Compact 4×5 Gb/s Silicon-on-Insulator OFDM Transmitter

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Abstract: We characterize an integrated silicon 4×5 Gb/s OFDM transmitter PIC (2.1×4.8 mm^2) with four modulators and an optical Fourier transform. This PIC features a channel spacing of 5 GHz and an 80-GHz free spectral range.

OCIS codes: (130.0130) Integrated optics; (220.0220) Optical design and fabrication; (230.0230) Optical devices; (070.0070) Fourier optics and signal processing.

1. Introduction

Orthogonal frequency division multiplexing (OFDM) is a promising candidate for transmitting data with high spectral efficiency and dispersion tolerance [1]. Generally, the OFDM signal generation methods can be divided into two groups, i.e. opto-electronic or all-optical. All-optical (AO) processing can reduce the digital signal processing (DSP) workload, and conveniently matches the optimum symbol rate for nonlinear transmission [2]. To implement AO-OFDM, photonic integrated circuits (PICs) [3] are highly desirable with respect to system compactness and cost, compared with other approaches such as using a liquid crystal on silicon (LCoS) filters [4]. In [5], 7×5-Gb/s OFDM generation based on discrete Fourier transforms (DFT) was demonstrated over 84 km of fiber. However, external modulators were used to modulate each subcarrier. From a practical perspective, the realization of fully integrated electro-photonic OFDM transmitters (Txs) will play a key role for the deployment and proliferation of OFDM transmission systems. Recently, Fraunhofer HHI proposed a 16 mm×28 mm 8-channel 25-GHz-spacing OFDM InP transmitter PIC, including in-phase (I) and a quadrature (Q) modulators with arrayed waveguide grating (AWG). The I/Q modulators work at 40 Gb/s [6]. However, InP technology is expensive and its AWGs and modulators occupy a large area.

In this paper, we report the characterization of a compact (2.1 mm×4.8 mm) silicon-on-insulator OFDM transmitter PIC including modulators and an AWG-based Fourier transform (FT). This provides four channels at a 5-GHz spacing, 80-GHz free-spectral range (FSR) and occupies only 2.3% of the area of the HHI PIC [6]. The PIC provides all designed functions, and the modulators' bandwidth will easily support the optimum symbol rate for nonlinear transmission (around 5 Gbaud).

2. Device description

Figure 1(a) shows the OFDM Tx PIC. This comprises seven 2×2 multi-mode interference (MMI) couplers, two input/output (I/O) coupler arrays, four travelling-wave Mach-Zehnder modulators (MZM), and an 8×8 AWG.

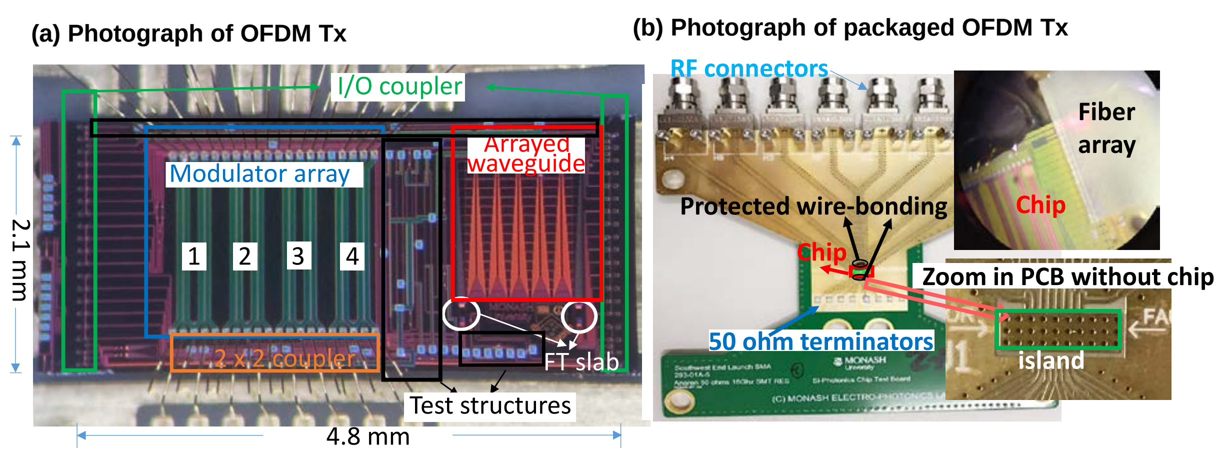

Fig. 1. (a) Photograph of a fabricated AO-OFDM Tx PIC. (b) Photograph of PCB-mounted OFDM Tx.

The AWG chip was wire-bonded on a custom printed circuit board (PCB) shown in Fig. 1(b), which connects the bond wires to radio frequency (RF) connectors (Southwest Microwave 293-01A-5). The PCB is made up of five layers (gold, R04003 dielectric, gold, FR4 dielectric and gold). The chip sits on a thermal island with vias to the base layer, underneath which is a Peltier element to control the chip's temperature. 50-ohm resistors on the PCB terminate the four ends of the modulators. I/O fiber connectors are on both sides of the chip; each has an eight-fiber array with 126-µm spacing, as shown in the inset of Fig. 1(b).

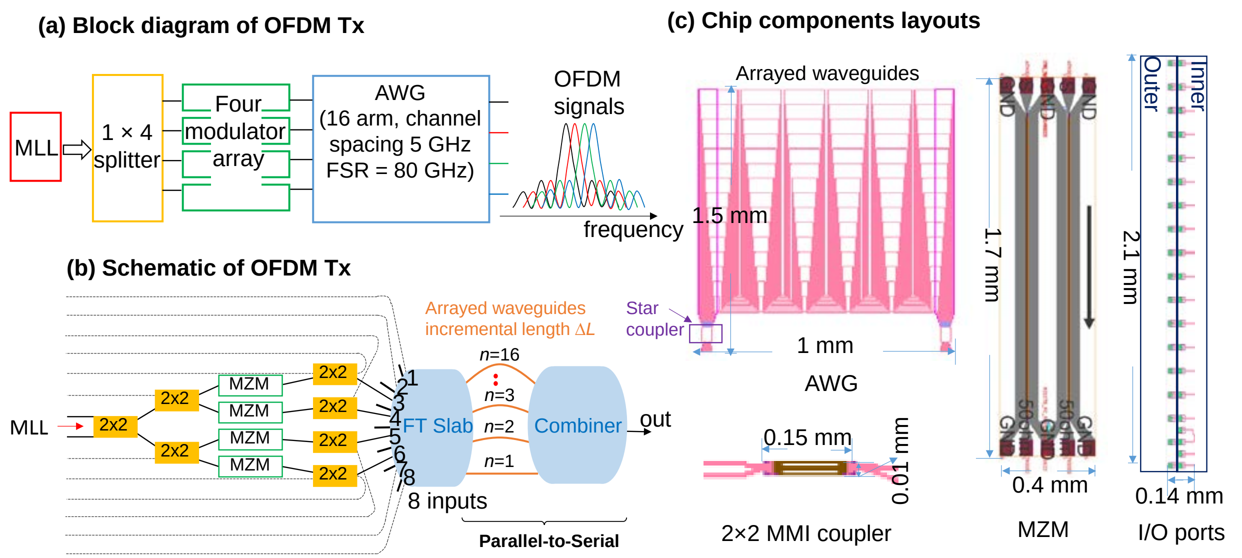

Fig. 2. (a) Block diagram and (b) schematic of the 4-channel AO-OFDM Tx PIC using AWG; (c) Layouts of OFDM Tx PIC components include a "u-wave-bend" arrayed waveguides, MZM, 2×2 MMI coupler, and two fiber connector arrays.

Figure 2(a) is a block diagram of the OFDM transmitter: a 1×4 power splitter provides a copy of each pulse from an external mode-locked laser to each of 4 modulators. Each intensity modulator is driven by an independent electrical data signal. An AWG acts as an inverse Fourier transform followed by a parallel-to-serial converter. Because there are 16 waveguides in the array, each OFDM symbol comprises 16 samples, separated by 12.5 ps, to give a FSR of 80 GHz, and a channel spacing of 5 GHz. Thus, each mode locked pulse becomes four superimposed modulated subcarriers in one OFDM symbol.

More detail is given in Figure 2(b). Here, the 1×4 power splitter is implemented as three 2×2 50%/50% MMI couplers. Each modulator is driven by an independent electrical data signal and modulates a portion of the input light. The four modulator outputs are fed in parallel to the four middle inputs of the AWG. In each feed path, a 2×2 MMI coupler is used as a monitoring tap, so that each modulator can be independently characterized.

Figure 2(c) show the chip layouts of the individual components. The AWG was designed from a "u-wave-bend" template from BP photonics. The waveguide propagation losses are 2.5 dB/cm, with little loss from the waveguide bends. This structure reduces the size and lowers the inter-arm phase errors caused by fabrication non-uniformity. The modulators are 2×2 travelling-wave Mach-Zehnder Interferometers (MZI), which is realized in IMEC ISIPP25G technology.

3. Device characterization

Each modulator has a 5-dB insertion loss, and its switching voltage V_π is 8.5 V at -2 V bias. The 2×2 MMI couplers have an imbalance of 5% and loss of 0.5 dB. Figure 3 shows the spectral transfer characteristic and impulse response of the 8×8 AWG. The spectral response of the AWG was measured with a LUNA two-port optical analyzer (VOA5000, 0.16-GHz resolution), and has distinct channel peaks which cross at 6-dB down from their peak responses, when 3 dB is expected. This is due to a design error, where the spacing between the input waveguides of the FT slab was doubled the required, so only even channels were available, thus the spacing of the main peaks of the OFDM subcarriers is 10 GHz. The insertion loss of the AWG is 15±2 dB excluding fiber-coupling losses. Ideally, for an inverse Fourier transform, the impulse response should have a rectangular envelope; however, this is impossible with a practical AWG design due to the non-rectangular beam patterns of the waveguides that couple to the FT slab; we measured a non-uniformity of 2 dB. This could be flattened using a dynamic waveform reshaping based on modulating the output of the transmitter [7].

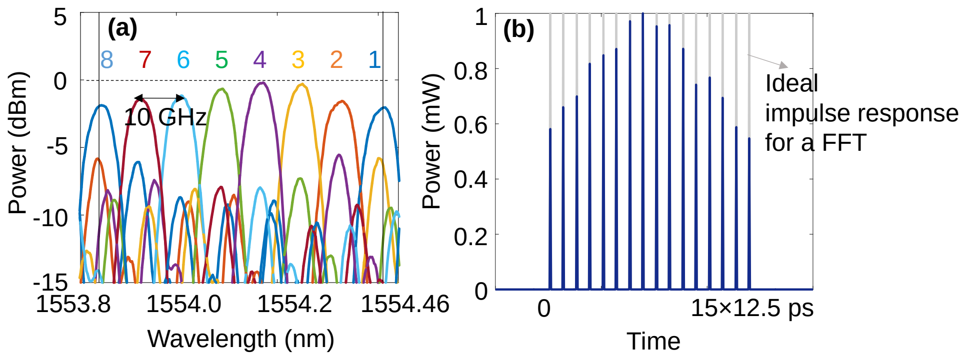

Fig. 3. (a) Spectral and (b) impulse responses of the AWG. (FFT: fast Fourier transform algorithm).

Figure 4 shows the small-signal electro-optical response measurements, measured by a vector network analyzer (ANRITSU 37247D); these show 3-dB bandwidths of 9±2 GHz. The reflection (S_{11}) is less than -10 dB up to 20 GHz. A 60-Gsamples/s arbitrary waveform generator provided a 10-Gbaud OOK signal. A polarized 15-dBm 1556-nm continuous-wave (CW) laser was coupled into the modulator. The monitor output after the modulator was amplified by an erbium-doped fiber amplifier (EDFA) and detected by a 16-GHz Discovery DSC-40S photodiode (PD), then digitized using an Agilent 28-GHz 80-Gsamples/s real-time sampling oscilloscope. Figure 4 also shows the eye diagrams at 10 Gb/s and 15 Gb/s. Although low compared with state-of-the-art, the bandwidth of the modulators is suitable for systems operating at the optimum symbol rate for nonlinear transmission.

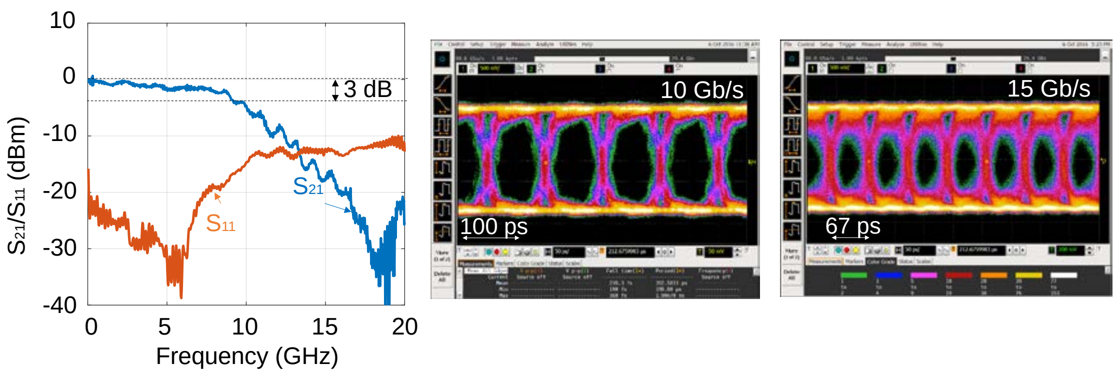

Fig. 4. Normalized electro-optical S_{21} and S_{11} as a function of frequency MZM and eye diagrams at 10 Gb/s and 15 Gb/s.

4. Conclusion

A 5-GHz channel spacing and 80-GHz FSR OFDM Tx PICs has been designed, fabricated and characterized. The PIC has a very small area 2.1×4.8 mm^2, and the modulators are capable of supporting 5 Gbaud. Despite the design error, this paper shows that the key elements of an OFDM transmitter can be integrated into a compact PIC using silicon-on-insulator technology.

Acknowledgements

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