Modulator-free Quadrature Amplitude Modulation Signal Synthesis

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Abstract: Coherent synthesis of a complex modulated signal is achieved by simultaneously injection locking two directly-modulated semiconductor lasers. Better modulation linearity and comparable performance to $LiNbO_3$ I-Q modulator is demonstrated.

OCIS codes: (060.1660) Coherent communications; (140.3520) Lasers, injection-locked; (140.3518) Lasers, frequency modulated

1. Introduction

Modern optical communication systems rely on advanced modulation formats and coherent detection. Advanced modulation formats such as optical Orthogonal Frequency Division Multiplexing (OFDM) and Quadrature Amplitude Modulation (QAM) require independent modulation of the amplitude and phase (or the in-phase and quadrature components) of a signal. This has been conventionally achieved by a $LiNbO_3$ I-Q modulator which consists of two Mach-Zehnder modulators (MZM) in a nested structure [1]. Although $LiNbO_3$-based modulators offer unparalleled performance, they are long (centimeter-scale), expensive, and difficult to integrate with the laser, making the dense integration of tens-to-hundreds of transmitters as now required challenging. Consequently, major effort has being directed to obtain equivalent performance using other materials for the modulator including InP [2,3], GaAs[4], and silicon[5]. However, besides parasitic residual phase modulation, these modulators suffer from high propagation loss, relatively larger modulation nonlinearity and requiring broadband RF amplifiers for driving. Nevertheless, through intensive research devices generating QAM signals have recently appeared enabled both by improved modulator design and the use of Digital Signal Processing (DSP) at both transmitter and receiver to compensate for the non-ideal phase and amplitude transfer functions [2,3].

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. However, current modulation of a directly-modulated semiconductor laser is associated with a large frequency chirp [6] which heavily compromises the independence of in-phase and quadrature component of a complex optical signal, limiting the directly-modulated lasers to applications requiring only intensity modulation. Additionally, when used in fiber optic communications, the modulation chirp broadens the optical spectrum (thus lowering the signal spectrum efficiency) and severely degrades the transmission reach.

Recently we proposed a wavelength-tuneable QAM transmitter using optical injection locking of directly modulated semiconductor lasers to suppress the frequency chirp allowing generation of complex modulation formats and showing distinct advantages over current and other currently researched solutions [7]. Our approach to I-Q modulation allows for all the benefits of direct modulation, including high linearity, reduced power consumption, small footprint and ease of integration and opens up a promising new route to the realization of cost-effective, high performance monolithically integrated QAM transmitters.

2. Operation Principle

The schematic of our transmitter is shown in Fig.1. 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 [8], the modulation chirp is suppressed and the lasers' modulation bandwidth can be significantly increased [9, 10]. 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 mutual coherence is critical in our transmitter—it allows us to combine the two directly modulated slaves with a 90° shift, as well as to provide carrier suppression through destructive interference with a component of the master signal.

Besides inherent linearity in the modulation response in our transmitter (that we discuss later), our transmitter (as compared to conventional $LiNbO_3$ IQ modulator) allows for easy manipulation of carrier tone. This carrier manipulation has many potential benefits in coherent optical communications such as easy carrier phase estimation

[11], effective fiber nonlinear compensation as well as all-optical carrier recovery [12]. As shown in Fig.1, our transmitter changes the carrier level by controlling the power of the CW light from the reflection branch. As a result, the carrier power can be manipulated without any waveform distortion. Control of the carrier signal using the MZM is usually done via tuning the modulator bias slightly away from its transmission zero. This is, however, accompanied by a parasitic nonlinear distortion of the output waveform, which degrades the system performance.

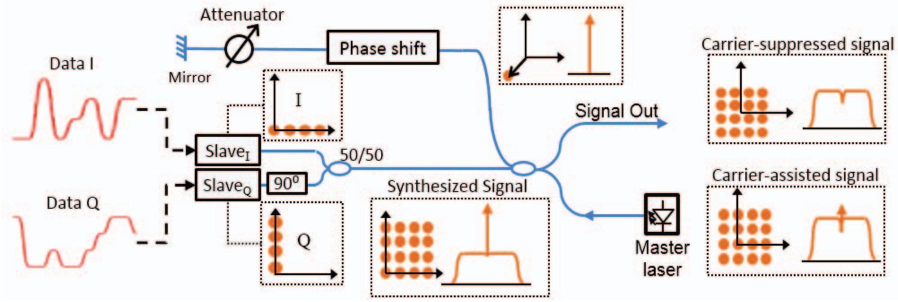

Fig.1 Operation principle of our transmitter.

3. Modulation linearity

The linearity of the modulation response is characterized by the spurious-free dynamic range (SFDR) [13]. Fig. 2 shows the SFDR of an injection-locked slave laser and an MZM operated over a limited range for minimizing non-linear modulation response ($V_{pp} = 1.2V_\pi$ applied in push-pull manner on two electrodes). As shown in Fig. 2, the SFDR of the linearity-optimized $LiNbO_3$ MZM and injection-locked directly-modulated laser was 29 dB and 33 dB respectively, highlighting the level of the inherent linear response expected from our transmitter.

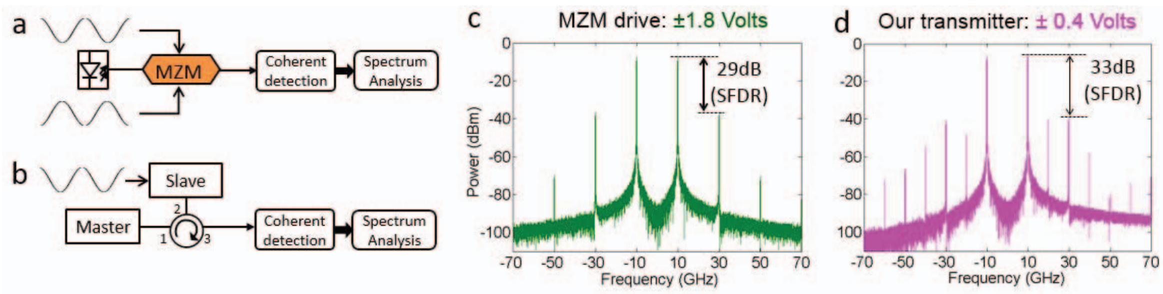

Fig.2 Setup for evaluating the SFDR of (a) $LiNbO_3$ MZM; (b) Injection-locked slave laser. The spectrum of the received signal (after DC block) is shown with at a resolution of 10 MHz for (c) $LiNbO_3$ MZM; (d) Injection-locked slave laser.

4. Proof-of-concept experiment

The experimental setup of our proof-of-concept is shown in Fig.3. A detailed description of the transmitter setup and control can be found in reference [7]. We generated 10-GBaud optical OFDM with subcarriers modulation with 16QAM (32.9 Gbit/s) and up to 28-Gbaud single-carrier QPSK (56Gbit/s) signals using our transmitter. A $LiNbO_3$-based IQ transmitter was used for performance comparison.

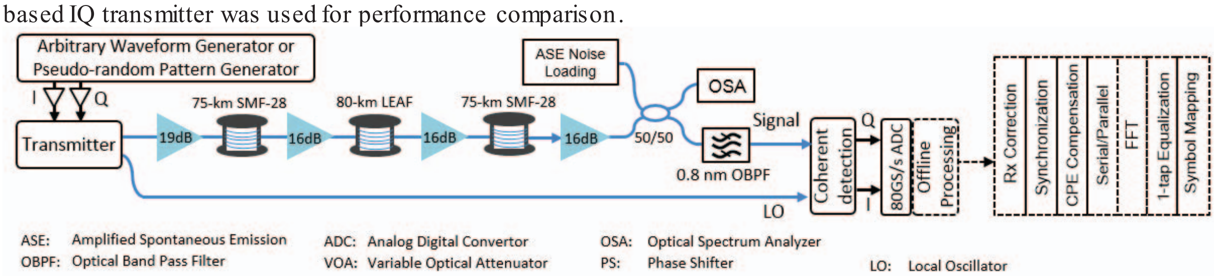

Fig.3 Experimental Setup

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) before pass a 0.8-nm optical band pass filter (OBPF). 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 transmission experiment, the optical carrier is not fully cancelled to generate OFDM with a carrier tone, which results in a carrier-signal ratio (CSR) of -7dB. To improve the linearity of the $LiNbO_3$ I-Q modulator, waveforms with a peak-to-peak drive voltage of ±1.8V (~±0.6V_π) were used, resulting in an increase in insertion loss (~2 dB). The carrier-assisted OFDM was generated by biasing the I-Q modulator 0.05V_π away from the null point.

5. Experimental Results

The bit error ratio (BER) curves for the OFDM and QPSK signals are shown in Fig. 4 (a) and (b), respectively. The spectra and constellation diagram (obtained after 230-km transmission) of the demodulated signals are shown on the right side of the BER results. Clear constellation clusters were obtained after signal demodulation. The BER characteristics show that although our transmitter is slightly inferior to our $LiNbO_3$ IQ modulator biased at V_π (0.5-dB OSNR penalty at a BER of 10^{-3}), it performs better than our $LiNbO_3$ IQ modulator biased at 1.05V_π (used to generate the carrier pilot tone). This improvement is mostly attributed to the better linearity of direct modulation. Further, we investigated the maximum baud rate at which we can operate our transmitter. As shown in Fig. 4(b), by injection locking the slave lasers optimized for 2.5 GHz operation, we achieved a modulation bandwidth of 14 GHz, allowing us to obtain error-free QPSK signal at 20 GBaud and sub-FEC limit 28-GBaud QPSK signal.

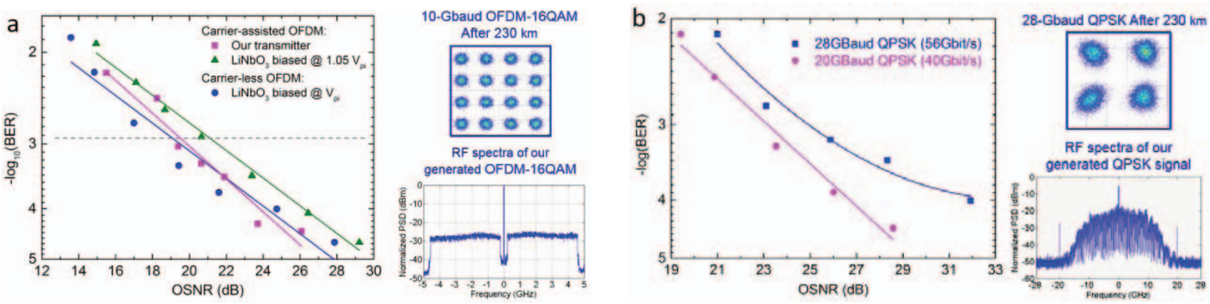

Fig.4 Performance of our transmitter with different modulation formats (a) OFDM-16QAM; (b) 20GBaud and 28GBaud QPSK.

6. Conclusion

We generated 10-GBaud coherent optical OFDM and up to 28-GBaud QPSK signals using a transmitter based on direct modulation of semiconductor lasers. Our transmitter provides good modulation linearity and need only half as many RF signals compared to Mach-Zehnder style IQ modulators. We expect significant improvements of modulation bandwidth when using optimized directly-modulated lasers, especially when these are integrated onto a single photonic chip (for example, InP) as we envisage doing. We consider that this makes our transmitter an ideal candidate for Metro and Access networks where power consumption is the primary concern.

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