Flexible All-Optical OFDM using WSSs

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Abstract: A LCOS WSS implements an optical inverse Fourier transform for 10-Tb/s OFDM signal generation and cyclic prefix insertion. After 857.4 km of dispersion uncompensated transmission, a second WSS implemented optically-banded digital subcarrier demultiplexing.

OCIS Codes: (060.4080) Modulation; (060.4230) multiplexing; (070.7145) ultrafast processing.

1. Introduction

Optical super-channels use densely packed subcarriers to achieve >1-Tb/s, overcoming the bandwidth limitations of electronics [1, 2]. All-optical orthogonal frequency division multiplexing (AO-OFDM) [3] is an attractive format for super-channels because it does not require digital to analog converters (DACs) or digital signal processing (DSP) at the transmitter. Data rates beyond 10 Tb/s [4, 5] and spectral efficiencies greater than 6 bit/s/Hz [1] have already been experimentally demonstrated. However, fast symbol transitions are required to maintain orthogonality between subcarriers and minimize inter-carrier interference (ICI).

To reduce the bandwidth of the electronics, subcarriers can be generated from modulated optical pulses using optical inverse Fourier transforms (OIFT) [6]. OIFTs based on fiber Bragg gratings [7], arrayed waveguide grating routers [6, 8, 9] and liquid crystal on silicon (LCOS) [5] have been used to optically multiplex OFDM subcarriers. Cyclic prefix (CP) insertion is essential because they reduce the required receiver bandwidths [10], but has only been optically implemented for a five-subcarrier system [7].

In this paper, we generate a 10.08-Tb/s AO-OFDM signal using a commercial LCOS wavelength selective switch (WSS). The WSS was programmed to perform a 'cyclically extended' OIFT, which multiplexed 252 colorless subcarriers onto orthogonal frequencies and inserted a CP. At the receiver, another WSS was used to create a strongly overlapping optical demultiplexer, which allows digitally demultiplexing of multiple subcarriers and simultaneous recovery of all subcarriers without the loss associated with star-couplers [11]. The 10.08-Tb/s signal was transmitted over 857.4 km of dispersion uncompensated fiber with EDFA-only amplification; the *Qs* of all subcarriers were >8.8-dB, corresponding to a BER of $<3\times10^{-3}$.

2. Optical multiplexing and digital demultiplexing of AO-OFDM signals

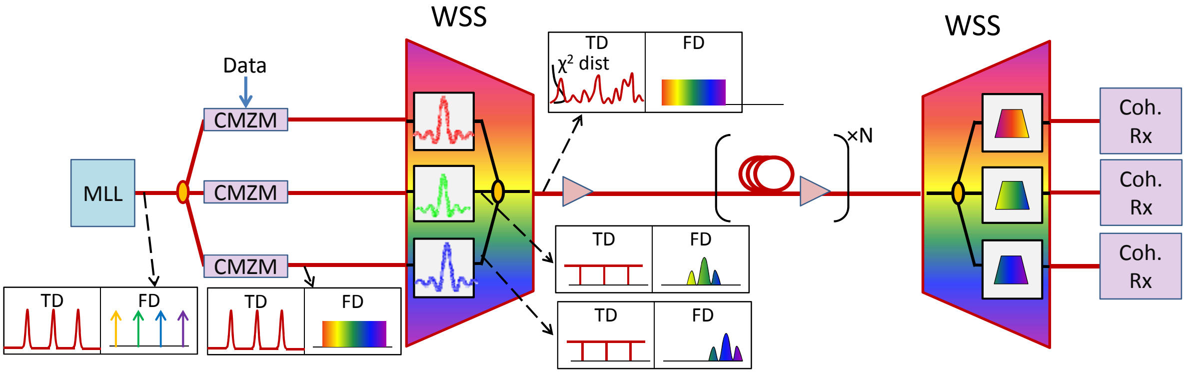

Fig. 1. Proposed architecture for AO-OFDM using WSSs. .

Fig. 1 shows the architecture of our system. At the transmitter, a single mode locked laser (MLL) is split into *N* paths and each is independently modulated at one symbol per pulse, converting the comb-line spectrum into a white spectrum. Each modulated pulse train is converted into a subcarrier by the OIFT, by convolving with a rectangular-envelope time-domain (TD) impulse response of duration 1/*R*, where *R* is the repetition rate of the MLL, corresponding to an *R*-rate sinc in the frequency domain (FD). This is analogous to electronically generated OFDM systems [12]. A CP is implemented by spacing the center frequencies of the subcarriers at >*R*. This CP is critical because it increases the tolerance to CD [1, 7, 13] and reduces the required receiver bandwidth [10]. This architecture allows optical super-channel generation without DACs or DSP, reducing energy consumption.

We use the configurable frequency response of an LCOS based WSS to program it as an OIFT for optical OFDM multiplexing and CP insertion [14]. The ability for simultaneous spectral shaping and combination, avoids the loss of a star coupler in an FBG implementation. It is reprogrammable, which allows greater flexibility than AWGRs and allows subcarriers to be multi-cast onto several frequencies [15] and dynamic subcarrier allocation – subcarriers can be inserted wherever free spectrum is available. Such functionalities could be obtained by reprogramming existing LCOS WSSs in a system.

Digital subcarrier demultiplexing allows precise compensation of CD before subcarrier demultiplexing [16], which is non-trivial for terahertz signals [17]. Although optical demultiplexing techniques [8, 9, 11] have been demonstrated, digital demultiplexing is more practical for long-haul transmission. In order to simultaneously receive all subcarriers, a strongly overlapping optical demultiplexer is required [11]. We create an optical demultiplexer with an overlap between neighboring digital channels by directing light to two ports of an LCOS WSS simultaneously. This allows all subcarriers to be simultaneously recovered without ICI. Each band is equalized independently after a coherent receiver, analogous to digital sub-banding [18]. Detecting and demultiplexing multiple subcarriers with each coherent receiver, enables the coherent receiver and CD compensator to be shared, reducing the net receiver cost and energy consumption [16].

3. Experimental setup

Fig. 2 shows the experimental setup. An MLL provides 2-ps pulses at 10.0-GHz, locked to an external RF clock. A highly-nonlinear fiber broadens the spectrum. A Finisar Waveshaper selects 3 THz of the spectrum and compresses the pulses. The pulses were then QPSK modulated by a complex optical modulator (CMZM) driven with 2×10-Gb/s signals, generated with a 2-port BERT. A polarization multiplexed (PM) signal was generated with a PM emulator with a 1-m delay, corresponding to exactly 50 symbols. The pol-mux signal was split into 4 paths; each path was decorrelated by an integer number of bit periods, differing in length by ~2 m, and then fed into the four inputs of a 4-port LCOS based WSS (Finisar). Each port is programed with the sum of 63 10-GHz sinc functions spaced 44-GHz with each port offset by 11 GHz, which inserts a 10% CP. The WSS simultaneously filters and combines the four inputs to create the 2.8-THz 10.08-Tb/s optical OFDM signal thus performing an OIFT.

Our recent numerical simulations with ideal components revealed that the Q factor of no-CP AO-OFDM was limited to ~13 dB with fully decorrelated subcarriers and four-times oversampling at the receiver. Yet we experimentally demonstrated Qs of >15 dB after 400-km transmission for a system where every fifth subcarrier contained the same data stream [5]. This suggests that without a CP, AO-OFDM cannot be effectively digitally demultiplexed at four-times oversampling, making many previous results contentious, including our own [5]. However, if a 10% CP allows Qs of >20 dB are obtained with independent subcarriers and four-times oversampling. Most importantly, no observable benefit resulted from having every fifth subcarrier carry the same data.

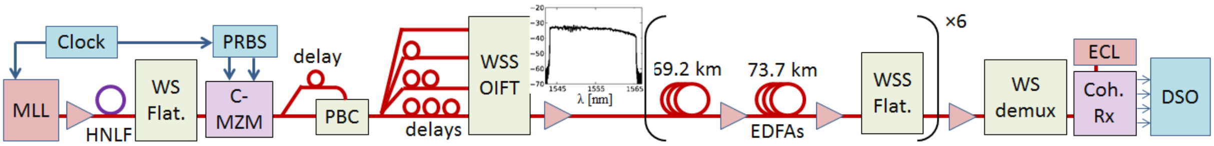

Fig. 2. Block diagram of the experimental setup. PRBS – bit pattern generator; WS - Waveshaper.

The signal was amplified and fed into an optical recirculating loop. A Waveshaper compensated for EDFAs' gain tilt, which were not gain flattened. Attenuations of up to 11 dB were used at some frequencies. The signal was received after six recirculations or 857.4 km.

At the receiver, another 4-port WSS was used to split the signal up into 66-GHz bands spaced 33-GHz apart; each frequency was directed to two output ports to create the spectral overlap required. A coherent receiver, with a carrier wave local oscillator, was used to down-convert the optical signal. A 4×80 GS/s real-time digital sampling oscilloscope (DSO) digitized the signal for offline signal processing. The signal was down-sampled to 60 GS/s before CD compensation was performed. A 25-tap 1/6-spaced TD-equalizer (TDE) was used to demultiplex the subcarriers and compensate for polarization mode dispersion (PMD) and residual CD. Using six-times oversampling allows three subcarriers to be demultiplexed simultaneously without penalty, after shared CD compensation, giving a net oversampling ratio of two-times. The 80 GS/s DSO outputs allow five subcarriers to be demultiplexed, further decreasing the net oversampling ratio. However, in our system, the first and fifth subcarriers carry the same data, which represents frequency diversity and gives a 3-dB sensitivity improvement relative to independent data transmission. This unrealistically improves performance. Down-sampling to 60 GS/s was performed to avoid gaining this advantage. The subcarriers were selected only by tap-initialization of the TDE [10]. Finally, Viterbi-Viterbi phase recovery is used for carrier phase recovery.

4. Experimental results

Fig. 3(a) shows the *Q* of all subcarriers after 857.4 km transmission. All subcarriers are have a *Q* >8.8 dB, which corresponds to the hard FEC limit of $3.0{\times}10^{-3}$. The subcarriers at the edge of the band are significantly compromised because the gains of the EDFAs' at the edges of the OFDM signal were significantly less than the middle, reducing the OSNR at the edges.

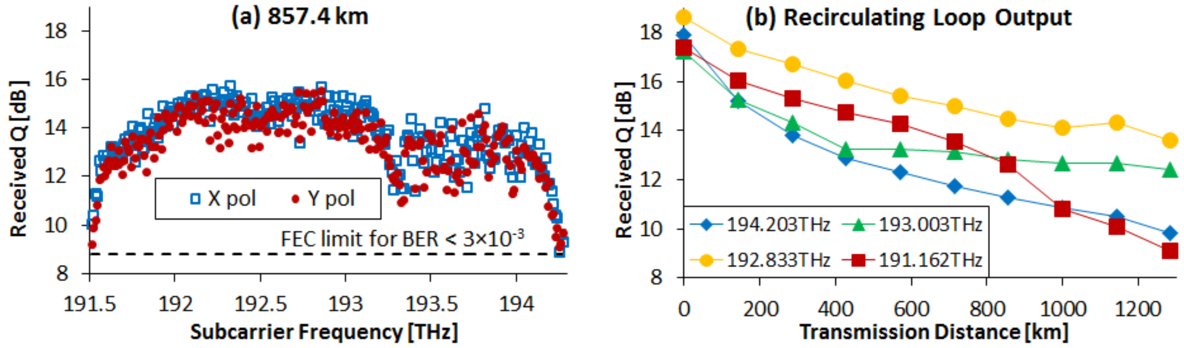

Fig. 3. Received signal *Q*s: (a) against subcarrier index after 857.4 km; (b) against transmission distance.

Fig. 3(b) shows the *Q* of subcarriers ten in from either edge and of two middle channels for different numbers of recirculations. All measured subcarriers are error free even after nine recirculations or 1286 km.

5. Conclusion

We use single LCOS-based WSS for optical OFDM multiplexing with simultaneous optical generation of a CP to reduce ICI. This enables DAC free generation of optical super-channels in existing optical networks using a single light source, increasing transmission capacity and energy efficiency. Additionally, the subcarrier wavelengths are determined only by the WSS, and so can be inserted wherever free bandwidth exists, increasing system flexibility. We demonstrated our technique by creating a 10.08-Tb/s AO-OFDM signal with a 10% CP using a WSS and a single MLL. We avoid obtaining a benefit from having correlated channels by having four decorrelated channels and a CP. Another WSS was programed to be an overlapping demultiplexer, which enables all subcarriers to be simultaneously equalized and demultiplexed at a net oversampling ratio of two. All subcarriers of the 252 40-Gbps super-channel were above the hard FEC limit of $3.0{\times}10^{-3}$ after 857.4 km transmission.

Acknowledgements

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