Simultaneous Generation and Transmission of Downstream Multiband Signals and Upstream Data in a Bidirectional Radio-Over-Fiber System

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***Abstract*—We propose and experimentally demonstrate simultaneous generation and transmission of downstream multiband signals and upstream data in a bidirectional radio-over-fiber system. The scheme is based on a dual-parallel Mach–Zehnder modulator and a following single-drive Mach–Zehnder modulator. Multiband data including baseband, frequency-doubled, and frequency-quadrupled signals are generated through optical carrier suppression and frequency-shifting techniques. Upstream data transmission is realized by remodulation of the downstream differential phase-shift-keying signal without the need of additional light source and wavelength management at the base station.**

***Index Terms*—Differential phase-shift keying (DPSK), dual-parallel Mach–Zehnder modulator (DPMZM), multiband signals, radio-over-fiber (RoF), wireline and wireless access.**

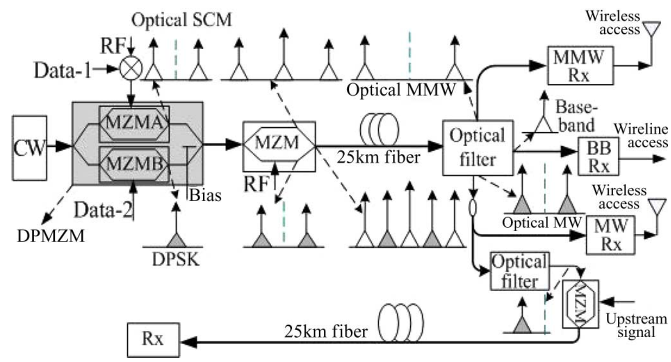

Fig. 1. Schematic diagram of the proposed bidirectional RoF system.

I. Introduction

THE future broadband wireline and wireless access networks demand large bandwidths and high data rates for data-intensive multimedia and real-time applications. It is desirable to simultaneously transmit baseband and radio-frequency (RF) signals using the same fiber infrastructure with cost-effective configurations [1]–[5]. Among them, the multiband optical modulation technique is an attractive method, which simultaneously delivers baseband, microwave (MW), and millimeter-wave (MMW) signals in radio-over-fiber (RoF) systems [4], [5]. It exhibits flexible application potential in future multiservice access networks since wireline and multiple wireless services are seamlessly converged in an integrated platform. Reference [4] has proposed a system where the multiband signals are generated using individual light sources and modulators, which provides good flexibility for different applications. A cost-effective and simple scheme to generate multiband signals has been demonstrated in [5], where multiband signals are superimposed in the electrical domain to drive an electroabsorption modulator. In these reports, uplink data transmission has not been demonstrated, while in practice, bidirectional data transmission needs to be considered.

Recently, we have concept-proved a unidirectional multiband RoF system [6] with preliminary demonstrations. In this letter, we show a full-duplex RoF system to generate and transmit downstream wireline baseband data, wireless MW and MMW signals on a single wavelength, using a dual-parallel Mach–Zehnder modulator (DPMZM) [7] followed by a standard single-drive Mach–Zehnder modulator (SDMZM). Upstream symmetric data transmission is obtained through remodulating the downstream differential phase-shift-keying (DPSK) signal [8], [9], therefore, the base station (BS) configuration cost is greatly reduced since no additional light source and wavelength management are required at the BS. The scheme can achieve simultaneous frequency doubling and quadrupling, and it is scalable in frequency band if higher speed devices are used. The frequency shifting by the fixed multiplication factor, however, is a possible limitation in selecting a particular frequency for certain applications.

II. Principle

The schematic diagram of the proposed RoF system is depicted in Fig. 1. The transmitter consists of a DPMZM [7] followed by an SDMZM. The DPMZM comprises a pair of x-cut $LiNbO_3$ MZMs (MZMA, MZMB) embedded in the two arms of a main MZM structure. The two sub-MZMs have the same structure and performance, and the main MZM combines the outputs of the two sub-MZMs. At the central station (CS), a continuous-wave (CW) laser is launched into the DPMZM. The MZMA is biased at its null point and driven by an RF signal loaded with data-1 to generate a carrier-suppressed optical subcarrier multiplexed (SCM) signal, whose repetition rate is twice that of the RF signal frequency. The MZMB is also biased at

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its null point and driven by another data-2 to produce a DPSK signal. The two optical signals are then added constructively by adjusting the bias of the main MZM, and they do not interfere with each other since the carrier of the optical SCM signal is suppressed. A following SDMZM biased at null point is driven by the same RF signal to shift the frequencies of the DPMZM outputs thus resulting in multiband signals. The output of the MZMA is modulated with the carrier suppression technique [10] by the SDMZM to generate the optical baseband and frequency quadrupled MMW signals with data-1; therefore, the wireline and wireless users can share the identical data service at the baseband and MMW, respectively, while the output of the MZMB goes through the same frequency-shifting process to achieve optical MW DPSK data. After the transmission, at the BS, two fiber Bragg gratings (FBGs) with optical circulators are used to separate each band, which are detected using individual receivers, respectively. The optical MW signal is split into two parts; one is detected by an MW receiver, and the other is filtered to obtain its lower sideband, which is remodulated by the upstream ON–OFF-keying (OOK) signal. The upstream signal is sent back to the CS and then detected by a low-speed optical receiver. Using this design, one can simultaneously deliver downlink multiband signals and uplink data with a single wavelength in a bidirectional RoF system. It should be noted that in real network implementations, a diplexer connected with the antenna is needed to broadcast downstream RF signals and receive upstream RF signals at the BS. The baseband upstream data is obtained by down-converting the RF signals from the diplexer.

III. Experimental Setup and Results

Fig. 2 shows the experimental setup for the proposed bidirectional RoF system. At the CS, a 10-GHz DPMZM (COVEGA Mach-10060, 5.8-dB insertion loss) is used to modulate a CW light from a tunable laser at 1549.86 nm. An SCM signal is obtained by mixing a 1.25-Gb/s pseudorandom bit sequence (PRBS) data of $2^7 - 1$ with a 10-GHz clock signal, the waveform is shown in inset (i) of Fig. 2. The sub-MZMA is biased at the null point and driven by the SCM signal to generate a carrier suppressed signal of 20-GHz rate, the waveform, the eye diagram, and the spectrum are shown in Fig. 2 as insets (ii) and (iii) and Fig. 3(a), respectively. Sub-MZMB is biased at the null point and driven by another 1.25-Gb/s PRBS data with a word length of $2^7 - 1$; the optical eye diagram of the generated DPSK data (inset (iv) of Fig. 2) shows certain imperfection due to the lack of a high-power modulator driver to provide an output swing of $2V_{\mathrm{pi}}$. The spectrum of the two optical signals that are constructively added is provided in Fig. 3(b). A following 10-GHz SDMZM (JDS Uniphase, 4.5-dB insertion loss) is biased at null point and driven by a 10-GHz clock signal to obtain the multiband signals. The baseband and 40-GHz MMW signals are generated by modulating the output of the MZMA, whose output spectrum is shown in Fig. 3(c). The 20-GHz MW signal is obtained by modulating the output of the MZMB; the eye diagram and spectrum are indicated in inset (v) of Fig. 2 and Fig. 3(d), respectively. The multiband signals are amplified by an erbium-doped fiber amplifier (EDFA) to reach an 8-dBm power level for transmission, and the spectrum is shown in Fig. 3(e). A tunable optical filter (TOF) is used to suppress amplified spontaneous emission (ASE) noise. Considering the fiber length and the powers of the multiband signals, the nonlinear effects are not significant in this system.

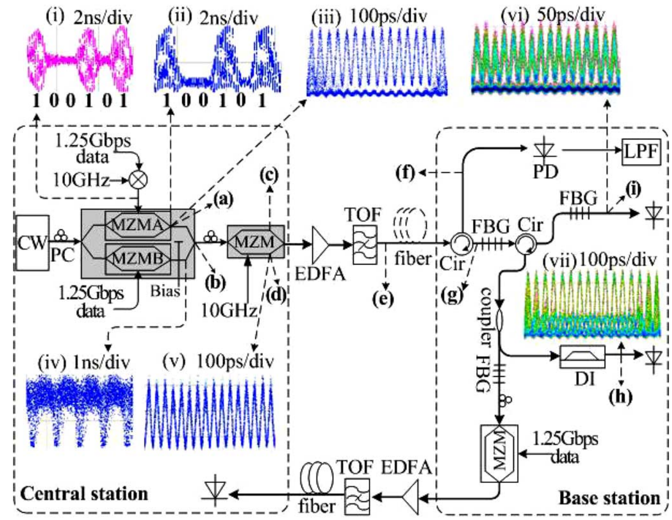

Fig. 2. Experimental setup of the proposed bidirectional RoF system. (i) The waveform of electrical SCM signal; (ii) the waveform of the optical SCM signal; (iii) the eye diagram of optical SCM signal; (iv) the eye diagram of DPSK signal; (v) the eye diagram optical MW signal; (vi) the eye diagram of optical MMW signal (back-to-back); (vii) the eye diagram of optical MW after MZDI (back-to-back). (a)–(i) correspond to the optical spectra shown in the Fig. 3.

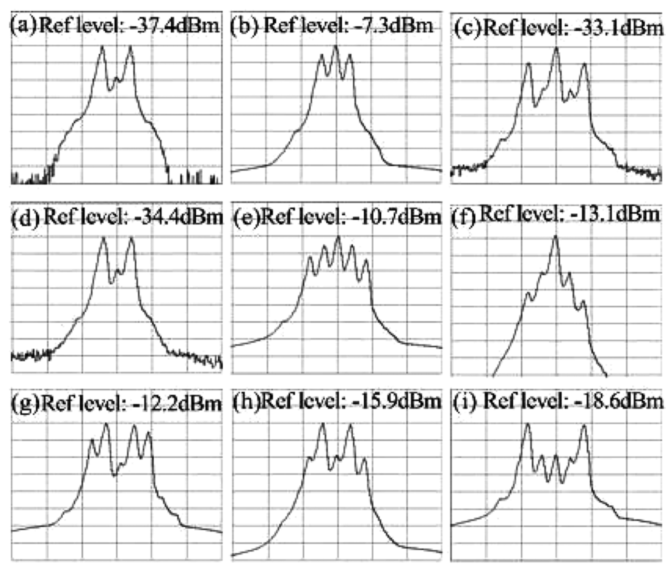

Fig. 3. Optical spectra taken at different positions as indicated in Fig. 2. Spectrum resolution: 0.07 nm; Start wavelength: 1548.86 nm; Stop wavelength: 1550.86 nm; X-axis scale: 0.2 nm/div, Y-axis scale: 5 dB/div. (a) Carrier-suppressed optical SCM signal; (b) DPMZM output signals; (c) baseband and MMW signals; (d) MW signal; (e) amplified multiband signals; (f) separated baseband signal; (g) passing signal from the first FBG; (h) separated MW signal; (i) separated MMW signal.

After transmission over 25-km standard single-mode fiber (SMF), at the BS, an FBG with a 3-dB bandwidth of 0.1 nm and a reflection ratio of 90% is used to separate the baseband data from the multiband signals; the spectra of the reflected baseband signal and the passing signals are shown in Fig. 3(f) and (g), respectively. The passing signals from the first FBG are injected into a second FBG with a 3-dB bandwidth of 0.2 nm and a reflection ratio of 90% to separate the optical MW and MMW

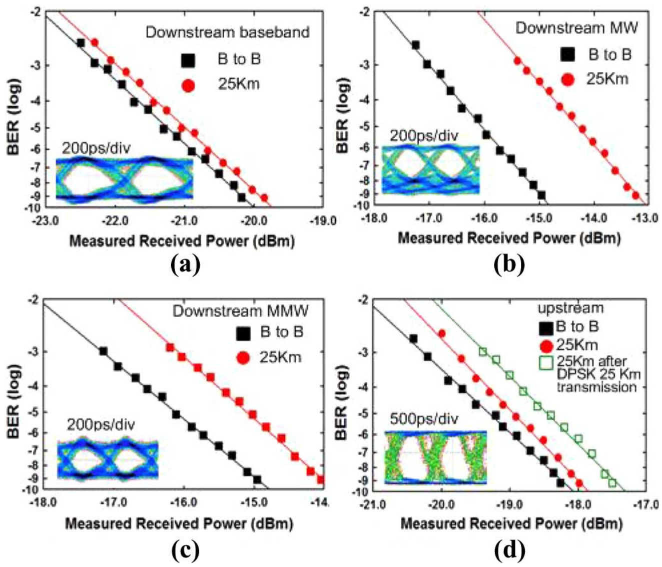

Fig. 4. BER curves and electrical eye diagrams. (a) Downstream baseband signal. (b) Downstream MW signal. (c) Downstream MMW signal. (d) Upstream remodulation signal.

signals; the spectrum of the reflected MW signal is indicated in Fig. 3(h), and the eye diagram and the spectrum of passing MMW signal are shown in inset (vi) of Figs. 2 and 3(i), respectively. A 2.5-GHz photodetector (PD) is used to detect the baseband signal and a low-pass filter with a 3-dB bandwidth of 1.35 GHz is employed to reject the undesired RF components. The reflected MW signal is divided into two parts; one is converted into the intensity signal by a 1-bit Mach–Zehnder delay interferometer (MZDI), with the optical eye diagram after MZDI provided in Fig. 2 as inset (vii). There are some ripples in the eye diagram due to the imperfect DPSK modulation. The other part is sent into a third FBG with an identical performance as the first FBG to filter its lower sideband, which is employed for remodulation using 1.25-Gb/s PRBS data with a 2^7-1 word length. A polarization controller is used to maintain good transmission performance. This limitation can be resolved using commercially available polarization-insensitive modulators. After transmission, over 25-km SMF, the upstream signal is detected by a 2.5-GHz PD. The power margins of the baseband, the MW, and the MMW signals employing such generation and detection schemes are $\sim$15, $\sim$2, and $\sim$3 dB, respectively. In practice, two high-speed receivers are needed to convert the optical MW and MMW signals to the electrical wireless signals. In this experiment, we mainly focus on demonstrating multiband signal generation and upstream signal remodulation, and the optical MW and MMW signals are demodulated using a 2.5-GHz PD by detecting their upper-sideband components for bit-error-rate (BER) measurements without a high-speed receiver. Simulations show that the difference of power penalty remains negligible after the transmission regardless of the demodulation methods.

Fig. 4 shows the measured BER results and electrical eye diagrams for the multiband signals and the upstream signal. After the transmission over the 25-km SMF, for the baseband data, the power penalty is $\sim$0.2 dB as the chromatic dispersion effect is negligible at this rate. For the MW signal, the power penalty is $\sim$1.7 dB, which can be attributed to the amplitude fluctuation of the residual optical MMW caused by the dispersion. A power penalty $\sim$1.2 dB is observed for the MMW signal mainly due to the dispersion of the SMF in the RF frequency [8], [10]. We also measured BER performance of the remodulated upstream OOK signal; the power penalty is less than 1 dB. The electrical eye diagrams of the multiband signals and the upstream signal are provided in insets of Fig. 4.

IV. Conclusion

We have proposed a novel bidirectional multiband RoF system and experimentally demonstrated the simultaneous generation and transmission of the downstream 1.25-Gb/s baseband, 20-GHz MW and 40-GHz MMW signals, and upstream symmetric data over the 25-km SMF. The system uses 10-GHz components to achieve frequency doubling and frequency quadrupling, and without the need of additional light source and wavelength management at the BS. Moreover, the scheme is scalable in the frequency band if faster electronic devices are available. Experimental results show that our scheme is a candidate solution to simultaneously deliver multiband signals in future optical access networks.

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