All-optical coherent OFDM transmission of 8 × 40 Gb/s using an on-chip AWGR-FT 1 × 8 decoder circuit

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Abstract: We experimentally demonstrate an 8 × 40 Gb/s all-optical coherent-OFDM system using an on-chip 1 × 8 Fourier-transform based on a modified arrayed-waveguide grating router, showing simultaneous receiving of 8 subcarriers with similar signal qualities.

OCIS codes: (060.2330) Fiber optics communications; (060.1660) Coherent communications; (060.4230) Multiplexing; (080.1238) Array waveguide device; (250.3140) Integrated optoelectronic circuits.

1. Introduction

Optical orthogonal frequency division multiplexing (OFDM) is a highly promising technique for transmitting data with very high spectral efficiency and high dispersion tolerance [1]. It can be generated by electrical or optical means. Electrically generated OFDM features high flexibility in subcarrier allocation and easy implementation of advanced symbol format such as cyclic pre/postfix, however, it requires heavy computational effort and the maximum producible symbol rate is limited by the sampling speed of the state-of-the-art digital-to-analog converter [2]. Alternatively, all-optical OFDM enables (de)multiplexing of the subcarriers in the optical domain. This is not only able to dramatically reduce the digital signal processing workload, but also allows the system to use slow modulators (e.g. bandwidth lower than baud rate) when operated with pulsed laser [3, 4].

To implement all-optical OFDM, the on-chip approach using photonic integrated circuits is highly desirable with respect to system compactness and cost, as compared to other approaches such as using a commercial Wave shaper based on liquid crystal on silicon (LCoS) technology [5]. From a practical perspective, the realization of fully-integrated electro-photonic OFDM transmitters and receivers will play a key role for the deployment and proliferation of OFDM transmission systems, where the expected system improvements in transmission capacity, spectral efficiency, energy consumption, and construction cost will justify their use.

In this work, we experimentally demonstrate an all-optical single-polarization QPSK-modulated OFDM transmission of 8 × 40 Gb/s, where the demultiplexing of 8 OFDM subcarriers is achieved using a particular on-chip 1 × 8 OFDM decoder circuit realized in silicon-on-insulator (SOI) technology [6]. In the previous studies, a few possible photonic integrated circuit solutions have been visited to address the all-optical OFDM demultiplexing. For example, an optical DFT filter based on tapped-delay-line structure has been demonstrated to filter out one of the multiplexed OFDM subcarriers at a time, with a symbol rate of 5 Gbaud [7]. In principle, with increased circuit complexity such filters can also be extended to a 1 × N structure to enable simultaneous demultiplexing of N subcarriers. The DFT can also be performed using a 1 × N arrayed waveguide grating router (AWGR), a study of which has demonstrated simultaneous demultiplexing of 8 OFDM subcarriers with a symbol rate of 12.5 Gbaud [8]. In [9], a demonstration is presented of a 10 × 10 Gbaud OFDM system using a slab coupler-based DFT circuit. In our demonstration, we verified that the circuit design implements the targeted 1 × 8 OFDM decoder functionality, and exhibited its use for a QPSK-modulated OFDM system with a symbol rate of 20 Gbaud.

2. OFDM decoder chip design and characterization

Figure 2a depicts the mask layout of the decoder chip, which consists of three sections. Its input is connected to a 1 × 8 binary-tree splitter consisting of seven 1 × 2 3-dB multimode interferometers (MMIs), which in the ideal case features a uniform power distribution at the 8 splitter outputs. Connected to the splitter outputs, an 8-arm delay-line array with a linearly increasing delay configuration is constructed. The delay lines are designed with an inter-arm delay difference of 6.25 ps resulting in a device free spectral range (FSR) of 160 GHz and therewith a channel frequency spacing of 20 GHz. Here, bended spirals are used to achieve high footprint efficiency. At the output side, an 8 × 8 slab coupler based on Rowland mounting is connected to the delay-line array, where dedicated waveguide tapers are used at its coupling ports to optimize the circuit performance. With respect to optical signal processing, the entire device is expected to perform the same DFT function as a conventional AWGR [4]. In this design, however, the use of a uniformly-distributed splitter instead of a regular Gaussian-distributed slab coupler would lead to an improvement in the envelop flatness of the device impulse responses and therefore result in better performance with respect to orthogonality when demultiplexing the OFDM subcarriers [4]. The chip was realized in silicon-on-insulator planar waveguide technology (mask design by VLC photonics and fabrication via Leti foundry service), using the 220-nm fully-etched waveguide with a width of 0.45 µm, a minimum bend radius of 10 µm, and 0.45-to-2 μm adiabatic tapers for mode transition. The effective and group indices are characterized by 2.3 and 4.15, respectively, at the operation wavelength of 1550 nm. The circuit measures 3.4 × 0.9 mm^2. Figure 2b depicts the power transmission characterizations of the chip. The channel spacing proves to be 20 GHz; the crosstalk is about 18 dB between the neighboring channels; the decoder circuit insertion loss is about 12 dB relative to a straight waveguide reference lying cross the chip; the fiber-chip coupling loss is estimated at 10 dB per facet. When used in systems, the total insertion loss is about 30 dB, however, we expected to be able to reduce the loss to 10 dB when the chip fabrication process and fiber-chip coupling alignment are optimized. Note that the design necessarily has more loss than a standard AWGR design, because the impulse response is designed to have a rectangular window, to give a sinc frequency response [4] In principle, such a decoder could also be designed for polarization-division-multiplexed OFDM transmission systems when using low-birefringence waveguide and two-dimensional grating couplers in place of the current single-polarization couplers.

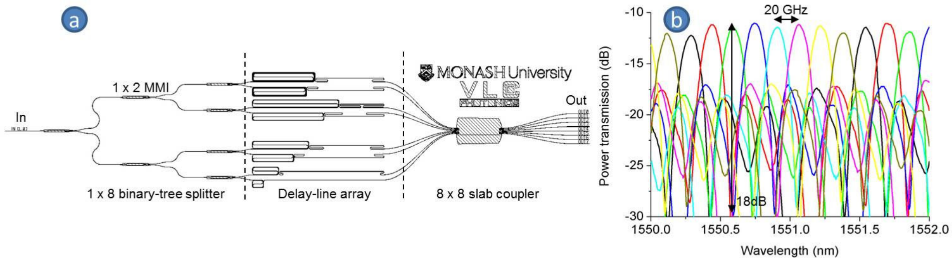

Fig. 1: (a) mask layout of the 1 x 8 OFDM decoder chip; (b) power transmission characterizations of the chip.

3. Demonstration of 8 × 40 Gb/s QPSK OFDM transmission

The system setup to demonstrate the 8 × 40 Gb/s single-polarization all-optical QPSK-OFDM transmission is depicted in Fig. 2. At the transmitter, an optical frequency comb source with a frequency spacing of 20 GHz is generated by passing the output of a 10 GHz external-RF-locked mode locked laser through a 1 × 2 delay-line interferometer whose inter-arm delay difference is set to be half of the input pulse interval, and the phase difference is controlled. The resulting spectrum is subsequently shaped by a Waveshaper to achieve 8 flat comb lines. The comb is then modulated by a complex optical modulator (CMZM), driven with 2 × 20 Gb/s signals. The driving signals are generated at a pair of complementary outputs of a pulse pattern generator using a 2^{31}-1 pseudo-random pattern and are time-aligned with the optical pulse stream. The pattern-decorrelation between the two driving signals is achieved using an adjustable electrical delay line. Then, the OFDM subcarriers are generated and multiplexed optically by means of the optical-pulse-train-modulation plus spectrum-shaping approach [10], where a multi-port Waveshaper based on LCoS technology is used to implement the desired optical pulse shaping. For clarity, in our setup the modulated optical pulse train is split into two equal portions and fed to two independent input ports of the Waveshaper, where one port carves the input spectrum into odd (1, 3, 5, 7) subcarriers with programmed sinc-shapes that equivalently performs the optical IDFT operation, while the other port performs the same function but generates the even (2, 4, 6, 8) subcarriers. The complete OFDM signal with a capacity of 8 × 40 Gb/s (20 Gbaud per subcarrier) is finally achieved by interleaving the two subcarrier groups into a common output. For the decorrelation between the odd and even subcarriers, an intentional delay difference is introduced before the Waveshaper inputs. To verify the processing steps explained above, the optical spectra at different positions in the OFDM transmitter were measured, and results are depicted in Fig. 2.

At the receiver, the demultiplexing of the OFDM subcarriers is implemented using the planar decoder circuit. The 8 decoder channels are frequency-aligned with the OFDM subcarriers, which equivalently performs the optical DFT operation such that each subcarrier can be received independently at one decoder output port. To guarantee correct signal processing operation and maximize the received signal power, polarization control is applied throughout the entire system. Figure 3a plots the measured error magnitude vectors (EVMs) of the demultiplexed QPSK-OFDM subcarriers based on a back-to-back transmission; Figures 3b and 3c show the received signal constellations of the best and worst channels, respectively. All 8 channels exhibit similar signal qualities, verifying the feasibility of simultaneous reception of 8 × 40 Gb/s QPSK-OFDM signals. The average EVM was measured to be about 15 dB, a 5-dB penalty with respect to a 20-dB EVM reference based on a single-carrier transmission. Besides, a relative quality difference of 1.6 dB is observed between different channels. We attribute this largely to the imperfect generation of the frequency comb. Recall that our 20-GHz spacing frequency comb is generated by frequency-aligning the notches of a 20-GHz FSR delay line filter to one of every neighboring two frequency lines of a 10-GHz spacing mode locked laser. However, we observed that the notch frequencies drift, which causes the frequency lines between the desired ones (20 GHz apart) to appear, and therewith introduces additional impairment to the signal channels after modulation. The decoder channels may have different losses for the measurements, due to device-level transmission deviations and manual fiber-chip alignment tolerances for different channels. Nevertheless, for the proof-of-concept, this penalty does not affect the verification of device functionality, and a significant reduction of it can be achieved by using a stable frequency comb and optimizing the measurement setup.

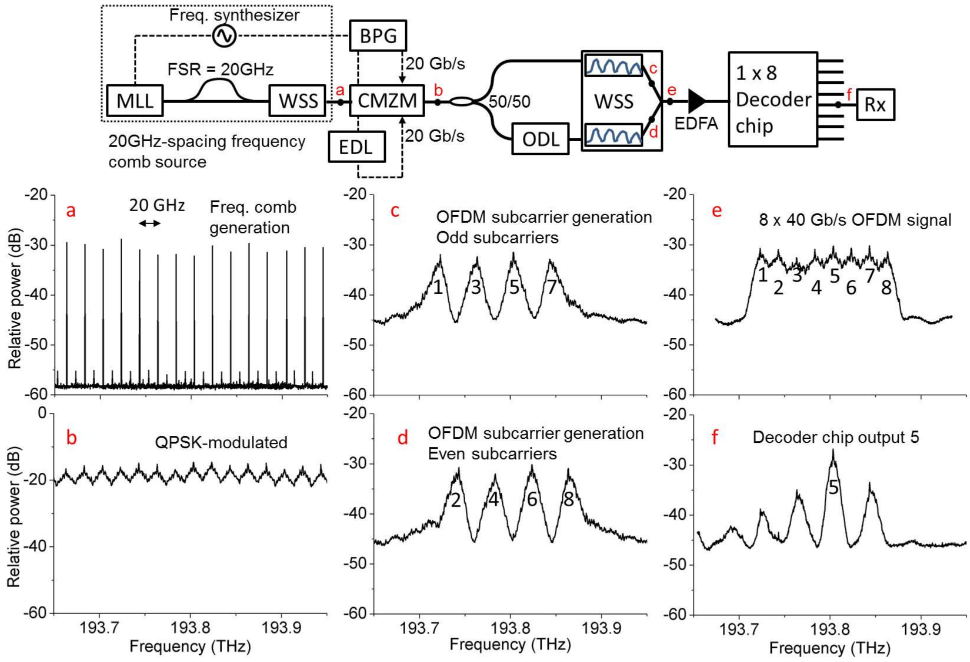

Fig. 2: 8 × 40 Gb/s single-pol. QPSK OFDM transmission demonstration setup and the measured spectra at different positions.

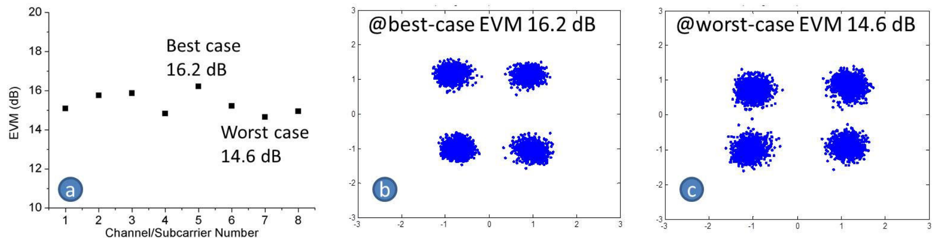

Fig. 3: (a) measured EVMs of the 8 outputs of the OFDM decoder chip; (b and c) received signal constellation for the best and worst cases.

4. Conclusion

By experiment, we verified the functionality of a particular design of an on-chip 1 × 8 OFDM decoder circuit featuring a channel spacing of 20 GHz. Using it, we demonstrated a 8 × 40Gb/s single-polarization all-optical QPSK OFDM transmission system. This result exhibits the feasibility of a full-integration solution for the future realization of all-optical OFDM transmitters and receivers.

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