

Novel 64×2.5 Gb/s all-optical OFDM symbol generator based on triangle waveform driving-LiNbO₃ modulators

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Received October 30, 2009

We propose a novel and simple all-optical 160-Gb/s orthogonal frequency division multiplexing (OFDM) symbol generator which is based on discrete triangle waveform driving-LiNbO₃ modulators to realize large-range linear optical shift. The entire system needs 64 discrete modulators: at the transmitter, a 2.5-Gb/s optical duobinary (ODB) modulator for data modulation and a 2.5-Gb/s triangle waveform driving-LiNbO₃ phase modulator for phase shift to generate each subcarrier; and at the receiver, a 2.5-GHz optical band pass filter (OBPF) using Faraday anomalous dispersion optical effect to separate them. Excellent bit error rate (BER) is observed after 1060 km of transmission without any dispersion compensation.

OCIS codes: 060.0060, 070.0070.

doi: 10.3788/COL20100805.0449.

Optical orthogonal frequency division multiplexing (OFDM) has become a promising technique in long-haul and high-speed optical transmission systems because of its high spectral efficiency, relatively low signal bit rate, and advanced robustness against chromatic dispersion and polarization mode dispersion (PMD)^[1-4]. There are two kinds of optical OFDM (OOFDM) coherent^[1] and all-optical^[2,3].

All-optical OFDM systems utilize all-optical transmitters, thereby eliminating the speed limitation set by electronics. In this kind of system, the key technology is the optical Fourier transformation (OFT), which has two kinds: continuous and discrete. In Ref. [2], Yang *et al.* used time lenses to realize a continuous OFT, which caused it to lose phase information in the OFT processing. Thus, it is not suitable for phase modulation system such as quadrature phase-shift keying (QPSK). On the other hand, the discrete OOFDM system is more popular. Its key technology is the optical discrete phase shift at the transmitter and optical filter (both time and frequency) at the receiver^[3,4]. Many researchers have tried to come up with practical ways to realize this. Three kinds of physically feasible discrete all-optical OFDM systems have been reported to date. One was proposed by Yu *et al.*^[3] In his paper, the phase shift was achieved by the LiNbO₃ phase modulator driving the sinusoidal waveform. Four subchannels generated by the phase modulator (one cascaded intensity modulator was used to equalize the optical power of each peak) were used. As the sinusoidal waveform driving leads to a nonlinear phase shift, proper driving voltage is needed and the phase shift range is limited. Another system required many phase shifts and delay lines that are not practical for many subcarriers^[4]. In Ref. [5], we followed Ref. [4] in proposing a planar lightwave circuit (PLC) based integrated optical discrete Fourier transformation device

based on the thermo-optic effect of SiO₂ in one silica chip. However, it is still not suitable for many subcarriers as the size of a silica chip is limited. Nevertheless, there are still some other ways to realize discrete optical phase shifts^[6].

Based on the concept presented in Ref. [3], triangle waveform LiNbO₃ modulators can bring about a linear large-range phase shift. Thus, the realization of all-optical OFDM may be simple. Moreover, if we use discrete phase modulators, many subcarriers can be realized, eliminating the integration limitation imposed on the number of subcarriers. The proposed symbol generator would make it physically realizable to build all-optical OFDM systems with a large number of subcarriers. A 160-Gb/s all-optical OFDM transmission system is designed by employing 64 symbol generators. Simulations show advanced chromatic dispersion tolerance and spectral efficiency. A performance comparison with a 160-Gb/s optical inverse discrete Fourier transformation (OIDFT) based all-optical OFDM system is given. This letter presents the design concepts of the proposed all-optical OFDM symbol generator and an all-optical OFDM system design example.

The power spectrum of OFDM signals has perfect orthogonality, as shown in Fig. 1. This spectral orthogonality can be obtained by LiNbO₃ phase modulators and a wavelength division multiplexer (WDM)^[3]. Figure 1 depicts the operating principle of the proposed all-optical OFDM symbol generator. The left part of Fig. 1 depicts the power spectrum of signals on a subcarrier. The horizontal axis indicates the frequency relative to the optical carrier frequency f_c . The unit of the horizontal axis Δf is the frequency spacing between neighboring subcarriers, which is equal to the signal bit rate on each subcarrier. The vertical axis indicates the normalized power, while f_c is modulated by N different parallel data streams.

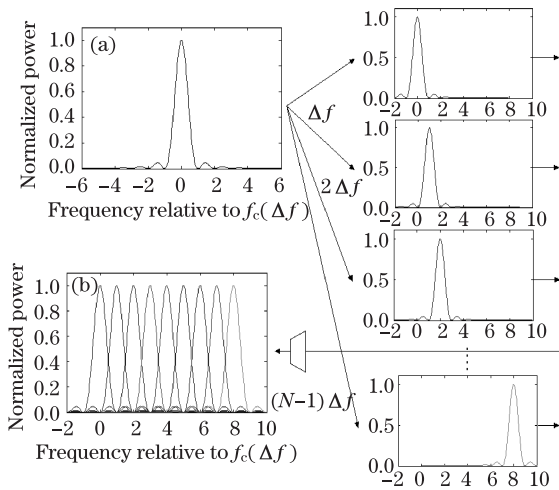


Fig. 1. Schematic illustration of the proposed symbol generator.

The spectra of signals on N subcarriers are identical, as shown in Fig. 1. The k th subcarrier is modulated by the k th LiNbO₃ phase modulator, which brings about a frequency shift of $k \cdot \Delta f$ to the power spectrum, where $k = 0, 1, 2, \dots, N-1$. A WDM combines the N frequency-shifted subcarriers to generate OFDM symbols. The orthogonal power spectrum is then obtained, as shown in Fig. 1(b). Time-domain OFDM symbols are obtained synchronously.

One major concern is the process of introducing a frequency shift of $k \cdot \Delta f$ using LiNbO₃ phase modulator. According to the Fourier transformation theorem, a frequency shift of frequency-domain spectrum corresponds to a phase modulation on time-domain waveform. If we set $F(f) = \mathcal{F}\{f(t)\}$, where \mathcal{F} , t , and f indicate the Fourier transform operator, variant in the time domain, and variant in the frequency domain, respectively, then the equation $\mathcal{F}\{f(t) \cdot \exp(j2\pi k\Delta f t)\} = F(f - k\Delta f)$ ($k = 0, 1, 2, \dots, N-1$) implies that a phase shift of $\phi(t) = 2\pi k\Delta f t$ must be modulated on the k th subcarrier in order to introduce a frequency shift of $k \cdot \Delta f$. For a LiNbO₃ waveguide electrooptic modulator, the phase shift is $\phi(t) = (\pi/V_\pi) \cdot V(t)$, where V_π and $V(t)$ are the half-wave voltage and the modulation voltage, respectively^[7]. The half-wave voltage $V_\pi = \lambda G / (n^3 \gamma \Gamma L)$ is determined by the structure parameters and material characteristics of the LiNbO₃ modulator, where λ , G , n , γ , Γ , and L are the optical wavelength, the electrode gap, the refractive index, the electrooptic coefficient, the overlap integral between the applied electric field and the optical mode, and the interaction length, respectively^[7]. The equation $\phi(t) = 2\pi k\Delta f t$ will be obtained when $V(t) = 2V_\pi k\Delta f t = (2V_\pi k/T) \cdot t$, where T is the OFDM symbol period. Therefore, the power spectrum of the k th subcarrier will shift $k \cdot \Delta f$ in the frequency domain when a modulation voltage of $V(t) = (2V_\pi k/T) \cdot t$ is applied to a LiNbO₃ waveguide electrooptic modulator. Figure 2 shows the ideal modulation voltages of the LiNbO₃ modulators that are needed for the second ($k = 1$) and third ($k = 2$) subcarriers as examples. The horizontal axis indicates two OFDM symbol periods, and the modulation voltages repeat themselves in every OFDM symbol period. The left and right vertical axes indicate the phase-shifting value and the modulation voltage

value, respectively. The line which represents the second ($k = 1$) subcarrier is linearly increasing from zero to $2V_\pi$ (2π) during every OFDM symbol period. The phase-shifting slope of the line ($k = 1$) is $2\pi/T = 2\pi\Delta f$, corresponding to a phase shift of Δf . The line which represents the third ($k = 2$) subcarrier is linearly increasing from zero to $4V_\pi$ (4π) during every OFDM symbol period. The phase-shifting slope of the line of the second subcarrier is $4\pi/T = 4\pi\Delta f$ ($k = 2$), corresponding to a phase shift of $2\Delta f$. Figure 2 demonstrates that when the phase-shifting requirements are higher than 2π , the corresponding modulation voltages required are higher than $2V_\pi$, which may exceed the maximum operating voltage of the LiNbO₃ modulators^[3]. In order to overcome this flaw, phase-shift values larger than 2π are subtracted by 2π . In Fig. 2, the dash lines ($k = 2$) are replaced by corresponding solid lines ($k = 2$). This method is reasonable since the effect of a 2π phase shift is the same as that of a zero phase shift. In addition, Fig. 2 shows the ideal modulation voltages for LiNbO₃ modulators and the fall edges of the physical modulation voltages.

Figure 3 illustrates the schematic diagram of a LiNbO₃ single-waveguide electrooptic modulator. The size of the LiNbO₃ waveguide is about $9 \mu\text{m} \times 40 \text{mm}$, while the electrode is typically about $15 \mu\text{m}$ wide. The total size of a LiNbO₃ single-waveguide electrooptic modulator is about $40 \mu\text{m} \times 40 \text{mm}$. A 4-inch (101.6 mm) LiNbO₃ wafer is able to produce more than 5000 phase modulators. Therefore, the number of OFDM subcarriers can be more than 5000. The proposed all-optical OFDM symbol generator eliminates the system's dependence on electronics and is suitable for high integration, making all-optical OFDM systems with a large number of subcarriers physically feasible. However, since $64 \times 2.5 \text{Gb/s}$ has been used to realize a 160-Gb/s OOFDM symbol, the 2.5-Gb/s modulator is very cheap and popular. In addition, there was no need to integrate the 2.5-Gb/s

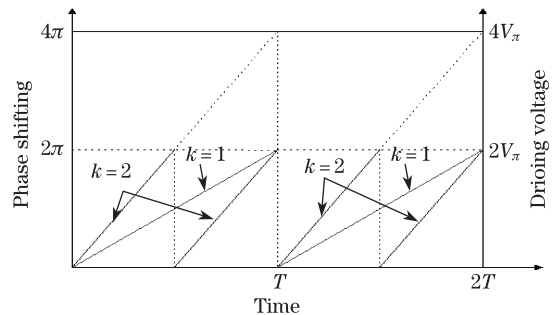


Fig. 2. Modulation voltages for the second and third subcarriers.

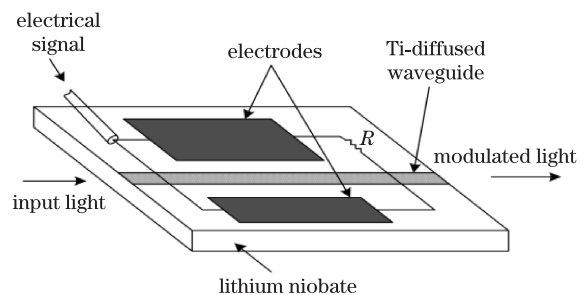


Fig. 3. Schematic diagram of a LiNbO₃ single-waveguide electrooptic modulator.

phase phase modulator on a chip; thus, we still used discrete phase modulators.

Figure 4 shows the architecture of a 64×2.5 Gb all-optical OFDM transmission system based on a phase shift as mentioned above. The system demands just one continuous wave (CW) laser and needs no electronic harmonic generators, fast Fourier transforms (FFTs), or digital-to-analog converters (DACs). Optical duobinary (ODB) modulation format was used in the all-optical OFDM system because of its high spectral efficiency. In the transmitter, a serial-to-parallel (S/P) processor converts a 160-Gb/s serial data stream into 64 2.5-Gb/s parallel data streams, which are then encoded by a 64-parallel duobinary encoder to generate ODB codes. A CW laser is split into 64 identical subcarriers, which are modulated by the 64 parallel 2.5-Gb/s ODB data streams. The 64 parallel optical subcarriers are simultaneously fed into 64 triangle waveform-driving phase modulators. The 2.5-GHz triangle waveform can be generated by an arbitrary waveform generator (AWG), which is fabricated by equipment companies such as Tektronix. The symbol generator introduces different frequency shifts to subcarriers and combines them to produce OFDM symbols. After transmission in optical fibers, odd (ch 1, ch 3, ..., ch 63) and even (ch 2, ch 4, ..., ch 64) channels are separated by a 5-GHz free spectral range (FSR) Mach-Zehnder interferometer (MZI). At the receiver, 64 tunable optical band-pass filters (OBPFs) are used to filter the undesired spectral components for every subcarrier. A 2.5-GHz optical filter is needed in order to separate each subcarrier. The optical filter can be realized to a minimum of 1 GHz by using the Faraday anomalous dispersion optical effect^[7]. Signals on 64 subcarriers are detected by photodiodes (PDs), and a parallel-to-serial (P/S) processor converts the 64 parallel data streams into a 160-Gb/s serial data stream.

Figure 5 depicts the power spectra of signals on subcarriers 1 and 2. The central frequency of subcarrier 1 is the same as the CW laser's central frequency (193.1 THz), while that of subcarrier 2 is shifted to 193.1025 THz because of the all-optical OFDM symbol generator ($\Delta f = 2.5$ GHz). The power suppression at the midpoint of the two neighboring subcarriers is 10.2 dB (Fig. 5). This suppression in the power spectrum is the most significant feature of the ODB OFDM symbol compared with the OOFDM using other modulation formats, such as non-return to zero (NRZ), differential phase-shift keying (DPSK), and differential QPSK (DQPSK), which have the modulation spectra entirely superimposed on the spectra neighboring subcarriers^[4]. According to this suppression, OBPFs combined with a MZI can successfully separate subcarriers. Figure 6 illustrates the power spectrum of OFDM symbols. The total signal bandwidth is 160 GHz, and the spectral efficiency is 1 (b/s)/Hz.

In this system, a 5-GHz FSR MZI was used to separate signals on odd and even channels (Fig. 7). The solid lines indicate the core layer waveguides. The MZI is a silica PLC consisting of two 3-dB directional couplers and an optical delay line, the length L of which is determined by the FSR. We used the equation $dL = c/(\Delta f \cdot n)$, where c is the light speed in vacuum, Δf is a half of the FSR, and n is the effective mode refractive index. We

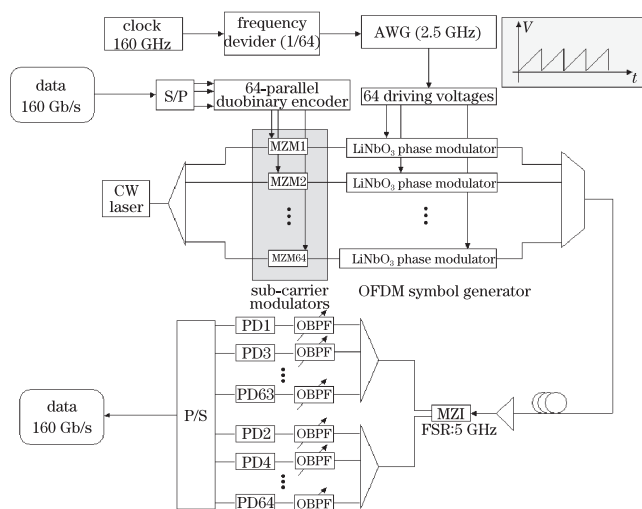


Fig. 4. Architecture of a 64×2.5 Gb/s all-optical OFDM system. MZM: Mach-Zehnder modulator.

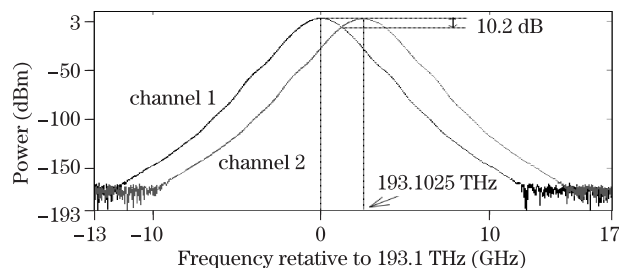


Fig. 5. Power spectra of signals on subcarriers.

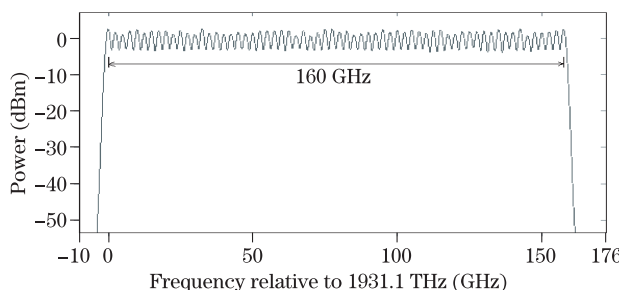


Fig. 6. Power spectrum of the OFDM symbols.

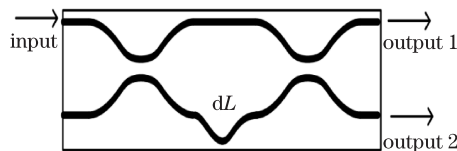


Fig. 7. Configuration of the MZI.

designed a silica PLC MZI using the integrated optics software OlympIOs V5.2. The size of the PLC MZI circuit is $147 \mu\text{m} \times 9 \text{ mm}$. Figure 8 depicts the transmission characteristics of the MZI. The central frequencies of the passbands on the ports of outputs 1 and 2 are $193.1025 \text{ THz} + p \times 5 \text{ GHz}$ and $193.1 \text{ THz} + q \times 5 \text{ GHz}$ (p and q are integers), respectively. The spectral channel spacing of outputs 1 and 2 is 5 GHz. The extinction ratio between outputs 1 and 2 is lower than -30 dB. Therefore, this MZI can separate the odd and even channels.

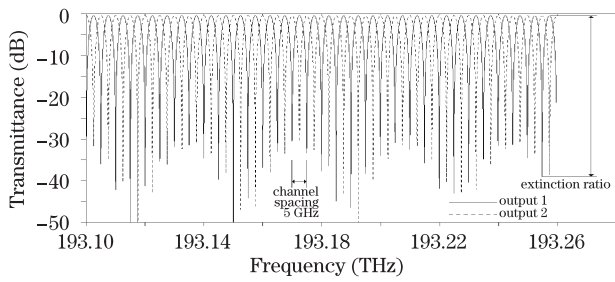


Fig. 8. Transmission characteristics of the MZI.

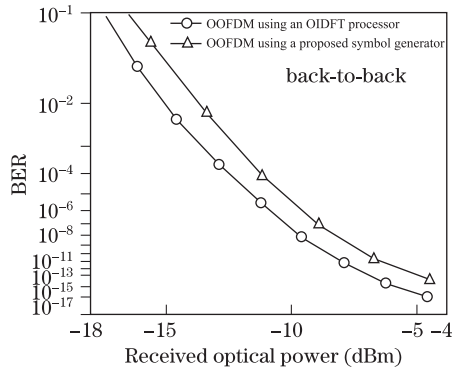


Fig. 9. BER performance of all-optical OFDM systems.

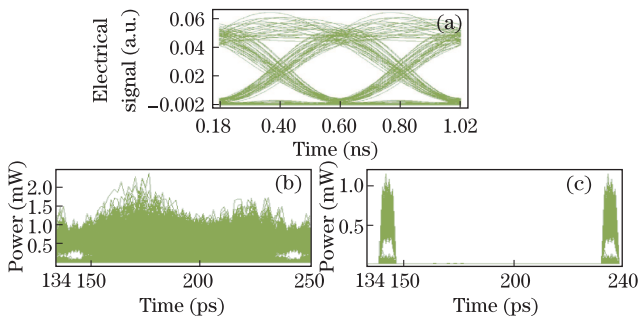


Fig. 10. Eye diagrams of received signals.

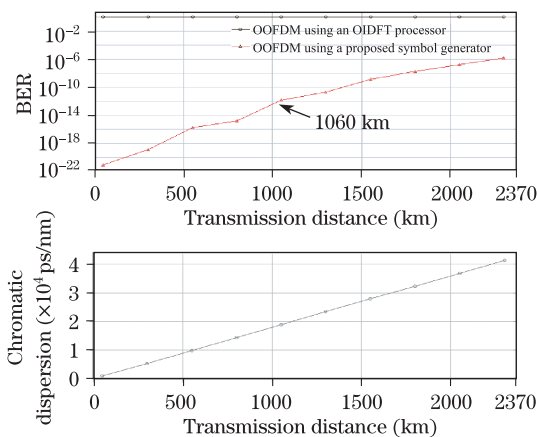


Fig. 11. Linear transmission characteristics of all-optical OFDM systems in SMFs.

We used the software VPItransmissionMaker V7.6 to evaluate the performance of our system. Figure 9 depicts the bit error rate (BER) characteristics under the back-to-back condition. The horizontal axis indicates the received optical power of every channel before demodulation, while the vertical axis indicates the BER value. The

power penalty of the proposed all-optical OFDM system is about 1.2 dB compared with the ODFT-based all-optical OFDM system. A BER of lower than 1×10^{-12} was achieved at a received optical power of -5.6 dBm. Figure 10 shows the eye diagrams: (a) for the proposed all-optical OFDM system; (b) and (c) for the ODFT-based all-optical OFDM systems obtained at the receiver before and after optical sampling, respectively^[4]. As shown in Fig. 10(b), it is clear that there are meaningless power components being distributed in the time domain that must be filtered by optical sampling before demodulation. Meanwhile, in the proposed all-optical OFDM system, no meaningless power components exist in the time domain (Fig. 10(a)). However, the received optical power contains meaningless components in the frequency domain; thus, OBPFs are needed before demodulation. Given that both all-optical OFDM systems have meaningless received power components, either in the time domain or in the frequency domain, their BER characteristics against the received optical power differ only slightly (Fig. 9).

Figure 11 depicts the linear transmission characteristics of all-optical OFDM systems in single-mode fibers (SMFs). No dispersion compensation was employed during simulations. Meanwhile, the 64×2.5 Gb/s all-optical OFDM signals produced by the proposed symbol generator were successfully transmitted through the 1060-km SMF without dispersion compensation when the BERs remained lower than 1×10^{-12} . This indicates that the ODFT-based all-optical OFDM system lost one of the conventional OFDM advantages, high chromatic dispersion tolerance, while the proposed all-optical OFDM system retained it.

Some of the limitations of this study are the devices and test equipment used, especially for the 2.5-GHz optical filter used at the receiver. The experiment can be continued and completed in the future when the filter is established.

OOFDM is widely accepted as a promising technique for long-haul and high-speed optical transmission systems. Most of the advantages of OFDM result from the large number of subcarriers. However, no all-optical OFDM systems with a large number of subcarriers have been reported so far. We propose a simple and convenient method to realize large-range linear optical phase shift by using a triangle waveform-driving LiNbO₃ phase modulator. By using discrete transmission with 2.5-Gb/s phase modulators, a 64×2.5 Gb/s all-optical OFDM transmission system can be established. Simulations show advanced chromatic dispersion tolerance. In addition, BERs are lower than 1×10^{-12} after transmitting through 1060-km SMFs without dispersion compensation. We believe that the proposed all-optical OFDM symbol generator is a good candidate for 100 Gb/s or higher optical transmission systems.

This work was supported by the National “973” Program of China (Nos. 2010CB328300 and 2010CB328303), the National Natural Science Foundation of China (No. 60772013), the National “863” Program of China (No. 2009AA03Z408), and the Open Fund of Key Laboratory of Optical Communication and Lightwave Technologies Beijing University of Posts and Telecommunications, Ministry of Education, China.

References

1. W. Shieh, X. Yi, Y. Ma, and Q. Yang, *J. Opt. Netw.* **7**, 234 (2008).
2. D. Yang and S. Kumar, *Opt. Express* **17**, 17214 (2009).
3. J. Yu, X. Zhou, M.-F. Huang, D. Qian, P. N. Ji, T. Wang, and P. Magill, *Opt. Express* **17**, 17928 (2009).
4. K. Lee, C. T. D. Thai, and J.-K. K. Rhee, *Opt. Express* **16**, 4023 (2008).
5. W. Li, X. Liang, W. Ma, T. Zhou, B. Huang, and D. Liu, *Opt. Fiber Technol.* **16**, 5 (2010).
6. W. Zhang, X. Feng, W. Zhang, and X. Liu, *Chin. Opt. Lett.* **7**, 188 (2009).
7. D. J. Dick and T. M. Shay, *Opt. Lett.* **16**, 867 (1991).