All optical discrete Fourier transform processor for 100 Gbps OFDM transmission

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Abstract: Optical orthogonal frequency division multiplex (OFDM) symbol generation by all-optical discrete Fourier transform (DFT) is proposed and investigated for 100-Gbps transmission performance. We discuss a design example for a 4x25Gbps OFDM transmission system and its performance comparison with that for a 100-Gbps single-channel return-to-zero data transmission in an optically amplified system.

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1. Introduction

Optical data transmission by OFDM [1,2,3] is a fast growing area of studies to cope with optical transmission penalties such as due to optical non-linearity [4-6], chromatic dispersion [7-8], and polarization modal dispersion [9-11]. An OFDM symbol is typically generated by an electronic inverse fast Fourier transform (FFT) to multiplex low-rate parallel data into multiple sub-carriers defined by orthogonal frequency components in the symbol, which is then used to generate an optical OFDM symbol waveform by an optical modulator. At a
receiver, a photodetector converts an optical OFDM waveform to the corresponding electrical waveform for electronic FFT and the FFT result is the retrieved transmission data at each subcarrier. In this system configuration, the system throughput is limited by two major components: the optical data modulator and the photodiode in a transmitter and receiver, respectively, and electronics for FFT. If the FFT process is achieved all optically in a way that lower data-rate optical data are directly multiplexed and demultiplexed, the OFDM transmission data rate can be increased by far.

Combining optical delays and phase shifters, an optical discrete Fourier transform circuitry can be composed in a way that can produce and retrieve optical OFDM symbols [12]. We report a novel optical DFT circuit design for Fourier and inverse Fourier transforms for OFDM symbol transmission. The proposed DFT OFDM model is applied to 100-Gbps transmission and investigated to understand transmission properties of all-optical OFDM by numerical simulations. The results show a comparable system performance of the proposed OFDM transmission with using even narrower optical bandwidth. This paper presents all-optical OFDM circuit design concepts in Section 2, a system design example in Section 3, with the transmission performance comparison with a return-to-zero (RZ) data transmission.

2. All-optical discrete Fourier transform circuit

Optical circuits for DFTs are coined by combination of optical phase shifters. Inverse and forward DFTs are defined by $e_m = \sum_{k=0}^{N-1} E_k e^{j2\pi mk/N}$ and $E_k = \frac{1}{N} \sum_{m=0}^{N-1} f_m e^{-j2\pi km/N}$, where $e_m$ and

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**Fig. 1.** Optical circuit model for an inverse DFT for an optical OFDM multiplexer (a), and schematic illustration (b) how the inverse DFT process is attained as an example of $\omega_4$ subcarrier in a 4 subcarrier OFDM symbol. Triangles in (a) represent power splitters or couplers.

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$E_m$ are the time and frequency domain samples at the $m$-th and $k$-th positions, respectively. Integer number $N$ is the total number of samples, and $0 \leq k, m < N$. The corresponding frequency and time positions are given by $\tau_m = m\tau$ and $\omega_k = k\delta$, where $\tau$ and $\delta$ are the sampling spaces of the time and frequency, respectively, such that $\delta \tau = 2\pi/N$. Here $\omega_k$'s correspond to the optical frequency of subcarriers. Investigating DFT expressions, one can infer that an optical circuit implementation of DFT is merely phase delays by precise optical path length adjustments combined by a power combination by a power coupler as shown in Fig. 1(a). The overall design of the inverse DFT looks like a wavelength division multiplexer, except that there is a careful arrangement of time delays and relative phase tuning in each path, so all wavelength components that correspond to the subcarriers of an OFDM are orthogonally multiplexed into one output port, as illustrated in Fig. 1(b). Note that the phase delays are defined with respect to the optical carrier frequency. In this arrangement, a short laser pulse can be used as input data at every subcarrier input. Only one part of the spectral component that corresponds to an optical OFDM subcarrier has constructive interference at the output port, while all other spectral components fed to the same input port have completely destructive interference at the output port. The narrow input pulse can be modulated to transmit information. If we consider the system transfer function of the IDFT processor, it manifests as a simple wavelength division multiplexer (WDM). However, the proposed IDFT maintains deterministic phase relations among subcarriers, so that one can manipulate the transmission system performance using OFDM techniques. A forward DFT can be constructed in the same way, as the circuit model is retro-propagation invariant except for the phase conjugation, requiring phase shifts negative to, and delays complementary to those in the inverse DFT.

All inputs of an optical inverse DFT circuit can be generated from replicas of one identical short laser pulse with the pulse width comparable with the time domain sampling space $\tau$, in order to derive a deterministic relative phase relation among different optical subcarrier frequency inputs. Hence, one can take advantages of optical OFDM transmission, such as pre-emphasis, power equalization, and nonlinearity mitigation [4]. This principle design concept can be applied to many variants as discussed in the following sections.

### 3. 100-Gbps transmission application

An optical DFT process has an unsurpassable advantage over electronic FFT process. The bandwidth of the optical processor is, in principle, unlimited, while the bandwidth of the electronic process is limited to tens of giga-bits per second at the moment. In fact, the optical DFT processing bandwidth is determined by the capability of generating phase-locked multiple subcarriers. The simplest implementation can be achieved by slicing spectrum from a repetitive short pulse. When the repetition period of a short pulse train is matched to the OFDM symbol period, the spectrum of the pulse train consists of many impulsive frequency tones separated by the OFDM subcarrier spacing.

Figure 2 illustrates how an OFDM transmitter and receiver are coined by optical DFTs, as an example for 4x25Gbps transmission, and the corresponding performance is evaluated by a numerical analysis. At the transmitter, an electro-absorption modulator as the pulse carver produces a short pulse with a 3-dB pulse width of 2.8 ps, which produces a spectrum of 3-dB full width of 160 GHz. Even though an ideal pulse spectrum desired to be a raised-cosine shape with the bandwidth of approximately the target OFDM symbol modulation bandwidth, the pulse spectrum shape is assumed to be gaussian with a wide-enough bandwidth for modeling a practical application. The pulses are then power split to four 25 Gbps modulators. The data modulated pulses are fed to subcarrier input ports of the optical inverse DFT. The phase shifts in this optical DFT are referenced to the midpoint frequency of optical subcarriers, instead of the lowest subcarrier frequency in the mathematical model described in Section 2. We refer to the midpoint frequency as the optical carrier frequency $f_C$, which corresponds to the wavelength of a continuous-wave source laser diode.
In this OFDM transmitter design, the spectrum shows impulse features at every 25 GHz centered at the optical carrier frequency as shown in various spectra of Fig. 3(a). A typical spectrum of power spectral density (PSD) of the OFDM transmitter output is shown as a solid curve in the upper part. The tone positions mismatch the subcarrier positions, and the data information is modulated between the tones as indicated in the lower part of the PSD data of Fig. 3(a). The solid and dotted curves show the PSD spectra, respectively, when either odd-number channels at \( f_1 \) and \( f_3 \), or even-number channels at \( f_2 \) and \( f_4 \), are selectively multiplexed. Here \( f_1, f_3, f_2, \) and \( f_4 \) are referred to as subcarrier detuning frequencies, which are located at \(-37.5, -12.5, +12.5, \) and \(+37.5 \) GHz, respectively. The device technology how one can accurately control subcarrier channel frequencies in inverse DFT and DFT sets the limit how to closely pack the subcarriers. The current arrayed-waveguide grating on silicon substrate can maintain channel accuracies within approximately 10 GHz, and the subcarrier spacing need to be greater than 10 GHz. This limits the scalability of the number of subcarriers.

![Fig. 2. A schematic circuit diagram of 4x25Gbps all-optical OFDM transmission system. Solid and dotted lines show optical and electrical connections, respectively. The fiber link consists of 80-km SMF-28 fibers and optical amplifiers with full dispersion compensation for the fiber links by dispersion compensation modules (DCM). Fiber spans are varied from 1 to 5 to change the OSNR at the receiver. Span input power of an OFDM channel is 0 dBm. The amplifier gain and noise margin are 20 dB and 6 dB, respectively.](image)

In our specific example of the optical inverse DFT, the optical carrier is chosen to be suppressed, when all subcarriers are used. The output from the inverse DFT is then fed to an optical bandpass filter to remove unnecessary spectrum. This filter function is assumed to be a forth-order super gaussian with a 3-dB full width of 160 GHz. The corresponding OFDM symbol eye diagram is presented in the upper part of Fig. 3(b), which can be found at the output from the optical inverse DFT. The diagram is composed by overlapping waveforms of various data modulation cases. A symbol consists of 10-ps features whereas the symbol period is 40-ps. The pre-emphasis control module between the pulse splitter and the optical...
inverse DFT can control different phase and amplitude of each subcarrier, in order to equalize each subcarrier performance at the receiver. In our transmission modeling, we choose an amplitude pre-emphasis of \{-1.3, -1, +1, +1.3\} for the subcarriers at detuning frequencies \(f_1, f_2, f_3,\) and \(f_4\), which equalizes receiver performances against optical amplifier noise and inter-subcarrier crosstalk penalties. Different choices of signs of the pre-emphasis change the waveform of OFDM symbols: Pre-emphasis with the same sign produces a single strong peak the center of an OFDM symbol waveform. In our case, there is a null at the centers located at 20 and 60 ps in Fig. 3(b), spreading the peak power to the neighboring 10-ps features. An optimized choice of pre-emphasis can offer for mitigation of fiber nonlinearity impairments.

In addition, the chromatic dispersion penalty can be mitigated to that of 25 Gbps transmission from that of 100 Gbps transmission by suitable choices of phase pre-emphasis at the transmitter. The transmission fiber system is assumed to have total dispersion of zero with suitable optical amplifiers, such as hundred kilometers of SMF-28 fibers and dispersion compensation fiber in the amplifiers. However, we assume that the transmission power is low enough not to cause strong nonlinear impairment.

At a receiver, an OFDM symbol is demultiplexed by an optical forward DFT, and the corresponding output waveforms are shown in the lower part of Fig. 3(b). Clear eye-openings are found at the center of a symbol period so that data information is retrieved within a narrow time window of 10 ps. In DFTs, the time domain waveforms have meaningful values only at the sampling positions. In order to implement this property, electro-absorption-modulator pulse carvers repeating at 25 GHz are used at all subcarrier outputs to convert the waveform to an RZ format, as found in Fig. 2. The pulse carver width is 8.8 ps. Then the RZ optical data are converted to electrical data by a photodiode with 3-dB bandwidth of 18 GHz. Note that all electronic components in this application have bandwidths lower than 25 GHz.

![Fig. 3. Power spectral density, (a), and optical waveforms, (b), of all-optical OFDM. The power spectral density resolution bandwidth is 0.02 nm (2.5 GHz).](image)

The aforementioned OFDM transmission is explicitly modeled by numerical simulation in order to make comparison with equivalent a single-channel 100-Gbps RZ data transmission, which can be achieved by 4×25 Gbps optical time division multiplex with the same complexity in the electronics. A split-step Fourier transform simulation tool is developed in-house using the Matlab package, benchmarked with a commercial product and experiments. For this analysis, the nonlinear propagation is not considered, since the main idea is related with linear property only. In an OFDM transmission with aforementioned pre-emphasis, the PSD spectrum in Fig. 4(a) shows a relatively flat spectrum on the shoulder of the curve, and relatively rapid decreases of the spectrum outside ±50 GHz. In the RZ transmission with RZ duty ratio of 30%, data spectrum extends farther than ±50 GHz. In the spectrum data, we also indicate the amplified spontaneous emission (ASE) noise floor that corresponds to an optical signal to noise ratio (OSNR) of 20 dB, measured with a 0.1-nm resolution. The Q-factor performances as a function of OSNR are also shown in Fig. 4(b). At the lower OSNR limit, namely in the ASE-limited performance regime, both OFDM and RZ transmissions show...
nearly the same performance. However, when impact from ASE is small, an OFDM inter-subcarrier cross talk manifests as Q penalty with respect to the equivalent single channel RZ transmission. At a Q factor of 8.5 dB, the OFDM case shows a 1.4 dB OSNR penalty. It is observed that this penalty substantially decreases as neighbor subcarriers are removed.

![Comparison between 4x25-Gbps OFDM and 100-Gbps RZ transmissions](image)

**Fig. 4.** Comparison between 4x25-Gbps OFDM and 100-Gbps RZ transmissions; (a), power spectral density observed with a 0.2-nm resolution bandwidth, and (b), Q factor performance versus OSNR.

### 4. Conclusions and Discussions

An all-optical discrete Fourier transform processor is introduced for an application of 4x25 Gbps optical data transmission by orthogonal frequency division multiplex. By use of optical DFTs in a transmitter and receiver, the requirements of the 100-Gbps bandwidth for OFDM electronics of analog-to-digital converters (ADC) and digital signal processors (DSP) are eliminated, and all electronics bandwidth requirements are mitigated to 25 Gbps. However, the proposed optical OFDM scheme may not be able to utilize the OFDM subcarrier channel control schemes directly, as is available in electronic OFDM schemes.

The performance comparison between 4x25 Gbps optical OFDM and 100 Gbps RZ transmissions in an amplified transmission is evaluated by numerical simulations. The results show the higher spectral efficiency in the optical OFDM with nearly the same Q versus OSNR performance. A small 1.4-dB OSNR penalty is observed in the optical OFDM case in the high OSNR limit where the bit-error rate is 10^-12. Comparisons with electronic OFDM may reveal other interesting merits and demerits, but we leave it as further studies.

The proposed DFTs can be attained with an arrayed waveguide grating (AWG) technology. A careful waveguide array design in an AWG wavelength division multiplexer (WDM) can achieve the phase delay required for DFT as shown in Fig. 2. Additions of required time delay waveguides at the single wavelength ports of an AWG WDM and a power combiner can provide the optical DFT function. We believe that our proposed optical DFT is a strong candidate for 100 Gbps or higher data rate transmission, such as for a 100G Ethernet physical layer, with capability for fiber nonlinearity control by pre-emphasis of each subcarrier.

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