Optical generation of high-power 0.1-THz continuous wave by external modulation

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We experimentally demonstrate that a high-power 0.1-THz continuous wave can be generated by external modulation. A low-noise electrical amplifier and a W-band antenna with a gain of 25 dBi are employed to enhance photodiode output power. Detection power exceeds 1 mW when an absolute terahertz power meter is used.

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A sub-terahertz (THz) has attracted increasing interest in recent years because of its promising potential in high data rate communication and high resolution imaging applications[1−5]. Obtaining low-phase noise, high power, and cost-effective sub-THz waves for real applications is currently a major issue. In addressing this requirement, photonic techniques are considered more superior to conventional techniques that are based on electronic devices. The optical frequency multiplication techniques based on external modulation, such as the use of an optical intensity modulator (IM), is a typical photonic solution to generating millimeter and sub-THz waves[6−15]. High-order optical sidebands can be generated given the inherent nonlinearity of an IM response. A sub-THz wave can be obtained by beating two high-order optical sidebands at a photodiode (PD). The cost of sub-THz systems can be reduced by using mature and cost-effective optical telecommunication components. O'Reilly *et al.* first demonstrated frequency doubling and quadrupling schemes by using a single Mach-Zehnder modulator (MZM) to generate millimeter waves[6,7]. Li *et al.* proposed frequency quadrupling, sextupling, and octupling in which two cascaded MZMs was used; they also generated a 0.1-THz signal by frequency octupling[13]. Sub-THz wave generation that uses two cascaded MZMs instead of a single MZM increases the frequency multiplication factor. The process is limited primarily by its high complexity, which is attributed to the requirements of simultaneously adjusting more than two parameters and high bias voltage accuracy. The output power of commercial p-i-n PD is in the order of microwatts over 0.1 THz because of the low saturation photocurrent, which significantly constrains the output power of the abovementioned schemes. A recently reported type of PD called uni-travelling-carrier PD (UTC-PD) can provide a high saturation photocurrent, and its output power can exceed 10 mW at 0.1 THz[14,15]. The UTC-PD exhibits potential in the production of high-power sub-THz wave signals, but mature commercial products are still unavailable.

In this letter, we propose an optical frequency quadrupling technique for generating optical 0.1-THz waves with an optical sideband suppression ratio (OSSR) larger than 25 dB. The technique uses a single IM. To address the power limitation caused by commercial p-i-n PD saturation, a low-noise electrical amplifier and a W-band antenna with a gain of 25 dBi are employed to amplify the weak output power of a commercial PD. The detected power exceeds 1 mW at a 2-cm distance from the antenna when an absolute THz power meter is used. We experimentally demonstrate that the 0.1-THz wave power improves when the depth of the IM with less than 2 dBm or the PD input power with less than 6 dBm increases.

Figure 1 shows the 0.1-THz wave generation principle based on external modulation. A continuous wave (CW) with an angular frequency ω_0 is generated by a CW laser. The optical carrier is modulated via an IM that is driven by a radio frequency (RF) sinusoidal clock. The IM output field can be written as[16,17]

$$\begin{aligned} &E_{\mathrm{out1}}(t)\\ &=\frac{E_0(t)\cos(\omega_0 t)}{10^{\alpha/20}}\left\{\gamma\exp\left[\mathrm{j}\pi\frac{V_{\mathrm{RF}}}{V_\pi}\cos(\omega_{\mathrm{RF}}t+\theta)\right]\right.\\ &\left.+(1-\gamma)\exp\left[\mathrm{j}\pi\frac{V_{\mathrm{RF}}}{V_\pi}\cos(\omega_{\mathrm{RF}}t)+\mathrm{j}\pi\frac{V_{\mathrm{bias}}}{V_\pi}\right]\right\}, \qquad (1)\end{aligned}$$

where E_0 is the amplitude of the optical field, V_π denotes the half-wave voltage of the modulator, V_{RF}, ω_{RF}, and θ are the voltage amplitude, angular frequency, and RF phase, respectively, V_{bias} represents the DC bias voltage applied to IM, γ is the power splitting ratio of the two IM arms, and α is the IM insertion loss. For an ideal IM, γ is approximately 0.5 and α is approximately zero. The optical signal field can be written as

$$\begin{aligned} E_{\mathrm{out1}}=\frac{E_0}{2}\{&\cos[\omega_0 t+\beta\cos(\omega_{\mathrm{RF}}t+\theta)]\\ &+\cos[\omega_0 t+\beta\cos(\omega_{\mathrm{RF}}t)+\varphi]\}, \qquad (2)\end{aligned}$$

where $\beta = \frac{\pi V_{\mathrm{RF}}}{V_\pi}$ is the modulation depth of the modula-

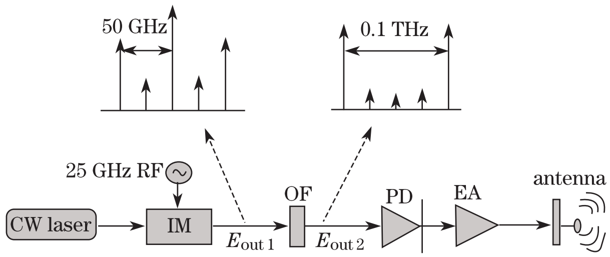

Fig. 1. Diagram of the 0.1-THz wave generation principle. EA: electrical amplifier.

tor and $\varphi = \frac{\pi V_{\mathrm{bias}}}{V_\pi}$ is the constant phase shift.

Setting $\varphi = 2k\pi$, $(k = 0, 1, 2 \cdots)$ and $\theta = \pi$ suppresses the odd-order optical sidebands. The optical signal can then be expressed as

$$E_{\mathrm{out1}} = E_0 \Bigg[\cos(\omega_0 t) J_0(\beta) + 2\cos(\omega_0 t) \cdot \sum_{n=1}^{\infty} (-1)^n J_{2n}(\beta) \cos(2n\omega_{\mathrm{RF}} t) \Bigg], \quad (3)$$

where J_n is the Bessel function of the first kind of order n. Upon eliminating the carrier using the optical filter (OF) and disregarding the higher than second-order Bessel functions, the signal has only two second-order optical sidebands, which can be approximately expressed as

$$E_{\mathrm{out2}}(t) \cong -E_0 \cdot J_2(\beta) \cdot [\cos(\omega_0 t + 2\omega_{\mathrm{RF}} t) + \cos(\omega_0 t - 2\omega_{\mathrm{RF}} t)]. \quad (4)$$

Beating using a square-law PD yields the generated signal

$$I_{\mathrm{THz}} = \mu \cdot E_0^2 \cdot J_2^2(\beta) \cdot \cos(4\omega_{\mathrm{RF}} t), \quad (5)$$

where μ is the responsivity of the PD. Setting $\omega_{\mathrm{RF}} = 25$ GHz generates a 0.1-THz signal (Fig. 1). By simplifying the model of the amplifier and antenna, the power of THz-wave radiation can be expressed as

$$P_{\mathrm{THz}} \propto G \left[\mu \cdot E_0^2 \cdot J_2^2(\beta) \right]^2, \quad (6)$$

where G is the gain of the electrical amplifier and antenna.

The experimental setup for 0.1-THz wave generation is shown in Fig. 2. A commercial distributed feedback laser diode (DBF-LD, Agilent 8163A) is used to achieve a CW lightwave at 1 542.7 nm with 9.5-dBm output power (Fig. 2(a)). The optical carrier is modulated using a single-arm $LiNbO_3$ MZM (LN-MZM, JDSU, 3 dB bandwidth, >25 GHz), which is driven by a 25-GHz RF signal. Here, the 25-GHz RF is obtained by doubling the 12.5-GHz RF using an electrical frequency doubler. Because the driving voltage of 7.1 V is close to $2V_\pi$ of the modulator, the odd-order optical sidebands can be largely transformed into even-order optical sidebands, thereby improving the efficiency of 0.1-THz wave signal generation. The modulator output power is 3.6 dBm, and the optical spectrum is shown in Fig. 2(b). The first-order optical sideband is 10 dB lower than the second-order optical sideband, and is separated by approximately 0.8 nm (corresponding to 0.1 THz). To obtain two second-order optical sidebands, we use a 50/100 GHz two-output interleaver to eliminate the optical carrier and first-order optical sideband. After passing through the interleaver, the optical power is −21.4 dBm and the OSSR is greater than 25 dB (Fig. 2(c)). After amplification by an erbium-doped fiber amplifier (EDFA), the optical signal power is 6 dBm, and the optical spectrum is shown in Fig. 2(d). The 0.1-THz electrical signal is generated by beating the two second-order optical sidebands with a high-speed PD (U2t, 100-GHz PD). The electrical signal is subsequently amplified by a low-noise electrical amplifier, and then the 0.1-THz wave is radiated from a W-band antenna with a gain of 25 dBi. The 0.1-THz wave is detected using an absolute THz power meter (Thoumas Keating Instruments THz power meter), and a chopper (TTI, c-995) with 30-Hz chopping frequency is positioned between the antenna and power meter at a distance of 2 cm. Figure 3 represents the detected power values. The power values during the first 330 s are calibrated, to keep them stable around zero. The detected 0.1-THz wave power value is stable at 1.3 mW during the next 600 s.

The relationship between the generated 0.1-THz wave power and the modulation depth of the IM is shown in Fig. 4. On the basis of the previous theoretical analysis, we conclude that THz wave power is proportional to

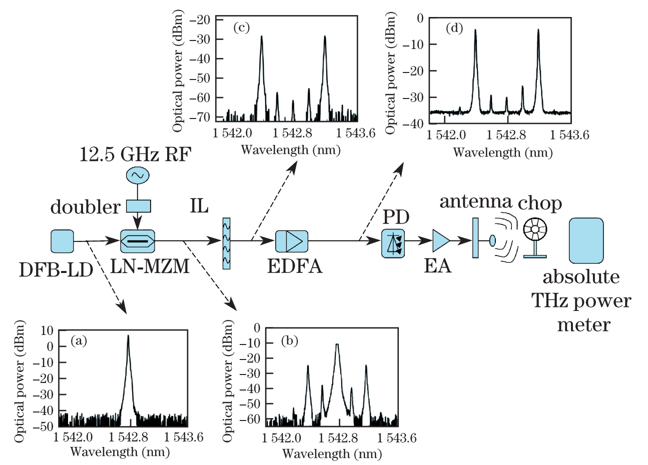

Fig. 2. Experimental setup and measured results for 0.1-THz wave generation. Doubler: electrical frequency doubler; IL: 50/100-GHz optical interleaver. The resolution for all the optical spectra is 0.01 nm in this letter.

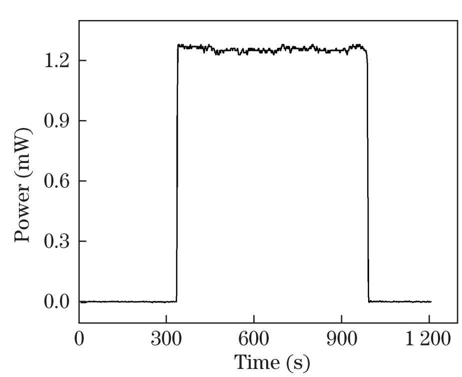

Fig. 3. Power radiated from the antenna.

$J_2^4(\beta)$, provided that all other variables remain constant. These theoretical results are shown in Fig. 4(a). The RF power is varied to obtain experimental verification (Fig. 4(b)). At a RF power that ranges from 0 to 8 dBm, the 0.1-THz wave power is almost zero. At a RF power greater than 8 dBm, the 0.1-THz wave power displays approximately exponential growth. The maximum available modulation depth is usually less than 2 for a commercially available LN-MZM. The 0.1-THz wave power can be further improved by using a RF driven by high power.

Figure 5 shows the dependence of the 0.1-THz power on the PD input optical power when a RF power of 16 dBm is supplied. The optical signal power injected to the PD can be tuned by adjusting the EDFA gain. The PD input power is less than 6 dBm, subject to a maximum PD input power of 10 dBm. The 0.1-THz wave power is almost proportional to the PD input optical power, and PD saturation is not observed. The results indicate that when the input PD power increases, the power of the 0.1-THz wave linearly improves.

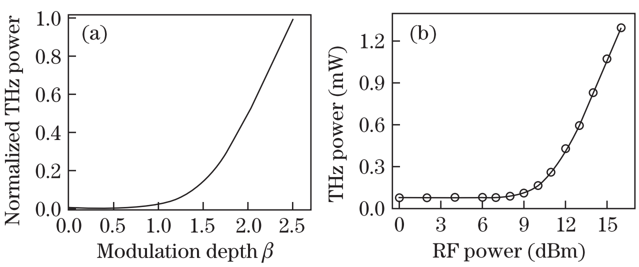

Fig. 4. Dependence of 0.1 THz power on the modulation depth of LN-MZM; (a) theoretical and (b) experimental values. Circles: measured power using power meter.

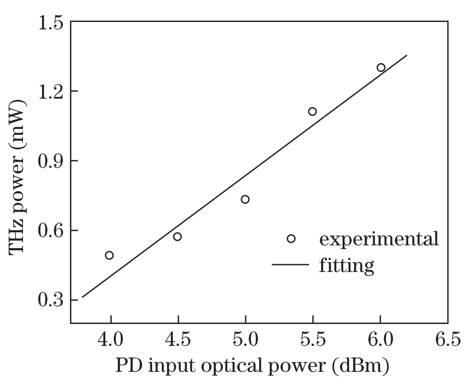

Fig. 5. Dependence of THz radiation power on PD input optical power.

In conclusion, a 0.1-THz CW generation scheme based on external modulation is proposed. This scheme generates a high-power 0.1 THz wave through an optical frequency quadrupling technique. We experimentally confirm that enhancing IM modulation depth or increasing PD input optical power can enhances THz wave power.

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