Digital coherent communication systems have been deployed in long-haul optical transport networks. The systems are now extended to metro-area optical networks, where small form factor and low-cost optical modules are crucial. Small-footprint PDM IQ optical modulator based on silicon-photonic platform and low-profile packaging technology for the silicon optical modulator are developed in Fujikura to meet the requirement of compact digital coherent transceivers in the metro networks. This review focuses on a monolithic silicon PDM IQ optical modulator copackaged with high-speed electrical modulator drivers in a small-footprint low-profile module and its transmission performance in optical-fiber links up to 1000 km in 128-Gb/s DP-QPSK for digital coherent communication in the metro networks.

1. Introduction

There is growing data transport in mobile communication on account of extended use of smart phones and tablets dealing with large-size contents. The mobile traffic in various routes is forwarded to long-haul back-bone optical transport networks, and thus higher transmission capacity is required to optical-fiber telecommunication. Digital coherent communication, in which optical signals are multiplexed in advanced modulation formats such as DP-QPSK, has taken the place of the conventional binary on-off keying (OOK) because of its capability of high-speed communication (1, 2). DP-QPSK are superior to OOK, because optical signals are multiplexed into 4 bits per symbol in DP-QPSK after 2-bit multiplication in QPSK and further 2-bit multiplication in two orthogonal polarization states, thereby 100 Gb/s transmission is realized with 25-Gbaud symbol rate. Layouts and configurations of optical devices and electric circuits for DP-QPSK are more complex than those for OOK due to the high multiplicity of transmission data. Therefore, small form factors and low costs are crucial to the deployment of digital coherent communication systems in optics networks such as metro-area optical networks consisting of a number of nodes, where huge number of optical transceivers in transport equipment are stationed. Digital coherent transceivers in metro-area optical networks are required to be ten times smaller in footprint according to roadmaps such as for compact pluggable digital coherent transceivers (3, 4).

Optical modulators designed and fabricated on silicon-photonic platform are most suited to compact form factor optical transceivers. High-index contrast optical waveguides formed in SOI wafer and monolithic integration of optical devices using design rules and CMOS-based fabrication technology lead to small-footprint photonic circuits constituting optical modulators for DP-QPSK such as photonic circuits for PDM, IQ optical phase modulation, and monitor photodetectors (PDs) for performance monitoring. Chip fabrication on large-scale SOI wafers of diameter as large as 200 mm or more has the advantage of cost reduction in production. Monolithic silicon PDM IQ optical modulator chips in 5 x 6.5 mm² in footprint per each chip have been designed and fabricated in Fujikura, and 128-Gb/s DP-QPSK modulation was proved on chip characterization (5, 6).

In this review, silicon DP-QPSK optical modulator module, in which a monolithic silicon PDM IQ optical modulator is copackaged with high-speed electrical modulator drivers in a small-footprint low-profile ceramic-based metal housing, is presented, and 128-Gb/s DP-QPSK modulation in optical-fiber transmission up to 1000 km is proved using the module as a candidate for compact digital coherent transceiver in metro-area optical networks.

2. 128-Gb/s silicon DP-QPSK optical modulator module

Top-view photograph of a silicon PDM IQ optical modulator chip is presented in Fig. 1 with schematic layout of building blocks in the chip. The chip was fabricated by CMOS-based fabrication processes on a 200-mm SOI wafer. In DP-QPSK modulation, 4-bit signal is produced per symbol in PDM of IQ modulation with the layout depicted in Fig. 1. The layout consists of the following four essential building blocks: (1) an input waveguide split into two parallel waveguides...
with 1x2 splitter consisting of a multi-mode interferometer, (2) two silicon IQ Mach-Zehnder (MZ) modulators, each of which consists of a silicon nested MZ interferometer (MZI) incorporating silicon single sub-MZIs on the both of parent MZI arms and operates in TE polarization state, (3) a polarization rotator (PR), with which polarization of light after one of the IQ MZ modulators is converted to TM polarization and (4) a polarization beam combiner (PBC) to multiplex TE and TM optical modulation signals. The all optical waveguides in the elements of IQ modulators, PR and PBC were designed under a common design rule, where all the waveguide sections have the same vertical heights in their rib parts and slab parts, and fabricated in common lithography and etching processes simultaneously with low process variation in heights.

A Si PDM IQ MZ modulator was monolithically integrated in a footprint as small as 5 x 6.5 mm² with germanium PDs for performance monitoring and silicon thermo-optic (TO) phase controllers to sustain phase separation of $\pi/2$ between I and Q optical phase components in each polarization by adjusting electrical heater currents to the TO phase controllers. The germanium PDs operate in a wide spectral range over C and L bands. The optical phase shifters in the sub-MZIs are driven with RF signals at a symbol rate of 32 Gbaud including a margin for forward-error-correction coding bits.

Top-view photograph of silicon DP-QPSK optical modulator module is presented in Fig. 2. A monolithic silicon PDM IQ optical modulator chip was copackaged with four high-speed electrical drivers, bias tees and RF terminators in a ceramic-based metal housing as illustrated schematically in Fig. 2. RF signals for QPSK components in the two orthogonal polarization states are fed through RF pins to the modulator drivers. The RF pins are disposed on one of the shorter side faces of 15-mm width. Input polarization-maintaining and output single-mode fiber pigtails are mounted on the other shorter side face. The ceramic base has the advantage of thermally stable low-strain assembly because the linear thermal expansion coefficient of ceramic is close to that of silicon crystal. The module has been hermetically sealed with a metal lid in a dimension of 15 x 35 mm² in footprint and 4.5 mm in height, thereby small-footprint low-profile module has been realized on the basis of silicon-photonic platform. DC pins for reverse biases to the silicon optical phase shifters and heater current to the TO optical phase controllers are disposed on one of the longer side faces of 35-mm width.

For low-profile packaging, butt coupling with input and output optical fibers has been adopted instead of conventional lens coupling. A suspended mode-field converter was designed and fabricated for low-loss butt coupling between the input and output optical fibers and the waveguides of the silicon PDM IQ optical modulator chip. The mode-field converter consists of a suspended silica waveguide, silica taper waveguide and a silicon nano-taper waveguide in series as illustrated in Fig. 3. Adiabatic mode conversion in the suspended mode-field converter allows optical energy transfer between the mode fields of 10-μm diameter in single-mode silica fibers and the mode fields in high-index contrast silicon waveguides of submicron diameter with coupling loss as low as 2.0 dB per facet.
Wavelength dependence of coupling loss was measured and is plotted in C and L bands in TE and TM polarizations in Fig. 4. Polarization-maintaining fiber was used in the measurements. The coupling loss is about 2 dB at a wavelength of 1550 nm for the both polarizations. Polarization dependence of the coupling loss is less than 0.3 dB over C and L bands. Therefore, the suspended mode-field converter is suited to low-loss fiber-waveguide coupling with high polarization diversity required for DP-QPSK modulation in C and L bands. The total optical insertion loss of the modulator module excluding modulation loss is 15 dB or lower in C and L bands. Further design refinements on silicon optical phase shifters as well as the suspended mode-field converter allow further reduction in the total optical insertion loss.

3. DP-QPSK transmission performances

Transmission performances of the silicon DP-QPSK modulator module have been characterized in the setup depicted in Fig. 5. Single-mode continuous-wave (CW) light at a wavelength of 1550 nm from a laser with emission linewidth narrower than 100 kHz was input to the module. The input light was separated through a fiber splitter and input also to a coherent receiver as LO light in homodyne coherent detection. PRBS electrical signals in 2\(^{31}\)-1 bit length at a symbol rate of 32 Gbaud were fed to RF input pins of the module. The PRBS electrical signals were amplified with the high-speed modulator drivers to peak-to-peak voltage amplitude of +/−3.25 V in 50-Ω impedance matching to generate DP-QPSK optical signals at a bit rate of 128 Gb/s.

The optical signals from the module were loaded into an optical-fiber link consisting of an optical burst switch and a fiber loop, which was connected to input and output optical fibers of the link with a 3-dB 2x2 optical coupler. The fiber loop was constructed with 100-km SMF, an EDFA and a BPF. Burst trains of DP-QPSK optical signals were generated by switching on/
off the burst optical switch and then input to the fiber loop. The burst period was determined to avoid contention between optical signals in specified loop turns and those in unspecified loop turns in the coherent receiver. Electrical signals after the coherent detection were output from the coherent receiver and input to offline digital signal processor (DSP). The electrical signals in the specified turns were selected and demodulated to plot constellation diagrams in the specified transmission distance in the offline DSP using electrical trigger pulses from the burst optical switch as a reference time base. An EDFA was inserted to compensate propagation loss in 100-km SMF and 3-dB splitter loss at the 2x2 coupler per turn. Amplified spontaneous emission noise from the EDFA was partially eliminated with a BPF, which has a spectral pass bandwidth of 1 nm around the peak of the optical spectrum of the DP-QPSK signals. Constellation diagrams of the DP-QPSK signals were acquired.

Constellation diagrams in back-to-back transmission (zero loop turn), 500-km transmission (five loop turns) and 1000-km transmission (ten turns) in two orthogonal linear polarization states (X and Y) are plotted in Fig. 6. Four constellation spots corresponding to four bit states in QPSK are clearly resolved in X- and Y-polarization states. BER was obtained as <10\(^{-5}\), ~1.1 x10\(^{-3}\) and ~5.3x10\(^{-3}\) in back-to-back, 500-km and 1000-km transmission distances, respectively. The BER in 1000-km distance is still lower than the limit of the forward error correction, thereby error-free transmission up to 1000-km SMF transmission has been proved. Therefore, the silicon DP-QPSK optical modulator module presented in this review is a candidate for small-footprint optical modulators in digital coherent transceivers of compact form factors to be deployed in metro-area optical networks.

### 4. Conclusion

A small-footprint monolithic silicon PDM IQ optical modulator chip fabricated on a 200-mm SOI wafer was copackaged with high-speed modulator drivers in a hermetically sealed ceramic-based metal housing of DP-QPSK optical modulator module. The module has a footprint as small as 15x35 mm\(^2\) and a height as low as 4.5 mm. Transmission performances of the module in 128-Gb/s DP-QPSK were characterized in the constellation measurements using an optical fiber link with a 100-km fiber loop. BER in the constellation diagrams in 1000-km transmission in the fiber link was lower than the upper limit of forward error correction, thereby error-free transmission is assured. The modulator module is a candidate for small-footprint low-profile modulators for compact form factor digital coherent transceivers to be deployed in metro-area optical networks.

### References

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