Coherent Optical OFDM based on Direct Modulation of Injection-locked Fabry-Perot Lasers

Zhixin Liu(1), Joseph Kakande(2), Brian Kelly(3), John O'Carroll(3), Richard Phelan(3), David J. Richardson(1), and Radan Slavík(1)

(1) Optoelectronics Research Centre, University of Southampton, Southampton, UK z.liu@soton.ac.uk
(2) Bell Labs, Alcatel-Lucent, Holmdel, NJ 07733, USA
(3) Eblana Photonics Inc., Dublin, Ireland.

Abstract *We demonstrate generation of coherent optical OFDM signals using direct modulation of two injection locked lasers. Comparable performance to a $LiNbO_3$ IQ modulator is achieved after 230-km transmission with coherent reception and standard DSP.*

Introduction

Modern optical communication systems rely on advanced modulation formats and coherent detection. Advanced modulation formats such as optical Orthogonal Frequency Division Multiplexing (OFDM) provide high spectral efficiency and allow software-defined bandwidth allocation, which is considered an enabling technology for future optical networks[1]. At the receiver side, coherent detection allows for extraction of the full optical field and thus enables compensation of various impairments using digital signal processors (DSPs)[2]. Generation of coherent optical OFDM signals requires independent modulation of both In-phase and Quadrature (I and Q) components such that the baseband signal can be *linearly* mapped from the electrical domain to the optical domain. To date, costly, bulky, and power-inefficient external modulator based schemes are used for the signal generation. In addition, the nonlinear modulation response of a Mach-Zehnder (MZ) based external modulator compromises system performance.

Compared to external modulation, direct laser modulation offers many advantages such as low cost, compactness, low power consumption, relatively low drive voltage and high output power[3]. However, current modulation of a directly-modulated semiconductor laser (DML) is associated with a large frequency chirp[4], which heavily compromises the independence of I and Q. As a result, only amplitude modulation based double side-band (DSB) OFDM has been achieved using direct laser modulation[5]. This modulation format, however, not only decreases the spectral efficiency, but also causes dispersion-dependent frequency fading, which decreases the total capacity[5].

Recently, we proposed a wavelength-tuneable QAM transmitter based on binary direct modulation of injection-locked (IL) semiconductor lasers to construct QAM signals[6-8]. In this paper, we optimize the transmitter and show that optical coherent OFDM can be generated by independently modulating I and Q components of a baseband single side-band (SSB) OFDM signal onto the two injection-locked lasers. Our direct modulation based vector transmitter provides better modulation

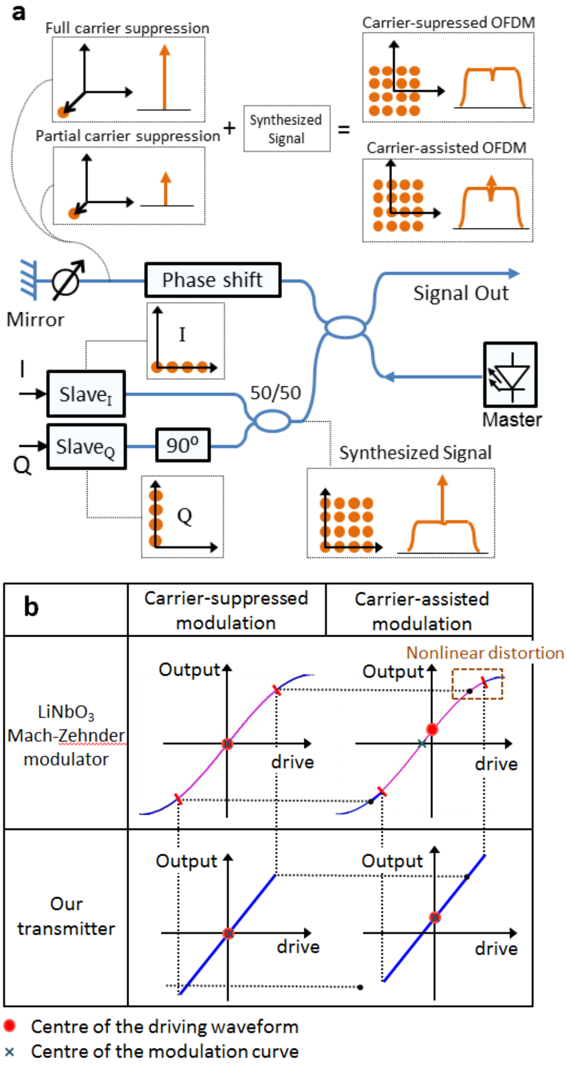

Fig. 1: (a) Schematic of our proposed vector transmitter. (b) Comparison of the modulation response (In-phase component) of $LiNbO_3$ IQ modulator and our vector transmitter.

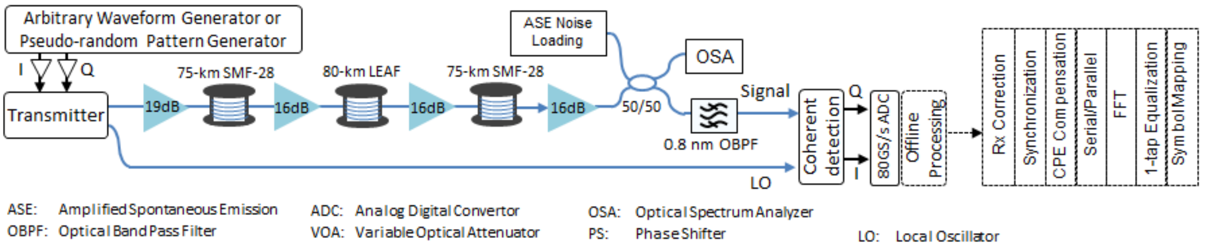

Fig. 2: Experimental Setup.

linearity and also allows for simple insertion of a carrier tone as is necessary in carrier-tone-assisted OFDM[9-10], still maintaining excellent modulation linearity. Using our vector transmitter, up to 33-Gb/s coherent optical OFDM (8.2-Gbaud/s OFDM-16QAM) is generated through direct modulation for the first time. The performance of the obtained signal after 230-km transmission through standard single mode fibre (SMF) is comparable to that obtained using a LiNbO$_3$ IQ modulator

Directly-modulated IQ Transmitter

The schematic of our transmitter is shown in Fig.1a. Continuous wave (CW) light from a master laser is fed into two slave lasers to phase lock their optical carrier. When the slave lasers are kept within the locking range[11], the chirp is suppressed and the lasers' modulation bandwidth can be significantly increased[12]. Moreover, locking the slaves to the master allows mutual coherence between the three lasers to be established, meaning that the slave frequency follows that of the master, even in the presence of modulation of the slave laser current. This allows I and Q to be independently modulated onto the two slave lasers and to be combined in the optical domain with a 90-degree phase shift. Following this, the carrier of the combined signal is suppressed by destructively interfering it with an appropriate CW component of the master laser light.

For coherent optical OFDM, a carrier tone is often inserted in the middle of the OFDM spectrum to facilitate easy common phase estimation and effective fibre nonlinearity compensation[10]. A common method to provide a carrier tone is to bias the MZ modulator slightly away from its transmission zero. However, as shown in Fig.1b, the shift of the bias point of the MZ modulator leads to nonlinear distortion of the output waveform, degrading the system performance. Unlike the MZ modulator, our vector transmitter changes the carrier level by controlling the power of the CW light from the reflection branch. As shown in Fig.1b, carrier-assisted modulation just moves the modulation field transfer function up, resulting in the appearance of a residual carrier component without any waveform distortion.

Experimental Setup

The experimental setup is shown in Fig.2. A detailed description of the transmitter setup and control can be found in reference 6 and 7. In the experiment, the slave lasers were biased at 43 mA and modulated by electrical waveforms corresponding to I and Q of a baseband OFDM signal. The waveforms were generated using a dual-channel arbitrary waveform generator (AWG), Tektronix AWG7122C with a bandwidth of 9.6 GHz and sampling rate of 10 GS/s.

The baseband OFDM waveform samples are calculated offline based on a PRBS of 2^{17}-1. Both QPSK and 16 QAM constellation mapping were employed. An inverse Fourier Transform size of 256 is used. Of the 256 subcarriers, 224 subcarriers are used for data transmission. Eight-sample cyclic prefix (CP) is placed before and after each OFDM symbol, resulting in a symbol rate of about 36.8 MSym/s for each subcarrier. The nominal data rate for QPSK and 16 QAM mapping are 16.5 Gbit/s and 32.9 Gbit/s, respectively. The two RF waveform streams were amplified by two RF amplifiers to 0.8 Volts peak-to-peak (V_{pp}) and used to directly-drive the two Slave lasers. A LiNbO$_3$-based IQ transmitter was used for performance comparison.

The transmission link consisted of three spans with total transmission distance of 230 km (comprising 150 km SMF-28 and 80 km large effective area fibre (LEAF)). The optical power launched into the transmission link was -1 dBm.

At the receiver side, ASE-generated noise loading was used to adjust the optical signal-to-noise ratio (OSNR). A 0.8-nm optical band pass filter (OBPF) was used to filter out the out-of-band noise. A component of CW light (6 dBm) was tapped from the master laser and used as a local oscillator (LO) for single-polarization homodyne reception. The polarization of the received signal was manually aligned with that of the LO at the receiver. After coherent detection the electrical signal was then sampled by a 32-GHz, 80-GS/s real time oscilloscope before offline processing.

In the experiment, the optical carrier is not

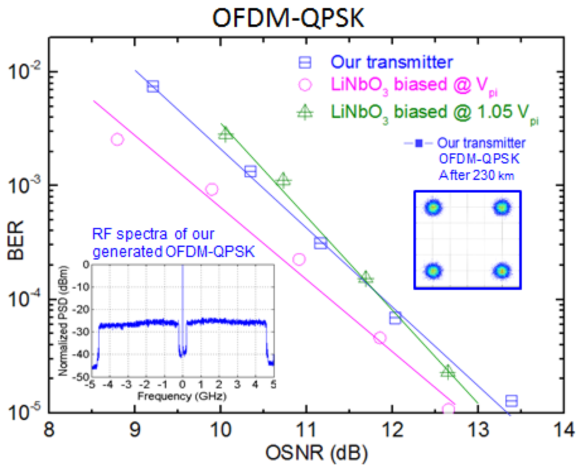

Fig. 3: Performance of our transmitter with OFDM-QPSK.

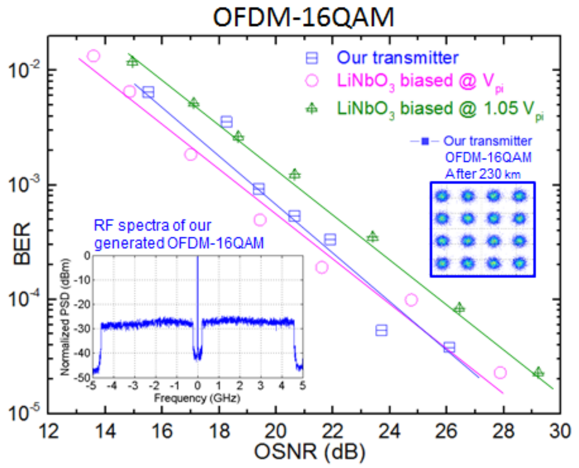

Fig. 4: Performance of our transmitter with OFDM-16QAM.

fully cancelled to generate OFDM with a carrier tone, which results in a carrier-signal ratio (CSR) of -7dB. For comparison, a LiNbO$_3$ IQ modulator was modulated by the same waveform with a peak-to-peak drive voltage of ~0.6 V_π . The carrier-assisted OFDM was generated by biasing the LiNbO$_3$ at 1.05V_π.

A 16% training overhead was used for symbol synchronization and channel estimation. After 1-tap equalization the bit error ratio (BER) was calculated.

Experimental Results

The experimental results for OFDM-QPSK and OFDM-16QAM are shown in Fig.3 and Fig.4, respectively. The spectra and constellation diagram (obtained after 230-km transmission) after equalization are shown as insets. As we see from the spectra, our transmitter shows a linear mapping of electrical signal to the optical domain and clear constellation clusters are obtained. The BER characteristics show that our transmitter is only slightly inferior to our LiNbO$_3$ IQ modulator biased at V_π (0.7-dB and 0.5-dB OSNR penalty for OFDM-QPSK and OFDM-16QAM, respectively, at a BER of 10^{-3}). Subsequently, we bias the LiNbO$_3$ I-Q modulator at 1.05V_π to generate the carrier pilot tone[9-10]. Compared with LiNbO$_3$ based carrier-assisted OFDM, our vector transmitter performed better for OFDM-16QAM and provides similar performance for OFDM-QPSK. This improvement is mostly attributed to the better linearity of direct modulation.

Conclusions

We generated coherent optical OFDM using our new vector transmitter based on direct modulation of semiconductor lasers. Our vector transmitter provides good modulation linearity and can generate carrier-assisted OFDM without nonlinear distortion. Performance comparable to a LiNbO$_3$ IQ modulator is obtained with standard receiver-side DSP only.

Acknowledgements

This research has received funding from EPSRC Fellowship (EP/K003038/1) and HyperHighway grant (EP/I061196X).

References

[1] W. Shieh, "OFDM for Flexible High-Speed Optical Networks," J. Lightwave Technol., Vol. 29, no. 10, p. 1560 (2011).

[2] Xiang Liu et al., "Intra-symbol frequency-domain averaging based channel estimation for coherent optical OFDM," Optics Express, Vol. 16, no. 26, p. 21944 (2008).

[3] R. P. Giddings, et al., "Experimental demonstration of a record high 11.25Gb/s real-time optical OFDM transceiver supporting 25km SMF end-to-end transmission in simple IMDD systems," Optics Express, Vol. 18, no. 6, p. 5541 (2010).

[4] B. W. Hakki, et al., "Evaluation of Transmission Characteristics of Chirped DFB Lasers in Dispersive Optical Fiber," J. Lightwave Techno., Vol. 10, no. 7, p. 964 (1992).

[5] T. Takahara, et al., "Discrete Multi-Tone for 100 Gb/s Optical Access Networks," Proc. OFC, M2I.1. (2014).

[6] R. Slavík, et al., "QAM Synthesis by Direct Modulation of Semiconductor Lasers under Injection Locking," Proc. OFC, JTh2A.32, Los Angeles (2013).

[7] R. Slavík, et al., "Wavelength-tunable QAM Synthesis by Direct Modulation of Injection-locked Fabry-Perot Semiconductor Lasers," Proc. OFC, PDP5B.5, Los Angeles (2013).

[8] R. Slavík, et al., "Optical and RF power requirements for a new injection-locked semiconductor laser diode method compared with conventional approaches for QPSK and QAM modulation," Proc. ECOC, P.3.22, London (2013).

[9] Z. Liu, et al., "Homodyne OFDM using Simple Optical Carrier Recovery," Proc. OFC, W4K.3, San Francisco, (2014).

[10] S. L. Jansen, et al., "Coherent Optical 25.8-Gb/s OFDM Transmission Over 4160-km SSMF," J. Lightwave Technol., Vol. 26, no. 1, p. 6 (2008).

[11] I. Petitbon, et al., "Locking bandwidth and relaxation oscillations of an injection-locked semiconductor laser," J. Quantum Electron. Vol. 24, no.2, p.148 (1988).

[12] E. K. Lau, et al., "Strong optical injection-locked semiconductor laser demonstrating >100-GHz resonance frequencies and 80-GHz intrinsic bandwidths," Optics Express, Vol. 16, no. 9, p.6609 (2008).