UWB-over-Fiber transmission system using a dual-output Mach-Zehnder modulator

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A novel scheme for ultra-wideband (UWB) monocycle pulse generation is proposed based on a dual-output push-pull Mach-Zehnder modulator (MZM). The MZM is driven by a non-return-to-zero (NRZ) data sequence and biased at the nonlinear point to generate edge-triggered pulses. To combine the complementary pulses forming a monocycle UWB pulse, two schemes are used to implement incoherent summation structure. A proof-of-concept experiment of UWB-over-fiber down-link system is set up. Further, by using digital signal processing (DSP) to calculate the bit error rate (BER), the transmission performance of two system configurations is studied.

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Ultra-wideband (UWB) has become a fast emerging technology for wideband personal access networks and sensor networks because of its low-power spectral density and immunity to multipath fading properties[1]. Impulse-radio UWB (IR-UWB) is one of the most attractive techniques since its carrier-free impulse modulation not only avoids complicated frequency mixer and filter circuits, but also has better pass-through characteristic due to base-band transmission. As the direct generation of IR-UWB pulse in the electrical domain is complicated and expensive, photonic generation of UWB signal has raised wide interest[2]. Optical fiber-based access technology, such as fiber-to-the-premises[3], is well known for its low-loss, high-capacity, and electrical signal transparency advantages. Fiber-based access architecture is complementary to the limited service area of UWB systems, and thus has aroused further research interest, especially on the convergence of UWB and optical fiber systems. The so-called UWB-over-fiber system appears as an attractive cost-effective solution for the distribution of UWB signal. UWB pulse is usually generated based on the implementation of the derivative of a Gaussian pulse using an optical differentiator, optical pulse-shaping by passive optical device like the fiber Bragg grating (FBG)[4], multiple laser source[5], or superstructure Mach-Zehnder modulator (MZM)[6]. UWB data encoding is usually implemented by on-off keying (OOK), pulse position[7], or pulse polarity (shape) modulation formats[8]. The major technique limitation of Refs. [4–8] lies in the insufficient exploitation of system nonlinearity, which results in strong dependence of generated signal on applied signal bandwidth. Consequently, the effective bitrate of UWB sequence is lower than that of the driving signal.

In this letter, we propose and experimentally demonstrate a novel IR-UWB over fiber system using an integrated dual-output Mach-Zehnder modulator (DOMZM). By exploiting the complementary transfer characteristics of two DOMZM outputs, a pair of positive and negative pulses can be triggered. By biasing the modulator at the nonlinear transmission point, the pulse pair corresponds to the switching edge of the driving signal. To form a monocycle pulse using the polarity-reversed pulse pair, two combined schemes were employed: 1) by using a polarization beam splitter to combine two orthogonal polarization states, and 2) by using a broadband amplified spontaneous emission (ASE) source to reduce coherence effect. For these two combined schemes, the UWB pulses with –10-dB bandwidths of 4 and 4.5 GHz have been respectively generated. In addition, by using a basic digital signal processing (DSP) algorithm to calculate bit error rate (BER), the transmission performance of the two combined schemes over a 25-km optical fiber link is also studied.

Figures 1(a) and (b) show the system configurations of the two combined schemes using DOMZM. The DOMZM integrates a MZM and a 1×2 waveguide coupler on a monolithic $LiNbO_3$ substrate. When output 1 achieves coherent destruction in the waveguide coupling area, output 2 collects the light power scattered into the substrate, and *vice versa*. Thus, when output 1 achieves extinction, output 2 maximizes its output, which gives a completely complementary transfer characteristic of two output ports[9]. In our experiment, the DOMZM was biased at the nonlinear transmission point. With an input data sequence of non-return-to-zero (NRZ) format driving the DOMZM, the rising or falling edges of the quasi-square data sequence trigger a pair of positive and negative pulse sequences. Since NRZ data format is used, the generated polarity-reversed pulse pair corresponds to the NRZ data 1/0 or 0/1 switching edge. Thus, the pulse generation system realizes a differential pulse codification with the intensity OOK modulation format. As the nonlinear biasing arrangement of the modulator enhances the generation of fast-variant spectral components, a UWB spectrum can be activated by using a relatively slow input signal.

After generating the pulse pair, a tunable delay-line was used to introduce a delay time τ to one of the outputs. Since this delay time is much smaller than the

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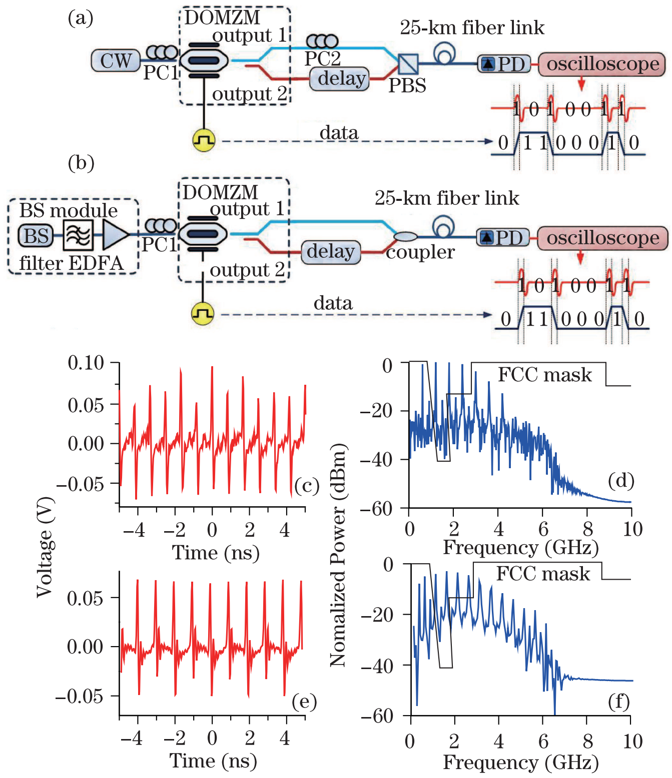

Fig. 1. Schematic diagram of UWB transmission systems based on (a) combined PBS scheme and (b) combined BS scheme. (c), (d) Generated UWB pulse sequence and electrical spectrum of PBS scheme; (e), (f) generated UWB pulse sequence and electrical spectrum of BS scheme. PC: polarization controller; PD: photodiode; BS: broadband source; PBS: polarization beam splitter.

coherent time of a narrow linewidth continuous wave (CW) source, the outputs from two light paths are coherent. To mitigate the coherent interference and obtain incoherent summation of two pulses, special consideration needs to be undertaken. In this study, two combined schemes are discussed. The first method is called the PBS scheme and has a CW laser source input. It uses a polarization beam splitter (PBS) to combine complementary pulses with orthogonal polarization states (Fig. 1(a)). A polarization controller is employed to inline-adjust the light polarization to the proper direction. Then, by combining the two pulses incoherently in PBS, a photonic UWB monocycle pulse is generated. The second method shown in Fig. 1(b) is called BS scheme. It employs a broadband ASE source (BS) whose coherent time is negligible with respect to the induced time-delay τ. Therefore, incoherent power summation can be obtained by directly coupling two outputs together using a 2×1 fiber coupler.

Unlike conventional UWB pulse generation techniques, the input NRZ data information is encoded according to the adjacent UWB pulses, which characterizes a differential encoding for the data sequence. On the other hand, with the nonlinear bias point arrangement, the frequency components of the data source experience a strong nonlinear transformation. The bandwidth is significantly broadened — the reason why a slow data edge can generate multiple frequency components of a UWB pulse. Moreover, with the usage of an integrated DOMZM, the positive and negative pulses are generated synchronically and share complete symmetry property, enabling the system to achieve higher stability and reconfigurability.

The transmission systems were experimentally implemented (Figs. 1(a) and (b)). For the PBS scheme, a photonic UWB monocycle pulse sequence was generated with the full-width at half-maximum (FWHM) of 83 ps (Fig. 1(c)). The electrical spectrum has a central frequency of 2.5 GHz and a –10-dB bandwidth of 4.0 GHz (Fig. 1(d)), which indicates that the fractional bandwidth of the monocycle pulse is 160%. Meantime, the bandwidth can also be adjusted by changing the delay time τ or by shaping the electrical drive signal. The fluctuation of the signal power level is due to the random coherence summation caused by non-ideal orthogonal polarization states and the imbalance waveforms of data having rising and falling edges, which result in alternate waveform distortion. From Fig. 1(d), the noise floor is –57.8 dBc with respect to the maximal unit spectral power. In the BS scheme (Fig. 1(b)), broadband source and 2×1 coupler were used as alternatives to CW laser and the PBS, respectively. The wavelength of the ASE source ranged from 1528 to 1563 nm, and the typical output power was 13.3 dBm. To reduce the transmission degradation induced by fiber dispersion, an optical filter with a passband of 0.3 nm and an erbium-doped fiber amplifier (EDFA) were cascaded following the source. Figures 1(e) and (f) show the UWB pulse sequence and its electrical spectrum. The FWHM, central frequency, and –10-dB bandwidth were 80 ps, 2.5 GHz, and 4.5 GHz, respectively. The fractional bandwidth was 180%. The noise floor was –45.4 dBc with respect to the maximal unit spectral power, which indicated that the noise induced by the broadband source was higher than that by the CW laser. Clearly, broadband source contributed mainly to ASE beat noise, while relative intensity noise (RIN) mainly influences CW laser noise[10]. As shown in Figs. 1(d) and (f), the two spectra were not completely compliant to the Federal Communication Committee (FCC) spectrum mask since the monocycle pulse profile configured by combining positive and negative pulses cannot fit the spectrum mask theoretically. Here, spectrum inconformity was the major limitation of such combined polarity-reversed pulses generation schemes. To form a more suitable pulse under the FCC mask regulation, DOMZM can be employed to generate high-order Gaussian derivatives, wherein the modulator is biased at a higher order nonlinear point and the differential is identified to combine two outputs.

Using the data signal operating at 1 Gb/s, with 15 bits fixed at the pseudo-random binary sequence (PRBS) pattern of “0000 1010 0110 111” applied to the DOMZM, the BERs of the transmission systems were calculated (Fig. 2(a)). With a 40-GSa/s digital storage oscilloscope, BER was computed offline based on an algorithm that distinguishes “1” and “0” bits and compares average power with optimally-determined decision threshold. For optical power greater than 0 dBm at the receiver end, each BER measurement point was calculated based on the transmitted and recorded 5×10^6 UWB bits[11,12]; for optical power lower than 0 dBm, each BER point was

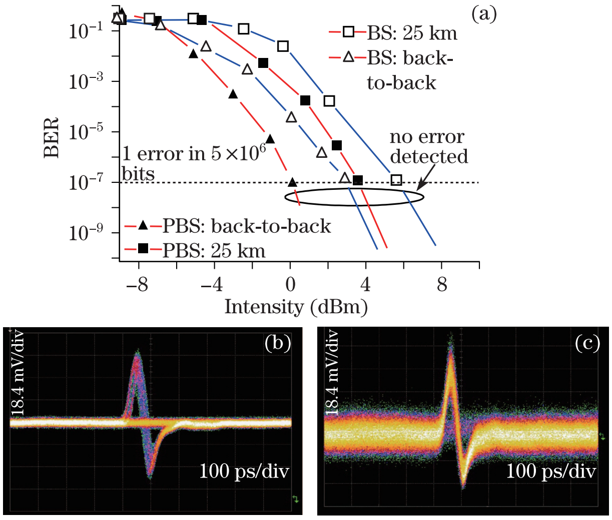

Fig. 2. (a) BER curves and eye diagrams of (b) PBS scheme and (c) BS scheme.

calculated based on 5×10^5 bits. For the PBS scheme, the BER curves show that the power penalty for a 25-km fiber transmission is about 2.8 dBm, which is caused by chromatic dispersion, and instability of the polarization. The eye diagram at the receiving end is shown in Fig. 2(b), whereas the eye diagram for the BS scheme is shown in Fig. 2(c). The back-to-back performance was relatively worse for the BS scheme due to the higher noise floor (also shown in the eye diagram). For the 25-km transmission link, the power penalty was 2.3 dBm, which was less than that of the PBS scheme, a result of optical filter usage. Waveform degradation was caused mainly by loss and dispersion.

For this experimental configuration, using slow data edge, MZM was biased at the point of maximum nonlinearity to produce as many frequency components as possible. This approach helps broaden the spectral range of signals, reducing the bandwidth requirement of the driving signal. However, this bias point arrangement degrades the modulation efficiency, thus increasing the receiver sensitivity. Therefore, a tradeoff between drive bandwidth and receiver sensitivity exists.

In conclusion, we realize experimentally the novel UWB generation scheme using DOMZM and the two combined incoherent schemes. By modulating 1-Gb/s NRZ signal at differential intensity modulation format, a UWB-over-fiber down-link system is demonstrated. The system is of particular interest for various applications of high bit rate transmission systems, enabling the implementation of key functionalities, such as switching of wideband personal area networks at unprecedented bit rates. Further, the proposed scheme can be integrated and is particularly attractive for distribution systems.

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