Multiband Ultra-Wideband Signal Generation With Quadrupled Capacity by a Single Modulator

Jizong Peng, Pan Cao, Jiayang Wu, Boyu Liu, Ciyuan Qiu, Yong Zhang, Ruili Liu, Christine Tremblay, *Member, IEEE*, and Yikai Su, *Senior Member, IEEE*

***Abstract*— We propose and experimentally demonstrate a photonic generation scheme for multiband ultra-wideband (MB-UWB) signal by employing a dual-drive Mach–Zehnder modulator (DDMZM). In this scheme, four electrical binary pulse streams with different bit rates are combined to drive one radio frequency (RF) port of the DDMZM, while the other RF port is modulated by the sum of their 1-b delayed duplicates. By properly adjusting the bit rate and the amplitude of each pulse stream, as well as the bias voltage of the DDMZM, an MB-UWB signal with four sub-bands can be obtained and the transmission capacity can be quadrupled. The feasibility of the proposed scheme is verified by a system demonstration, where the signal modulated by amplitude-phase-shift-key format reaches a high bit rate of 2 Gb/s.**

***Index Terms*— Ultra wideband (UWB), pulse modulation, amplitude-phase-shift-keying (APSK) modulation.**

I. Introduction

COMBINING the advantages of high bit rate, low power consumption, and coexistence with other wireless communication systems, ultra-wideband (UWB) has been considered as a promising solution for future short-distance wireless access networks [1]. For unlicensed use of UWB signal regulated by Federal Communications Commission (FCC), the fractional bandwidth is 20% larger than the central frequency, or the 10-dB bandwidth is at least 500 MHz in a frequency range from 3.1 to 10.6 GHz. The spectral density is also limited to below –41.3 dBm/MHz [2], [3]. The two types of UWB signals, called impulse-radio UWB (IR-UWB) and multiband UWB (MB-UWB) signals, exhibit different spectral characteristics [4], as illustrated in Fig. 1(a). Compared with IR-UWB signals, MB-UWB signals possess one or multiple narrow electrical sub-bands, permitting more efficient bandwidth utilization and multiuser support [4], as shown in Fig. 1(b). However, the communication coverage range of UWB signals is limited due to the low spectral density. For that reason, UWB-over-fiber (UWBoF) technology has been proposed and widely studied to extend signal's transmission distance via optical fibers [5]–[7]. Moreover, photonic generation of UWB signals exhibits attractive merits such as high bandwidth, reduced system complexity, and low cost [8], [9]. It is therefore desirable to generate MB-UWB signals directly in the optical domain.

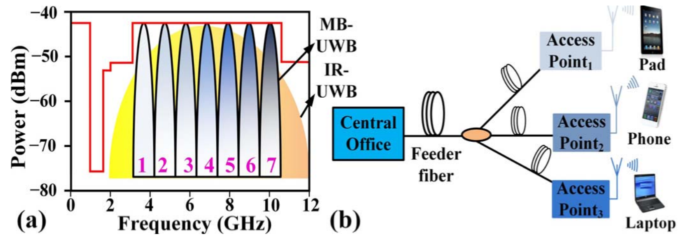

Fig. 1. (a) Electrical spectra of IR-UWB and MB-UWB signals. (b) MB-UWB signals over fiber system for multiusers.

Photonic generation of MB-UWB signals has been reported by utilizing binary data streams from pulse pattern generators (PPGs) [10]–[13]. In [10], flexible MB-UWB signals were obtained using synchronously-apodized polarization modulation and birefringence-induced time delay. Another scheme with large tuning range was realized with optical switches based on polarization modulation [11]. A MB-UWB signal generator was also demonstrated by employing an incoherent optical source, three arrayed waveguide gratings (AWGs), two electro-optical modulators, and a dispersive element [13]. However, these methods require complex system architectures and costly devices. Furthermore, the generated MB-UWB signals possess one single sub-band, resulting in limited transmission capacity.

In this letter, we propose and experimentally demonstrate a photonic generation scheme for MB-UWB signal by employing a single dual-drive Mach-Zehnder modulator (DDMZM). In the proposed scheme, four electrical binary pulse streams with different bit rates and numbers of '10' patterns are combined to drive one radio frequency (RF) port of the DDMZM. The other RF port is modulated by the sum of their respective 1-bit delayed duplicates. By properly setting the bit rate and the amplitude of each pulse stream, as well as the bias voltage of the DDMZM, the low-frequency components of the obtained signal can be eliminated to meet the FCC requirements. By this means, a MB-UWB signal with four sub-bands can be generated by using driving pulse streams of four different bit rates, which occupy different frequency sub-bands. Benefiting from four available electrical sub-bands, the transmission capacity can be improved by a factor of four compared with previous works [12], [13].

Manuscript received December 22, 2015; revised March 17, 2016; accepted April 12, 2016. Date of publication April 28, 2016; date of current version June 22, 2016. This work was supported in part by the 863 High-Tech Program under Grant 2015AA015503, in part by the National Natural Science Foundation of China under Grant 61505104, and in part by the Chinese Academy of Sciences.

J. Peng, P. Cao, J. Wu, B. Liu, C. Qiu, Y. Zhang, R. Liu, and Y. Su are with the State Key Laboratory of Advanced Optical Communication Systems and Networks, Department of Electronic Engineering, Shanghai Jiao Tong University, Shanghai 200240, China (e-mail: pengjizong@sjtu.edu.cn; caopan@sjtu.edu.cn; jiayangwu@sjtu.edu.cn; charlesliu@sjtu.edu.cn; qiuciyuan@sjtu.edu.cn; yongzhang@sjtu.edu.cn; ruililiu@sjtu.edu.cn; yikaisu@sjtu.edu.cn).

C. Tremblay is with the Laboratoire de Technologies de Réseaux, École de Technologie Supérieure, Montréal, QC H3C 1K3, Canada (e-mail: christine.tremblay@etsmtl.ca).

Color versions of one or more of the figures in this letter are available online at http://ieeexplore.ieee.org.

Digital Object Identifier 10.1109/LPT.2016.2555838

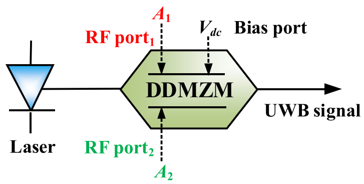

Fig. 2. Schematic illustration of the generator in our proposed scheme. A_1, A_2: driving signals for two RF ports. V_{dc}: bias voltage of the modulator.

The MB-UWB signal in our proposed scheme can be simultaneously generated and modulated. In order to verify the feasibility of the proposed scheme and to validate our method as an effective solution for photonic generation of MB-UWB signals, a system demonstration with a 2-Gb/s amplitude-phase-shift-keying (APSK) modulated signal is performed. The experimental results validate our method as an effective solution for photonic generation of MB-UWB signals.

II. Operation Principle

Figure 2 shows the schematic illustration of the MB-UWB signal generator, which consists of a laser and a DDMZM. In our proposed scheme, the RF signals that drive the two arms of the DDMZM can be described by:

$$A_1 = \sum_{i=1}^{k} s_i(t), \tag{1}$$

$$A_2 = \sum_{i=1}^{k} s_i(t - T_i), \tag{2}$$

respectively, where $s_i\ (t)$ is a Gaussian-like binary pulse stream and T_i denotes its bit period. For an input optical field E_{in}, the modulated optical field can be expressed as [14]:

$$E_{out} = \frac{E_{in}}{2}\left\{\exp\left[j\pi\frac{A_1}{V_\pi}\right] + \exp\left[j\pi\frac{A_2 + V_{dc}}{V_\pi}\right]\right\}, \tag{3}$$

where V_π and V_{dc} are the half-wave voltage and bias voltage of the DDMZM, respectively. After optoelectronic conversion, the alternating current (AC) term of the photocurrent can be written as:

$$\begin{aligned} i_{AC} &\propto \frac{|E_{in}|^2}{2}\left\{\cos\left[\frac{\pi}{V_\pi}(A_1 - A_2 - V_{dc})\right]\right\} \\ &= \frac{|E_{in}|^2}{2}\left\{\cos\left[\frac{\pi}{V_\pi}(S_1 + S_2 + S_3 + S_4 - V_{dc})\right]\right\}, \end{aligned} \tag{4}$$

where the four signals are:

$$\begin{aligned} &S_1 = s_1(t) - s_1(t - T_1), \quad S_2 = s_2(t) - s_2(t - T_2), \\ &S_3 = s_3(t) - s_3(t - T_3), \quad S_4 = s_4(t) - s_4(t - T_4). \end{aligned} \tag{5}$$

Figure 3 shows in detail the principle of the proposed scheme. Four binary pulse streams $s_i(t)$ in Eq. (1) and their 1-bit delayed duplicates $s_i(t - T_i)$ in Eq. (2) are depicted in Fig. 3(a). Note that these pulse streams having different bit rates share the same period T_0, the numbers of '10' patterns are not identical. Owing to these different bit rates, S_1, S_2, S_3, and S_4, built from their respective $s_i(t)$, exhibit different central frequencies, and their waveforms are depicted in Fig. 3(b) [8]. Moreover, using phase interference between a bit stream and its delayed duplicate by the DDMZM makes it possible to suppress the low-frequency components and shape the signal to satisfy FCC spectral requirement [15]. As described in Eqs. (1) and (2), the four streams are combined to drive RF port 1 of the DDMZM, while RF port 2 is modulated by the sum of their 1-bit delayed duplicates. The combined signals and the output optical waveform are provided in Fig. 3(c). One can see from Eq. (4) that the electro-optical conversion can be considered quasi-linear if the bias voltage is set to $V_\pi/2$ and the electrical signal peaks are limited to below $V_\pi/2$ [16]. The photo-detected signal can therefore be regarded as the combination of S_1, S_2, S_3, and S_4, resulting in a received signal with multiple sub-bands. Figure 3(d) shows the electrical spectrum of the photo-detected MB-UWB signal that exhibits four central frequencies with almost the same 10-dB bandwidth. Moreover, benefiting from these sub-bands separated in the electrical domain, the transmission capacity can be increased. Note that theoretical analysis of dispersion effect is not included, which is not significant due to the narrow sub-bands and a small fiber transmission distance [5].

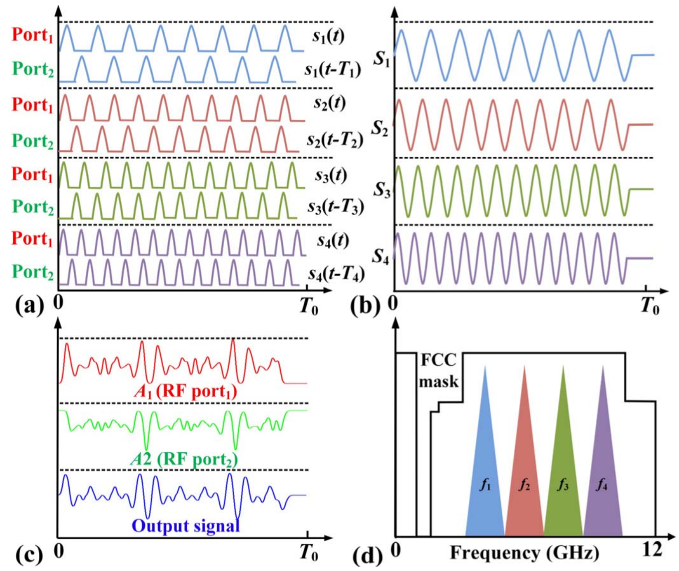

Fig. 3. (a) Waveforms of four binary pulse streams and their duplicates with 1-bit delays. (b) Waveforms of S_1, S_2, S_3, and S_4. (c) Combined signals at the two RF ports of the DDMZM, and the resulting MB-UWB signal accordingly. (d) Illustration of the spectrum for the generated MB-UWB signal.

To add data information onto the four sub-bands of the MB-UWB signal, APSK modulation is employed. Figure 4(a) shows the waveforms of the four binary pulse streams in two consecutive periods. For each sub-band, the amplitude information is determined by the amplitudes of both the pulse stream and its duplicate, while the phase information is defined by the relative time delay between them. As illustrated in Fig. 4(a) and (b), the amplitude information is '1' if the pulse stream and its duplicate exceeds a given threshold, and vice versa. The phase information is '1' if the pulse stream is delayed by 1 bit with respect to its duplicate on RF port 2, and vice versa. Thus one sub-band can carry 1-bit amplitude and 1-bit phase information during one period. Insets (i) and (ii) define explicitly the amplitude and phase information for one sub-band, respectively, and Fig. 4(b) depicts the modulated waveforms of S_1, S_2, S_3, and S_4. By this technique, the four available sub-bands of the MB-UWB signal can be simultaneously generated and modulated.

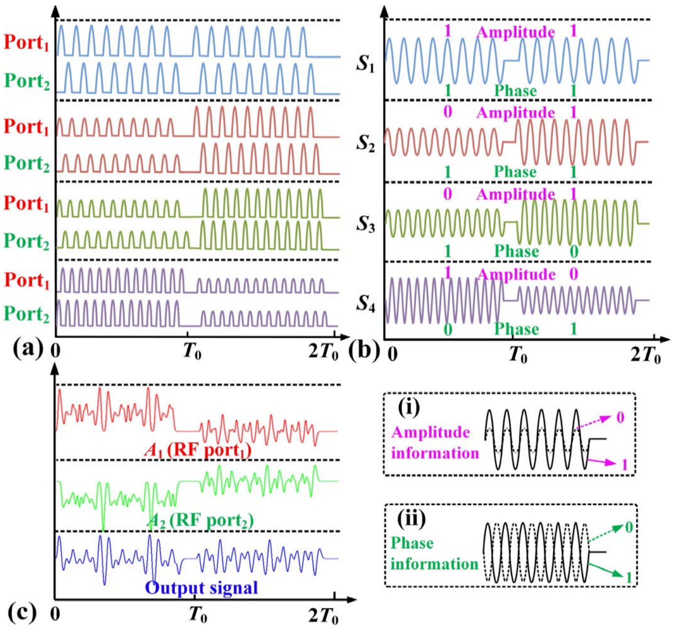

Fig. 4. (a) Waveforms of four binary pulse streams and their duplicates with amplitude and phase information. (b) Modulated waveforms of S_1, S_2, S_3, and S_4. (c) Combined signals at the two RF ports of the DDMZM and the resulting optical signal. Insets (i) and (ii): definitions of amplitude and phase information, respectively.

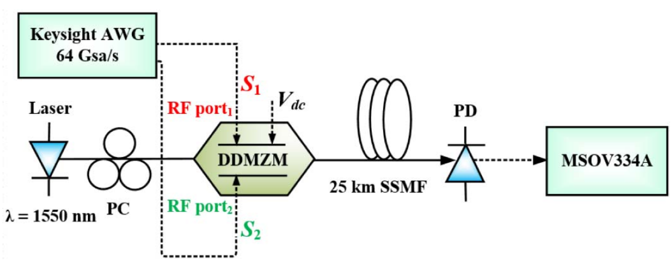

Fig. 5. Experimental setup of the proposed scheme for photonic generation of UWB signal by employing a single DDMZM. SSMF: standard single mode fiber.

The combined signals after modulation and the resulting optical waveform are shown in Fig. 4(c). Furthermore, it is worthy to note that our proposed scheme uses simple transmitter structure without electrical oscillators and multipliers [17].

III. Experimental Setup and Results

A proof-of-concept experiment was conducted to verify the feasibility of the proposed scheme for photonic generation of MB-UWB signal by employing a DDMZM. The schematic diagram is shown in Fig. 5. Due to the unavailability of multiple PPGs, the combined signals are generated offline by Matlab and output by an arbitrary waveform generator (AWG) (Keysight M8195A). The binary pulse streams are modulated by symbols mapped from a $2^{31} - 1$ pseudo random binary stream (PRBS). Here, the central frequencies of the four sub-bands are set to 4, 5, 6, and 7 GHz, respectively. The symbol period is fixed to 4 ns, which is chosen in consideration of a bit rate of 2 Gbit/s. A DDMZM (Fujitsu FTM-7921ER) is used to modulate a continuous wave (CW) light from a distributed feedback (DFB) laser at 1550 nm. A polarization controller (PC) is utilized to achieve maximum modulation efficiency. The MB-UWB signal is then obtained by properly

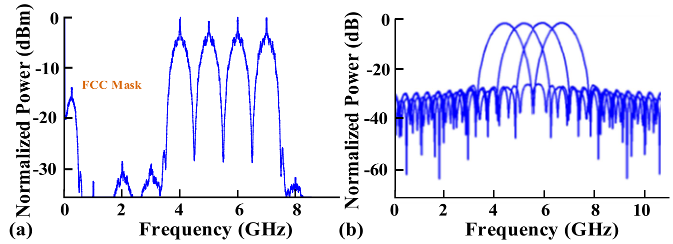

Fig. 6. (a) Simulated spectrum of the APSK-modulated UWB signal. (b) Amplitude responses of the FIR filters.

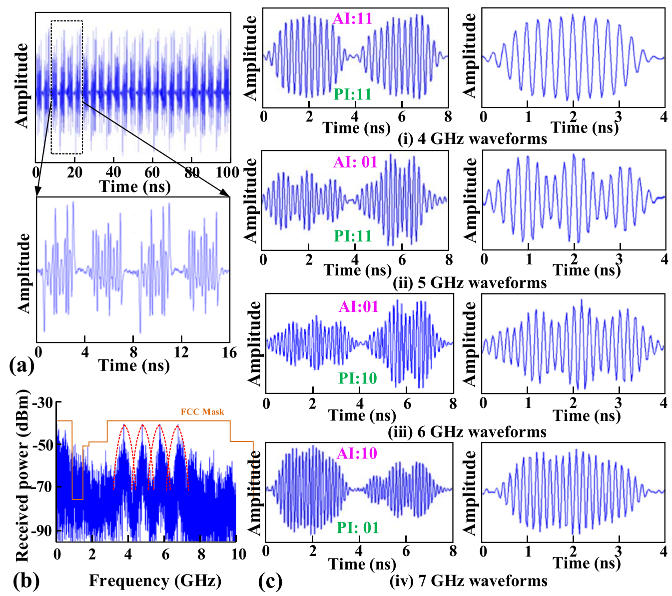

Fig. 7. (a) Measured frames of the APSK-modulated MB-UWB signal. (b) Electrical spectrum of the APSK-modulated MB-UWB signal. (c) Waveforms of the sub-bands under different time scales after DSP filtering, and the transmitted information. AI: amplitude information, PI: phase information.

adjusting the bias voltage of the DDMZM and the amplitude of the RF signals. The launch power is 5 dBm. After 25-km fiber transmission, the modulated light is detected by a photodetector (PD), and sampled by a real-time oscilloscope (Keysight MSOV334A) with an 80-GS/s sampling rate. The amplitude and phase information are recovered by calculating the overall power of a received frames, and by determining the phase shift between two consecutive frames, respectively. The bit error ratio (BER) is calculated from the average of 30 received signals due to the memory limitations of the AWG. In total, 15360 bits are considered.

The simulated APSK-modulated signal spectrum is provided in Fig. 6(a). The received signal shows very small low-frequency components, satisfying the FCC requirement [3]. To recover the information of each sub-band, finite impulse response (FIR) filters are used for digital signal processing (DSP). The amplitude responses of the four FIR filters are presented in Fig. 6(b), where the filter order and 10-dB bandwidth are fixed at 70 and 0.9 GHz, respectively. The central frequencies of the four DSP filters are 4, 5, 6, and 7 GHz, respectively.

Figure 7(a) presents the frames of the measured MB-UWB signal and the zoom-in view shows the detailed waveforms. The electrical spectrum of the MB-UWB signal is shown in Fig. 7(b). One can observe that the 10-dB bandwidth

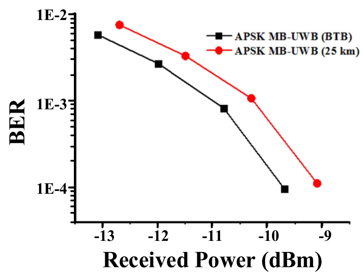

Fig. 8. BER performance of the APSK modulated MB-UWB signal.

of each sub-band is about 0.8 GHz in the range of 3.1 to 10.6 GHz. The optical spectrum could not be obtained due to the limited resolution of our optical spectrum analyzer (0.02 nm). Figure 7(c) shows the waveforms of the four sub-bands after DSP filtering under different time scales. Note that the waveform distortions can be attributed to the limited bandwidth of the DDMZM and the non-ideal DSP filters. Moreover, a small length difference between the two used electrical cables may greatly affect the signal's waveforms and the spectra, which explains the increased low-frequency components with respect to the FCC mask. These issues can be solved by integrated electrical circuits.

One can retrieve the transmitted information by comparing the power of each frame and the phase shift between two consecutive frames. The experimental results are also presented in Fig. 7. To recover the amplitude information of one sub-band after filtering, one can measure the total power over a whole period and then compare it with an optimum decision threshold. The amplitude information is '1' if the total power of the frame is higher than this threshold, and vice versa. As for the phase information, the relative phase shift between two consecutive frames can be examined and the information can be extracted. In addition, time-delay interference [7] or integrated micro- ring resonator (MRR) [18] can be implemented in optical links as an alternative method to convert phase information into intensity changes, which can bring a higher receiver sensitivity and simplify the symbol decision. As illustrated in Fig. 7(c), the amplitude information for the four sub-bands in the two adjacent periods is '11', '01', '01', and '10', respectively, while the corresponding phase information is '11', '11', '10', and '01'. Since the symbol rate of the MB-UWB signal is fixed at 0.25 GBaud/s and the signal has four sub-bands, the total bit rate reaches $0.25 \times 2 \times 4 = 2$ Gbit/s. Higher bit rate can be achieved by reducing the symbol period. However, the crosstalk might become a major limiting factor.

Figure 8 shows the mesured BER performance of the APSK-modulated MB-UWB signal, where the power penalty is ~0.5 dB after 25-km fiber link transmission. Only a BER of $\sim 10^{-4}$ is obtained due to the high sampling rate and the memory length limitation of the AWG. In practical applications, the photo-detected signal can be sampled by an analog-to-digital (ADC) chip, and field programmable gate array (FPGA)-based DSP can be used to recover the carried information [19]. The experimental results validate that our proposed method can significantly increase the transmission capacity in comparison with those where the symbol rate of the MB-UWB waveform was lower than 0.2 GBaud/s and only one sub-band was generated [12], [13].

IV. CONCLUSION

Photonic generation of MB-UWB signal of four sub-bands has been proposed and investigated experimentally with simplified system complexity. In our proposed scheme, by employing a single modulator, the MB-UWB signal can be simultaneously generated and modulated. A system demonstration using an APSK modulated signal with a significantly improved bit rate of 2 Gb/s has been performed. Experimental results suggest that our proposed scheme could become an effective solution for MB-UWB signal generation in the optical domain.

REFERENCES

[1] D. Porcino and W. Hirt, "Ultra-wideband radio technology: Potential and challenges ahead," *IEEE Commun. Mag.*, vol. 41, no. 7, pp. 66–74, Jul. 2003.

[2] F. Liu, T. Wang, Z. Zhang, M. Qiu, and Y. Su, "On-chip photonic generation of ultra-wideband monocycle pulses," *Electron. Lett.*, vol. 45, no. 24, pp. 1247–1249, Nov. 2009.

[3] J. Li *et al.*, "Photonic polarity-switchable ultra-wideband pulse generation using a tunable Sagnac interferometer comb filter," *IEEE Photon. Technol. Lett.*, vol. 20, no. 15, pp. 1320–1322, Aug. 1, 2008.

[4] H. Chen, M. Chen, T. Wang, M. Li, and S. Xie, "Methods for ultra-wideband pulse generation based on optical cross-polarization modulation," *J. Lightw. Technol.*, vol. 26, no. 16, pp. 2492–2499, Aug. 1, 2008.

[5] S. Pan and J. Yao, "UWB-over-fiber communications: Modulation and transmission," *J. Lightw. Technol.*, vol. 28, no. 16, pp. 2445–2455, Aug. 15, 2010.

[6] Q. Chang, Y. Tian, T. Ye, J. Gao, and Y. Su, "A 24-GHz ultra-wideband over fiber system using photonic generation and frequency up-conversion," *IEEE Photon. Technol. Lett.*, vol. 20, no. 19, pp. 1651–1653, Oct. 1, 2008.

[7] J. Zheng, N. Zhu, L. Wang, J. Liu, and H. Liang, "Photonic generation of ultrawideband (UWB) pulse with tunable notch-band behavior," *IEEE Photon. J.*, vol. 4, no. 3, pp. 657–663, Jun. 2012.

[8] A. J. Seeds and K. J. Williams, "Microwave photonics," *J. Lightw. Technol.*, vol. 24, no. 12, pp. 4628–4641, Dec. 2006.

[9] J. Yao, "Microwave photonics," *J. Lightw. Technol.*, vol. 27, no. 3, pp. 314–335, Feb. 1, 2009.

[10] H. Chen, T. Wang, M. Li, M. Chen, and S. Xie, "Optically tunable multiband UWB pulse generation," *Opt. Exp.*, vol. 16, no. 10, pp. 7447–7452, 2008.

[11] Y. Du, J. Zheng, L. Wang, H. Wang, N. Zhu, and J. Liu, "Widely-tunable and background-free ultra-wideband signals generation utilizing polarization modulation-based optical switch," *IEEE Photon. Technol. Lett.*, vol. 25, no. 4, pp. 335–337, Feb. 15, 2013.

[12] M. Bolea, J. Mora, B. Ortega, and J. Capmany, "Photonic arbitrary waveform generation applicable to multiband UWB communications," *Opt. Exp.*, vol. 18, no. 25, pp. 26259–26267, Dec. 2010.

[13] M. Rius, M. Bolea, J. Mora, B. Ortega, and J. Capmany, "Multiband-UWB signals generation based on incoherent microwave photonic filters," *IEEE Photon. Technol. Lett.*, vol. 26, no. 2, pp. 142–145, Jan. 15, 2014.

[14] K.-P. Ho and H.-W. Cuei, "Generation of arbitrary quadrature signals using one dual-drive Modulator," *J. Lightw. Technol.*, vol. 23, no. 2, pp. 764–770, Feb. 2005.

[15] P. J. Winzer and R. J. Essiambre, "Advanced optical modulation formats," *Proc. IEEE*, vol. 94, no. 5, pp. 952–985, May 2006.

[16] P. Cao, X. Hu, J. Wu, L. Zhang, X. Jiang, and Y. Su, "Reconfigurable UWB pulse generation based on a dual-drive Mach–Zehnder modulator," *IEEE Photon. J.*, vol. 6, no. 5, Oct. 2014, Art. no. 7903206.

[17] R. Hui, B. Zhu, R. Huang, C. T. Allen, K. R. Demarest, and D. Richards, "Subcarrier multiplexing for high-speed optical transmission," *J. Lightw. Technol.*, vol. 20, no. 3, pp. 417–427, Mar. 2002.

[18] K. Xu *et al.*, "Amplitude and phase modulation of UWB monocycle pulses on a silicon photonic chip," *IEEE Photon. Technol. Lett.*, vol. 28, no. 3, pp. 248–251, Feb. 1, 2016.

[19] R. Schmogrow *et al.*, "Real-time OFDM transmitter beyond 100 Gbit/s," *Opt. Exp.*, vol. 19, no. 13, pp. 12740–12749, 2011.