

Monolithic Polarization and Phase Diversity Coherent Receiver in Silicon

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Abstract—In this paper, we realized a monolithic silicon photonic integrated circuit (PIC) for polarization and phase diversity coherent detection. The PIC includes two polarization beam splitters, two 90° optical hybrids, and four pairs of balanced photodiodes implemented as integrated germanium detectors. We tested the PIC using polarization-division multiplexed quadrature phase-shift keyed signals at 43 and at 112 Gb/s.

Index Terms—Crystals, germanium, gratings, integrated optics, integrated optoelectronics, silicon.

I. INTRODUCTION

COHERENT detection converts the amplitude, phase, and polarization of an optical signal into the electrical domain, offering high sensitivity, high spectral efficiency, and the possibility of electronic compensation of signal impairments [1]–[4]. However, a coherent receiver requires many individual optical and optoelectronic components, including two polarization beam splitters, two 90° optical hybrids, and eight photodetectors (PDs) for its preferable implementation using balanced detection. Balanced detection requires accurately matched insertion losses and path lengths in many of the intercomponent connections. Because of this complexity, today's coherent receivers often use only single-ended detection. The drawbacks of single-ended detection are that the local oscillator (LO) power must be at least ~15-dB higher than the signal, the LO laser intensity noise must be low, and the signal dynamic range is small [5]–[7].

Monolithic integration of the entire coherent receiver in a photonic integrated circuit (PIC) miniaturizes the optoelectronic front end. Furthermore, lithographic connections facilitate path-length matching and balancing, so the superior performance of

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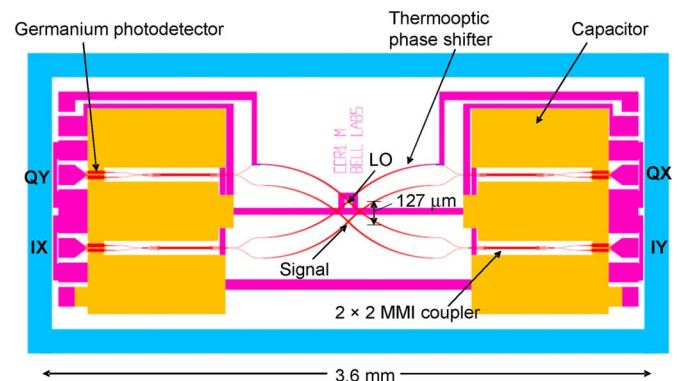


Fig. 1. Layout of the coherent receiver PIC. Chip size is $3.6 \times 1.6 \text{ mm}^2$. “Signal” and “LO” point to the two grating couplers.

balanced detection is readily obtained. Compared to hybrid integration, PICs can significantly reduce the size and packaging cost of optical communication modules [8].

Regarding coherent receivers, there were demonstrations of monolithic single-polarization, single-quadrature PICs [9], [10] and a monolithic dual-polarization, single-quadrature PIC [11] about 20 years ago. Recently, with the resurgence of interest in coherent detection, a monolithic single-polarization dual-quadrature PIC was reported [12]. In this paper, we further characterize a monolithic dual-polarization, dual-quadrature PIC [13]. This PIC is made using silicon-on-insulator waveguides with integrated germanium PDs.

II. DESIGN AND FABRICATION

The layout of the silicon PIC is shown in Fig. 1. The waveguides are 220-nm-high crystalline silicon strips with $\sim 2 \mu\text{m}$ of oxide upper cladding and $2.0 \mu\text{m}$ of oxide lower cladding on a silicon substrate. The signal and LO enter the chip vertically through two grating couplers.

A. Grating Couplers

A grating coupler is a photonic crystal that couples a wave traveling normal to a substrate to a wave guided parallel to the substrate [14]. A closeup of one of the couplers is shown in Fig. 2. It consists of a 2-D photonic crystal with a lattice period equal to the wavelength for the transverse-electric (TE) mode in the silicon waveguide (590 nm) and hole etch depth of 90 nm. Light that impinges on the grating from the vertical direction is scattered and phase-matched to travel in the plane of the substrate in a certain direction at the design wavelength and polarization.

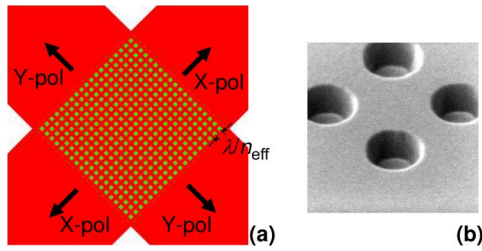


Fig. 2. Closeup of one of the grating couplers. (a) Layout and (b) scanning electron microscope (SEM) image of some of the holes. λ is the free-space wavelength of interest, and n_{eff} is the waveguide effective index for TE-polarized light.

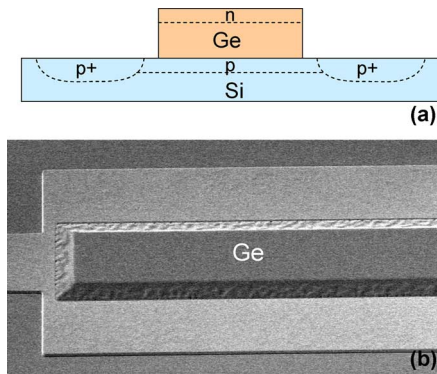


Fig. 3. Details of the PD: (a) cross section schematic and (b) SEM image of top view.

Each grating coupler acts simultaneously as a fiber coupler with an integrated spot-size converter, a polarization splitter [15], and two 50/50 splitters. Usually grating couplers are used with the fiber at an angle so that each polarization couples to only one waveguide in the wavelength region of interest. In this paper, we orient the fiber exactly perpendicular to the substrate so that each grating coupler has the novel added use of serving as two of the 50/50 couplers in our coherent receiver. Also, by orienting the fiber with zero angle to the normal, we ensure that all polarizations in the fiber have the same coupling efficiency, thus minimizing the polarization-dependent loss [16], [17]. The small second-order in-plane reflection associated with a zero-angle fiber orientation [15] does not cause a significant problem here because the back reflection from the integrated Ge photodetectors is negligible and thus no unwanted Fabry–Perot interferometer is created. Although the intended shape of the holes is square, the holes are nearly circular after lithography. Fig. 2(b) shows the holes after etching. There may be unwanted scattering of light from circular holes into the $\pm 90^\circ$ directions in plane from the propagation direction, as was used to create a 2-D photonic crystal laser [18].

There is one grating coupler for the signal and one for the LO. They are spaced by the commercial fiber array pitch of $127 \mu\text{m}$.

B. Photodetectors

The germanium evanescently coupled waveguide PDs are $8 \mu\text{m} \times 100 \mu\text{m}$ and are grown on top of the silicon core with n doping in the Ge on top and p doping in the Si underneath the Ge and to the sides as described in [19] and shown in Fig. 3. The Ge thickness is 500 nm.

The Ge growth details are as follows. Prior to the Ge epitaxy, the wafers were passivated with 60 nm of SiO_2 . Windows for selective epitaxial growth were then defined via plasma partial etching followed by dilute HF etching to expose the Si surface. Substrate cleaning prior to epitaxy comprises 5 min in SC-1 (1 : 1 : 5 solution of $\text{NH}_4\text{OH} + \text{H}_2\text{O}_2 + \text{H}_2\text{O}$) followed by 2 min in dilute HF (1 : 200). Rinsing in deionized water was carried out after each cleaning step. The Ge epitaxy growth started with an *in situ* baking in N_2 ambient at 800°C for native oxide removal. This was followed by the deposition of a thin Si buffer ($\sim 5 \text{ nm}$) at 530°C . A thin $\text{Si}_{0.8}\text{Ge}_{0.2}$ layer was then deposited, so as to have a gradual transition from pure Si to pure Ge at the interface. A Ge seed layer (30 nm) was grown at a low temperature of 370°C before Ge growth (500 nm) at a higher temperature of 550°C . Precursor gases of pure disilane Si_2H_6 and diluted germane GeH_4 (10% GeH_4 : 90% Ar) were used for the epitaxial growth of SiGe and Ge layers. The Ge layer was doped via ion implantation followed by dopant activation at 500°C for 5 min. Two levels of Al were used for interconnection.

Integration of the Ge photodetectors must be performed after the high temperature Si processes have been completed, such as the implant activation for Si. On the other hand, the thermal budget impact due to the integration of Ge photodetectors has to be low so that its effect on other active components on the Si is minimized. Hence, a low thermal budget Ge growth process had to be developed. Except for a brief *in situ* baking step at 800°C , the rest of the process steps were of a much lower thermal budget, with the main Ge growth process step being performed at 550°C .

The eight PDs are arranged in four pairs. The PDs in each pair are connected in series, with the n contact of one connected to the p contact of the other. All of the pairs are connected to the same two bias connections. These bias connections have on-chip capacitors which connect to the high-speed ground pads.

C. Thermo-Optic Phase Shifters

There is a thin metal strip on the oxide over a waveguide on two of the grating coupler output waveguides. Current can be sent through these metal strips to act as thermo-optic phase shifters to adjust the phases in the 90° hybrids.

D. Principle of Operation

The principle of operation is illustrated in Fig. 4. The signal enters in an arbitrary polarization, and the LO enters in a polarization parallel to one of the chip facets. Using the basis set of linear polarizations oriented 45° to the chip facets, the signal and LO are divided into “X” and “Y” polarizations. Once coupled in, all of the light on the chip is TE polarized, but the X polarization propagates along one diagonal and the Y polarization along the other. The four signal and four LO portions from the grating couplers pass through eight waveguides of equal path length and are interfered in four 2×2 multimode interference (MMI) couplers. The outputs of the MMI couplers proceed to the four germanium PD pairs.

For example, in the upper diagram of Fig. 4(a), one sees that the X polarization portions of the signal and LO follow the lower left to upper right diagonal. The portions traveling

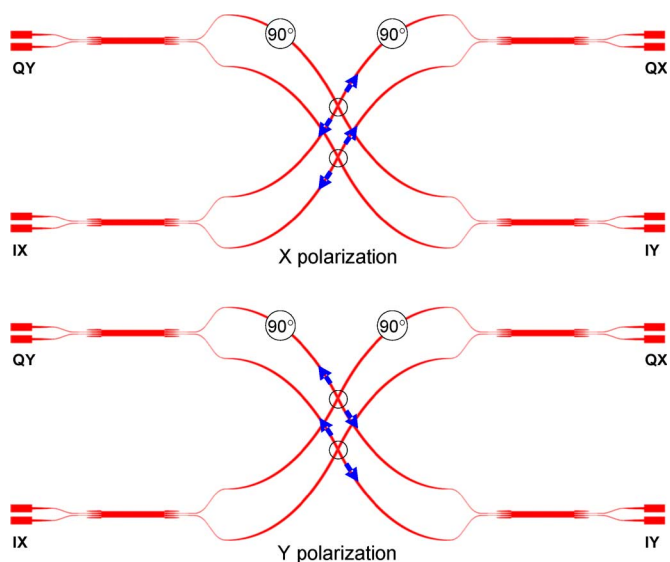


Fig. 4. Operating principle of the coherent receiver. The two small circles indicate the entrance points of the signal and LO (it does not matter which is for which). The upper and lower figures indicate operation for the “X” and “Y” polarizations (which are 45° polarized in this case), respectively.

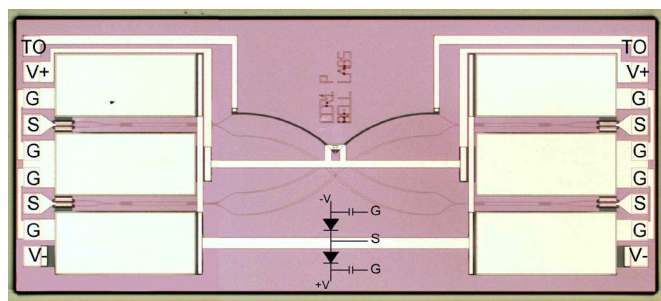


Fig. 5. Photograph of the PIC. The electrical connections are indicated. “S” = signal and “G” = ground.

toward the lower left have the same phase when they interfere in their MMI coupler and thus produce the in-phase X -polarization component “IX.” The portions traveling toward the upper right have a 90° phase difference, as set by one of the thermo-optic phase shifters, when they interfere in their MMI coupler and thus produce the quadrature X -polarization component “QX.” The operation is likewise for the Y polarization but along the upper left to lower right diagonal.

E. Complete PIC

The PIC was made on an 8'' silicon wafer using a research-and-development complementary metal–oxide–semiconductor (CMOS) commercial foundry using stepper lithography. Deep ultraviolet lithography (248 nm) and plasma etching were used to define the optical structures. No additional process steps were used to improve the surface roughness of the waveguides. The processes were selected with manufacturability in mind. The finished PIC is shown in Fig. 5.

III. DEVICE RESULTS

The dark current at -1 V for each PD is ~ 100 nA. Although this is more than 100 times that of a typical InGaAs/InP PD, it is

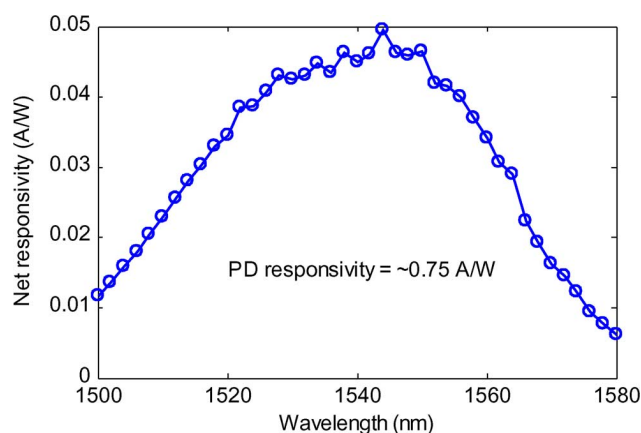


Fig. 6. Measured fiber-to-PD responsivity versus wavelength. This value includes the inherent 6-dB splitting loss of the 90° hybrid.

TABLE I
ESTIMATED INSERTION LOSS BREAKDOWN

Component	Estimated insertion loss
Grating coupler	4 dB
Waveguide propagation	1 dB
2 × 2 MMI coupler	1 dB
PD responsivity	2 dB
Total	8 dB

low enough for a coherent receiver, where typical average photocurrents are 1 mA or higher. The waveguide-to-PD responsivity is ~ 0.75 A/W. The PD 3-dB bandwidth with a 50-Ω load is ~ 5 GHz, limited by high junction capacitance, estimated to be ~ 480 fF. This could be improved by reducing the PD size. It is predicted that the length could be shortened by more than half without sacrificing responsivity. For the experiment, we used terminated 50-Ω probes, and thus the load is 25 Ω. However, because each PD pair has two diodes connected in series, the capacitance is doubled and thus the bandwidth is still ~ 5 GHz.

We coupled to the top of the PIC using a standard nonangled fiber v-groove array, with index-matching oil between the fiber and the PIC. The responsivity from the fiber to any PD versus wavelength is shown in Fig. 6. The wavelength dependence is due to the grating couplers; the 3-dB bandwidth is 54 nm. The overall responsivity includes the inherent 6-dB splitting loss of the 90° hybrids, so the excess loss at 1544 nm from fiber to photocurrent is 8 dB (the ideal responsivity is 1.25 A/W). This is 1 dB better than reported in [13], because we did not use index-matching oil in that previous experiment. The roughly estimated loss breakdown is shown in Table I. This reported grating coupler efficiency is when the fiber coupling is optimized for one polarization. When optimizing for both polarizations simultaneously, there is an additional ~ 3 -dB insertion loss due to the fact that the grating is not apodized [20]. This is because a nonapodized grating gives an exponentially shaped optical field, and thus the optimum position for coupling to any particular output waveguide is not in the center of the grating coupler in a nonapodized grating.

We observed some dependence of the hybrid phase on the signal or local oscillator polarization. This may be due to some coupling from the fiber to the transverse magnetic polarization in the waveguides.

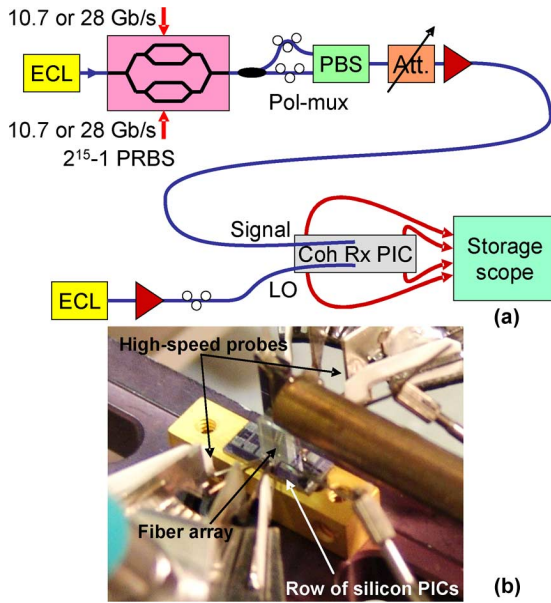


Fig. 7. Experimental setup.

IV. SYSTEM CHARACTERIZATION

We tested the system performance of the PIC by launching a 43-Gb/s polarization-division multiplexed (PDM) quadrature phase-shift-keyed (QPSK) signal with in-phase (I) and quadrature (Q) components consisting of delayed copies of a $2^{15}-1$ -long pseudorandom bit sequence (PRBS) into the signal port and continuous-wave light into the LO port, both at 1547 nm, as shown in Fig. 7(a). Both signal and LO lasers were external cavity lasers with ~ 100 -kHz linewidths. We set the LO polarization to make the LO power split in equal portions for the X - and Y -polarizations on the chip. We used two 50- Ω terminated dual ground-signal-ground probes and connected them to a real-time oscilloscope. We applied ± 1.3 V to the PD bias connections. We drove the two thermo-optic phase shifters with ~ 2 and ~ 4 V, respectively, to achieve the proper phases for the 90° hybrids. By comparing the received signal with and without the LO present, we measured the common-mode rejection ratio of the balanced detection to be ~ 10 dB over all frequencies of interest.

We recorded traces with 10^6 samples at 50 GSamples/s and a nominal 8-b resolution (the effective resolution is ~ 5 b). We processed the data offline to recover the symbol constellations and calculate the bit error rate (BER). We used the constant modulus algorithm (CMA) in a butterfly structure for blind adaptive equalization and source separation and standard algorithms for the frequency and phase estimation [3]. The impulse response of each of the four butterfly subfilters spanned eight symbols. We used differential decoding to avoid cycle slips.

The 43-Gb/s results are shown in Fig. 8. We achieved a BER of 10^{-3} at 12.4 dB optical signal-to-noise ratio (OSNR). This performance is 1.6 dB from reported receivers using discrete components [4] and ~ 2.7 dB from the theoretical limit.

We repeated the experiment but this time at 112 Gb/s and 1550.12 nm. Despite the fact that the limited PD bandwidth severely limited the performance (the symbol rate is 28 GHz, yet the PD bandwidth is 5 GHz), at full OSNR we recovered

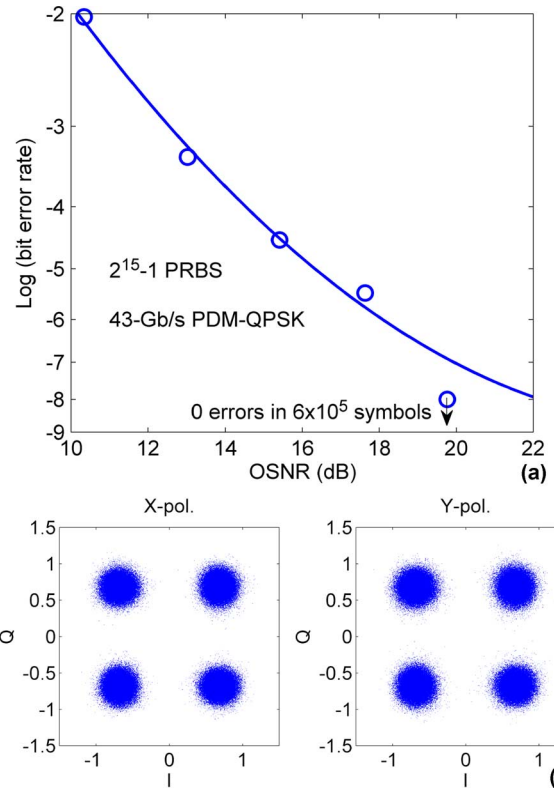
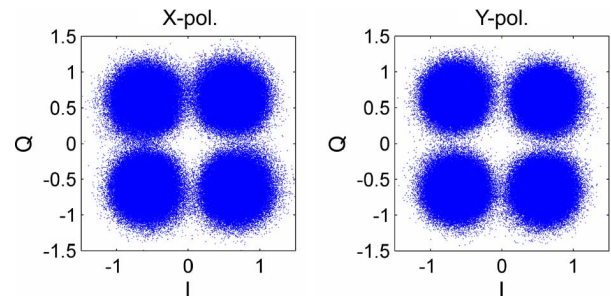


Fig. 8. Results at 43 Gb/s. OSNR bandwidth is 0.1 nm. Constellations in (b) taken at an OSNR of 22 dB.

Fig. 9. Results at 112 Gb/s. BER is 1.7×10^{-3} . OSNR is greater than 30 dB.

the signal constellations shown in Fig. 9. This indicates that the frequency roll-off of the PD response is gradual and so can be somewhat compensated for digitally.

V. CONCLUSION

We proposed and realized a monolithic polarization and phase diversity coherent receiver in silicon and tested it at 43 and 112 Gb/s. Because it is made in silicon it can be made on large wafers with similar equipment used for high volume electronics, favoring low cost. It could eventually be monolithically integrated with CMOS transistor circuits, such as linear transimpedance amplifiers, which benefit from a short distance between the PD and the transistors.

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REFERENCES

- [1] T. Okoshi and K. Kikuchi, *Coherent Optical Fiber Communications*. Boston, MA: Kluwer, 1988.
- [2] F. Derr, "Coherent optical QPSK intradyne system concept and digital receiver realization," *J. Lightw. Technol.*, vol. 10, no. 9, pp. 1290–1296, Sep. 1992.
- [3] A. Leven, N. Kaneda, U.-V. Koc, and Y.-K. Chen, "Coherent receivers for practical optical communication systems," presented at the Opt. Fiber Commun. Conf., Anaheim, CA, 2007, OThK4.
- [4] H. Sun, K.-T. Wu, and K. Roberts, "Real-time measurements of a 40 Gb/s coherent system," *Opt. Exp.*, vol. 16, pp. 873–879, 2008.
- [5] S. Yamashita and T. Okoshi, "Suppression of common-mode beat noise from optical amplifiers using a balanced receiver," *Electron. Lett.*, vol. 28, pp. 1970–1972, Oct. 1992.
- [6] S. Ryu and Y. Horiuchi, "Use of an optical amplifier in a coherent receiver," *IEEE Photon. Technol. Lett.*, vol. 3, no. 7, pp. 663–665, Jul. 1991.
- [7] A. Carena, V. Curri, P. Poggiolini, and F. Forghieri, "Dynamic range of single-ended detection receivers for 100GE coherent PM-QPSK," *IEEE Photon. Technol. Lett.*, vol. 20, no. 15, pp. 1281–1283, Aug. 2008.
- [8] R. Nagarajan, C. H. Joyner, R. P. Schneider, Jr., J. S. Bostak, T. Butrie, A. G. Dentai, V. G. Dominic, P. W. Evans, M. Kato, M. Kauffman, D. J. H. Lambert, S. K. Mathis, A. Mathur, R. H. Miles, M. L. Mitchell, M. J. Missey, S. Murthy, A. C. Nilsson, F. H. Peters, S. C. Pennypacker, J. L. Pleumeekers, R. A. Salvatore, R. K. Schlenker, R. B. Taylor, H.-S. Tsai, M. F. Van Leeuwen, J. Webjorn, M. Ziari, D. Perkins, J. Singh, S. G. Grubb, M. S. Reffle, D. G. Mehuys, F. A. Kish, and D. F. Welch, "Large-scale photonic integrated circuits," *J. Sel. Topics Quantum Electron.*, vol. 11, no. 1, pp. 50–65, Jan.–Feb. 2005.
- [9] H. Takeuchi, K. Kasaya, Y. Kondo, H. Yasaka, K. Oe, and Y. Imamura, "Monolithic integrated coherent receiver on InP substrate," *IEEE Photon. Technol. Lett.*, vol. 1, no. 11, pp. 398–400, Nov. 1989.
- [10] T. L. Koch, U. Koren, R. P. Gnall, F. S. Choa, F. Hernandez-Gil, C. A. Burrus, M. G. Young, M. Oron, and B. I. Miller, "GaInAs/GaInAsP multiple-quantum-well integrated heterodyne receiver," *Electron. Lett.*, vol. 25, pp. 1621–1623, 1989.
- [11] R. J. Deri, E. C. M. Pennings, A. Scherer, A. S. Gozdz, C. Caneau, N. C. Andreadakis, V. Shah, L. Curtis, R. J. Hawkins, J. B. D. Soole, and J.-I. Song, "Ultracompact monolithic integration of balanced, polarization diversity photodetectors for coherent lightwave receivers," *IEEE Photon. Technol. Lett.*, vol. 4, no. 11, pp. 1238–1240, Nov. 1992.
- [12] H.-G. Bach, A. Matiss, C. C. Leonhardt, R. Kunkel, D. Schmidt, M. Schell, and A. Umbach, "Monolithic 90° hybrid with balanced PIN photodiodes for 100 Gbit/s PM-QPSK receiver applications," presented at the Opt. Fiber Commun. Conf., San Diego, CA, 2009, OMK5.
- [13] C. R. Doerr, P. J. Winzer, S. Chandrasekhar, M. Rasras, M. Earnshaw, J. Weiner, D. M. Gill, and Y. K. Chen, "Monolithic silicon coherent receiver," presented at the Opt. Fiber Commun. Conf., San Diego, CA, 2009, PDPB2.
- [14] T. Tamir, "Beam and waveguide couplers," in *Integrated Optics*. New York: Springer-Verlag.
- [15] D. Taillaert, H. Chong, P. I. Borel, L. H. Frandsen, R. M. De La Rue, and R. Baets, "A compact two-dimensional grating coupler used as a polarization splitter," *IEEE Photon. Technol. Lett.*, vol. 15, no. 9, pp. 1249–1251, Sep. 2003.
- [16] F. Van Laere, W. Bogaerts, P. Dumon, G. Roelkens, D. Van Thourhout, and R. Baets, "Focusing polarization diversity grating couplers in silicon-on-insulator," *J. Lightw. Technol.*, vol. 27, no. 23, pp. 612–618, Mar. 2009.
- [17] F. Van Laere, T. Stomeo, C. Cambournac, M. Ayre, R. Brenot, H. Benisty, G. Roelkens, T. F. Krauss, D. Van Thourhout, and R. Baets, "Nanophotonic polarization diversity demultiplexer chip," *J. Lightw. Technol.*, vol. 27, no. 4, pp. 417–425, Feb. 2009.
- [18] D. Ohnishi, T. Okano, M. Imada, and S. Noda, "Room temperature continuous wave operation of a surface-emitting two-dimensional photonic crystal diode laser," *Opt. Exp.*, vol. 12, pp. 1562–1568, 2004.
- [19] J. Wang, W. Y. Loh, K. T. Chua, H. Zang, Y. Z. Xiong, T. H. Loh, M. B. Yu, S. J. Lee, G.-Q. Lo, and D.-L. Kwong, "Evanescent-coupled Ge p-i-n photodetectors on Si-waveguide with SEG-Ge and comparative study of lateral and vertical p-i-n configurations," *IEEE Electron Device Lett.*, vol. 29, no. 5, pp. 445–448, May 2008.
- [20] W. Bogaerts, D. Taillaert, P. Dumon, D. Van Thourhout, R. Baets, and E. Pluk, "A polarization-diversity wavelength duplexer circuit in silicon-on-insulator photonic wires," *Opt. Exp.*, vol. 15, pp. 1567–1578, Feb. 2007.



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