Novel Flexible-Format Optical Modulator with Selectable Combinations of Carrier Numbers and Modulation Levels Based on Silica-PLC and $LiNbO_3$ Hybrid Integration

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Abstract: We devised a novel flexible-format optical modulator that can optically select optimum sets of carrier numbers and modulation levels according to transmission conditions. The modulator with PLC-LN hybrid integration was successfully operated at 200 Gbps.
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1. Introduction

Channel capacity is limited by the signal bandwidth and signal-to-noise ratio of a channel according to Shannon's well-known theory. An effective way of preserving the required channel capacity with the efficient use of spectral resources is to adjust the spectrum resource allocation according to the optical signal-to-ratio (OSNR) of the channel [1]. A multi-carrier format using frequency division multiplexing (FDM) in the optical domain is suitable for adjusting the spectrum allocation because it is a simple method that only involves changing the number of carriers without any change in the baud rate, which would be difficult to achieve at a high bit rate [2]. Figure 1 shows schematic diagrams of the spectra and constellations of 4-carrier binary phase-shift keying (BPSK), 2-carrier quaternary phase-shift keying (QPSK), and 1-carrier 16-quadrature amplitude modulation (16-QAM) format signals, where the combinations of the number of FDM carriers and modulation levels are different, while the channel capacity and baud rate is maintained. A 4-carrier BPSK signal is very robust as regards OSNR degradation because of the long distance between the constellation symbol points in the signal space diagram. However, the 4-carrier BPSK signal occupies a four-channel bandwidth. On the other hand, the 1-carrier 16-QAM signal has high spectral efficiency because the signal occupies just a one-channel bandwidth, but the OSNR robustness of the signal is 9.8 dB lower than that of the BPSK signal because the distance between the constellation symbol points is short [3]. Therefore, a transmitter that supports multiple formats such as those mentioned above will be useful. Furthermore, dynamic switching to an appropriate format according to the OSNR condition might be beneficial for the efficient use of the spectral resource in future flexible transparent networks.

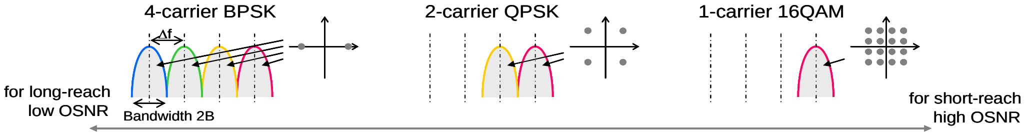

Fig. 1. Schematic diagrams of spectra and constellations of 4-carrier BPSK, 2-carrier QPSK, and 1-carrier 16-QAM signals.

A hybrid configuration with silica planar lightwave circuits (PLCs) and $LiNbO_3$ (LN) phase modulators is promising for those advanced format modulators because this structure has the merits of the large erector-optic bandwidth of LN phase modulators and the excellent transparency and design flexibility of PLCs. We have demonstrated several higher-level modulators that employ hybrid integration technology [4, 5].

In this study, we first devised a novel flexible-format optical modulator with which we can dynamically select the modulation format from the 4-carrier BPSK, 2-carrier QPSK, and 1-carrier 16-QAM formats. We fabricated the modulator with dual polarization by using PLC-LN hybrid integration technology. With the modulator, we successfully demonstrated 200-Gbps operation in each modulation format.

2. Design of devised modulator

Figure 2 shows schematic diagrams of the modulators for 4-carrier BPSK, 2-carrier QPSK, and 1-carrier 16-QAM formats with optical signal synthesis, which eliminates the need for high-speed electronic digital-to-analog converters (DACs) and suppresses inter-symbol interference. The 4-carrier BPSK modulator consists of three interleave filters (ILFs) for demultiplexing carriers, four Mach-Zehnder modulators (MZMs) as four BPSK modulators, and three 2x1 couplers. The 2-carrier QPSK modulator consists of one ILF, two nested MZMs as two QPSK modulators, and one 2x1 coupler. The 1-carrier 16-QAM consists of a parallel-quad MZM as a 16-QAM modulator.

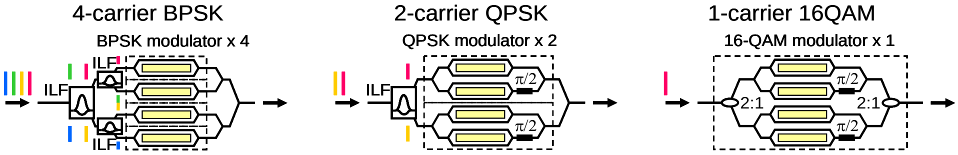

Fig. 2. Schematic diagrams of optical modulators for each format.

These modulators have almost the same configuration except for certain passive components such as ILFs and couplers. To provide these three configurations with a common design, we devised a modulator with a novel configuration that consists of three tunable ILFs (TILFs), four MZMs, two 2x1 couplers, and one variable coupler (VC) as shown in Fig. 3 (a). To use the modulator as a 4-carrier BPSK modulator (4-carrier BPSK mode), TILF1-3 are operated normally as carrier-demultiplexers as shown in Fig. 3 (b) and then the VC is set with a 3-dB coupling ratio. To use the modulator as a 2-carrier QPSK modulator (2-carrier QPSK mode), TILF2 and TILF3 are changed so that they operate as 3-dB couplers at the carrier frequency for carrier channel1 and channel2, respectively, to tune the phase condition of the TILFs. For use as a 1-carrier 16-QAM modulator (1-carrier 16-QAM mode), TILF1, 2, and 3 are changed so that they operate as couplers with coupling ratios of two-to-one, 3 dB, and 3 dB, respectively, at the carrier frequency, and then VC is set with a two-to-one coupling ratio. Thus, the devised modulator enables us to select the modulation format flexibly from the 4-carrier BPSK, 2-carrier QPSK, and 1-carrier 16-QAM formats.

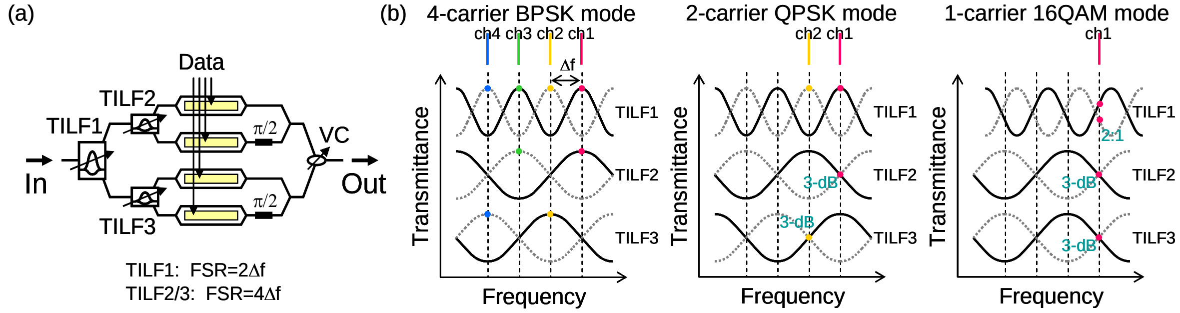

Fig. 3. (a) Schematic diagram of devised flexible-format modulator. (b) TILF operation for each format mode

3. Fabricated modulator

Figure 4 (a) shows the configuration of the fabricated modulator, which generates a 200-Gbps optical signal in total by employing eight 25 Gbaud electrical signals with a dual polarization operation. We used PLC-LN hybrid integration technology for the fabrication because the modulator required such high level integration. As shown in Fig. 4 (a), we used two PLCs (PLC-I and -O) and an X-cut LN chip. The LN chip has an array of sixteen straight phase modulators with eight signal electrodes (coplanar waveguides). PLC-I consists of three TILFs and 1x2 couplers. Each TILF is composed of three Mach-Zehnder interferometers (MZIs) with thermo-optic (TO) phase shifters. One MZI is the main TILF, which has two output ports. The others, which have only one output port, are added to obtain high isolation for demultiplexing. The free spectral range (FSR) of TILF1 is 100 GHz. Those of TILF2 and 3 are both 200 GHz. PLC-O consists of 2x1 couplers, TO phase shifters for IQ phase tuning, VCs, a half-wave plate as a polarization rotator, and a polarization beam combiner (PBC). The PBC consists of an MZI with stress-release grooves to control waveguide birefringence [6]. We arrange the MZMs in an alternating layout to share the TILFs for X- and Y-polarization. The PLC-I, LN, and PLC-O chips are 33 x 13.5, 64 x 6.0, and 35 x 4.4 mm, respectively. We bonded the chips together with UV-curable adhesive. Then we mounted them on a package with RF connectors and a temperature control device. The fabricated modulator is shown in Fig. 4 (b). The module size is 184 x 18.7 x 13 mm.

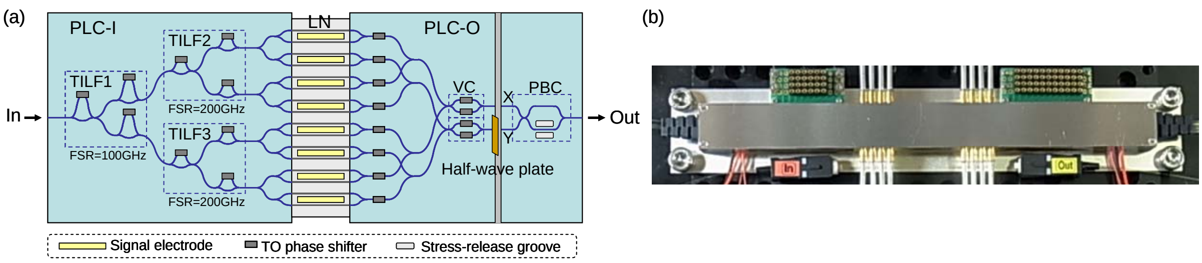

Fig. 4. (a) Configuration of fabricated modulator with dual polarization. (b) Photograph of fabricated modulator.

4. Characteristics

The insertion loss of the modulator was 8.8 dB at a wavelength of 1550 nm when all the TO phase shifters were tuned so that the transmittance was maximum. The 3-dB bandwidths of the electro-optic frequency response were around 25 GHz for all the MZMs.

We tested the modulator in the back-to-back self-homodyne setup shown in the inset of Fig. 5. Four tunable laser diodes (TLDs) with a 50-GHz spacing were used as a multi-carrier light source. The modulator was driven with eight 25-Gbps non-return-to-zero (NRZ) 2^{11}-1 pseudo-random bit sequences (PRBSs) with different delays for 200-Gbps operation. We changed the modulation modes by using the tunable ILFs and VCs as described above, while making no change to the driving signals. The number and wavelengths of the TLDs constituting the multi-carrier source were changed with the modulation mode. The output optical signal was received with an optical spectrum analyzer and an optical modulation analyzer (Agilent N4391A), combined with a 50-GSample/s storage oscilloscope (Tektronix DPO74004B), and analyzed offline. To use self-homodyne detection for constellation measurement, the light from the TLD that corresponded to the measured carrier channel was changed to that from the local oscillator (LO) in the optical modulation analyzer. We used the digital equalizer included in the N4391A analyzer software.

Figure 5 shows the measured optical output spectra and constellations of X-polarization signals. Those for the Y-polarization signals are almost the same. Clear spectra and constellations were obtained in each modulation mode. Thus, we achieved selectable operation from 4-carrier BPSK, 2-carrier QPSK, and 1-carrier 16-QAM, all with a bit rate of 200 Gbps and a symbol rate of 25 Gbaud.

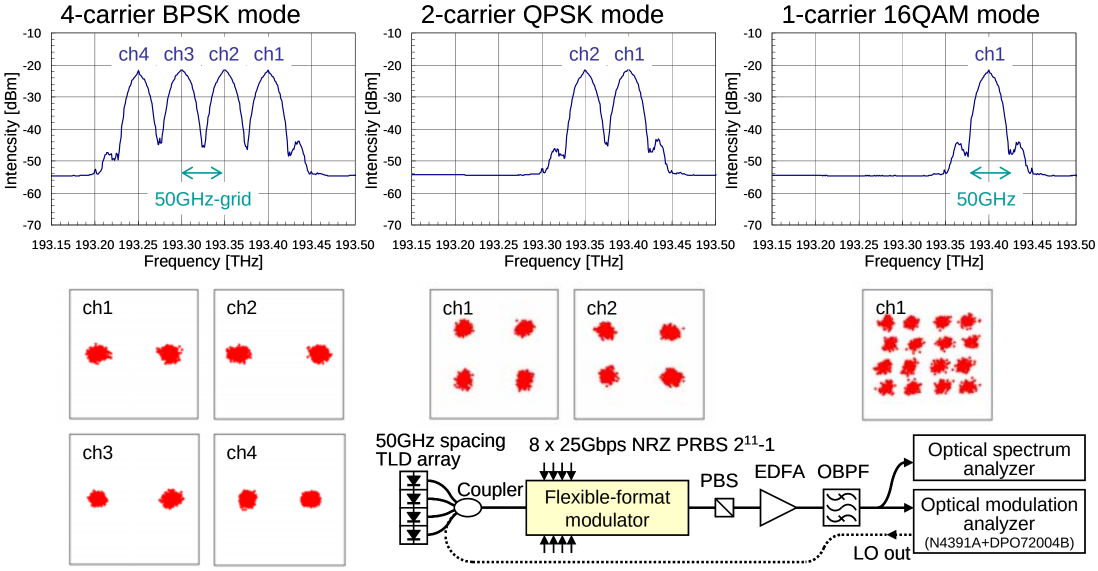

Fig. 5. Measured optical output spectra and constellations of X-polarization signals for 200-Gpbs operation in 4-carrier BPSK, 2-carrier QPSK, and 1-carrier 16-QAM modes. The inset shows the measurement setup.

4. Conclusion

We devised a novel flexible-format optical modulator that enables us to select the modulation format from the 4-carrier BPSK, 2-carrier QPSK, and 1-carrier 16-QAM formats simply by using a tunable ILF and a variable coupler and by changing carrier numbers. The modulator with a total bit rate of 200 Gbps was successfully demonstrated by using PLC-LN hybrid integration technology. We can also readily cover orthogonal-FDM (OFDM) by changing the FSR of the tunable ILFs. The flexible-format modulator is promising as regards achieving the efficient use of the spectral resources in flexible optical networks.

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