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Terahertz wireless communication in a 560-GHz band using a Kerr micro-resonator soliton comb

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Abstract: Terahertz (THz) waves have attracted attention as carrier waves for next-generation wireless communications (6 G). Electronic THz emitters are widely used in current mobile communications; however, they may face technical limitations in 6 G with upper-frequency limits. We demonstrate wireless communication in a 560-GHz band by using a photonic THz emitter based on photomixing of a 560-GHz-spacing soliton microcomb in a uni-travelling carrier photodiode together with a THz receiver of Schottky barrier diode. The on-off keying data transfer with 2-Gbit/s achieves a Q-factor of 3.4, thus, satisfying the limit of forward error correction.

1. Introduction

Terahertz (THz) waves are a promising candidate for carrier waves in next-generation wireless communications (beyond 5 G or 6 G, expected carrier frequency > 300 GHz), providing a higher data rate than present wireless communications (5 G, carrier frequency = 28 GHz or more) owing to the use of high-frequency carrier waves [1]. In particular, the use of specific THz waves, corresponding to multiple frequency windows available for broadband data transfer in frequencies higher than 350 GHz, is expected for wireless mobile fronthaul and backhaul in 6 G for a much higher data rate while avoiding interference with general 6 G mobile communication and other applications. One key feature of 6 G is its THz emitter. Although electronic THz emitters based on frequency multiplication have been used up to 5 G, they may face technical limitations in 6 G owing to too high frequency for electronics. For example, higher-order frequency multiplication would largely increase their phase noise owing to the quadratic-dependent increase in phase noise on the number of frequency multiplications. In addition, signal attenuation in electric

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transmission lines largely increases in such high frequency. These limitations are inherent to electronic THz emitters and may require a different approach.

Another approach for THz emitters is the use of photonic technology because the THz frequency band is located at the boundary between the photonic and electronic regions. Photomixing for optical-to-electric conversion is a promising approach to generate millimeter wave and even THz wave. A pair of near-infrared single-mode CW laser lights with an optical frequency separation of THz order interferes with each other, and the resulting optical beat signal is then converted into a THz wave by photomixing in a uni-travelling carrier photodiode (UTC-PD) [2,3]. This method not only provides higher-frequency THz wave up to a few THz [4], but also has a high affinity to optical communication due to fiber-based technology at a telecommunication band of 1.55 μm [5]. In addition, this high affinity enables the easy modulation in the optical region by mature optical modulators and modulation protocols. However, when two independent free-running CW lasers are used for photomixing, fluctuations of frequency and phase in the generated THz wave are synthesized from those of two independent light sources. Such fluctuations often require estimation and/or correction of frequency and phase with a relatively large amount of computation in digital signal processing of THz receiver.

The use of an optical frequency comb (OFC) instead of two CW lasers is a promising approach for the generation of low-phase-noise THz waves, in which two OFC modes with THz frequency spacing are extracted and used for photomixing. Because the frequency spacing f_{rep} of the OFC is inherently stable and its relative phase noise is considerably low owing to mode-locking oscillation and active control in the OFC, the resulting THz wave benefits from the excellent frequency and phase stability in f_{rep}. Mode-locked fiber laser (ML-FL) OFCs [6,7] and electro-to-optic-modulator (EOM) OFCs [8–10] have been successfully used for the generation of microwave and millimeter waves. However, when this approach is extended to THz waves, two OFC modes with a large frequency separation (= mf_{rep}) must be used for photomixing because the THz wave frequency f_{THz} is much larger than the f_{rep} of these OFCs. For example, when the ML-FL OFC with f_{rep} of 100 MHz is used for generation of 560-GHz THz wave via photomixing, m is achieved to 5600. Such high-order optical frequency multiplication of f_{rep} spoils the low phase noise of f_{rep} characteristic in ML-FL OFC and largely increases the phase noise of the resulting THz wave, similar to the electronic frequency multiplication in electronic THz emitters. In addition, existing OFCs are still bulky, complicated, and expensive for wireless communications.

Recently, the on-chip Kerr micro-resonator soliton comb, namely the soliton microcomb, has attracted attention as a small, simple, and cost-effective OFC benefiting from batch mass production of semiconductor processes. Moreover, micro-resonators largely increase f_{rep} up to a few tens of GHz to a few THz, which is much larger than f_{rep} in ML-FL OFCs or EOM OFCs, while achieving soliton mode-locking oscillation with low phase noise. Such a soliton microcomb enables photomixing of two adjacent OFC modes without the need for optical frequency multiplication for the generation of microwaves [11], millimeter waves [12,13], and even THz waves [14]. Furthermore, a combination of a stabilized microcomb with UTC-PD-based photomixing generates an ultralow-phase-noise (≈ -100 dBc/Hz at the 10 kHz frequency offset) THz wave at 300 GHz [15] and 560 GHz [16]. However, there have been no attempts to apply such microcomb-based THz waves to high-frequency THz wireless communication for wireless mobile fronthaul and backhaul in 6 G. In this study, we demonstrate THz wireless communication of on-off keying (OOK) in a 560-GHz band. The 560-GHz THz wave was generated by photomixing of a 560-GHz-spacing soliton microcomb in a UTC-PD, whereas the transmitted THz wave was detected by a Schottky barrier diode (SBD).

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2. Results

We first evaluated the basic performance of the soliton microcomb and the resulting THz wave. Figure 1 shows a schematic of the experimental setup for the generation and evaluation of them. The output light of a single-mode CW laser (pump laser, TLX-1, Thorlabs, Inc., wavelength = 1560.7 nm, optical frequency = 192.09 THz, optical power = 20 mW) after passing through a dual-parallel Mach-Zehnder modulator (DP-MZM, FTM7962EP, Fujitsu Optical Components Lim., data rate = 40 Gbps) was amplified by a homemade erbium-doped fiber amplifier (EDFA1) via polarization-maintained fibers (PMFs). The resulting pump light (optical power = 500 mW) was coupled into a Si_3N_4 (SiN) micro-resonator (custom, LIGENTEC, S.A., free spectral range = 560 GHz, Q factor ≈ 10^6) via a single-mode fiber (SMF). To generate a single soliton microcomb with an f_{rep} of 560 GHz, the DP-MZM rapidly tunes the optical frequency of the pump light around the resonant frequency of the micro-resonator [17]. We rejected the residual pump light from the generated soliton microcomb by a homemade optical notch filter (ONF, stop wavelength = 1560.7 nm, stop optical frequency = 192.09 THz) because the remaining pump light largely decreases the efficiency of optical-to-electric conversion in UTC-PD due to the limited input power in UTC-PD. The resulting soliton microcomb (total power = 1 mW) was further amplified to 100 mW using a commercialized EDFA (EDFA2, EDFA100P, Thorlabs, Inc., output power > 20 dBm). Parts of the soliton microcomb (optical power = a few mW) were fed into an optical spectrum analyzer (OSA, AQ6370D, Yokogawa Electric Corp., minimum wavelength = 600-1700nm) for optical spectrum measurement and a two-wavelength delayed self-heterodyne interferometer (TWDI) for the phase noise evaluation of its f_{rep} [18–20]. The residual of the soliton microcomb was incident onto an antenna-integrated UTC-PD (IOD-PMAN-13001-2, NTT Electronics Corp., output frequency of 200–600 GHz, output power of 10 μW at 600 GHz) via PMF to generate THz waves by photomixing. The generated THz wave passed through a pair of Teflon lenses (LAT100, Thorlabs, Inc., focal length = 91 mm) and was incident on a sub-harmonic mixer (SHM, WR1.5SHM, Virginia Diodes, Inc., input local-oscillator frequency = 250–375 GHz, input radio-frequency = 500–750 GHz, output intermediate-frequency = DC–40 GHz). After the 27-times frequency multiplication of a local oscillator (LO) signal synthesized by a microwave frequency synthesizer (E8257D, Agilent Tech., Inc., frequency = f_{LO} = 10.37 GHz) with a frequency multiplier (FM), SHM generates a heterodyned beat signal (frequency = f_{IF}) between THz waves (frequency = $f_{THz} = f_{rep}$) and the 54-th higher harmonic component of f_{LO} (frequency = $54f_{LO}$). The resulting radio-frequency (RF) beat signal was measured using an RF spectrum analyzer (RSA, 89441A, Agilent Tech., Inc., frequency = DC–2.65 GHz) for the spectrum observation of f_{THz}.

Figure 2(a) shows the optical spectrum of the soliton microcomb after passing through ONF (resolution bandwidth or RBW = 0.2 nm). We confirmed that multiple OFC modes were distributed at intervals of 560 GHz, around the wavelength of the pump light. In addition, a broad spectrum of amplified spontaneous emission (ASE) appears as the optical background signal of the soliton microcomb, which influences the optical signal-to-noise ratio (OSNR) of each OFC mode. We later discuss the influence of such an ASE background on the quality of data transfer in OOK wireless communications. Figure 2(b) shows the single sideband (SSB) phase noise power spectrum density (PSD) of f_{rep}, corresponding to the relative phase noise between the two OFC modes, measured by TWDI. The SSB phase noise of our soliton microcomb is -60 dBc/Hz at an offset frequency of 10 kHz, which can be completely transferred to the THz wave generated from the soliton microcomb without additional phase noise in UTC-PD [16]. The detailed evaluation of phase noise is given elsewhere [17]. To determine f_{THz} and investigate its spectral features in detail, we measured the RF spectrum of the heterodyned beat signal (frequency = f_{IF}) between f_{THz} and $54f_{Lo}$ (RBW = 1 MHz), as shown in Fig. 2(c). The resulting RF spectrum indicated a spectral peak at 150 MHz (= f_{IF}). We determined f_{THz} to be 560.13 GHz from the measured f_{IF} and the known f_{LO}; it is exactly equal to f_{rep}.

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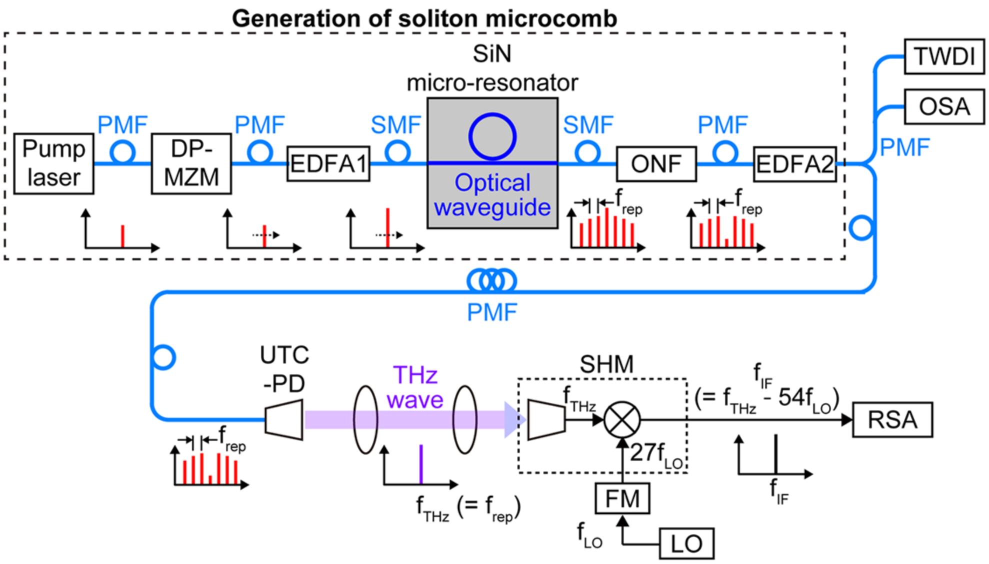

Fig. 1. Experimental setup for generation and evaluation of a soliton microcomb and THz wave.

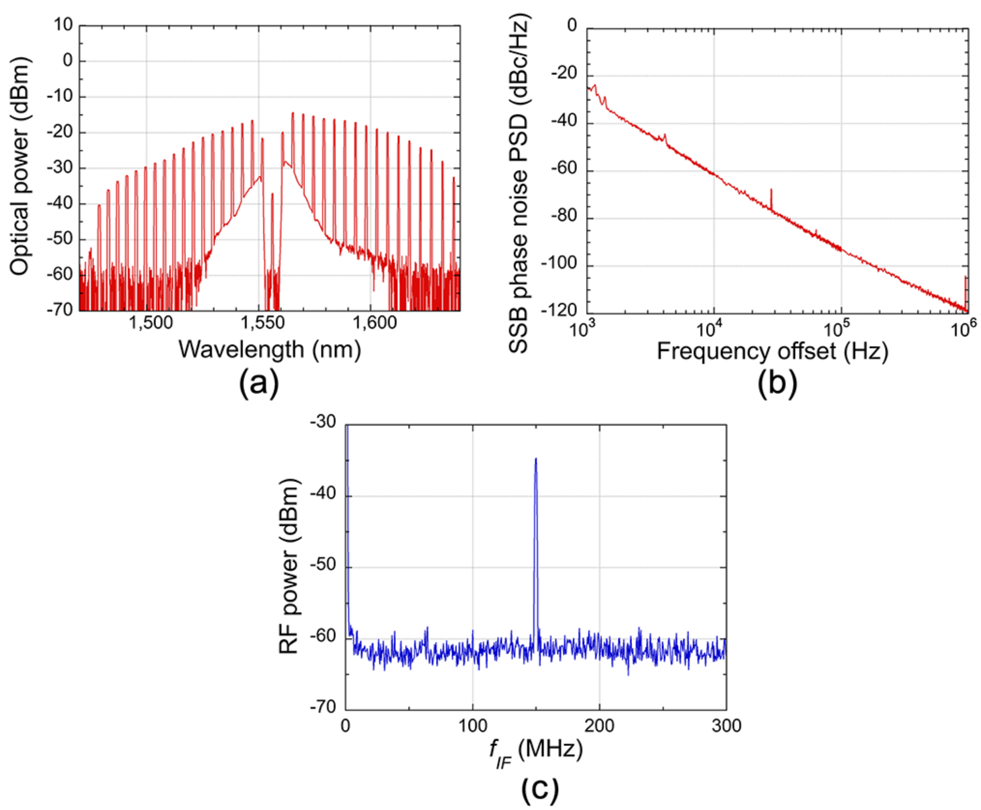

Fig. 2. Fundamental property of a soliton microcomb and THz wave. (a) Optical spectrum and (b) phase noise of f_{rep} in a 560-GHz-spacing microcomb. (c) RF spectrum of heterodyned beat signal.

We next demonstrated OOK wireless communication with a 560-GHz THz wave. Figure 3 shows a schematic of the experimental setup for the THz wireless communication. We generated a soliton microcomb without residual pump light (f_{rep} = 560 GHz, optical power = 100 mW) using the experimental setup of microcomb generation in Fig. 1. Two adjacent microcomb modes with a relatively higher OSNR (OFC-M1, wavelength = 1533.87 nm, optical frequency = 195.448 THz, optical power = 3.7 mW; OFC-M2, wavelength = 1538.28 nm, optical frequency = 194.888 THz, optical power = 2.1 mW) were extracted from the soliton microcomb using a programmable optical filter (WaveShaper 4000S, Finisar, filter bandwidth = 10 GHz). One of the two extracted microcomb modes (OFC-M1) was delivered to a $LiNbO_3$ modulator (LN-MOD, T.MXH1.5-20PD-ADC-LV, Sumitomo Osaka Cement Co., Ltd, wavelength = 1.55 µm, modulation rate = 40 Gbit/s, optical bandwidth > 20 GHz) for OOK modulation. The OOK signal of a 2-Gbit/s non-return-to-zero (NRZ) signal with a DC bias, generated by an arbitrary waveform generator (AWG, M8196A, Keysight Tech., Inc., sample rates < 92 GS/s, analog bandwidth = 32 GHz), was applied to the LN-MOD as a modulation signal. The OOK-modulated OFC-M1 was amplified by an EDFA (EDFA3), and the residual ASE background outside was removed by a tunable optical bandpass filter (OBPF1, WTF-200, Alnear Inc., optical bandwidth < 0.3 nm). The other microcomb mode (OFC-M2) passed through another EDFA (EDFA4) and another OBPF (OBPF2) without OOK modulation. The modulated OFC-M1 and unmodulated OFC-M2 were combined by a fiber coupler, and the resulting two microcomb modes (power of OFC-M1 = 15 mW, power of OFC-M2 = 15 mW, total power = 30 mW) were fed into the UTC-PD to generate a THz wave at an f_{THz} of 560 GHz. The OOK-modulated THz wave propagated in free space (transmittance distance = 0.6 m) via a pair of Teflon lenses and was then detected by SBD (Virginia Diodes, Inc., WR1.9ZBD, RF frequency = 400–600 GHz, responsivity = 1000 V/W). The electric output signal from the SBD was amplified using an electric amplifier (AMP, ZX60-V62+, Mini-Circuits, frequency range = 0.05–6 GHz, gain = 14.4 dB at 6 GHz) via a bias-T (not shown), and was then measured by a real-time oscilloscope (UXR0402AP, Keysight Tech., Inc., max. bandwidth = 40 GHz, max. sample rate = 256 GSa/s).

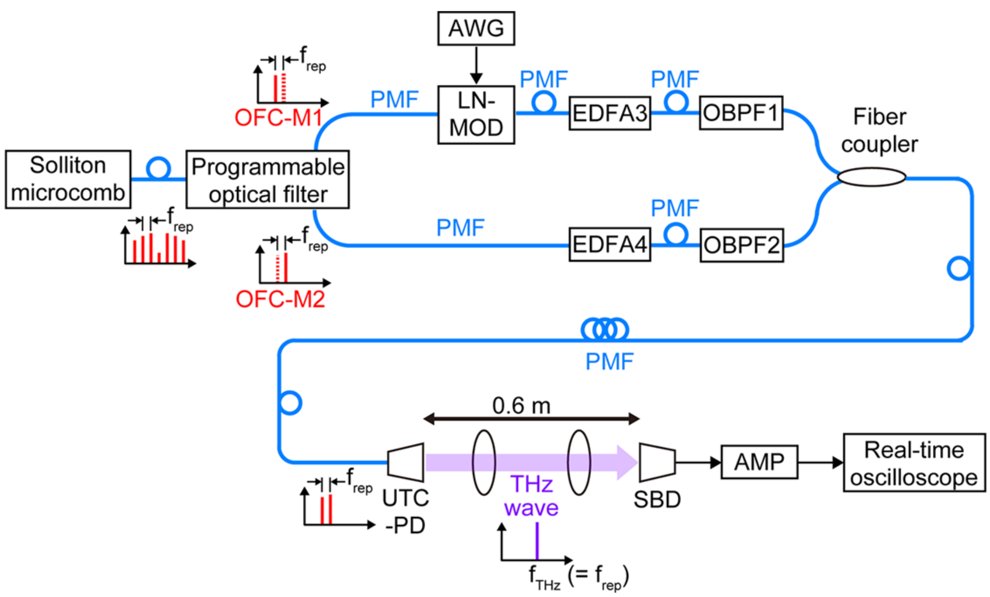

Fig. 3. Experimental setup for OOK wireless communication at 560 GHz.

To suppress the ASE background while securing the required optical amplification, an optical

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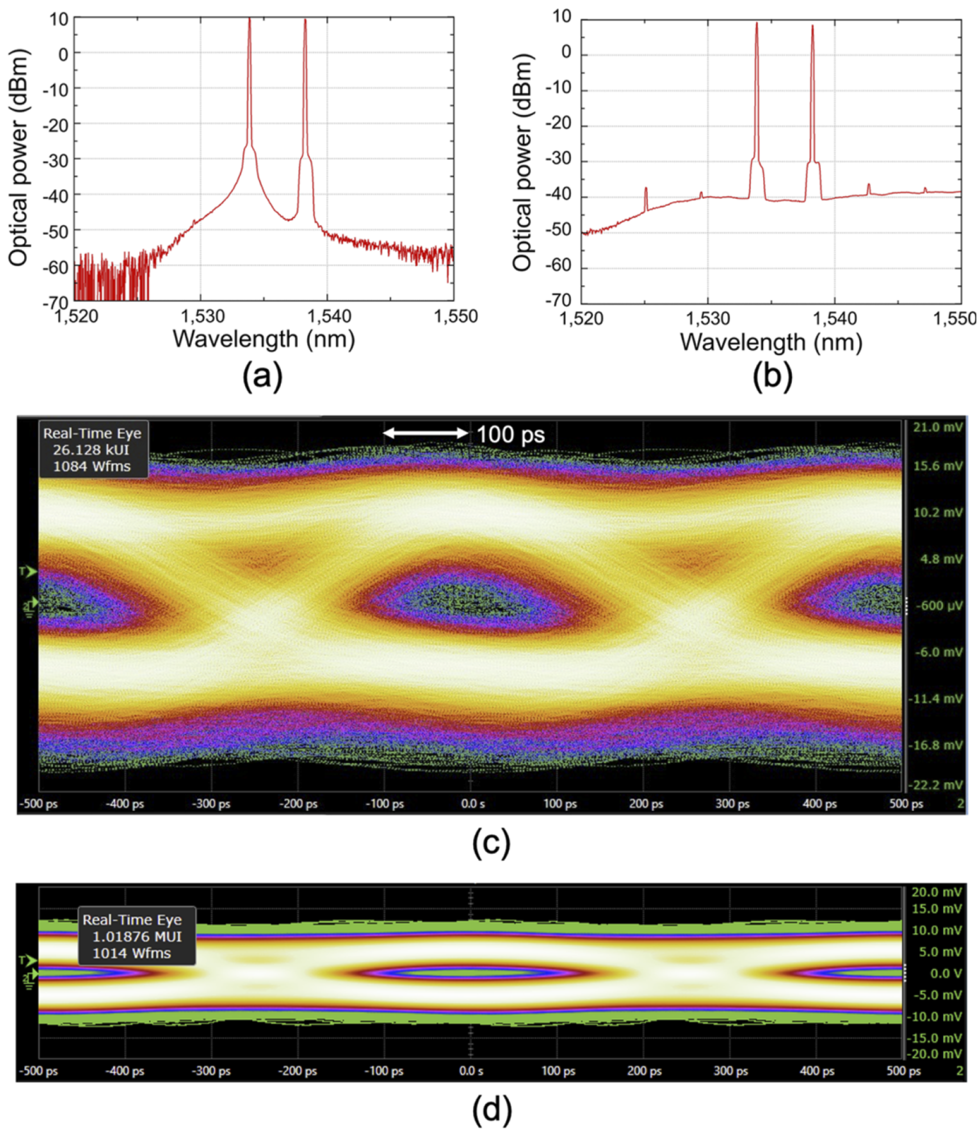

Fig. 4. Results of 2-Gbit/s OOK wireless communication at 560 GHz. Optical spectrum of two microcomb modes obtained by (a) two pairs of EDFAs (EDFA3 and EDFA4) and OPBFs (OBPF1 and OBPF2) before fiber coupling and (b) OPBFs (OBPF1 and OBPF2) and an additional EDFA after their fiber-coupling. Eye pattern of OOK signal with 2 Gbit/s (c) when two microcomb modes were used for generation of THz carrier wave and (d) when two free-running CW lasers were used for generation of THz carrier wave.

input signal with a suitable power must be fed into EDFAs because an extremely weak optical input increases ASE unnecessarily. Although the OSNR improves with filtering of ASE in EDFA1 (see Fig. 1), we did not use the filter in the present setup because the resulting decreased pump power would be insufficient and the soliton comb could not be generated stably. Instead, we precisely adjusted the optical input signal of the EDFA3 and EDFA4 (namely, the modulated OFC-M1 and unmodulated OFC-M2) for a better OSNR. We further reduced the ASE background outside of two amplified microcomb modes by fine tuning of OPBFs. Figure 4(a) shows the optical spectrum of the two amplified microcomb modes immediately before being sent to the UTC-PD (RBW = 0.2 nm). These microcomb modes appear to have a sufficient dynamic range (≈ 40 dB) from the ASE background level around -30 dBm. For comparison, we removed EDFA3 and EDFA4 in Fig. 3, and then simultaneously amplified the combined OFC-M1 and OFC-M2 after passing through OBPFs and the fiber coupler by an additional EDFA (not shown in Fig. 3). Figure 4(b) shows the optical spectrum of the resulting OFC-M1 and OFC-M2 immediately before being sent to the UTC-PD (RBW = 0.2 nm). In this case, the broad ASE background remains outside of two microcomb modes even though OSNR was achieved to 40 dB. Some smaller sidebands indicate residual microcomb modes. Such difference of ASE background between them in the same OSNR influences the result of OOK wireless communication.

The 560-GHz THz wave, generated by photomixing of two microcomb modes in Fig. 4(a), was used for OOK wireless communication. Figure 4(c) shows an eye diagram of OOK with 2 Gbit/s measured by the real-time oscilloscope; thus, the eye was opened. The Q-factor of this eye pattern was determined to be 3.40. This Q-factor satisfied the limit of forward error correction (FEC limit, Q-factor = 2.33). Accordingly, the eye diagram of 2-Gbit/s OOK THz data transfer was confirmed in the 560-GHz band within the FEC limit. For comparison, we performed the similar experiment of OOK data transfer when two free-running CW lasers were used in place of two microcomb modes. Figure 4(d) shows an eye diagram of OOK with 2 Gbit/s. The resulting Q-factor was 3.46, which is comparable to that in two microcomb modes (= 3.40). Also, when two microcomb modes in Fig. 4(b) were used for THz generation, the eye was fully closed (not shown), indicating that two pairs of EDFAs (EDFA3 and EDFA4) and OBPFs (OBPF1 and OBPF2) separately for two microcomb modes plays an important role in the present wireless communication.

3. Discussion

We first discuss the causes of the relatively low Q-factor of the measured OOK signal. One possible reason for it is atmospheric attenuation caused by water vapor absorption. The 560-GHz band is close to the water absorption line of 1_{10}-1_{01} (center frequency = 557 GHz, pressure broadening linewidth ∼ several GHz at atmospheric pressure). As the attenuation coefficient of water vapor is 7.1 dB/m at 560 GHz [21], the 0.6-m propagation of THz wave causes the THz attenuation by 4.26 dB. Use of such considerably attenuated THz wave limits the present Q factor. If THz wave at 565 GHz is used in place of 560 GHz, the atmospheric attenuation reduces to 1.14 dB from an attenuation coefficient of 1.9 dB/m at 565 GHz [21]. In this case, Q-factor in OOK data transfer will be largely improved. From this comparison, a main limiting factor of Q-factor is the propagation loss rather than the detector noise. By appropriately designing the diameter of a micro-resonator and utilizing a micro-heater deposited on the micro-resonator, it is possible to easily set f_{rep} of a microcomb to the desired THz frequency as long as the frequency bandwidth of UTC-PD covers the f_{rep}. Another possible reason for the relatively low Q-factor is the existence of ASE background remaining around modulated OFC-M1 and unmodulated OFC-M2 [see Fig. 4(a)]. One promising approach to further reduce the ASE background is optical injection locking to transfer the phase noise of a soliton microcomb in addition to the amplification of the microcomb mode without degrading the OSNR [22]. Work is in progress to apply this for generation of THz wave in THz wireless communication.

We next discuss the performance of OOK data transfer using two microcomb modes for generation of THz carrier wave compared with two free-running CW lasers. As shown in Figs. 4(c) and 4(d), when the transmitted OOK THz wave was square-law-detected by SBD, there are little difference of Q-factor between two microcomb modes and two free-running CW lasers. This is because the square-law detection is insensitive to the phase fluctuation of THz carrier wave. However, we consider that the performance difference between them can be clearly confirmed when the transmitted OOK THz wave is heterodyne-detected by SHM for the enhanced detection

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sensitivity. For example, we assume to observe the real-part or imaginary-part component of the OOK baseband signal that has been down-converted from the THz band to the RF band by an SHM. Our preliminary numerical simulation predicts that the eye pattern of OOK will open when two microcomb modes are used for generation of THz carrier wave because the phase of THz wave is stable. However, when two free-running CW lasers are used, since the phase of the THz wave is unstable, the eye pattern of OOK closes. The detailed numerical simulation and the experimental verification on them are our future work.

4. Conclusions

We demonstrated 2-Gbit/s OOK wireless communication in the 560-GHz band based on a hybrid system of photomixing-based photonic THz generation and SBD-based electric THz detection. Photomixing of two adjacent microcomb modes via UTC-PD enables the generation of THz waves without the need for optical frequency multiplication. Although such a higher-frequency band is accessible by UTC-PD-based photomixing, the combination of photomixing with the soliton microcomb benefits from the inherently low phase noise of f_{rep} in the soliton microcomb. A pair of OOK-modulated and unmodulated microcomb modes with an OSNR over 40 dB was used to generate the OOK-modulated THz wave. The achieved Q-factor was 3.40, which was within the range of the FEC limit.

The achieved phase noise of f_{rep} remained around -60 dBc/Hz at an offset frequency of 10 kHz because of the use of the free-running soliton microcomb; however, there is still room to further decrease the phase noise down to -99 dBc/Hz at an offset frequency of 10 kHz by active control of the soliton microcomb [16]. Reducing phase noise is an advantage for multi-level modulation using phase instead of multi-level modulation for amplitude only.

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Data availability. Data underlying the results presented in this paper are not publicly available at this time but may be obtained from the authors upon reasonable request.

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