Demonstration of Wireless Transmission of QPSK Signals at 2 THz

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Abstract: Wireless transmission of QPSK signals at 2 THz has been demonstrated using modulator-based optical combs for the transmitter and hot electron bolometer mixers combined with phase-locked terahertz quantum cascade lasers for the receiver.

1. Introduction

In recent years, demonstrations of high bitrate transmission in the sub-terahertz (THz) frequency range have been actively studied [1]. There are mainly two approaches to realize THz communications; one is an electronics approach and the other is photonics. In the electronics approach, transmitter and receiver devices operating in the 300 GHz band are mainly being developed. On the other hand, in the photonics approach, signal generation in a frequency range exceeding 1 THz is possible. Although in the 2 to 3 THz-bands, the base attenuation is increased to 100 dB/km, they can be used to very short-distance transmission such as several meters. For instance, there are some windows at around 3.1 and 3.4 THz, in which the bandwidth is approximately 50 to 100 GHz. The purpose of this study is development of new bands for THz communication above 2 THz. For this purpose, we have key techniques. For the transmitter, Photonics-based systems using optical combs can be adopted, and hot electron bolometer mixers (HEBMs) combined with a phase-locked THz quantum cascade lasers (THz-QCLs) as a local oscillator (LO) can be used for the heterodyne receiver. In this paper, we have demonstrated wireless transmission of QPSK signals at 2 THz using a modulator-based optical combs for the transmitter and the HEBM combined with the THz-QCL for the receiver.

2. Photonics-Based Transmitter System

Figure 1(a) shows a schematic illustration of a photonics-based transmitter system. This transmitter system generates

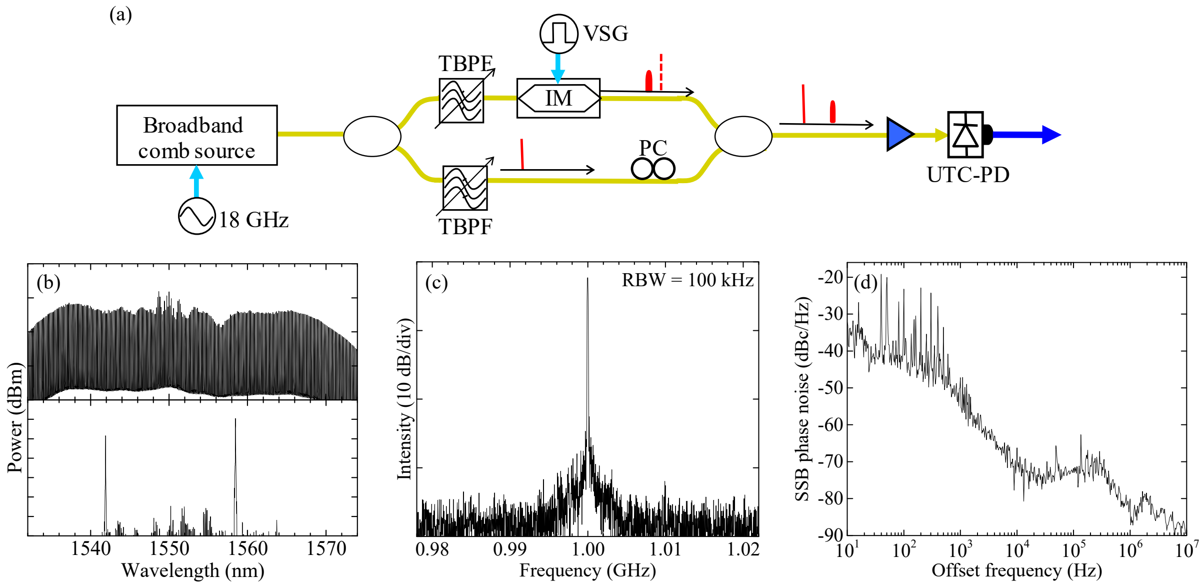

Fig. 1 Schematic illustration of the photonics-based transmitter system. (a) The configuration of the transmitter system. (b) Optical spectra of broadband optical comb (upper) and an optical two-tone (bottom). (c) A beat spectrum of a generated CW-THz signal with the phase-locked THz-QCL. (d) SSB phase noise characteristics of the THz signal.

THz signals from optical two-tones extracted from optical combs. To obtain both high stability and high flexibility in frequency of THz signals, an optical modulator-based comb source was adopted. For data modulation, one mode of the optical two-tone is modulated by an optical modulator. By photomixing of the optical two-tone using a uni-traveling-carrier photodiode (UTC-PD), modulated THz signals are generated.

To generate broadband optical combs, a combination of a Mach-Zehnder-modulator-based flat comb generator (MZ-FCG) and a highly nonlinear dispersion shifted fiber (HNL-DSF) was adopted. The detailed configuration and performances of the optical comb source were described in Refs [2-4]. The top figure of Fig. 1(b) shows a spectrum of a generated broadband optical comb. The MZ-FCG was driven with a microwave signal of 17.966 182 956 522 GHz to 18 GHz, and a broadband optical comb with a spacing of corresponding to the microwave signal was observed. The bandwidth of the optical comb was greater than 40 nm (> 5 THz), so that the frequency of THz waves can be tuned in a wide range. Optical two-tones were extracted from the broadband optical comb by a pair of tunable bandpass filters (TBPFs) with a minimum pass-bandwidth of 6 GHz. The bottom figure of Fig. 1(b) shows a spectrum of the optical two-tone. By using the TBPFs, optical two-tones with high signal-to-noise ratio (SNR) were extracted. The frequency separation of the optical two-tone can be coarsely tuned by selecting the comb mode in the range from 18 GHz to 5 THz and precisely (in the order of hertz) tuned by changing the frequency of the microwave driving signal of the MZ-FCG. The optical two-tones were converted to THz signals by photomixing using an UTC-PD, radiating into air through a silicon hemispherical lens. The THz wave at 2066.111 040 GHz (= 17.966 182 956 522 GHz × 115) generated by the photonics-based THz transmitter was measured by the heterodyne receiver. Figure 1(c) shows a measured beat spectrum. A sharp line, in which the linewidth was narrower than the minimum resolution bandwidth (RBW) of the spectrum analyzer (1 Hz), was observed. The frequency difference between the THz-QCL and the photonics-based THz transmitter was set to 1 GHz, which was consistent with the observed signal. The SNR was greater than 35 dB at an RBW of 100 kHz. Figure 1(d) shows single-sideband (SSB) phase noise characteristics of the THz wave. The phase noise at an offset frequency of 100 kHz was lower than -70 dBc/Hz. Because the multiplication factor from the driving signal (18 GHz) to the THz signal (2.067 THz) was 115, the expected degradation of the phase noise was about 41 dBc/Hz (typical value of the phase noise of the microwave signal generator at a frequency offset of 100 kHz is -110 dBc/Hz). Thus, the measured phase noise was comparable to that estimated from the driving signal of the MZ-FCG.

3. THz Receiver System

Figure 2(a) shows the configuration of a heterodyne receiver system. This system consisted of an HEBM cooled to 4 K using a mechanical cooler and a phase-locked THz-QCL as an LO source. The HEBM device consists of a Ni-NbN superconductor strip and a log-spiral antenna, and a Si-lens was attached on the input surface of the device [5]. The corrected receiver noise temperature of the quasi-optical HEBM is 570 K [6]. The THz signals emitted by the photonics-based THz transmitter was input to the HEBM along with the LO signal (LO1). The oscillation frequency of the THz-QCL was ~ 2.067 THz, and the output power was 0.6 mW. Because THz-QCLs typically have a linewidth on the order of MHz, phase-locked loop (PLL) systems are required to stabilize the oscillation frequency [7]. First, a fraction of THz waves emitted from the THz-QCL was received by a superlattice harmonic mixer (SLHM). In the SLHM, the THz signal was mixed with harmonics of the LO signal (LO2), and the intermediate

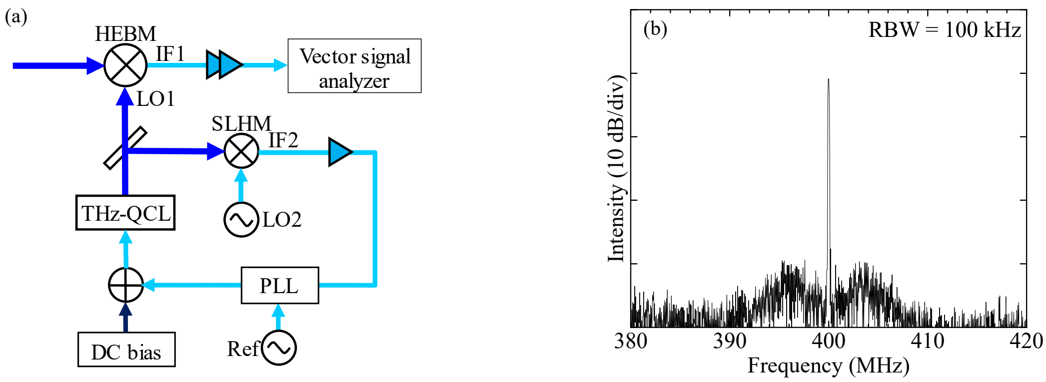

Fig. 2 Schematic illustration of the receiver system. (a) Configuration of the receiver system. (b) A spectrum of the THz-QCL measured by the SLHM.

frequency (IF) signal (IF2) was input to a PLL system. A frequency reference signal at 400 MHz was input to the PLL system, and by comparing IF2 with a reference signal, frequency error signals are output from the PLL system. By feeding back the error signal to the drive voltage of the THz-QCL, phase locking is established. Figure 2(b) shows a spectrum of THz signals from the THz-QCL measured by a SLHM (an IF signal). A THz signal with an extremely narrow linewidth was observed. The linewidth was narrower than 1 Hz (lower than the minimum RBW of the spectrum analyzer). This linewidth is sufficient for wireless transmission experiments.

4. Data Transmission

For data modulation, the optical intensity modulator inserted to one mode of the two-tone signal was driven with a vector signal generator (VSG). From the VSG, basic LTE FDD R9 uplink signals with a configuration of full filled QPSK 1.4 MHz (6 RB) were fed to the modulator. The bias point of the intensity modulator was set to the null point, so that the carrier signal at 1 GHz was suppressed. By photomixing of the modulated optical two-tones, THz signals with data modulation are generated, and fed to a THz receiver. The IF signal of the HEBM (IF1) was analyzed by a demodulator. Figure 3(a) shows a spectrum of modulated THz signal. Because the carrier frequency

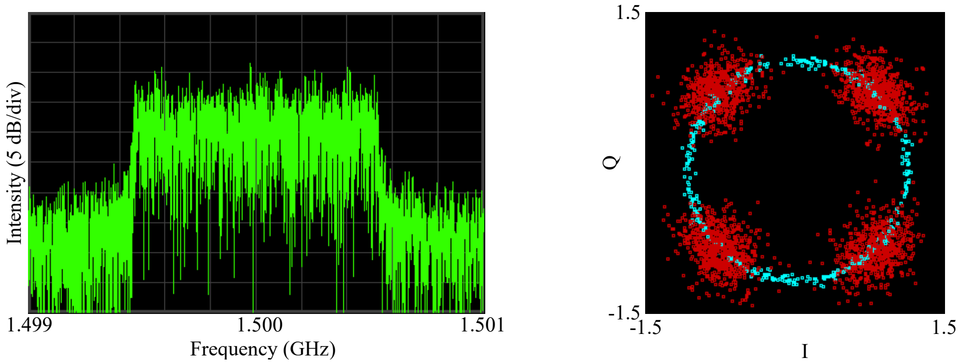

Fig. 3 (a) A spectrum of a down-converted THz signal. (b) A constellation map of a demodulated signal.

was set to 500 MHz, the modulated signal was observed at 1.5 GHz. The SNR was about 15 dB. Figure 3(b) shows a constellation of a QPSK signal. QPSK signals were successfully demodulated, in which the error vector magnitude (EVM) of the demodulated signal was about 22 %.

5. Conclusions

Wireless transmission of QPSK signals at 2 THz has been demonstrated. For the transmitter, THz signals were generated from optical two-tones extracted from the modulator-based optical comb. For the receiver, the HEBM combined with the THz-QCL as an LO source was adopted. In the transmission experiment, QPSK signals were successfully demodulated, in which the EVM of the demodulated signal was about 22 %.

References

[1] H.-J. Song, and N. Lee, "Terahertz Communications: Challenges in the Next Decade," IEEE Trans. THz Sci. Technol. **12,** 105-117 (2022).
[2] T. Sakamoto, T. Kawanishi, and M. Izutsu, "Asymptotic formalism for ultraflat optical frequency comb generation using a Mach-Zehnder modulator," Opt. Lett. **32**, 1515-1517 (2007).
[3] I. Morohashi, T. Sakamoto, H. Sotobayashi, T. Kawanishi, and I. Hosako, "Broadband wavelength-tunable ultrashort pulse source using a Mach-Zehnder modulator and dispersion-flattened dispersion-decreasing fiber," Opt. Lett. **34**, 2297-2299 (2008).
[4] I. Morohashi, Y. Irimajiri, A. Kanno, A. Kawakami, N. Yamamoto, N. Sekine, A. Kasamatsu, and I. Hosako, " Geneation of Coherent Terahertz Carriers in the 3 THz Range Using Optical-Comb-Based THz Source for Terahertz Communications," in 2018 IEEE Int. Top. Meeting on Microw. Photon. (MWP), 199-201 (2018).
[5] Y. Irimajiri, A. Kawakami, I. Morohashi, M. Kumagai, N. Sekine, S. Nagano, S. Ochiai, S. Tanaka, Y. Hanado, Y. Uzawa, and I. Hosako, "Development of a Superconducting Low-Noise 3.1-THz Hot Electron Bolometer Receiver," IEEE Trans. THz Sci. Tech. **5**, 1154-1159 (2015).
[6] Y. Irimajiri, A. Kawakami, M.-J. Wang, W.-C. Lu, "Development of a waveguide-type hot electron bolometer mixer at 2 THz," in Proc. 46th Int. Conf. Infrared, Millimeter, THz Waves, 1-2 (2021).
[7] Y. Irimajiri, M. Kumagai, I. Morohashi, A. Kawakami, S. Nagano, N. Sekine, S. Ochiai, S. Tanaka, Y. Hanado, Y. Uzawa, and I. Hosako, "Precise Evaluation of a Phase-Locked THz Quantum Cascade Laser," IEEE Trans. THz Sci. Tech. **6**, 115-120 (2016).