Photonic generation of high quality frequency-tunable millimeter wave and terahertz wave

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Received August 22, 2011; accepted October 13, 2011; posted online December 28, 2011

A scheme for the photonic generation of frequency-tunable millimeter wave and terahertz wave signals based on a highly flat optical frequency comb is proposed and demonstrated experimentally. The frequency comb is generated using two cascaded phase modulators (PMs) and an electro-absorption modulator (EAM). The frequency comb covers a 440-GHz frequency range, with 40-GHz comb spacing and less than 2-dB amplitude variation. By filtering out two of the comb lines with 50 dB out of the band suppression ratio, high frequency-purity and low phase noise millimeter wave or terahertz wave signals are successfully generated, with frequencies ranging from 40 to 440 GHz.

OCIS codes: 250.4110, 350.7420.

doi: 10.3788/COL201210.042501.

Millimeter and terahertz waves are very important for ultra-broadband wireless communications and spectroscopic sensing applications[1−5]. Generating such signals based on electrical devices is always a challenging problem. In recent years, the generation of millimeter and terahertz waves by photonic technologies has attracted much attention, because millimeter or terahertz signals at very high frequencies can be generated easily using optical methods. In addition, the photonic generation of such signals brings many other advantages, such as reducing the cost of electrical circuits or devices, and providing more convenience for use in radio-over-fiber (ROF) systems. Several approaches for the photonic generation of millimeter and terahertz waves have been reported recently. The basic principle of such schemes is heterodyning two light waves with a wavelength difference at a photo-mixer or photo-detector. The challenge for this technique is that the two light waves must be phase correlated. A simple way is to employ the output from a dual-wavelength fiber laser[6]. However, the generated terahertz wave has a large phase noise. Two phase-correlated optical waves can also be generated by selecting out two four-wave mixing (FWM) components[7−9], but the major problems associated with the FWM effects are the ultralow conversion efficiency and complicated transmitter. Another method is filtering out two spectral lines from an optical frequency comb generated by external modulators[10−16]. The last method is the most promising one because of its simplicity, high stability, and ease of frequency-tunability. For instance, an optical frequency comb consisting of multiple optical spectral lines is generated from external modulators. Moreover, with two narrowband optical filters used to select two of these spectral lines, two phase-correlated light waves with a frequency spacing tunable from the reference frequency to times the reference frequency are obtained. In this method, the generated frequency comb must be flat, stable, and as wide as possible. Equal amplitude comb with minimum frequency spacing of 30 MHz can be generated by multi-frequency phase modulation[17]; however, an arbitrary function generator must be used and large fundamental frequency may be limited by the available radio frequency (RF) signal bandwidth. Only four comb lines with 4.5-GHz comb spacing are generated using an intensity modulator and a phase modulator (PM)[18]. A PM and a Mach-Zehnder modulator (MZM) are cascaded to generate the optical frequency comb with 25-GHz frequency spacing, through which the electrical signals with frequency as high as 325 GHz are generated[19]. Two MZMs and two PMs are used to generate the flat comb with 38 comb lines (10-GHz comb spacing and maximum frequency of 370 GHz)[20]. However, using these increases the complexity and cost of the procedure.

In this letter, we propose and experimentally demonstrate a method for the photonic generation of frequency-tunable millimeter wave and terahertz wave signals based on a highly flat optical frequency comb. The comb is generated using two cascaded PMs and an electro-absorption modulator (EAM). It covers a 440-GHz frequency range with 40-GHz comb spacing and less than 2-dB amplitude variations. The frequency range of our frequency comb is wider than those reported in previous works, which used cascaded MZM and PM; in addition, the variation is much smaller[17−20]. Moreover, the frequency comb is very stable and has high optical signal-to-noise ratio (OSNR). By filtering out 2 comb lines using a programmable optical processor with 50 dB out of band suppression ratio, millimeter or terahertz wave signals with frequency ranging from 40 to 440 GHz, and frequency spacing of 40 GHz are generated successfully. The generated millimeter and terahertz waves have high frequency-purity and very low phase noise.

Figure 1 shows the experimental setup of the proposed photonic millimeter and terahertz wave generation scheme. A continuous wave (CW) light at 1 549.5 nm with the power of 19 dBm was first modulated by 2 cascaded 40-GHz PMs with V_π of 10 V at 40 GHz. The two PMs were both driven by 40-GHz sinusoidal RF signals from a low phase noise signal synthesizer (Agilent E8257D). Since the spectrum bandwidth or the number of comb lines can be determined by the strength of phase modulation introduced by the PMs, we set the amplitude of the PM driving signals as large as possible to sufficiently broaden the optical spectrum. Here, the powers of the 2 driving signals were measured at 27 and 30 dBm, respectively. Then, the outputs of the two PMs were sent to a 40-GHz EAM, which was properly DC biased and driven by a 40-GHz sinusoidal RF signal. In the setup, two electrical phase shifters (PSs) were used for synchronization. The EAM was used instead of a MZM, because the optical pulses generated by the EAM were much shorter than those generated by MZM, and the resulting optical spectrum was much flatter[20]. The full-width at half-maximum (FWHM) of the generated 40-GHz repetition-rate optical pulse from the EAM can be tuned from 5 to 8 ps by adjusting the applied DC bias and the driving RF signal amplitude; the typical value for pulses generated using a 40-GHz MZM is about 10 ps. The very short duration of the optical pulse makes the following phase modulation more likely to be a quadratic phase modulation, and near-ideal linear chirp is imposed on each optical pulse. Thus, at the output of the EAM, a flat optical frequency comb with comb spacing of 40 GHz can be obtained.

In order to generate the millimeter and terahertz waves, the generated optical frequency comb was sent to a programmable optical processor (Finisar Waveshaper 4000S) after being amplified by an erbium-doped fiber amplifier (EDFA). The programmable optical processor can manipulate both the amplitude and the phase of the input optical spectrum with 1-GHz resolution, and the out of band suppression ratio can be as high as 50 dB. Here, we used the processor to select out two of the comb lines, which led to the generation of the sinusoidal waveform in the time domain. Generally, after optical-to-electrical conversion, the millimeter and terahertz wave signals with frequencies equal to the frequency spacing between two selected comb lines can be generated. In our experiment, the comb spacing was 40 GHz, and its flat top was composed of 12 lines. Thus, the generated millimeter or terahertz wave signals cover the frequency range from 40 to 440 GHz, with 40-GHz spacing. Figure 1 also shows the designed filter shape for selecting out two comb lines. Each square band-pass has a bandwidth of 10 GHz and out of band suppression ratio of 50 dB, which guarantees the high spectral-purity of generated millimeter or terahertz signals. In our experiment, the related optical spectra were measured with an optical spectrum analyzer (OSA) with 0.02-nm resolution; the optical time-domain waveforms were then observed with an optical sampling oscilloscope (OSO) (EXFO-PSO-102). We provided full analysis for the generated 40-GHz millimeter signal, including the optical and electrical spectra, as well as the electrical phase noise measured by an electrical spectrum analyzer (ESA) (Agilent E4447 3 Hz-43 GHz). Since no high speed photo-detector was available, only the optical spectra and optical time-domain waveforms were monitored for the generated signals above 40 GHz.

First, we measure the optical spectrum after the two cascaded PMs, as shown in Fig. 2. In order to generate

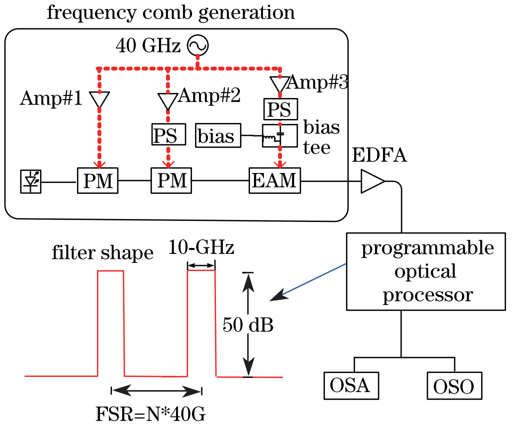

Fig. 1. Experimental setup of the proposed scheme for the photonic generation of millimeter and terahertz wave signals. Amp: amplifier; FSR: free spectral range.

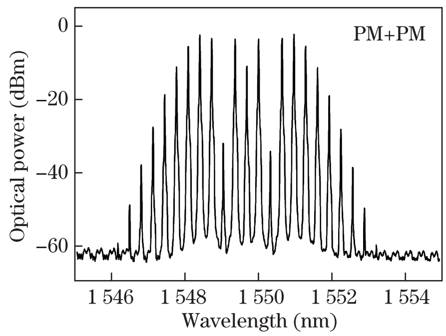

Fig. 2. Optical spectrum of the two cascaded PMs.

millimeter and terahertz wave signals with high frequency, we made the optical spectrum as broad as possible by applying high power electrical driving signals to the PMs. Figure 2 shows that the optical spectrum is fully broadened after phase modulation. The suppression of the specific frequency components in Fig. 2 is related to the power of the driving RF signals; however, the resulting un-flatness of the spectrum does not affect the ultimate flat frequency comb generation.

The DC bias voltage and the peak to peak amplitude of the driving RF signal applied on EAM are optimized to be −1.2 and 3.1 V, respectively, and the generated optical frequency comb after EAM is shown in Fig. 3. Figure 3 also shows the obtained highly flat optical frequency comb with power variation less than 2 dB over 440 GHz (12 lines at the top). The OSNR obtained from the spectrum is as high as 45 dB. In this scheme, the RF source directly decides the comb line spacing. One advantage of our scheme, which uses EAM instead of MZM, is that the generated optical frequency comb is much flatter. For comparison, the resulting optical frequency comb when EAM is replaced by a 40-GHz MZM (Fujitsu FTM7938EZ) is shown in Fig. 4, where the power variation among 440 GHz (12 top lines) is 3.6 dB. Compared with the spectrum shown in Fig. 3, the frequency comb generated by the PM+PM+MZM scheme apparently has higher power variation than that obtained using the PM+PM+EAM scheme. Thus, the latter scheme is more suitable for flat optical frequency comb generation.

Then, we present the results and analysis of the generated millimeter waves and terahertz waves. Figure 5 shows the optical spectra and optical time-domain waveforms when selecting two comb lines with frequency spacings of 40, 80, 160, 200, 320, and 440 GHz. The results show that all the un-wanted spectral lines are suppressed by 50 dB, and the corresponding optical time domain sinusoidal function waveforms (after amplification by an EDFA) are well generated with uniform amplitude observed through the OSO. After optical-to-electrical conversion, the millimeter and terahertz waves ranging from 40 to 440 GHz with frequency spacing of 40 GHz can be generated.

Using a 50-GHz photo-detector for optical-to-electrical conversion, the 40-GHz millimeter wave is obtained and subsequently analyzed by the ESA. Figures 6(a) and (b) show the electrical spectrum and the measured phase noise of the generated 40-GHz millimeter wave signal, respectively. It can be observed that a strong electrical signal at 40 GHz is generated, and the measured phase noise of the 40-GHz millimeter wave signal is –98.3 dBc/Hz at a 10-kHz frequency offset. The high frequency-purity and very low phase noise verify the good quality of our generated 40-GHz millimeter wave signal. However, due to the lack of high speed photo-detector, only the electrical properties of 40-GHz millimeter wave are analyzed. For the generation of millimeter or terahertz wave signals with frequencies above 40-GHz, the obtained optical spectra shown in Fig. 5 have out-of-band suppression ratios of as high as 50 dB, thereby ensuring the high frequency and purity of the generated millimeter and terahertz wave signals. Moreover, the temporal waveforms shown in Fig. 4 have time jitters lower than 65 fs, indicating the low phase noise of the generated millimeter wave or terahertz wave signal.

In conclusion, we propose and experimentally demon-

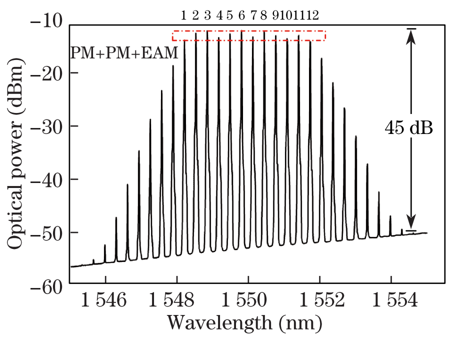

Fig. 3. Optical spectrum of the generated comb using PM+PM+EAM.

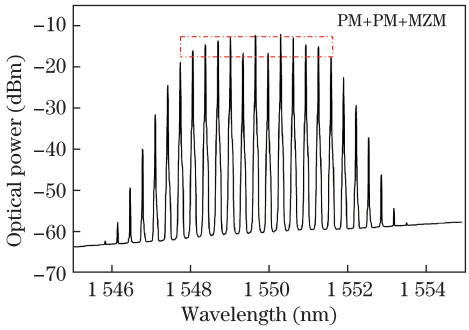

Fig. 4. Optical spectrum of the generated comb using PM+PM+MZM.

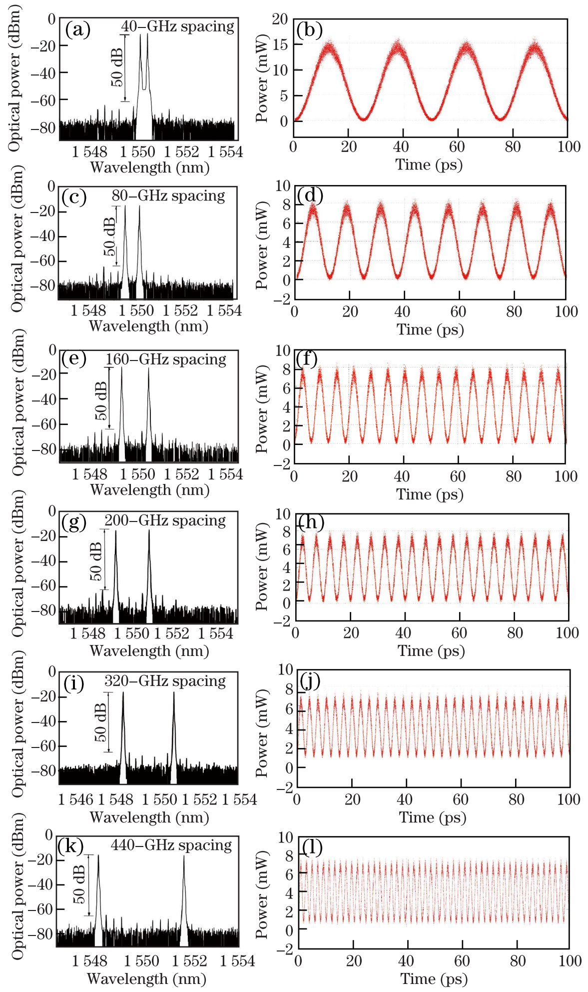

Fig. 5. Spectra of the two selected comb lines with (a) 40-, (c) 80-, (e) 160-, (g) 200-, (i) 320-, and (k) 440-GHz spacings and corresponding (b) 40-, (d) 80-, (f) 160-, (h) 200-, (j) 320-, and (l) 440-GHz optical sinusoidal waveforms.

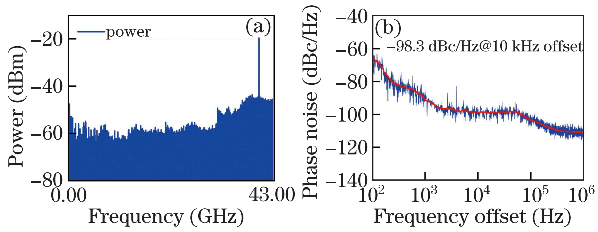

Fig. 6. (a) Electrical spectrum in the full span; (b) measured phase noise of the generated 40-GHz millimeter wave.

strate a novel method for the photonic generation of frequency-tunable millimeter and terahertz waves based on a highly flat optical frequency comb. The generated flat optical frequency combs using 2 PMs and an EAM cover a 40–440-GHz frequency range, with 40-GHz comb spacing and amplitude variation of less than 2 dB. By filtering out two the comb lines, millimeter or terahertz wave signals with frequencies ranging from 40 GHz to as high as 440 GHz, and frequency spacing of 40 GHz are successfully generated. The proposed system also features a simple and compact structure, which can be applied in spectroscopic sensing and ultra-broadband wireless communications.

This work was supported in part by the National "973" Program of China (No. 2011CB301702), the National Natural Science Foundation of China (Nos. 61001121, 61006041, 60736036, and 60932004), and the Fundamental Research Funds for the Central Universities.

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