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

Erik C. M. Pennings, Member, IEEE, Dolf Schouten, Giok-djan Khoe, Fellow, IEEE, René A. J. C. M. van Gils, and Geert F. G. Depovere

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 Gbit/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 insertion 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 (<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
employs a nonpolarizing 50% beam splitter followed by two polarization coatings, all in- and output beams become parallel and equidistant, thereby increasing alignment tolerances.

This led to the observation that a fabrication-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 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–Perot 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 1.001² - 0.999² ≈ -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 ∆L and the free spectral range ∆λ₀ of the interferometer are interrelated by

<table>
<thead>
<tr>
<th>Coating</th>
<th>AR</th>
<th>AR/TT</th>
<th>AL (&gt;)2.5%</th>
<th>AR&lt;1%</th>
<th>AR&lt;0.3%</th>
<th>AR&lt;0.1%</th>
<th>AR&lt;0.03%</th>
<th>AR&lt;0.01%</th>
<th>AR&lt;0.005%</th>
</tr>
</thead>
</table>
| Glass-Air | No | No | 8% | 95% | 99% | 99.5% | 99.9% | 99.95% | 99.99%
| Glass-Cement | No | No | 4% | 99% | 99.9% | 99.95% | 99.99% | 99.995% | 99.999%
| Glass-Glass | No | No | 4% | 99% | 99.9% | 99.95% | 99.99% | 99.995% | 99.999%

The most critical coating is the NPBS coating, for which 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. 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 1.001² - 0.999² ≈ -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 ∆L and the free spectral range ∆λ₀ of the interferometer are interrelated by

\[ \Delta \lambda_0 \approx \frac{\lambda_0^2}{n \Delta L} \]

a very large value of ∆λ₀ ≈ 63 nm is found when taking ∆L = 25 μm, meaning that FM-to-AM conversion efficiency is negligible.

D. Optical Design

Coatings were specially designed for optimum performance at λ₀ = 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
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). Whereas the polarization splitting coatings have a very pure transmitted beam (polarization extinction ratio). Whereas the polarization splitting coatings have a very pure transmitted beam (polarization extinction ratio). Whereas the polarization splitting coatings have a very pure transmitted beam (polarization extinction ratio).

### Table I

| Coating   | $R_1$ (%) | $T_1$ (%) | $R_2$ (%) | $T_2$ (%) | $|\Delta \lambda_0|$ (nm) |
|-----------|-----------|-----------|-----------|-----------|-----------------|
| Mirror    | 100       | ~ 0       | 98        | 2         | 110             |
| PS        | 100       | ~ 0.1     | 1 ~ 3     | 99 ~ 97   | 360             |
| BS$_{p-pol}$ | >99       | <1        | 49        | 51        | 80              |
| BS$_{s-pol}$ | 48        | 52        | <3        | >97       | 300             |
| NPBS      | 47        | 53        | 53        | 47        | 45              |

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 2$w_0 = 0.33$ 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 ×
with cover removed.

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

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

<table>
<thead>
<tr>
<th>Port</th>
<th>O₁</th>
<th>O₂</th>
<th>O₃</th>
<th>O₄</th>
<th>Ins. Loss</th>
<th>Balance</th>
</tr>
</thead>
<tbody>
<tr>
<td>l₁</td>
<td>p-pol.</td>
<td>45.3%</td>
<td>42.0%</td>
<td>0.08%</td>
<td>0.18%</td>
<td>0.58dB</td>
</tr>
<tr>
<td></td>
<td>s-pol.</td>
<td>0.12%</td>
<td>0.05%</td>
<td>43.4%</td>
<td>49.4%</td>
<td>0.92dB</td>
</tr>
<tr>
<td>Ext. Ratio</td>
<td>25.8dB</td>
<td>20.5dB</td>
<td>27.6dB</td>
<td>24.5dB</td>
<td></td>
<td></td>
</tr>
<tr>
<td>l₂</td>
<td>p-pol.</td>
<td>49.8%</td>
<td>45.7%</td>
<td>0.14%</td>
<td>0.15%</td>
<td>0.50dB</td>
</tr>
<tr>
<td></td>
<td>s-pol.</td>
<td>0.06%</td>
<td>0.15%</td>
<td>51.8%</td>
<td>42.5%</td>
<td>0.25dB</td>
</tr>
<tr>
<td>Ext. Ratio</td>
<td>29.1dB</td>
<td>24.7dB</td>
<td>25.6dB</td>
<td>25.6dB</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

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

<table>
<thead>
<tr>
<th>Port</th>
<th>O₁</th>
<th>O₂</th>
<th>O₃</th>
<th>O₄</th>
<th>Ins. Loss</th>
<th>Balance</th>
</tr>
</thead>
<tbody>
<tr>
<td>l₁</td>
<td>p-pol.</td>
<td>37.7%</td>
<td>47.6%</td>
<td>0.10%</td>
<td>0.17%</td>
<td>0.69dB</td>
</tr>
<tr>
<td></td>
<td>s-pol.</td>
<td>0.17%</td>
<td>0.14%</td>
<td>42.5%</td>
<td>38.8%</td>
<td>0.90dB</td>
</tr>
<tr>
<td>Ext. Ratio</td>
<td>23.6dB</td>
<td>25.4dB</td>
<td>26.9dB</td>
<td>23.6dB</td>
<td></td>
<td></td>
</tr>
<tr>
<td>l₂</td>
<td>p-pol.</td>
<td>51.0%</td>
<td>39.5%</td>
<td>0.23%</td>
<td>0.13%</td>
<td>0.44dB</td>
</tr>
<tr>
<td></td>
<td>s-pol.</td>
<td>0.17%</td>
<td>0.14%</td>
<td>35.4%</td>
<td>49.5%</td>
<td>0.71dB</td>
</tr>
<tr>
<td>Ext. Ratio</td>
<td>24.8dB</td>
<td>24.6dB</td>
<td>21.8dB</td>
<td>25.8dB</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

9 mm³ 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-Perot laser (λ₀ = 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

\[
CMRR = -20 \log \left( \frac{P(O₁) - P(O₂)}{P(O₁) + P(O₂)} \right)
\]

with \(P(O₁)\) denoting the optical power at output O₁ and where a similar relation holds for the O₃ and O₄ outputs [17]. For the BM-version, balancing for the O₁/O₂ ports (p-pol.) is better than for the O₃/O₄ ports (s-pol.), which is independently determined by the quality of the BS₁ and BS₂ 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.

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 I₂ → O₄ 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 O₄ 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 O₃ and O₄ 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 O₃ output. No reflection was measured for any other port, including the two input ports, indicating \(|r|^2 < −60\, \text{dB}\), 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_{⊥} 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 Δλ_{0} ≈ 90 nm is found. Taking into account that the hybrid can be used for λ_{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_{∥} coating and the reflected beam of the BS_{⊥} 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 N₂ environment using laser welding.

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 Gbit/s and a wavelength λ_{0} = 1.552 μm. Philips’ three-section DBR lasers were used both as signal
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 28 mW ex facet and 5 MHz, respectively.

Fig. 4 shows the bit error rate (BER) measurements for p- and s-polarizations, respectively. The receiver sensitivity equals -39.5 dBm for a 223−1 pseudo-random bit pattern, which is equivalent to ηP = -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.
Erik C. M. Pennings (S’88–M’90) was born in Sassenheim, The Netherlands, on November 3, 1960. He received the M.Sc. degree (cum laude) in applied physics from Groningen University in 1986, and the Ph.D. degree in electrical engineering from Delft University of Technology, The Netherlands, in 1990. His thesis describes modeling and experiments on bends in optical waveguides and on multimode interference couplers.

He subsequently joined Bell Communications Research in Red Bank, NJ, as a Post-Doctoral Member of Technical Staff, where he worked on InP-based photonic integrated circuits. In 1992, he joined the group Wideband Communication Systems of Philips Research Laboratories, Eindhoven, The Netherlands, where he developed micro-optical components for high bit rate optical communication systems. From 1994–1995, he participated in a multimedia strategy project located in Redhill, UK. In 1995, he joined the Philips Optoelectronics Centre, Eindhoven, the Netherlands, where his responsibilities include the business development of advanced products such as micro-optical components, tunable lasers, semiconductor laser amplifiers, and WDM components. He has written and coauthored more than 50 scientific papers and conference contributions, six invited papers, and holds several patents.

Dr. Pennings is a member of the Dutch Physical Society (NNV) and the OSA.

Dolf Schouten was born in Ulft, the Netherlands, in 1968. He studied electrical engineering at the Poly-Technic in Enschede, the Netherlands, where he graduated in 1991. He subsequently joined Philips Research Laboratories in Eindhoven, where he has been actively involved in the design of several optical components, such as a polarization diversity hybrid and a polarization controller. This research forms part of the European RACE project R2065, COBRA.

Giok-djan Khoe (S’71–M’71–SM’85–F’91) was born in Magelang, Indonesia, on July 22, 1946. He received the degree of Elektrotechnisch Ingenieur (cum laude) from the Eindhoven University of Technology, Eindhoven, The Netherlands, in 1971. He worked at the FOM Institute of Plasma Physics, Rijnhuizen, The Netherlands, on laser diagnostics of plasmas from 1971–1972. In 1973, he joined Philips Research Laboratories and, in addition, he was appointed as part time Professor at the Eindhoven University of Technology in 1983. He became a full Professor at the same University in 1994. His work has been devoted to single-mode fiber systems and components. He has 40 United States Patents, has authored and coauthored more than 60 papers, invited papers, and books.

Mr. Khoe has served on technical committees of conferences and editorial boards of journals, as a member, associate, or as chairman. He is closely involved in European Community research programs and Dutch national research programs, as participant, evaluator, and program committee member.

René A. J. C. M. van Gils was born in Tilburg, The Netherlands, in 1967. In 1990, he graduated from the Eindhoven University of Technology, working on optical pseudo-homodyne CPFSK systems. After military service, he joined Philips Research in 1992. Since then, he has been working on optical coherent communication systems. Presently, his main activities includes systems and electronics design of optical cross-connects within the European RACE COBRA R2065 project.

Geert F. G. Depovere was born in Roeselare, Belgium, on March 26, 1965. He received the M.Sc. and Ph.D. degrees in electrical engineering from the University of Gent, Belgium, in 1988 and 1992, respectively. His thesis describes optical fiber measurement systems and includes experimental as well as theoretical work on coherent and subcarrier multiplexed optical communication systems.

He joined the Philips Research Laboratories, Eindhoven, The Netherlands, in 1992. Since then, he has been working in the field of high-bitrate coherent multichannel systems and broadband optical network architectures in the group Wideband Communication Systems. His present activities include the coordination of the RENO demonstrator within the RACE COBRA R2065 project.