Fast Wavelength Switching Digital Coherent OFDM Transceiver

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Abstract Digital dynamic frequency offset removal and DC pilot tone assisted phase noise compensation enables the use of commercially available DS-DBR lasers as both the transmitter and LO in a coherent wavelength switched OFDM transceiver. A 1.5dB penalty relative to low linewidth static lasers is demonstrated under fast wavelength switched operation.

Introduction
The combination of higher order spectrally efficient modulation formats, digital coherent reception and fast wavelength switching semiconductor tunable lasers, provide the platform for truly dynamic sub-wavelength switched optical networks, with nanosecond reconfiguration times at both the transmitter and the digital receiver [1]. The inherent frequency selectivity of coherent detection and the wavelength tunability of semiconductor tunable lasers offer significant potential to inter data center networks or converged metro networks that utilize burst or packet switching, as it can provide either rapid bandwidth provisioning or fast protection switching.

The authors have previously demonstrated the performance of a fast switching DS-DBR laser within a burst mode transmitter and as a dynamic local oscillator within a digital burst mode receiver [1,2]. Blind equalization was utilized within the receiver digital signal processing (DSP) and a global burst-timing clock was employed to ensure optimum burst detection was achieved. However, burst detection and dynamic channel estimation, based on a burst header, is an important aspect of a burst mode receiver in a practical network. Header design and recovery has been previously investigated for single carrier coherent burst mode receivers [3].

In this work, the authors demonstrate for the first time, to the best of our knowledge, a fast switching coherent orthogonal frequency division multiplexing (OFDM) transceiver that utilizes commercially available fast switching semiconductor tunable lasers at both the transmitter and as the LO within a digital coherent receiver. We exploit the framing and training symbols that are inherent to OFDM systems, for burst detection, time synchronization and channel estimation [4]. We demonstrate that coherent optical OFDM is compatible with the large laser phase noise (1-2MHz) and low frequency 1/f noise (~100MHz) that is typically associated with fast tunable semiconductor lasers. In addition to this, the use of the cyclic prefix in OFDM systems to accommodate chromatic dispersion, also solves the problem of fast channel dispersion estimation that is required in single carrier systems, to accommodate the variable path history that occurs in burst switched networks.

Coherent OFDM Transceiver
The coherent OFDM transceiver experimental setup is illustrated in Fig. 1. A commercially available DS-DBR tunable laser switched between two 50GHz spaced channels on the ITU grid (193 and 193.057GHz), with a burst length equal to the OFDM frame period (1.8µs). Four current tuning sections of the DS-DBR laser and the integrated semiconductor optical amplifier (SOA) were directly driven from a 250MS/s arbitrary waveform generator (AWG), which allowed it to be rapidly tuned (to within ±100MHz of the desired channel frequency in 50ns) between the two ITU channels [5].

The OFDM frames for each burst channel were generated offline in MATLAB. An FFT size of 512 was used, of which 256 carriers were encoded with quadrature phase shift keyed (QPSK) modulation. Twenty training symbols, at the beginning of each frame, were used for synchronization and channel estimation. A number of subcarriers (15-subcarriers) were removed around DC, which allows for the detection of a DC component at the receiver, thus enabling DC pilot assisted dynamic frequency offset removal and phase noise compensation, as explained in the proceeding.
The OFDM waveforms were quantized and uploaded to two 12GS/s AWGs that provided the in-phase and quadrature components for each polarization, which were subsequently applied to an integrated dual-polarization IQ modulator. The actual bit rate per WDM carrier after the OFDM and forward error correction (FEC) overhead has been removed was 18Gb/s. It is important to note that the upper limitation of this bit rate is due to the electrical bandwidth response of the AWGs available to us at the time of this work.

The burst switched DP-OFDM signal was amplified to overcome the insertion loss of the integrated modulator before being passed into a digital coherent receiver. A second DS-DBR laser, driven in an identical fashion to the transmitter, was used as the LO in the coherent burst mode receiver. The LO frequency was tuned to coincide with the transmitted burst channels. The side mode suppression ratio for each channel was greater than 45dB and the output power was 12dBm. The transmitted channels were coherently detected and processed offline using MATLAB. An amplified spontaneous emission (ASE) noise source was employed to vary the receivers optical signal to noise ratio (OSNR).

Receiver DSP

At the transmitter, the ODFM symbol length ($L_{sym}$) was set to 512 samples, to which a cyclic prefix (CP) ($L_{cp}$) of 30 symbols was appended in order to accommodate chromatic dispersion. To cope with the combined linewidth (> 2MHz) of the tunable transmit and local oscillator lasers it is essential to first track the intermediate frequency (IF) and to subsequently compensate for the phase variation. An RF pilot tone based technique similar to that proposed by Jansen et al. [6] was employed. The RF pilot was placed at the center of the OFDM spectrum by adding a DC bias to the X-polarization IQ modulator drive voltage. To sufficiently accommodate the 2MHz laser linewidth, 1/f noise and to avoid crosstalk from the data carriers, a guard-band of 350MHz was inserted between the RF pilot tone and data carriers.

The burst mode OFDM receiver used block based processing that is suitable for implementation on an ASIC and a schematic illustration of the important DSP blocks are illustrated in Fig. 2. The received signals are sampled and firstly converted from serial to parallel into blocks of length, $L_s = L_{sym} + L_{cp}$. To track the dynamic intermediate frequency (IF) variation that arises from the laser switching, as seen in Fig. 3(a), the RF pilot was identified per block using a fast Fourier transform (FFT) and peak search. To improve the frequency estimate, a quadratic interpolation technique was used to find the maximum of the FFT by using three points around the peak of the calculated frequency spectrum [7].

![Fig. 2: Receiver DSP functions](image)

The estimated frequency offset was subsequently removed from each block. The RF pilot tone was then filtered from the signal using a 140MHz bandwidth low-pass filter (LPF), conjugated and then multiplied with the signal block to compensate the phase variation, as seen in Fig. 3(b). The frame timing (synchronization) was subsequently recovered using the Schmidl and Cox approach [8] and the cyclic prefix was removed. The training symbol (TS) based channel estimation scheme proposed by Liu et al. [9] was used to estimate the channel where the response was averaged over 20 symbols. A MIMO equalizer compensated the channel response and 16 data pilots were used to compensate any remaining phase error within each symbol.

![Fig. 3: (a) Received coherent optical OFDM signal and (b) frequency offset and phase noise compensated OFDM signal](images)

Results and Discussion

Figure 4 illustrates the power profile and the intermediate frequency of the two burst channels when both the transmitter DS-DBR laser and the receiver DS-DBR laser were switching synchronously. Both the power and instantaneous frequency are estimated on a block per block basis as depicted in Fig. 2. It is evident from Fig. 4(b) that the IF for both burst channels varies over approximately 100MHz. In order to track this frequency effectively, the output of both burst switched lasers must be blanked for a sufficient amount of time to allow each laser to switch to within a few hundred
MHz of the desired channel frequency. This is achieved by turning the integrated SOA off for a very short period of time, which varies slightly over the switching map [10].

To analyze the performance of the coherent optical OFDM transceiver, the system was initially characterized using two low linewidth static lasers to provide a performance benchmark. The transmitter laser was a RIO fiber laser (10kHz linewidth) and the LO in the coherent receiver was a conventional external cavity laser (ECL) with a 200kHz linewidth. Fig. 5 illustrates the measured bit error rate (BER) as a function of the received OSNR (measured over a 0.1nm bandwidth). This low linewidth laser combination incurred a 1.8dB OSNR penalty relative to theory at a BER of 3.8x10^-3.

Conclusions

The authors have demonstrated the first coherent optical burst switched OFDM transceiver that utilizes commercially available semiconductor tunable lasers. An OSNR penalty of 3.2dB was incurred relative to the theoretical limit under burst switched operation.

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