Ultracompact 100 Gbps coherent receiver monolithically integrated on silicon

This content has been downloaded from IOPscience. Please scroll down to see the full text.
2016 Jpn. J. Appl. Phys. 55 04EC04
(http://iopscience.iop.org/1347-4065/55/4S/04EC04)

View the table of contents for this issue, or go to the journal homepage for more

Download details:

IP Address: 162.105.81.109
This content was downloaded on 30/03/2016 at 02:57

Please note that terms and conditions apply.
Ultracompact 100 Gbps coherent receiver monolithically integrated on silicon

Zhijuan Tu, Pan Gong, Zhiping Zhou*, and Xingjun Wang*

State Key Laboratory of Advanced Optical Communication Systems and Networks, School of Electronics Engineering and Computer Science, Peking University, Beijing 100871, China

*E-mail: zzhou@pku.edu.cn; xjwang@pku.edu.cn

Received September 24, 2015; accepted January 4, 2016; published online March 11, 2016

This work describes an ultracompact coherent receiver monolithically integrated on silicon. The coherent receiver integrates one 1D grating coupler, one 2D grating coupler, two 90° hybrids, and eight Ge photodetectors in an area of only 1.3 × 1.4 mm², which is about half the size of the smallest previously reported receiver. The design and performances of the components and the integrated coherent receiver are presented. The receiving of 100 Gbps polarization-division-multiplexed quadrature phase-shift keying (PDM-QPSK) signals is also successfully demonstrated.

© 2016 The Japan Society of Applied Physics

1. Introduction

With the rapid evolution of Internet traffic, global information, and communication networks, there has been continuously increasing demand for the optical communication systems with a high bandwidth, high spectral efficiency, and low cost.1–3) In order to satisfy the standards for clients and line side interfaces, the IEEE Ethernet and the International Telecommunication Union-Telecommunication optical transport network (ITU-T OTN) standardization sector ratified 100 Gbps as the first optical transport bitrate hierarchy.3) However, optical systems with channel data rate of 100 Gbps are difficult to achieve. A promising solution is optical coherent communication, which was extensively studied in the 1980’s.5) In coherent communication systems, owing to the utilization of polarization-division-multiplexed quadrature phase-shift keying (PDM-QPSK) or even more advanced modulation formats, the individual components can operate at a lower data rate. Thus the bandwidth demands on the components can be not so stringent.3,4) Therefore, coherent transmission has become a key technology for high-capacity, long-haul communications systems with a 100 Gbps channel data rate and beyond.4,6) In coherent receiving or detection systems, the polarization, amplitude, and phase of the modulated optical signal can be converted back to the electrical domain by balanced detection. Another merit is that optical coherent receivers based on semiconductor photonic integrated circuits (PICs) are urgently needed.

Among the semiconductor PICs, there are two main material systems, namely the group III–V material (InP, GaAs) systems and the group IV material (Si, Ge) systems.8,9) In recent years, there have been many reports on high-performance coherent receivers based on InP.10–13) The reason why group III–V material systems are popular may lie in the fact that they have a direct bandgap. Consequently, ternary or quaternary compounds with good material properties can be easily acquired, and high-efficiency lasers can be achieved.14) However, since indium is quite scarce (only 0.000005% mass content of the Earth’s crust), PICs based on III–V materials have a high cost. Therefore, other material systems that are not so expensive have been explored. The use of Si, with 27% mass content of the Earth’s crust, can lead to much cheaper material systems. Although Si is an indirect-bandgap material making it difficult to be used as a laser source, it is expected that these problems can be resolved. High-performance III–V based lasers on Si substrates have already been reported. These lasers are fabricated by direct epitaxy14–16) or wafer bonding methods.17–19) A more noteworthy result may be the successful demonstration of lasing in a GeSn alloy on a Si substrate.20) Moreover, Si PICs are attracting considerable attention because of their advantages such as their compatibility with complementary metal oxide semiconductor (CMOS) technology, small footprint, high yield, and thus low cost.

So far, many high-performance building blocks for Si PICs have been achieved, including passive components,22) modulators,22–24) and photodetectors,25–27) whose performances are almost comparable with those of PICs based on group III–V materials. In a Si PIC, the building components can be interconnected by optical waveguides on the same Si chip so that it becomes much easier to ensure a well-matched optical path length. Recently, there have also been many reports of high-capacity monolithically integrated coherent receivers on Si PICs,28–34) which demonstrate the major advantages of Si PICs and pave the way for the realization of next-generation coherent receivers on Si platforms.

In this paper, a coherent receiver with ultracompact polarization and phase diversity is demonstrated using the Si PICs. The footprint of the coherent receiver is about half as large as the smallest previously reported value (3 × 1.3 mm²).30) For the reception of high-speed PDM-QPSK signals, it only requires an optical signal-to-noise ratio (OSNR) of 17 dB at a bit error rate (BER) of 10⁻⁷.

2. Design of the Si PIC

A schematic of the coherent receiver is shown in Fig. 1. The coherent receiver PIC includes one two-dimensional (2D) grating coupler, one one-dimensional (1D) grating coupler,
also optimized to achieve maximum coupling efficiency. The holes etching depth is 70 nm. The diameter of the holes is 600 nm, and the period of the photonic crystal is determined by the calculated states and propagates along the waveguides. The lattice can be divided into two transverse-electric (TE) polarization states from the splitter at the same time. Once light with an arbitrary polarization state from the fiber is coupled into the chip, it can be divided into two transverse-electric (TE) polarizations by the 2D grating coupler, a polarization rotator, and a beam splitter at the same time. Via the 2D grating, the optical signal from the optical fiber can be coupled into the PIC. Once it is coupled, the signal light is divided into light with two TE polarizations. Meanwhile, the TE polarized LO light is coupled into the chip through the 1D grating coupler. The light in the Si waveguide is evanescently coupled to the Ge region. The Ge thickness is 500 nm. For balanced detection, the PDs are connected in series in each pair. Every two pairs on each side of the PIC share the same direct current (DC) bias connections. On-chip capacitors are also designed to have good connection with the ground pads to allow high-speed signals.

2.1 1D and 2D grating couplers

The 1D grating coupler is designed to obtain high-efficiency and broad-band coupling between the optical fiber and the Si chip. The period and duty factor are optimized to maximize the coupling efficiency. The 2D grating coupler is based on a 2D photonic crystal structure as shown in Fig. 2(b). It can act as a grating coupler, a polarization rotator, and a beam splitter at the same time. Once light with an arbitrary polarization state from the fiber is coupled into the chip, it can be divided into two transverse-electric (TE) polarization states and propagates along the waveguides. The lattice period of the photonic crystal is determined by the calculated wavelength of the TE mode in the waveguide (600 nm) and the holes etching depth (70 nm). The diameter of the holes is also optimized to achieve maximum coupling efficiency.

2.2 90° hybrids

In order to mix and split the incoming modulated optical signal and the local oscillation light, 90° hybrids are adopted in the coherent receiving systems. To achieve this, we have developed a 90° hybrid that includes a wedge-shaped 2 × 4 MMI coupler and a 2 × 2 MMI coupler, as shown in Fig. 2(c). This cascaded MMI-based 90° hybrid operates in the TE mode, for which the main advantages include no need for additional phase shifters and no waveguide crossing for the coherent reception of the balanced PDs. Based on the detailed explanations in Ref. 36, the restricted interference enables wedge-shaped 2 × 4 MMI to be shorter than a rectangular 2 × 4 MMI with the same width Wb, as shown in Fig. 2(c). Owing to this merit, our 90° hybrid is compact with a total length of 107 µm, which is of the smallest length among the recently reported MMI-based 90° hybrids. Additionally, in order to obtain a high extinction ratio (ER), the imbalances of the four output channels are further optimized by using the three-dimensional (3D) BPM method.

2.3 Ge photodetectors

The width and length of the Ge PDs are designed to achieve a high bandwidth and high responsivity at the same time.37) The light in the Si waveguide is evanescently coupled to the Ge region. The Ge thickness is 500 nm. For balanced detection, the PDs are connected in series in each pair. Every two pairs on each side of the PIC share the same direct current (DC) bias connections. On-chip capacitors are also designed to have good connection with the ground pads to allow high-speed signals.

2.4 Working principle

The working principle of the coherent receiver can be elaborated as follows. Via the 2D grating, the optical signal from the optical fiber can be coupled into the PIC. Once it is coupled, the signal light is divided into light with two TE polarizations. Meanwhile, the TE polarized LO light is coupled into the chip through the 1D grating coupler. Then it is divided into two by the 1 × 2 MMI splitter. The divided signal and LO light propagate in two different directions, and proceed to the corresponding 90° hybrids.36) The outputs of the 90° hybrids are detected by the balanced PDs. The balanced detection on both sides of the receiver can generate the corresponding in-phase and quadrature components. By subsequent off-line DSP, the amplitude and phase information of the received signal can be obtained.

The coherent receiver PICs were fabricated on a silicon-on-insulator (SOI) wafer with a top Si thickness of 220 nm. The fabrication processes were performed by using the standard foundry service for Si PICs, mainly including the formation of passive devices by dry etching method such as for the Si waveguide, grating couplers, and 90° hybrids; by Ge epitaxy on the Si substrate by using the two-step growth in an ultrahigh vacuum chemical vapor deposition (UHVCVD) epitaxy reactor; by n+-Ge ion implantation with phosphorous and subsequent rapid thermal annealing to obtain good ohmic contacts; by SiO2 deposition for surface passivation; and by metallization and final bond pad opening. More details of the fabrication process conditions can be found in Ref. 38. An optical microscope image of the fabricated coherent receiver PIC is shown in Fig. 3. The coherent receiver only occupies a small area of 1.3 × 1.4 mm², which is about half the size of the smallest previously reported receiver (3 × 1.3 mm²).30)

3. Experimental results

For the 1D grating coupler, we achieved a coupling efficiency of −3.66 dB, and the 3 dB bandwidth of the optical spectrum...
is about 50 nm, as shown in Fig. 4(a). For the 2D grating coupler, the coupling efficiency is $-8$ dB, the extinction ratio is larger than 25 dB, and the 3 dB bandwidth was measured to be 50 nm, as shown in Figs. 4(a) and 4(b).

For the 90° hybrid, the extinction ratio was more than 20 dB, as shown in Fig. 5(a). In addition, since the wedge-shaped 2 × 4 MMI can eliminate the dispersion of the higher-order modes effectively, the phase errors at the corresponding output channels can be improved. As can be seen in Fig. 5(b), the phase deviations for C-band wavelengths are within $5^\circ$.

For the Ge PD with the size of $1.6 \times 10 \, \mu\text{m}^2$, the dark current is $0.23 \, \mu\text{A}$ at $-1 \, \text{V}$ bias, and the responsivity is $0.6 \, \text{A/W}$ at $-1 \, \text{V}$. The 3 dB bandwidth is larger than 26.5 GHz at $-4 \, \text{V}$ with $50 \, \Omega$ load, as shown in Figs. 6(a) and 6(b).

In order to check the viability of the integrated coherent receiver in 100 Gbps optical transmission systems, we initially performed the following experiments. Prior to further packaging with trans-impedance amplifiers (TIAs), both parts of the coherent receiver PICs can only be measured separately using our currently available probe systems. A schematic of the measurement setup is shown in Fig. 7. For measurement using the upper part in Fig. 1(b), we launched a TE polarized 50 Gbps QPSK signal of $9.98 \, \text{dBm}$ at $1547.715 \, \text{nm}$ wavelength into the 2D grating port and a CW laser signal of $15.5 \, \text{dBm}$ with TE polarization into the 1D grating LO port. The 50 Gbps QPSK signal was generated by a commercial high-speed transmitter module that integrates both a bit-pattern generator (BPG) and a quadrature amplitude modulation (QAM) transmitter. The bias voltages for the balanced PDs are $\pm 1 \, \text{V}$. The outputs of the balanced PDs were probed by the high speed $50 \, \Omega$ terminated ground–signal–ground–signal–ground (GSGSG) probes and then fed to an $80 \times 10^9$ samples/s real-time oscilloscope. Subsequently, the data sampled by the oscilloscope were processed off-line using standard DSP algorithms. After off-line processing, we obtained good signal constellations as shown in Fig. 8(a). By comparing millions of received data with the original launched signals, we calculated the BER for different OSNRs. As seen in Fig. 8(c),
an OSNR of about 17 dB is required at a BER of $10^{-3}$. Then we changed the 50 Gbps QPSK signal into a TM polarized signal and probed the outputs of the lower part of the receiver shown in Fig. 1(b). Following the same sampling and off-line processing methods, we obtained similar constellations as shown in Fig. 8(b). Both parts of the coherent receiver demonstrated satisfactory performance at 50 Gbps. By polarization multiplexing, we can achieve the coherent detection of 100 Gbps polarization and phase diversity signals. After packaging with TIAs, both the upper and lower parts of the coherent receiver can work simultaneously to demodulate the polarization multiplexed signals. From the above results, we conclude that our coherent receiver is capable of receiving 100 Gbps PDM-QPSK signals. Further package design and measurement work are underway.

4. Conclusions

We demonstrated a monolithically integrated coherent receiver on Si with an ultrasmall footprint of $1.3 \times 1.4$ mm$^2$. The coherent receiver can successfully detect a 100 Gbps PDM-QPSK signal. This high-level integration makes Si PICs highly suitable for providing low-cost transceivers for future optical communication systems with a 100 Gbps channel data rate and beyond.

Acknowledgments

This work was partially supported by the National High Technology Research and Development Program of China (Grant No. 2011AA010302) and the Natural Science Foundation of China (Grant No. 61177058).