Millimeter-Wave UWB Signal Generation Via Frequency Up-Conversion Using Fiber Optical Parametric Amplifier

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***Abstract*—We propose and demonstrate a novel approach to generate millimeter-wave (MMW) ultra-wideband (UWB) signal via frequency up-conversion using fiber optical parametric amplifier (OPA). The baseband UWB signal is amplified by a high-repetition-rate pulsed pump and generates many sidebands separated by the modulation frequency of the pump. By selecting two or three of the sidebands and beating in the photodetector, we can obtain an up-converted signal in the MMW band. In our experiment, we have successfully demonstrated UWB signal up-conversion from 3 to ∼19 GHz with 18-dB optical gain using fiber OPA.**

***Index Terms*—Frequency up-conversion, millimeter-wave (MMW), optical parametric amplifier (OPA), ultra-wideband (UWB).**

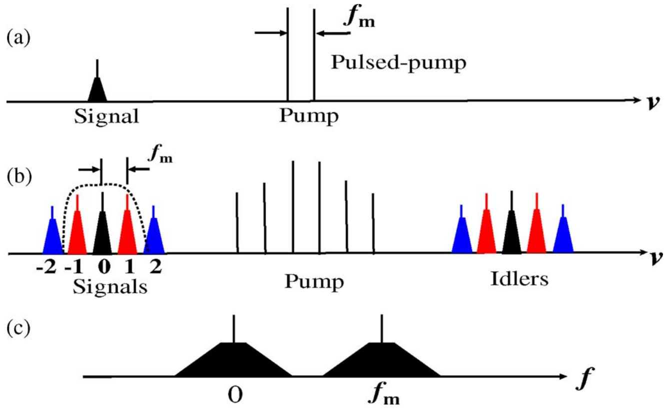

Fig. 1. Principle of operation. (a) Input spectrum. (b) Output spectrum. (c) Filtered output electrical spectrum.

I. INTRODUCTION

ULTRA-WIDEBAND (UWB) technology has attracted great interest recently to overcome the scarcity of available radio-frequency resource. The UWB communication system is regulated to operate mainly in two frequency bands, the baseband (7.5 GHz) and millimeter-wave (MMW) band (24 and 60 GHz). The baseband UWB is proposed for high-speed wireless personal area network while MMW UWB is mainly for vehicular radar applications. Since UWB communication systems can only operate within a short distance, to distribute UWB signals through optical networks can significantly extend its coverage area [1]. Therefore, it is highly desirable to generate and process UWB signals directly in the optical domain to reduce system cost. Many methods have been proposed to generate baseband UWB signals [2]–[5]. To implement MMW UWB over fiber, all-optical frequency up-conversion is needed because it is cost-effective by centralizing broadband mixing in the center office instead of each base station. Several approaches have been reported to realize frequency up-conversion for MMW UWB signal generation. One method is based on self-heterodyne technique using an arrayed waveguide grating [6], which requires special Mach–Zehnder modulator (MZM) with high extinction ratio to suppress residual carrier to meet the UWB emission mask. However, this method has a good tolerance to fiber dispersion. Another method is based on direct modulation in an MZM in the nonlinear regime [7], which is simple and compact. Nevertheless, it needs expensive high-speed electronic devices which make it difficult to be upgraded to a 60-GHz frequency up-converter. A method based on nonlinear polarization rotation in a semiconductor optical amplifier is also demonstrated with a broad conversion range of the whole C-band [8]. But it suffers from the slow carrier recovery speed which limits its performance in the high-frequency regime. Furthermore, the MMW UWB signal after fiber transmission is analyzed in [9], which shows the doublet pulse has better tolerance to fiber dispersion than the monocycle pulse.

In this letter, we propose a fiber optical parametric amplifier (OPA)-based frequency up-converter which exhibits a large mixing bandwidth owning to its ultrafast response property dominated by $\mathcal{X}^{(3)}$ in the optical fiber. In addition, this method can be upgraded to a 60-GHz up-converter by selecting the higher order sidebands without using high-frequency electrical components. Furthermore, it can be deployed in the remote local oscillator delivery scheme to mitigate the dispersion effect in the long reach access networks and serves as both frequency up-converter and signal amplifier in a local exchange [10] because of its all-optical operation and positive optical gain.

II. PRINCIPLE

The principle of UWB frequency up-converter is shown in Fig. 1. The pump consists of two narrowly spaced equal-power continuous monochromatic waves with a frequency separation

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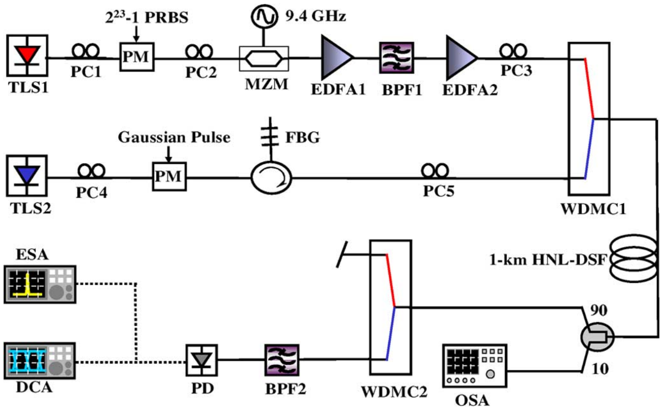

Fig. 2. Experimental setup for MMW UWB frequency up-conversion using fiber OPA. Refer to text for detailed description.

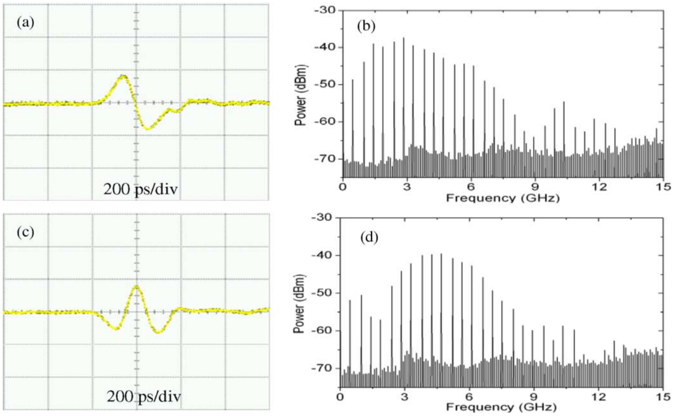

Fig. 3. (a), (c) UWB monocycle and doublet pulse. (b), (d) Power spectrum of the corresponding monocycle and doublet pulse (resolution bandwidth (RBW) is 3 MHz).

of f_m, which can equally be viewed as a single wave with average frequency ν_c and a cosine-squared modulation at the beat frequency f_m. Then the high power pump is copropagating with a weak signal along a spool of nonlinear fiber. After parametric amplification, the signal spectrum at the output of the nonlinear fiber will consist of multiple discrete frequency peaks separated by a frequency of f_m, and each frequency peak contains the replica of the input signal spectrum as shown in Fig. 1(b). It is the same for the idlers generated at the other side of the pump except that the spectrum of each idler is inverted with respect to that of the original signal. The newly generated frequency peaks beside the original two pump waves are due to the self-phase modulation effect [11]. According to a quasi-continuous-wave (CW) calculation, the output signal spectrum can be written as

$$B_s(L,f) = \sum_{n=-\infty}^{\infty} a_n B_s(0, f - nf_m)$$

where $B_s(0,f)$ is the input signal spectra, $B_s(L,f)$ is the output signal spectra, and a_n is conversion coefficients for each newly generated sidebands. As the sidebands are inherited from parametric gain from the pump, they are phase-correlated with each other. Therefore, we can select two or three neighboring frequency components by using a narrowband optical filter and launch them into the photodetector (PD). After beating between the sidebands, a stable MMW signal at frequency f_m will be generated and the spectrum of the original signal will also be up-converted to this frequency as shown in Fig. 1(c). Furthermore, if two second-order sidebands ($n = -2, 2$) as shown in Fig. 1(b) of the output signal spectrum are selected by specially designed fiber Bragg gratings (FBGs) and beat in the PD, baseband signal can be up-converted to an even higher frequency.

III. EXPERIMENT

Fig. 2 shows the experimental setup for UWB monocycle and doublet pulses generation and up-conversion. A tunable laser source (TLS2) is used to generate a CW signal. It is then phase modulated by a phase modulator (PM) with a train of Gaussian pulses with a duty ratio of 1/20 at a bit rate of 9.4 Gb/s. So the repetition rate of the generated pulse is 470 Mb/s. Then the phase-modulated signal is launched into a circulator and an FBG to achieve phase modulation to intensity modulation conversion by using the FBG as a frequency discriminator [4]. In our experiment, the center wavelength of the FBG is located at 1557.701 nm with a 3-dB bandwidth of 0.20 nm, the wavelength of the signal was chosen to be 1557.596 or 1557.647 nm to generate baseband UWB monocycle or doublet pulse. Since the output power of the UWB signal is around -9.5 dBm which is too small for detection, we use another erbium-doped fiber amplifier (EDFA) to amplify it before characterizing its temporal and spectral performance as shown in Fig. 3. It can be observed that the monocycle pulse has a center frequency of 2.82 GHz and a -10-dB bandwidth of 5.82 GHz, while the doublet pulse has a center frequency of 4.69 GHz and a -10-dB bandwidth of 4.82 GHz. Meanwhile, TLS1 is served as the pump with a wavelength of 1543 nm. It is phase-modulated by a 10-Gb/s $2^{23}-1$ pseudorandom binary sequence (PRBS) to suppress stimulated Brillouin scattering (SBS). Then the pump wave is coupled into an MZM biased at the transmission null to act as a double sideband with optical carrier suppressed (DSB-OCS) modulation. The MZM is driven by an electrical sine wave with a frequency of 9.4 GHz to generate two pump waves separated by 18.8 GHz. The frequency chosen as 18.8 GHz instead of 24 GHz is mainly limited by the electrical spectrum analyzer (ESA) used which has a range up to 26 GHz. However, this method also works for 24-GHz up-conversion case due to the ultrafast response time in the optical fiber. Then the pump is amplified by a two-stage EDFA (EDFA1 and 2) to a power of 25.44 dBm. A bandpass filter (BPF1) is used to suppress amplified spontaneous emission (ASE) noise. The pump and signal waves are coupled together by a wavelength-division-multiplexing coupler (WDMC1) and launch into 1-km highly nonlinear dispersion-shifted fiber (HNL-DSF) with zero-dispersion wavelength of 1542 nm and nonlinear coefficient of 10.4 $\mathrm{W}^{-1} \cdot \mathrm{km}^{-1}$. Polarization controllers (PC3 and PC5) are located in the signal and pump branches to align the state of polarization of the two waves to maximize OPA gain. The optical spectrum after the HNL-DSF is analyzed in the optical spectral analyzer (OSA) as shown in Fig. 4(a). An on–off OPA gain of 18 dB has been achieved in the experiment which shows reamplification capability of the original signal. Fig. 4(b) shows the spectrum of the output signal in a larger scale with a resolution of 0.01 nm. Because of the OPA gain, many sidebands which contained the replica of the original signal spectrum are generated around the original

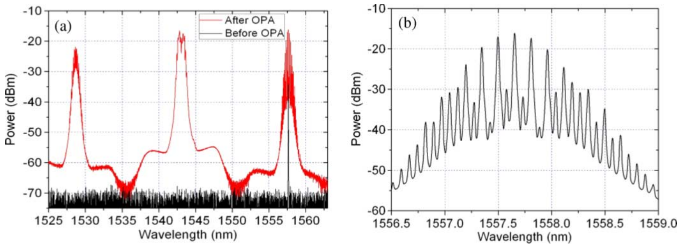

Fig. 4. (a) OPA spectrum. (b) Zoomed-in spectrum of the amplified signal.

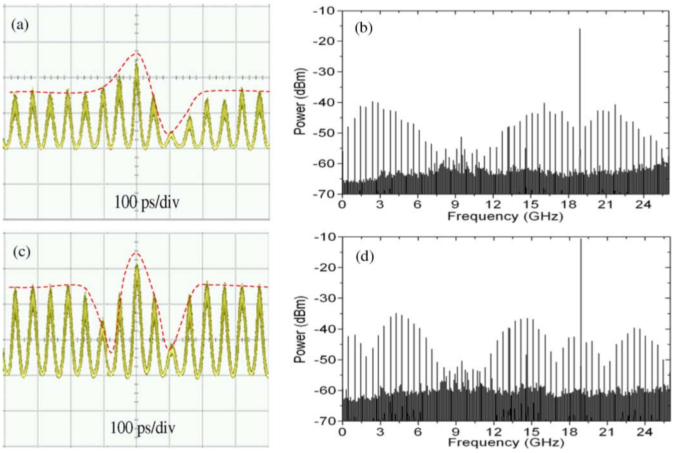

Fig. 5. (a), (c) Up-converted UWB monocycle and doublet pulse. (b), (d) Power spectrum of the corresponding monocycle and doublet pulse (RBW is 3 MHz).

signal spectrum with a frequency separation of 18.8 GHz. Then the pump wave is discarded using another WDMC2 and the up-converted signal is further filtered by a narrowband BPF2 to select the three frequency peaks in the center of the spectrum. If we select only two of them, the electrical power generated would be rather low for detection. Then the three waves are injected into a PD, and finally monitored in the digital communication analyzer (DCA) and the ESA.

Fig. 5(a) and (c) shows the waveforms of the up-converted UWB monocycle and doublet pulse, respectively. It can be observed that the carrier is a pulse train with a frequency of 18.8 GHz and the envelopes resemble the original baseband UWB signals as shown in the waveforms with red dashed lines. The corresponding power spectra of the up-converted UWB signals are shown in Fig. 5(b) and (d). It can be seen that both baseband and MMW UWB signals are obtained in the spectra just as the theory predicts. The MMW monocycle pulse has a center frequency of 21.73 GHz and a -10-dB bandwidth of 5.76 GHz, while the MMW doublet pulse has a center frequency of 23.14 GHz and a -10-dB bandwidth of 4.24 GHz. It is clearly observed that the bandwidth is almost maintained during the up-conversion process. The greater deviation of bandwidth for doublet pulse is attributed to limited bandwidth of PD used which is only 22 GHz. However, the -10-dB bandwidth of the lower sideband of the up-converted doublet spectrum is measure to be 4.66 GHz which means the upper sideband should have a bandwidth almost the same as that of the baseband signal. A strong frequency component also appears at 18.8 GHz in the spectrum due to the beating between the optical carriers, which can be mitigated by carrier suppression using FBGs. Electrical UWB filters located at 24-GHz band should be used to eliminate undesirable low-frequency or baseband components to avoid interference with other wideband services before radiation. As an efficient way, the baseband spectral lines can be reused for the baseband UWB communication. Although up-converted signals are not located in the frequency range from 22 to 29 GHz, it can be extended into a 24-GHz UWB signal generator by using a higher modulation frequency. Furthermore, we can also extend this method into a 60-GHz up-conversion case by beating the two second-order sidebands in the PD using a modulation frequency of only 7.5 GHz.

IV. CONCLUSION

We have demonstrated a novel approach to implement all-optical frequency up-conversion for MMW UWB over fiber systems by using fiber OPA. The power spectrum of the up-converted UWB signal shows many sidebands separated by the modulation frequency of the pump. By selecting the three main sidebands and detected using a PD, we can obtain up-converted MMW UWB signals. Although a ~ 19-GHz frequency up-conversion is demonstrated here, this method can be extended into 60-GHz up-conversion system.

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