate the light from a glass fiber to a Gaussian beam of spot size $2w_0 = 0.33$ mm and which show ultralow reflection ($|r|^2 < -60$ dB). Employing lens ferrules constitutes, in fact, a *modular* approach, where local oscillator (LO) laser, polarization diversity optics and photodetectors are interconnected by means of fibers, as opposed to an *integrated* approach combining two or more of these components in a single device.

Three factors contribute to the convenience of the modular approach. Firstly, isolators are required between the LO laser and the polarization diversity optics, since reflections adversely effect the coherence properties of the LO laser. At present, it is uncertain whether the isolator can be abandoned in integrated solutions, since little is known about reflections occurring in waveguide devices. Secondly, high-speed operation requires that the photodetectors be close to the front-end electronics and that proper electromagnetic shielding is used. This requirement favors integration of the photodetectors with the front-end electronics rather than with the polarization diversity optics. Thirdly, since the lens ferrules can be adjusted longitudinally in the package, our design allows for easy fine-tuning of the length of each individual output path (O_1–O_4 in Fig. 1). It is critical that *all four* intermediate frequency (IF) phase delays be equal; not only does proper balancing of the LO laser noise require identical lengths for the equal-polarization output paths [18], a proper generation of a polarization-independent baseband signal also requires identical lengths for the orthogonal-polarization output paths.

B. Basic Principle

Whereas the lens ferrules are rather tolerant to lateral displacements, they are extremely sensitive to *angular* misalignments, causing critical fabrication tolerances and alignment

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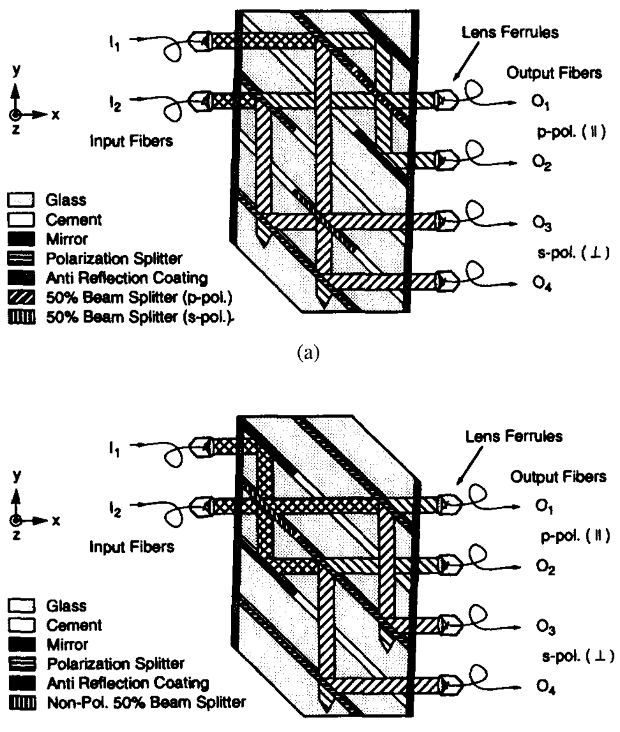

Fig. 1. Schematic layout of micro-optical polarization diversity hybrid. (a) Shows the "BM-version," which consists of two polarization splitters followed by two 50% beam splitters, and (b) shows the alternative "WH-version," which employs a nonpolarizing 50% beam splitter followed by two polarization splitters. By using highly parallel glass plates and additional reflecting coatings, all in- and output beams become parallel and equidistant, thereby increasing alignment tolerances.

problems in previous micro-optical polarization diversity hybrids [10], [14]. This led to the observation that a fabrication-tolerant design should be based on avoiding angles. The central concept of our design thus keeps all input and output beams parallel, which is achieved by employing highly parallel glass plates of identical thickness and by using dielectric mirror coatings to redirect the light (see Fig. 1). Such glass plates can be fabricated with a high degree of flatness. Equal thickness is ensured by simultaneous polishing of all glass plates. Multiple dielectric coatings are evaporated onto each glass plate. In this way, no critical angles occur and assembly is not critical. Note, for example, that this design is completely invariant for translation of the hybrid along all three Cartesian axes.

Two different polarization diversity hybrids were designed. In the design shown in Fig. 1(a) (which we have coined "BM-version"), polarization splitters (PS) first split the input beams (signal and local oscillator) into a transmitted p-polarization and a reflected s-polarization. The p-components of each input beam are then redirected by means of two dielectric mirrors in such a way that they are combined in a p-type 50% beam splitter ($BS_{\|}$) and that they exit the hybrid in the same direction as the input beams. The s-components of each input beam are combined in an s-type 50% beam splitter ($BS_{\perp}$), but they are redirected by means of polarization splitters (PS) rather than mirrors in order to increase the polarization extinction ratio, as explained in Sections II-D and IV-B. In the second design, which is shown in Fig. 1(b) ("WH-version"), the input beams are first combined in a nonpolarizing 50% beam splitter (NPBS). The two resulting beams are then split by two polarization splitters. The reflected s-polarization beams are redirected by a second set of polarization splitters (PS) such that all output beams are parallel. The WH-version offers the advantage that it can also function as a phase diversity hybrid when employing specific states of polarization of the input beams as explained in [19] and can thus be used in phase diversity and image rejection receivers.

C. Reflection Properties

Coherent transmission systems are very sensitive to reflections, which can cause a deterioration of the coherence properties of the lasers and which can lead to increased noise due to FM-to-AM conversion. In our design, reflections were avoided by applying tilts (fibers are cut at 10° and hybrid is tilted at 1.5° around the z-axis) and antireflection coatings to all refracting surfaces (an AR coating reduces the reflectivity of air-glass interfaces from 4% to some 0.3% or -25 dB). These precautions successfully eliminate Fabry–Pérot interference due to multiple reflections.

In the proposed design, care was also taken to avoid a potential second type of interference, i.e., of the Mach–Zehnder type, when beams are split and later on combined due to reflections at uncoated surfaces. The effect of Mach–Zehnder interference is negligible for three reasons. Firstly, careful matching of the refractive index of glass and cement reduces (unwanted) Fresnel reflections to < -30 dB. Secondly, interference due to a single unwanted reflection occurs between beams of complementary polarization, thereby influencing polarization cross-talk only. Interference between equal-polarization beams requires two unwanted reflections (< -60 dB) and can be safely neglected (a reflection of -60 dB causes a maximum power fluctuation of $1.001^2 - 0.999^2 \approx -24$ dB). Thirdly, when using highly parallel glass plates of equal thickness, the arms of the Mach–Zehnder interferometer are equal to within several 10 μm. Since this length difference ΔL and the free spectral range $\Delta\lambda_0$ of the interferometer are interrelated by

$$\Delta\lambda_0 \approx \frac{\lambda_0^2}{n\Delta L},$$

a very large value of $\Delta\lambda_0 \approx 63$ nm is found when taking $\Delta L = 25$ μm, meaning that FM-to-AM conversion efficiency is negligible.

D. Optical Design

Coatings were specially designed for optimum performance at $\lambda_0 = 1.55$ μm using conventional designing techniques [20]. Table I lists some properties of the coatings. All coatings except the nonpolarizing beam splitter (NPBS) coating were fabricated using vacuum evaporation techniques and their composition is given in [16]. A multilayer dielectric mirror coating was used for maximum reflectivity; metallic coatings (Au) show too high absorption (>2.5%) and a totally reflecting glass-air interface has been discarded as being too vulnerable. The most critical coating is the NPBS coating, for which

TABLE I
DIELECTRIC COATING PARAMETERS: R_s, T_s, R_p, and T_p DENOTE REFLECTED AND TRANSMITTED POWERS FOR S- AND P-POLARIZATIONS, RESPECTIVELY. $\Delta\lambda_0$ IS THE SIMULATED WAVELENGTH RANGE FOR 2.5% CHANGE IN PERFORMANCE. CENTER WAVELENGTH IS $\lambda_0 = 1.55$ μm

Coating	R_s(%)	T_s(%)	R_p(%)	T_p(%)	$\Delta\lambda_0$(nm)
Mirror	100	~ 0	98	2	110
PS	100	~ 0.1	$1 \sim 3$	$99 \sim 97$	360
$BS_{\parallel}$(p-pol)	>99	<1	49	51	80
$BS_{\perp}$(s-pol)	48	52	<3	>97	300
NPBS	47	53	53	47	45

a special technique was developed based on sputtering of different high-index Si-based compounds.

Table I shows how the coatings affect the polarization extinction ratio. Whereas the polarization splitting coatings have a very pure transmitted beam (polarization extinction ratio of $\approx$30 dB), the reflected beam (s-pol) has a polarization cross-talk of approximately 15–20 dB. The polarization cross-talk can, therefore, be enhanced by using polarization splitters in place of mirrors for the reflected s-polarization beams, as shown in Fig. 1. Note, that the p-type 50% beam splitter ($BS_{\parallel}$) improves the polarization extinction ratio for transmitted beams, whereas the s-type 50% beam splitter ($BS_{\perp}$) improves the polarization extinction ratio for reflected beams.

Dielectric multilayer coatings can be used in a large wavelength range. According to Table I, the usable spectral operating range of the BM-version is expected to be limited by the $BS_{\parallel}$ coating to $\Delta\lambda_0 \approx 80$ nm, whereas it is limited to $\Delta\lambda_0 \approx 45$ nm for the WH-version as determined by the NPBS coating.

III. FABRICATION AND PACKAGING

A. Prototype Fabrication

Several glass plates of Schott glass BaLF5 ($n = 1.53$) were fabricated in a simultaneous polishing operation to identical thicknesses, parallel within $\lambda_m/20$ and flatness better than $\lambda_m/4$ (measured at $\lambda_m = 535$ nm). Evaporation masks with openings were used to define the area for coating deposition; positioning of these masks is uncritical within a large tolerance of 3 mm. Special cement (Summers M62 lens-bond) was used for low absorption and matching refractive index. In order to maintain parallelism, "spacers," i.e., two narrow additional coatings at both ends of the glass plates, were used. Assembly was done by simple stacking of all glass plates in a special holder, such that parallelism could be monitored before curing the cement.

After assembly of the hybrid, front and end faces are polished parallel to each other. Because of the large thickness of some dielectric coatings (e.g., 13 μm for the mirror), the cement showed some minor irregularities caused by stress, especially close to the polarization splitters. No measurable effects due to the irregularities were found but their formation indicates that care must be taken in selecting the appropriate cement and in avoiding stress formation during fabrication (e.g., by minimizing heat treatments when curing the cement).

Note that the cement in the micro-optical hybrid performs a very different function from that in polarization-maintaining fiber (PMF) couplers. The cement in PMF couplers has both a mechanical and an optical function, since the cement functions as the coupling layer between the two fibers, *along* which light propagates. Since couplers are extremely sensitive to the properties of the coupling layer, even minute changes of the optical properties of the cement can affect the coupler performance and can thus lead to reliability problems. The cement in the micro-optical hybrid, on the other hand, has a purely mechanical function. Optical beams are incident at an angle of 45° to the cemented interfaces and minor variations in the properties of the cement, therefore, do not affect the performance of the hybrid.

B. Assessment of Parallelism

After finishing the prototype, the locations of all input and output beams were determined using a Fabry–Pérot laser ($\lambda_0 = 1.55$ μm), a lock-in amplifier and two separate lens ferrules on independent translation stages as described in [16]. We measured that 1) all optical beams are perfectly parallel (along the x-axis), so that no subsequent *angular* realignment of the lens ferrule is required for any input or output beam, 2) all beams lie in a single plane (z = constant), and 3) all beams are equidistant to within 20 μm from the design pitch value of $\Delta y = 7$ mm (a beam spot size of $2w_0 = 0.33$ mm corresponds to 0.1 dB loss increase for a 25 μm lateral offset). In addition, we verified that 4) the performance of the hybrid is unaffected during translation along all three Cartesian axes and that 5) the sensitivity of the hybrid with respect to rotations is much reduced for the transmitted beams when compared to the reflected beams (because these rotations transform into lateral displacements for the transmitted beams).

C. Packaging

The concept of using parallel glass plates does not only ease fabrication, but it also affects packaging. The hybrid thus allows for a housing where all input and output ferrules lie in parallel ports at fixed predetermined locations, thereby eliminating the need for elaborate adjustment procedures: the only remaining degree of freedom of the ferrules involves adjustments along and rotations around the x-axis. Out of each prototype, eight hybrids were sawn with a thickness of 1.4 mm each, resulting in a compact size and promoting low-cost production. Each individual hybrid was subsequently reinforced on the top and bottom sides with 0.4 mm thick glass plates for support. Packaging was performed using a specially designed alignment stage, where the housing (rather than the hybrid) is aligned. This allows for a larger and therefore more accurate alignment stage, and it avoids the use of adjustment mechanisms *inside* the housing. Aligning the housing with respect to the hybrid is extremely easy; the parallel concept ensures that the optimization of the transmission to all output ports can be accomplished in one step. After optimum positioning, the hybrid is glued to the housing using three glass posts and UV curing adhesive. Fig. 2 shows the compact packaged hybrid (size of 52 × 42 ×

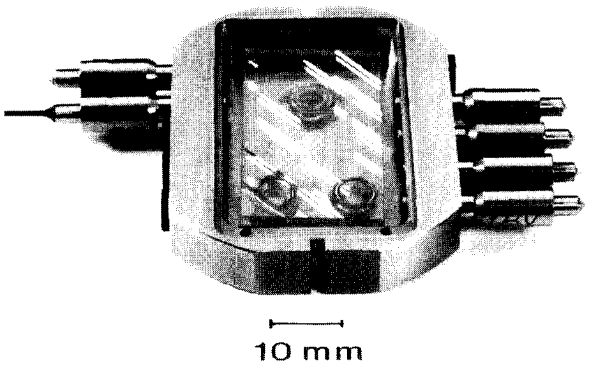

Fig. 2. Photograph of packaged polarization diversity hybrid (BM-version), with cover removed.

TABLE II
MEASURED PERFORMANCE OF POLARIZATION DIVERSITY HYBRID: BM-VERSION

Port		O_1	O_2	O_3	O_4	Ins. Loss	Balance
I_1	p-pol.	45.3%	42.0%	0.08%	0.18%	0.59dB	50±1.9%
	s-pol.	0.12%	0.05%	43.4%	49.4%	0.32dB	50±3.2%
	Ext. Ratio	25.8dB	29.5dB	27.6dB	24.5dB		
I_2	p-pol.	49.8%	45.7%	0.14%	0.15%	0.20dB	50±2.1%
	s-pol.	0.06%	0.15%	51.8%	42.5%	0.25dB	50±4.9%
	Ext. Ratio	29.1dB	24.7dB	25.8dB	24.6dB		

9 mm^3) with all input and output lens-ferrules. The different coatings as well as the three glass posts which hold the micro-optical hybrid in its optimum position can be clearly seen in the photograph.

IV. CHARACTERIZATION

A. *Transmission*

Characterization of the polarization diversity hybrids was performed using a Fabry–Pérot laser ($\lambda_0 = 1.55$ μm) and a HP8509A polarization analyzer. Polarization was adjusted by means of three loops of fiber. Light was coupled into and out of the polarization diversity hybrid using a single set of lens ferrules. Tables II and III list the performance of a representative sample of the BM-version and the WH-version. Very low insertion losses have been found (0.3 ± 0.2 dB for BM-version and 0.7 ± 0.2 dB for WH-version). Since the insertion loss of the lens ferrules is 0.4 ± 0.2 dB, the total fiber to fiber loss is 0.7 ± 0.3 dB for the BM-version and 1.1 ± 0.3 dB for the WH-version.

Balancing varies from 50 ± 2% to 50 ± 5% with an average of 50 ± 3% for the BM-version, whereas it varies between 50 ± 2% and 50 ± 8% with an average of 50 ± 6% for the WH-version. These average values of the balancing correspond to common mode rejection ratios of 24 dB and 18 dB for the BM- and WH-versions, respectively, where the common mode rejection ratio (CMRR) is defined by

$$\mathrm{CMRR} = -20 \log \left[\frac{\mathrm{P}(\mathrm{O}_1) - \mathrm{P}(\mathrm{O}_2)}{\mathrm{P}(\mathrm{O}_1) + \mathrm{P}(\mathrm{O}_2)}\right]$$

with $\mathrm{P}(\mathrm{O}_i)$ denoting the optical power at output O_i and where a similar relation holds for the O_3 and O_4 outputs [17]. For the BM-version, balancing for the $\mathrm{O}_1/\mathrm{O}_2$ ports (p-pol.) is better than for the $\mathrm{O}_3/\mathrm{O}_4$ ports (s-pol.), which is independently determined by the quality of the $\mathrm{BS}_{\|}$ and $\mathrm{BS}_{\perp}$ 50% beam splitter coatings, respectively. The performance of the BM-version is better than that of the WH-version, due to difficulties in fabricating the NPBS coating and the sputtering process that was employed involving high index materials.

TABLE III
MEASURED PERFORMANCE OF POLARIZATION DIVERSITY HYBRID: WH-VERSION

Port		O_1	O_2	O_3	O_4	Ins. Loss	Balance
I_1	p-pol.	37.7%	47.6%	0.10%	0.17%	0.69dB	50±5.8%
	s-pol.	0.17%	0.14%	42.5%	38.8%	0.90dB	50±2.2%
	Ext. Ratio	23.6dB	25.2dB	26.2dB	23.6dB		
I_2	p-pol.	51.0%	39.3%	0.23%	0.13%	0.44dB	50±6.5%
	s-pol.	0.17%	0.14%	35.4%	49.5%	0.71dB	50±8.3%
	Ext. Ratio	24.8dB	24.4dB	21.8dB	25.8dB		

B. *Polarization Handling*

Very good polarization extinction ratios (22–30 dB) have been observed, with values in excess of 25 dB for the BM-version. When determining the $\mathrm{I}_2 \rightarrow \mathrm{O}_4$ polarization extinction ratio of the BM-version, the transmitted p-polarization beam at the second polarization splitter (see the "arrows" in Fig. 1) was, at first, found to be reflected into the O_4 output by the outside glass-air interface. After roughening this interface, an improvement of the polarization extinction ratio was observed from 15 to 25 dB, which demonstrates that the large extinction ratios of the O_3 and O_4 ports result from the combined action of two polarization splitters in series.

C. *Reflection Properties*

The reflection properties of a packaged BM-version polarization diversity hybrid were assessed using a HP8504A precision reflectometer, which was gauged using the Fresnel reflection of −14.7 dB of a microscope cover glass. At first, some minor reflections in the order of −40 dB were found for two output ports, which was traced back to the two nonfunctional side faces of the hybrid. Application of a black absorbing coating to these faces, caused a reduction of the reflection to −58.0 dB for the O_3 output. No reflection was measured for any other port, including the two input ports, indicating $|r|^2 < -60$ dB, i.e., the sensitivity of the measurement setup. These measurements indicate that if, in addition to applying an absorbing coating, the nonfunctional faces had also been roughened, all reflections would have been smaller than −60 dB.

D. *Wavelength Dependence*

In order to fully exploit the transmission capacity of the glass fiber in the 1550 nm window, optical components should have an optical bandwidth at least equivalent to the width of the transmission window of the fiber. A particular advantage of dielectric multilayer coatings is precisely their wide usable spectral operating range as indicated in Table I. The wavelength dependence of a packaged polarization diversity hybrid ("BM-version") was measured using a HP8168A tunable laser and a HP8509A polarization analyzer. The results are shown in Fig. 3. Optimum performance is indeed very close to the target wavelength of 1550 nm. Fig. 3(a) shows that the insertion loss stays between 0.1–0.8 dB for both input ports and for both polarizations over the entire measured wavelength range from 1464–1572 nm, i.e., a span of 108 nm. For this range of 108 nm, the average insertion loss varies between 0.2–0.55 dB. Balancing for the O_3/O_4 ports (s-pol.) is 50 ± 4% and is almost independent of the wavelength, which is in agreement with the operating range of the $BS_\perp$ coating as listed in Table I. Balancing for the O_1/O_2 ports (p-pol.) shows an optimum of 50 ± 1% around 1540–1550 nm. Setting a balancing of 50 ± 5% (CMRR = 20 dB) as a conservative limit, an operating range of $\Delta\lambda_0 \approx 90$ nm is found. Taking into account that the hybrid can be used for $\lambda_0 > 1.572$ μm, the actual usable spectral operating range is even larger than 90 nm.

The polarization extinction ratio varies between 25–42 dB at the target wavelength, and is better than 20 dB for the entire wavelength range of 108 nm. Differences between the extinction ratios, as shown in Fig. 3 and as listed in Table II, are caused by differences in linewidth between the HP8168A tunable laser and the Fabry–Pérot laser, respectively. The differences and similarities between the measured polarization extinction curves are in agreement with the polarization properties of the coatings as discussed in Section II-D, notably the large (reduced) extinction ratios of the transmitted (reflected) beams of the PS coating and the improved polarization extinction ratios for the transmitted beam of the $BS_\parallel$ coating and the reflected beam of the $BS_\perp$ coating. It is thus seen that the consistently large polarization extinction ratio of all outputs is a combined effect of using several PS coatings in series and of the polarizing effects of the 50% beam splitters.

E. Temperature Sensitivity

Temperature sensitivity was evaluated by placing the polarization diversity hybrid on two Peltier elements. No change in performance could be measured in a temperature range from room temperature (20°) up to 75°, which is indicative for the stability of the micro-optical hybrid (coatings and cement) and of the packaging. It is the complete invariance of the performance of the hybrid with respect to translations along all three axes which leads to the robust performance of the packaged hybrid. For temperatures considerably below room temperature, transmission properties are affected (though not permanently) by condensation of water vapor on the hybrid. Condensation problems can, of course, be easily avoided by a hermetic sealing of the hybrid in an N_2 environment using laser welding.

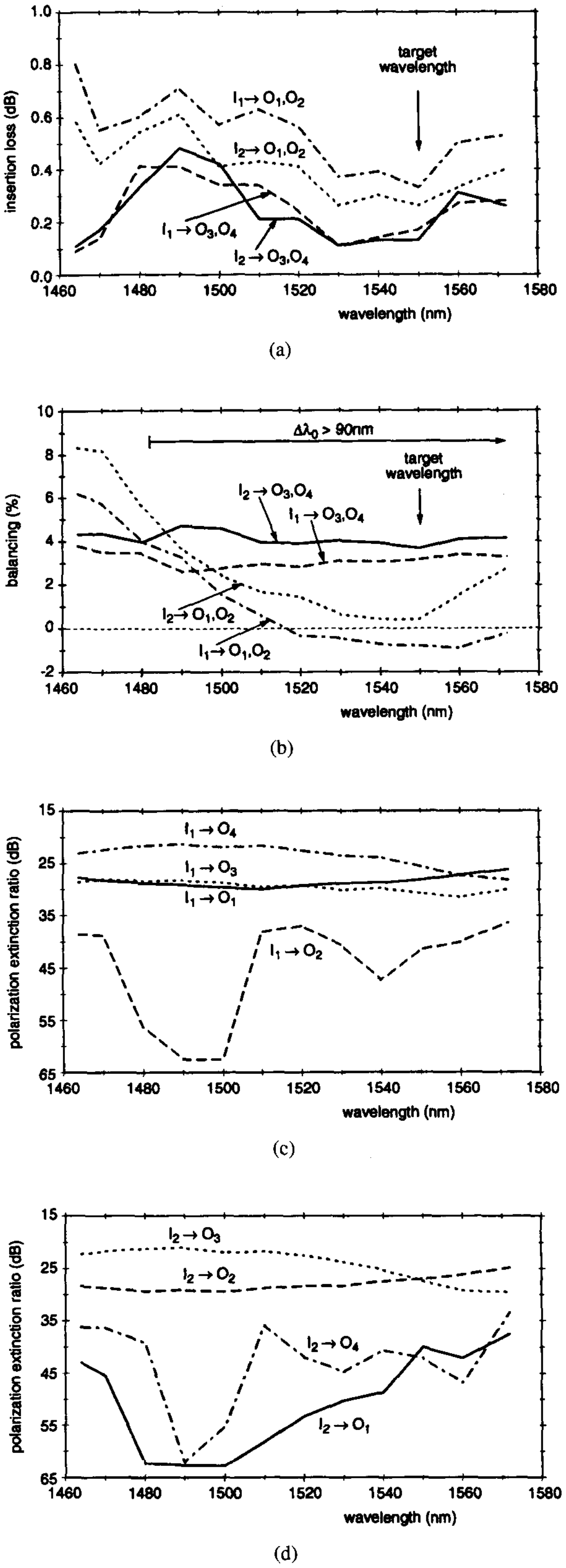

Fig. 3. Performance of packaged polarization diversity hybrid (BM-version) as a function wavelength; (a) insertion loss, (b) balancing (a balancing of 5% corresponds to a splitting ratio of 55%/45% and to a common mode rejection ratio of 20 dB), (c) polarization extinction ratio for input I_1, and (d) polarization extinction ratio for input I_2.

V. SYSTEM RESULTS

The packaged micro-optical hybrid was tested in a coherent polarization diversity CPFSK transmission experiment, which operated at a bit rate of 2.5 Gbt/s and a wavelength $\lambda_0 = 1.552$ μm. Philips' three-section DBR lasers were used both as signal

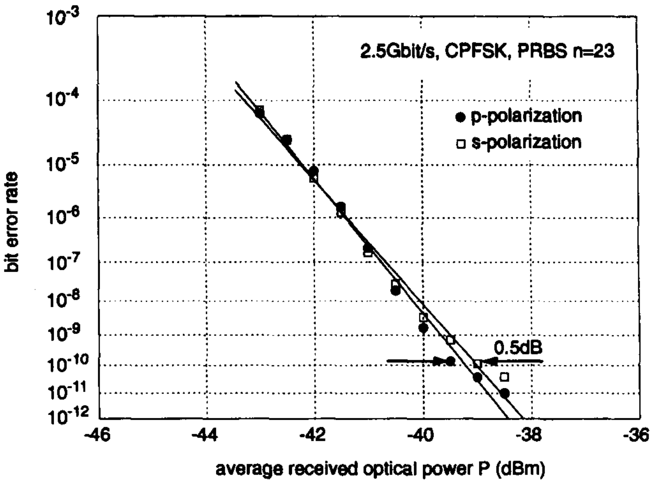

Fig. 4. Bit error rate measurements for two orthogonal polarizations.

and local oscillator laser. The lasers have a tuning range of 6 nm and show nearly wavelength-independent output power and linewidth of 28 mW ex facet and 5 MHz, respectively [22]. Using electrical equalization, a flat FM response was obtained from 10 kHz up to 3 GHz (within ±1.5 dB). A novel detection scheme was employed which consisted of a balanced delay-line frequency discriminator with an electrical 90°-coupler and which resulted in a very low IF frequency of only 2 GHz (i.e., lower than the bit rate) [21]. This detection scheme offers the additional advantage of compatibility with dispersion equalization in the electrical domain.

Fig. 4 shows the bit error rate (BER) measurements for p- and s-polarizations, respectively. The receiver sensitivity P equals -39.5 dBm for a $2^{23}-1$ pseudo-random bit pattern, which is equivalent to $\eta P = -42$ dBm when correcting for the quantum efficiency η of the photodiodes. A maximum polarization dependence of the receiver sensitivity of only 0.5 dB was measured at a BER of 1×10^{-10}. Two fully engineered coherent transmission links incorporating a micro-optical polarization-diversity hybrid were built for use in a laboratory demonstration of an SDH compatible optical cross-connect [1]. The polarization-diversity hybrids have functioned reliably in these receivers for over a year.

VI. CONCLUSION

In this paper, we have reported a novel approach to fabricate a micro-optical polarization diversity hybrid consisting of highly parallel glass plates with multiple dielectric coatings. No critical angles or alignments are required during fabrication; this not only affects the fabrication tolerances, but also packaging, tolerances to operational parameters and robustness. Two different high-performance polarization diversity hybrids were fabricated; for the BM-version, average fiber-to-fiber loss is 0.7 dB, polarization extinction ratios are better than 25 dB, and balancing is 50 ±3%. Reflection is lower than -58 dB and a usable spectral operating range in excess of 90 nm was measured. The novel design is very general and can be applied to a wide range of optical devices.

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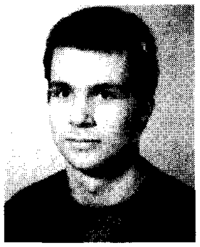

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