All-Optical OFDM With Cyclic Prefix Insertion Using Flexible Wavelength Selective Switch Optical Processing

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***Abstract*—We demonstrate that the optical Fourier transform and cyclic prefix in an all-optical OFDM transmitter can be simultaneously implemented using a liquid crystal on silicon wavelength selective switch (WSS). The design uses phase-modulated optical pulses at the inputs of the WSS; this has the advantage that the optical modulators are only sampled by the optical pulses once per data-symbol, so that the transition times between the data symbols are irrelevant to the performance of the system, allowing slow optical modulators to be used. Furthermore, each input of the WSS can be assigned to any combination of output subcarrier frequencies, including frequencies unrelated to the modal frequencies of the comb source. This is especially useful for testing in-service ultra-high bandwidth systems by applying additional wavelengths. As an example, we generate a 10.08 Tb/s signal and transmit along 857.4 km of fiber using 252 10-Gbaud subcarriers with a 10% cyclic prefix. We use an optically-banded digital subcarrier demultiplexer to simultaneously detect three subcarriers using a single coherent receiver.**

***Index Terms*—All-optical OFDM, liquid crystal on Silicon (LCoS), optical communications, optical modulation, Orthorgonal Frequency Division Multiplexing (OFDM), transmission, wavelength selective switch (WSS).**

I. Introduction

As the demand for communications capacity increases, there is a corresponding imperative to use the available bandwidth of optical fibers more efficiently, to reduce the cost per bit. Optical super-channels, based on techniques such as orthogonal frequency division multiplexing (OFDM) [1], [2] and Nyquist wavelength division multiplexing (N-WDM) [3], [4] offer high spectral efficiencies, and data bandwidths of more than 1 Tb/s.

Because optical modulators and associated electronics have a limited bandwidth, a superchannel must be assembled from lower-bandwidth channels. N-WDM and traditional OFDM rely on high-bandwidth electronic digital to analog converters (DACs) at the transmitter for signal generation, together with passive optical couplers to combine the OFDM superchannels or N-WDM channels. All-optical OFDM (AO-OFDM) [5] is a method of generating the OFDM superchannel without needing high-bandwidth (DACs) or digital signal processing (DSP) at the transmitter. Recent developments in high-speed DACs has made N-WDM more attractive, because of the lower required receiver bandwidth. However, the increased transmitter complexity of N-WDM may mean AO-OFDM techniques are more cost and energy efficient for future systems. Studies have suggested that the performance of N-WDM and CO-OFDM are similar [6].

AO-OFDM experiments have now achieved data rates beyond 10 Tb/s [7], [8] and spectral efficiencies greater than 6 bit/s/Hz [9]. However, it is extremely important to minimize inter-carrier interference (ICI) and maintain orthogonality between the subcarriers. Traditionally AO-OFDM signals have been generated by passively combining individual signals spaced at the baud rate [5], [7], [10], [11]. For this method, regularly spaced frequency comb lines, usually generated by a mode-locked laser, are first demultiplexed before each is modulated with data symbols. These modulated comb lines, called subcarriers, are then recombined using a frequency-independent coupler. With this technique, the orthogonality between the subcarriers, and thus the quality of the demultiplexed symbols after the receiver Fourier transform, relies on having very fast transitions between subsequent modulated symbols, and is therefore limited by the bandwidth of the transmitter electronics and the modulator. To circumvent this problem, the subcarriers can be generated by splitting the output of the comb source into several paths, each containing identical pulses; that is, the splitter is frequency-independent. Each path is then modulated with data symbols. The center wavelength and spectral profile of each path is then defined using an optical inverse Fourier transform (OIFT) after the modulators, which also combines the subcarriers [12]. When considered in the time domain, the optical pulses sample the states of the modulators only at the centers of the data symbols. Thus the speed of the transitions between symbols becomes much less critical. In practice, the OIFT can be implemented using multiple fiber Bragg gratings [13], an arrayed waveguide grating router [12], [14]–[16], circuits with trees of delay line interferometers [17], or a liquid crystal on silicon (LCoS) wavelength selective switch (WSS) [8], [18].

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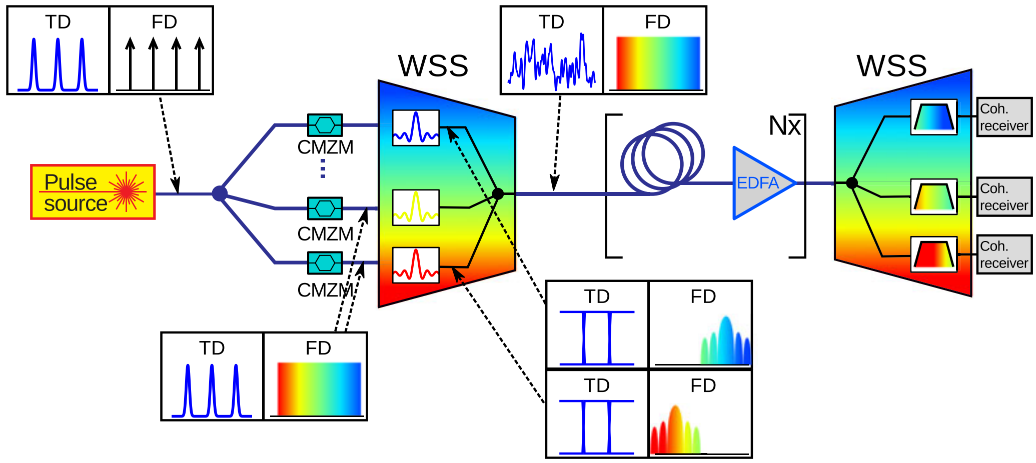

Fig. 1. Operating principle of the optical OFDM multiplexer and demultiplexer. TD, FD: time domain and frequency domain, CMZM: complex Mach–Zehnder modulator.

To achieve low inter-subcarrier-interference in the presence of component imperfections, band-limited receivers and uncompensated dispersion, the extension of data symbols using a Cyclic Prefix (CP) insertion is essential [19]. In electrical OFDM, this is achieved by prepending the end of each symbol to the start of the same symbol. A similar functionality can be achieved in AO-OFDM, but has only been optically implemented for a five-subcarrier system [13].

In this paper, we show that a commercial LCoS WSS can be used to implement the OIFT and the cyclic prefix, and another WSS can be used at the receiver to demultiplex the subcarriers. We demonstrate a 10.08 Tb/s AO-OFDM superchannel, containing 252 colorless subcarriers each with a 10% CP. At the receiver, another WSS was used to create a strongly overlapping optical demultiplexer, which allows digitally demultiplexing of the spectrally overlapping OFDM subcarriers, and simultaneous recovery of all subcarriers without the loss associated with star-couplers [20]. To demonstrate the quality of the signal, it was transmitted along 857.4 km of dispersion uncompensated fiber with EDFA-only amplification. After transmission the signal qualitiy (Q) of every subcarrier was better than 8.8-dB, corresponding to a BER of less than 3×10^{-3}.

II. Principle

Fig. 1 depicts the operating principle of our system. At the OIFT transmitter, the output of a mode locked laser (MLL) is passively split into N paths. Each path is then independently modulated with one quadratic-amplitude modulation symbol per optical pulse. The short optical pulses from the MLL sample the modulator's state at the middle of each symbol. The modulation converts the discrete comb-line spectrum of the MLL into a continuous white spectrum. Each modulated pulse train is then coupled to the parallel inputs of the LCoS WSS.

A. Optical Inverse Fourier Transform Filter

The functionality of the inverse Fourier transform in an OFDM transmitter and the forward Fourier transform in an OFDM receiver can be implemented in the optical domain using interferometric circuits [17], [21]–[23], specially designed arrayed waveguide gratings [12], [14]–[16] and FBGs [13]. The OIFT is implemented by multiplying the white spectrum of an input by a filter with a sinc-shaped spectral transfer function of width f_R and center frequency f_0. To generate the OFDM super-channel, the different inputs to the OIFT filter are shaped by sinc-filters with their centre frequencies spaced at f_R if no CP is added. The resulting spectra are then passively combined to form the super-channel. This is analogous to the digital processes in electrical OFDM systems [8], [18], [24]. In the time domain (TD) the OIFT corresponds to a convolution of the modulated pulse train with a rectangular envelope of duration $1/f_R$, and optical carrier wave f_0, where f_R is the baud rate of a single subcarrier.

In contrast to electronic OFDM, where the CP is inserted by duplicating the extreme time-samples and then repeating them at the other end of the OFDM symbol, to implement a CP in AO-OFDM, the spacing of the center frequencies of the subcarriers is increased, while the baud rate and MLL pulse rate are kept as before. Importantly, the spectral width of the sinc-filters is kept at the baud rate f_R. This adjustment effectively reduces the OFDM symbol duration (the inverse of the subcarrier spacing) to shorter than the MLL pulse spacing (the inverse of the baud rate), to leave time for the CP. The CP is automatically generated because the duration of the impulse response of the filter equals the MLL pulse spacing, so fills the entire time interval between the MLL pulses (see reference [25] for a detailed discussion). This CP is critical because it increases the tolerance to CD [7], [13], [26] and reduces the required receiver bandwidth [19].

We use the advanced functionality of a LCoS-based WSS to implement the OIFT and CP insertion. Multi-input (or output) transfer function filters can be created by using the ability for wavelength-dependent, programmable combination of light from different ports with phase and attenuation control for each input wavelength component [24]. Thus, by choosing the correct transfer-function, i.e. a sinc-shaped profile centred at different frequencies for different input ports combined into a single output, it is possible to implement the OIFT and CP insertion simultaneously. A theoretical transfer function of such an OIFT

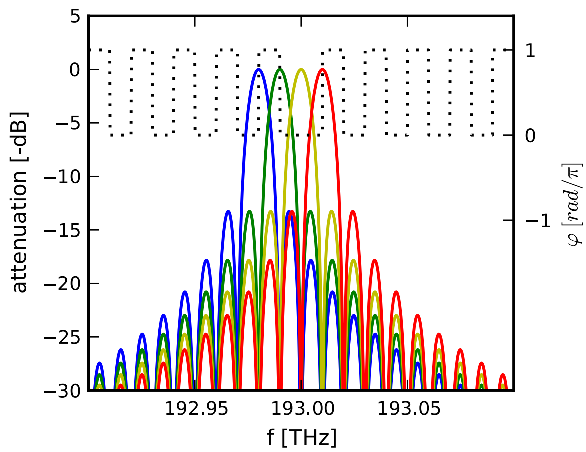

Fig. 2. Ideal transfer function of an OIFT filter for combining four subcarriers: solid colours—the attenuation profiles for the different inputs into the OIFT filter, note that the attenuation profiles are plotted on an inverted scale for clarity reasons; dotted black—Phase response for the yellow channel.

filter is shown in Fig. 2. The ability to simultaneously spectrally shape and combine input paths avoids the intrinsic loss of using a star coupler in an FBG implementation. The WSS is also readily reprogrammable, allowing greater flexibility than AWGRs. This enables good control over the frequency responses (and therefore the impulse responses) for light from each input port to the common port, tailoring the responses as required. In particular this flexiblity means that the baudrate to the inputs be varied at will, while the frequency (impulse) responses are modified to track this change. In contrast, in other AO-OFDM implementations this rate is fixed due to the inflexible photonic structure of the OIFT filter. The Flexibility further allows each input can be allocated to any output frequency, even a frequency that is not a mode of the MLL. Therefore, subcarriers can be inserted wherever there is room in the fiber's spectrum. Also, inputs can be to be multi-cast onto several frequencies. This is especially useful when creating ultra-wide bandwidth test signals for loading prototype optical systems [27].

B. Digital Demultiplexer

All-optical demultiplexing of AO-OFDM subcarriers has been previously demonstrated [7], [20], [22], [28], [29]. However, demultiplexing the individual AO-OFDM subcarriers all-optically requires near-perfect CD compensation before the demultiplexer to avoid inter-symbol interference (ISI), which is very difficult to implement optically for signals with terahertz bandwidths [30]. Addtionally, the subcarrier frequencies of the demultiplexer must exactly match those of the multiplexer on the transmitter side. This would require trimming and perhaps active control of the optical demultiplexer. We chose to perform the demultiplexing partially using digital signal processing (DSP). Fig. 3 shows the concept of our receiver. The super-channel is first banded optically using an optical demultiplexer. Multiple subcarriers (three in the figure) are electrically demultiplexed and equalized with each coherent receiver using self-optimizing digital equalizers. The self-optimizing equalizers improve system performance by compensating for the exact CD in the

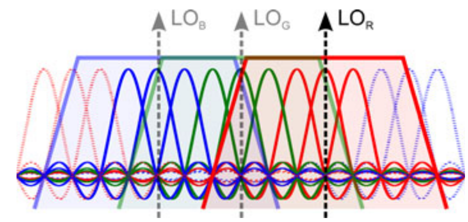

Fig. 3. Conceptual spectrum illustrating the banding at the receiver.

system before subcarrier demultiplexing [10] and by automatically tuning to the center frequency of the subcarrier, which was determined by the multiplexer at the transmitter [19].

In order to demultiplex OFDM digitally without ICI, the coherent receiver must capture a significant portion of the spectral tails of all the subcarriers that are being demultiplexed (the bandwidth requirements of receivers is discussed in more detail in Section III). Therefore, each port of the optical demultiplexer must be "strongly overlapping" with neighboring ports, to enable all subcarriers to be detected simultaneously with multiple coherent receivers. This could be provided by using a star coupler, feeding a bank of lower-bandwidth coherent receivers. However, the power penalty would be proportional to the number of coherent receivers needed, thus this solution is not scalable. Our solution is to program the LCoS WSS to have output ports with overlapping spectral bands; each frequency is output to two output ports simultaneously. The power penalty associated with this design is 3 dB plus the loss of the LCoS WSS and is scalable to the number of ports on the WSS. Each band of subcarriers is down-converted using a separate coherent receiver. The CD is estimated and compensated using a frequency-domain equalizer. A self-optimizing fractionally-spaced time-domain equalizer (FS-TDE) is then used to simultaneously equalize the polarization mode dispersion (PMD) and demultiplex the individual subcarriers. Algorithms commonly used for single-carrier systems, such as the constant modulus algorithm and least-mean square algorithm, are all suitable for AO-OFDM systems [19], [31]. For sensible CP lengths of 10–20%, around four-times the Nyquist bandwidth is needed for single subcarrier demultiplexing without significant ICI. This implies that to reduce ICI requires that either: (a) the receiver's bandwidth and sampling rate are increased, or (b), the duration of the CP relative to the OFDM symbol is increased. To demultiplex an additional subcarrier, the oversampling factor must be increased by one; thus, an oversampling factor of five will support reception of two subcarriers, oversampling by six will support three subcarriers, and so forth. Therefore, depending on the baud rate of the subcarriers and the bandwidth and sampling rate of the receiver, several subcarriers can be received simultaneously using the same receiver. Detecting multiple subcarriers is more efficient as it allows the CD compensator to be shared between multiple subcarriers, reducing the multiplications per bit associated with CD compensation [10]. Additionally, signals with a symbol rate of a few gigahertz are optimal in nonlinearity-limited links [32]–[34]. Thus, sharing a moderate-bandwidth receiver and subsequent processing between a several subcarriers spaced at a few-GHz is desirable in a nonlinearity-limited optical system and furthermore allows to re-use coherent receivers from established 100 GE systems. Compared to receivers that demultiplex OFDM using optical FTs [21], [28], we use the DSP for demultiplexing, plus CD and PMD compensation.

III. Importance of CP

AO-OFDM both with [21], [28] and without CP [8], [35], [36] has been experimentally demonstrated. However, in order to demultiplex an OFDM signal without ISI and ICI, an entire OFDM symbol without symbol transitions must be captured by the demultiplexer, typically an optical Fourier transform [21], [23], [37] or a digital finite impulse response (FIR) filter [19], [35]. Therefore, this theory implies that to demultiplex an OFDM signal without any CP requires the entire OFDM channel to be captured by the demultiplexer. Since AO-OFDM signals usually have much greater bandwidths than the coherent receiver, digital demultiplexing of AO-OFDM signals without a CP is impossible.

Experimental demonstrations of AO-OFDM have predominantly used 'odd-and-even channels' [7], [36], [38]. This method involves generating two different data streams to make adjacent channels different in an attempt to obtain an indication of ICI in a realistic scenario, where all subcarriers carry different data. However, recent experimental demonstrations have shown that 'odd-and-even channels' produce unrealistically good results, especially in cases where no CP is used, because the adjacent subcarriers produce the same interference [39], [40].

In order to produce results indicative of a installed system, which would obviously carry different data on each subcarrier, we have recently demonstrated AO-OFDM with four decorrelated subcarriers [8], [18]. In this system, the neighbors on either side are different and therefore should estimate performance accurately. These experiments suggested that using four-times oversampling at the receiver was sufficient to demultiplex an AO-OFDM super-channel without a CP [8], which is consistent with previous observations [38]. However, numerical simulation results of our system with independent data on all subcarriers were several dB worse than the experimental results, suggesting that even four decorrelated subcarriers is insufficient to generate realistic results. This finding suggests that numerous experimental demonstrations performed using two or four decorrelated subcarriers, including some of our own, would be unrepeatable if all subcarriers contained independent data.

To systematically investigate this, three seven-subcarrier systems with different degrees of decorrelation between the subcarriers were simulated. Each system was simulated with no CP and a 10% CP. The center subcarrier was detected with a coherent receiver followed by FIR filtering, which demultiplexed and equalized the center subcarrier. The sampling rate of the receiver was varied; the bandwidth of the receiver was set to be the Nyquist bandwidth of the receiver's sampling rate. The system performance plotted against the oversampling ratio is shown in Fig. 4.

Fig. 4 illustrates that systems without a CP produce near perfect results if the oversampling ratio is equal or greater than the number of decorrelated channels. This confirms the conclusion of [39] that AO-OFDM systems demonstrations can produce unrealistic results. In addition, it shows that using four decorrelated channels is still insufficient to accurately indicate performance, and suggests that fully decorrelated subcarriers are necessary. For perfect digital demultiplexing without any CP, the entire AO-OFDM super-channel must be captured by a single coherent receiver, which is unrealistic in most cases. In contrast, if a 10% CP is added, the degree of decorrelation becomes unimportant and the performance becomes dominated by the sampling rate of the receiver. Therefore, using multiple copies of a few decorrelated subcarriers is acceptable in laboratory demonstrations only if a CP is used.

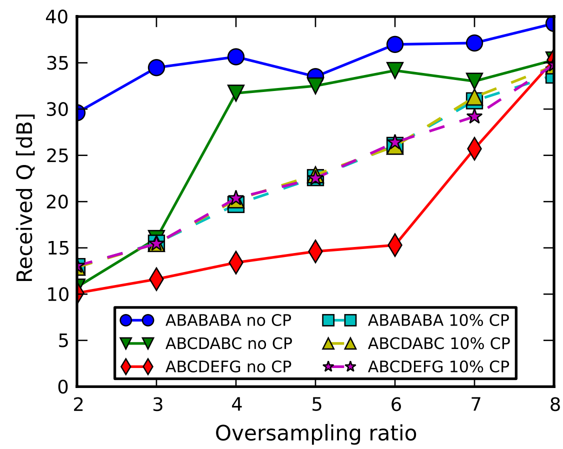

Fig. 4. Q versus oversampling ratio for different amounts of decorrelation.

IV. Experimental Setup

Fig. 5 shows the experimental setup. A 10.0 GHz MLL, locked to an external RF-clock, provides 2-ps pulses. The output of the MLL is then amplified and spectrally broadened using self-phase modulation in 300 m of highly nonlinear fibre (HNLF). A Finisar Waveshaper [41] selects and flattens 3 THz of the spectrum and partly compensates for the spectral phase accumulated inside the HNLF, compressing the pulses back to about 2 ps. The pulses were then QPSK modulated by a complex optical modulator (CMZM), driven with $2 \times$ 10-Gb/s signals from the two independent output ports of a bit-error rate tester. A polarization multiplexed (PM) signal was generated with a PM emulator with a 1-m delay together with a variable delay line line, adjusted to exactly 50-symbols delay. The PM signal was split into 4 paths; each path was decorrelated by an integer number of symbols, using lengths of fibre differing by $\sim$2 m in length, and then fed into the four inputs of a 4-port LCoS-based WSS (Finisar). Each port k is programmed with a filter with a transfer function given by:

$$H_k(f) = \sum_{j=-N/2}^{N/2} i^j \operatorname{sinc}\left(\frac{f - f_0^k - jMf_R(1+CP)}{f_R}\right) \quad (1)$$

Where N is the number of subcarriers, f_R is the baud rate, CP is the cyclic prefix fraction, M is the order of the discrete Fourier transform (DFT) of the filter and $f_0^k = f_0 - kf_R(1 + CP)$ is

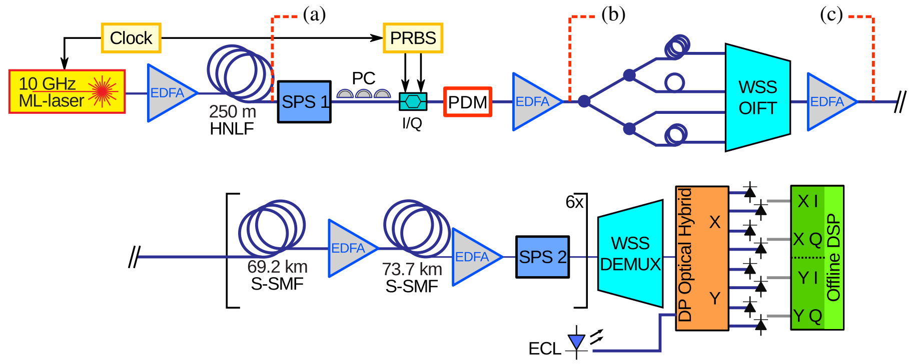

Fig. 5. Experimental setup. ML: mode-locked, HNLF: highly nonlinear fibre, PRBS: pseudo-random bit sequence, I/Q: complex Mach–Zehnder modulator, EDFA: Erbium-doped fibre amplifier, WSS: wavelength selective switch, OIFT: optical inverse Fourier transform, SPS: Finisar Waveshaper spectral pulse-shaper, PDM: polarization multiplexing emulator.

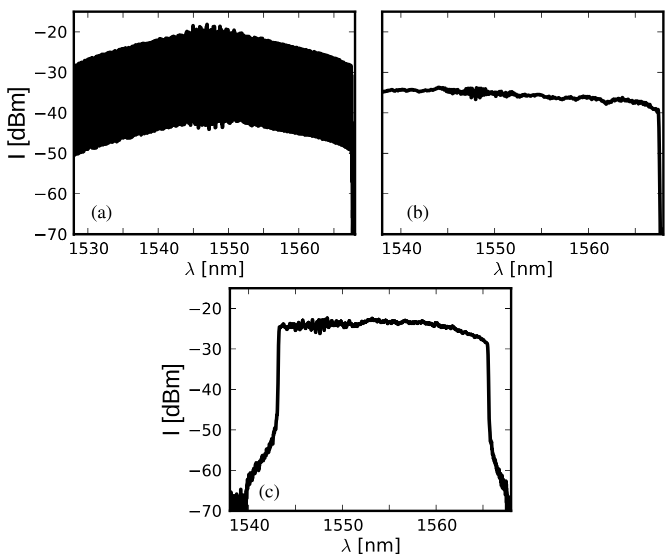

Fig. 6. (a)–(c) Measured optical spectra at the positions indicated in Fig. 5.

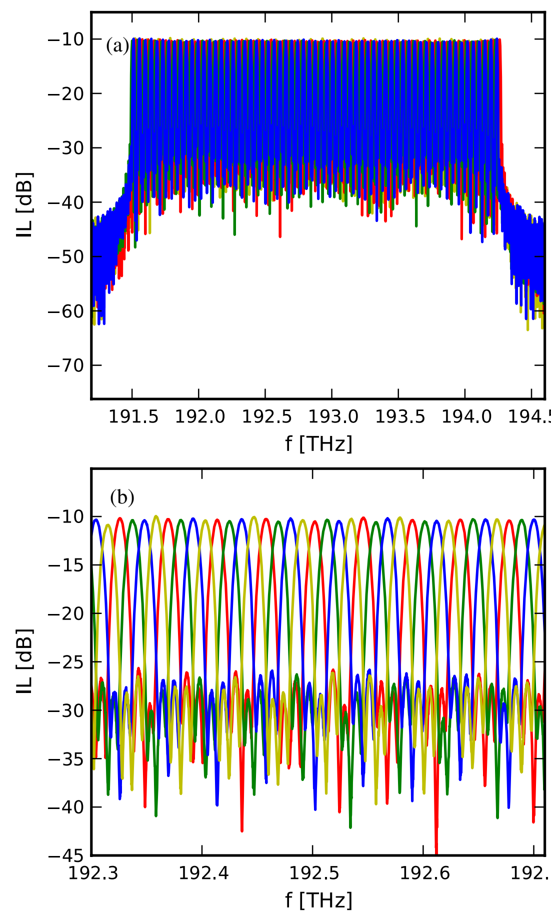

Fig. 7. Measured insertion loss of the OIFT filter ports (port 1: red, port 2: yellow, port 3: green, port 4: blue) for the generation of the 252 channel, 10.2 Tb/s OFDM superchannel. (a) Full spectrum, (b) Enlargement around 192.5 THz.

the center frequency of the kth port. Here we use values of $N = 63$, $f_R = 10$ GHz, $CP = 0.1$ and $M = 4$. Therefore, every port performs the equivalent of a 4-tap DFT with a 10% CP. The WSS simultaneously filters and combines the four inputs to create a 2.8 THz wide optical OFDM super-channel of 252 subcarriers carrying 10.08 Tb/s.

Fig. 6(a)–(c) show the optical spectrum of the broadened but unflattened MLL spectrum, the spectrum of the modulated pulses and the spectrum of the OFDM super-channel respectively.

It should be noted that due to the limited number of input ports on the WSS, the OIFT was programmed to perform the equivalent of a 4-tap DFT function, i.e. every fourth channel carries the same data. This technique is similar to interleaving of odd and even channels employed by previous experiments; however, it uses four decorrelated subcarriers. As shown in Section III, the linear performance of systems with a CP with two or four decorrelated subcarriers is identical to using fully decorrelated subcarriers. Four decorrelated channels will produce more indicative results than two decorrelated subcarriers in the fiber nonlinearity limited region [39].

The transfer function of the WSS-based OIFT filter was measured using an optical vector analyser (Luna OVA 5000) and is depicted in Fig. 7(a) and (b) for the full signal band and a 400 GHz wide section of the signal band respectively.

After generation, the OFDM superchannel was amplified and fed into an optical recirculating loop comprising a 69.2-km span of SMF, one EDFA, a 73.7 km span, a second EDFA and then a Waveshaper to compensate for the gain tilt of the non-flattened EDFAs. To achieve a flat EDFA gain, some spectral components had to be attenuated by up to 11 dB by the Waveshaper. The signal was received after six recirculations, that is after 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 an external cavity laser as a local oscillator, was used to down-convert the optical signal and a 4×80 GS/s, 32 GHz 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. The subcarriers were then demultiplexed using a 25-tap 1/6-spaced TD-equalizer (TDE) which also compensated 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. It should be noted that the 80 GS/s DSO enables up to 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 is frequency diversity that would give a 3-dB sensitivity improvement relative to independent data transmission, unrealistically improving performance. To avoid gaining this advantage, we down-sampled the data to 60 GS/s. The subcarriers were demultiplexed and equalized using a FS-TDE. Each subcarrier was selected by initializing the taps to be matched to the desired subcarrier; no pre-filtering was used. Finally, Viterbi-Viterbi phase recovery is used for carrier phase recovery.

V. Experimental Results

The Q-values of all subcarriers after 857.4 km transmission are shown in Fig. 8(a). All subcarriers exhibit a $Q > 8.8$ dB, which corresponds to the hard FEC limit of 3.0×10^{-3}. It is evident that the subcarriers at the edge of the band are compromised. While the subcarriers at the center of the band mostly have Qs greater than 12 dB, the 5-10 outermost subcarriers at either end of the superchannel have significantly lower Qs. This can be attributed to the non-flat gain-shape of our EDFAs; the gain provided by our EDFAs was much lower at the edges of the OFDM signal compared with at the center of the signal, reducing the OSNR at the edges. Fig. 8(b), shows the Q of selected subcarriers as a function of transmission distance, selected by setting the number of recirculations of the loop before detection. The chosen subcarriers were the tenth in from either edge and two middle subcarriers. All subcarriers are error free even after nine recirculations corresponding to a propagation of 1286 km. It is therefore safe to assume that the transmission distance could be improved further by upgrading the experiment with gain-flattened EDFAs.

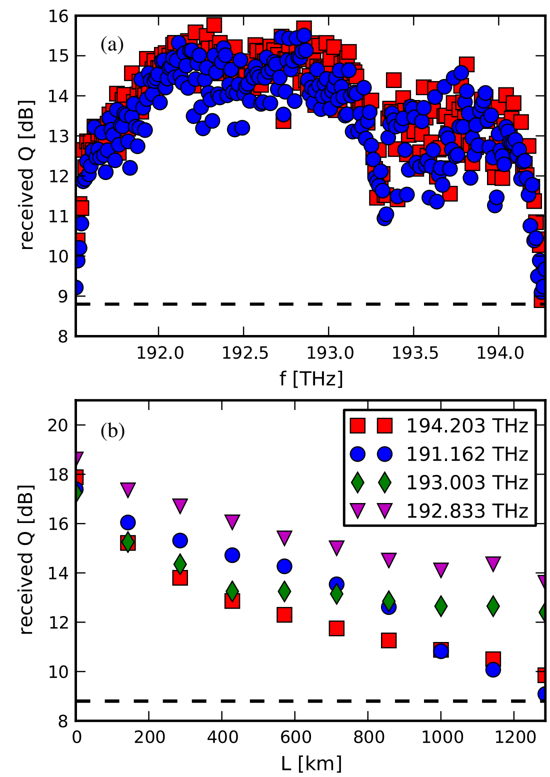

Fig. 8. (a) Received Q for all subcarrier of the 10.2 Tb/s OFDM signal after transmission over 857.4 km (blue circles) X-polarization, (red squares) Y-polarization. (b) Q as a function of transmission distances for four subcarriers, two are at a position ten from the either edge of the superchannel (red squares and blue circles), and two are from the middle of the signal band (green diamonds and magenta triangles).

VI. Conclusion

We have demonstrated a reconfigurable optical OFDM multiplexer based on implementing an optical inverse Fourier transform inside an LCoS-based WSS, thus performing the equivalent operation as electronic OFDM signal generation in the optical domain. Furthermore, our device is capable of generating a CP for ICI reduction all-optically. This technique enables DAC-free generation of extremely broadband optical superchannels in existing optical networks, which could increase both transmission capacity and energy efficiency. Furthermore, because the subcarrier wavelengths are determined only by reprogramming the WSS, the channel bandwidth and wavelength can be easily adjusted to respond to variable bandwidth demands and the availability of unused spectrum. Our method therefore greatly increases system flexibility and would be ideal for techniques such as elastic networking.

We have experimentally demonstrated our transmitter by creating a 10.08-Tb/s AO-OFDM signal with a 10% CP using a single MLL and WSS. We avoided obtaining an unfair advantage from having correlated channels by using four decorrelated channels and a CP. At the receiver end, another WSS was programmed 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 3.0×10^{-3} after 857.4 km transmission. The spectral efficiency was 3.6 bits/s/Hz (not accounting for FEC).

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