Wireless transmission using coherent terahertz wave with phase stabilization

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Abstract: In this paper, we present a photonics-based approach to generating a highly stable coherent terahertz (THz) wave for application to wireless transmission. We introduce a novel system to stabilize the phases of optical carrier signals at different frequencies extracted from an optical frequency comb. By performing an error-free (bit error rate is less than 10^{-11}) transmission at 12.5 Gbit/s based on amplitude-shift keying modulation and heterodyne detection schemes with a carrier frequency of 100 GHz, we were able to verify the importance of phase stabilization.

Keywords: wireless transmission, coherent carrier, THz wave, optical frequency comb, phase stabilization

Classification: Fiber optics, Microwave photonics, Optical interconnection, Photonic signal processing, Photonic integration and systems

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1 Introduction

Terahertz (THz) wireless communication has attracted a great deal of interest in the use of short-distance transmission of ultrahigh data-rate signals such as HDTV and 4K-TV signals [1, 2]. Until now, 30 Gbit/s error-free (bit error rate: $\text{BER} < 10^{-11}$) transmission has been demonstrated using intensity modulation and direct detection scheme at 300 GHz [3, 4]. One of the promising ways to enhance the data rate is to introduce multi-level modulation techniques, such as quadrature phase-shift keying (QPSK) and quadrature amplitude modulation (QAM) using coherent THz wave [5]. Photonics-based generation of the THz wave in the coherent wireless link is a key technology for future optical/wireless seamless networks. There are two candidates for photonics-based THz wave generation: free-running laser-based approach [5] and optical frequency comb (OFC)-based approach [6, 7].

In the free-running laser-based approach (see Fig. 1 (a)), the frequency spacing of the two lasers is not constant and their phases fluctuate independently. Therefore, in this approach, all the experiments have been performed with the use of digital signal processing (DSP), and the transmission under an error-free condition has not yet been achieved. Recently, Pang et al. demonstrated a photonicallly up-converted 25 Gbit/s fiber-wireless QPSK data transmission ($\text{BER} > 10^{-6}$) link at the W-band (75–110 GHz) with free-running laser-based approach [5]. In this incoherent radio-over-fiber (RoF) system, a DSP-based receiver was employed for offline digital down-conversion and signal demodulation together with carrier phase noise correction.

Fig. 1. Photonics-based THz wave generation. (a) Free-running laser-based approach. (b) OFC-based approach. OC: optical fiber coupler. UTC-PD: uni-traveling-carrier photodiode. OFCG: optical frequency comb generator. AWG filter: arrayed-waveguide grating filter.

In the OFC-based approach (see Fig. 1 (b)), the frequency-detuned optical signals for THz wave generation were extracted from the OFC with an optical arrayed-waveguide grating (AWG) filter and then coupled with

an optical fiber coupler (OC). Even though each frequency comb component is phase-locked before the extraction, the generated THz wave shows phase fluctuations because of path length fluctuations in optical fibers for the two modes between the AWG filter and the OC. This approach requires DSP-based carrier phase noise correction at the receiver side. Using the DSP-based receiver, Kanno et al. demonstrated a 40 Gbit/s (BER=1.90 × 10⁻³) W-band 16-QAM RoF system with the OFC-based THz wave generation [6]. One of the effective ways to reduce the phase fluctuation is to integrate the AWG filter and the OC on a planar light-wave circuit (PLC) substrate in order to make the optical path length difference insensitive to ambient temperature and other external noise [7]. At this moment, however, it is not easy and cost-effective to integrate active devices such as optical modulators on PLCs to construct such systems as used in [6].

In this paper, we propose a practical phase stabilization scheme in the OFC-based THz wave generation without the use of PLCs in the transmitter, and demonstrate a 12.5 Gbit/s error-free transmission without the use of DSP and error correction in the receiver. In Sec. 2, we explain our approach to OFC-based coherent THz wave generation and show how the phase changes in the previous system without phase stabilization. Next in Sec. 3, we describe our experimental system based on amplitude-shift keying modulation and heterodyne detection schemes at a carrier frequency of 100 GHz. In Sec. 4, we demonstrate data transmission using our system, as a proof-of-concept experiment to verify the importance of phase stabilization in the error-free coherent wireless link.

2 Phase stabilization system

Fig. 2 shows a schematic diagram of the THz wave generation system with an OFC generator (OFCG). The phase of a single frequency laser is modulated with a Mach-Zehnder modulator (MZM) to generate the OFC. The THz wave is generated by photo-mixing two optical carrier signals at different frequencies extracted from the OFC using an AWG filter. The phases of the optical carrier signals ($\varphi_a(t)$ and $\varphi_b(t)$) fluctuate independently due to temperature fluctuations and acoustic noise in optical fiber cables between the AWG filter and the OC. The coherence of the THz wave is dependent on the stability of the phase differences between the optical carriers, as shown in the equation below:

Fig. 2. Schematic diagram of the THz wave generation.
MZM: Mach-Zehnder modulator.

$$\Delta\varphi(t) = \varphi_b(t) - \varphi_a(t). \quad (1)$$

Therefore phase fluctuations in the optical fibers between the AWG filter and the OC are a practical problem in the OFC-based coherent THz wave generation. In our scheme, $\Delta\varphi(t)$ is stabilized by locking the phases of the two optical carriers ($\varphi_a(t)$ and $\varphi_b(t)$) to those of the OFC signals ($\varphi_{0a}(t)$ and $\varphi_{0b}(t)$), where the relative phases between the OFC components are mutually locked.

Fig. 3 shows a schematic diagram of the coherent THz wave generator with phase stabilization system. The dither signals f_a and f_b , are applied to the frequency components f_1 and f_5 , respectively. The phase fluctuations relative to the phase of reference OFC ($\varphi_a(t) - \varphi_{0a}(t)$ and $\varphi_b(t) - \varphi_{0b}(t)$) are detected on the basis of a two-stage down conversion with a PD and an electronic mixer, where $\varphi_{0a}(t)$ and $\varphi_{0b}(t)$ are the phases of the OFC components of f_1 and f_5 , respectively. In the PD, the extracted optical carriers and the OFC components are mixed. By using the PD with a cutoff frequency below f_{RF} , the photo-mixing between optical carriers of the same frequency is output. The AC components of the output signal is $V_a + V_b$, where

$$\begin{aligned} V_a &= \cos[\varphi_a(t) - \varphi_{0a}(t) + D \sin \omega_a t] \\ &= \sum_{n=-\infty}^{\infty} \{J_n(D) \cos[\varphi_a(t) - \varphi_{0a}(t) + n\omega_a t]\}, \end{aligned} \quad (2)$$

$$\begin{aligned} V_b &= \cos[\varphi_b(t) - \varphi_{0b}(t) + D \sin \omega_b t] \\ &= \sum_{n=-\infty}^{\infty} \{J_n(D) \cos[\varphi_b(t) - \varphi_{0b}(t) + n\omega_b t]\}. \end{aligned} \quad (3)$$

By mixing the output signal with dither signals and cutting off the higher frequency components with low pass filters, phase fluctuations relative to the phase of the OFC can be detected independently. The detected signals are:

$$V_a = \cos[\varphi_a(t) - \varphi_{0a}(t)]. \quad (4)$$

Fig. 3. Schematic diagram of the coherent THz wave generator with a phase stabilization system. PS: phase shifter. PPG: pulse pattern generator.

$$V_b = \cos[\varphi_b(t) - \varphi_{0b}(t)]. \quad (5)$$

Our phase stabilization technique can be extended to multi-carrier format, such as THz-OFDM using different dither signals for each sub carrier.

The detected phase fluctuations are negatively fed back to a phase shifter (PS), with a PID controller to stabilize the phase fluctuation. As a result of using phase stabilization system, $\varphi_a(t) - \varphi_{0a}(t)$ and $\varphi_b(t) - \varphi_{0b}(t)$ are locked. Under phase stabilization, the phase of the generated THz wave can be expressed as:

$$\Delta\varphi(t) = \varphi_b(t) - \varphi_a(t) = \varphi_{0b} - \varphi_{0a}, \quad (6)$$

where $\varphi_{0b} - \varphi_{0a}$ is a constant value.

In the experiment, the frequency of the dither signals f_a and f_b applied to optical frequency components, f_1 and f_5 , was 12.8 kHz and 16 kHz, respectively. The cutoff frequency of the PD (Thorlabs Inc.: PDA10CS) is 33 kHz. The parameters of the PID controller (Stanford Research Systems: SIM960) were set to 1.0×10 in the proportional gain, 1.0×10^3 s in the integral gain and 1.0×10^{-5} 1/s in the derivative gain. The gain-bandwidth of the PID controller is up to about 20 Hz.

Fig. 4 (a) and (b) show the phase fluctuations of $\varphi_a(t) - \varphi_{0a}(t)$ and $\varphi_b(t) - \varphi_{0b}(t)$ detected as the voltages of V_a and V_b without and with phase stabilization, respectively. As shown in Fig. 5, each frequency component of the detected phase fluctuations below 20 Hz decreases significantly with phase stabilization as compared to the values of the components without the stabilization. In Sec. 4, we demonstrate the above approach to the

Fig. 4. Phase fluctuations. (a) Without phase stabilization. (b) With phase stabilization. Upper trace: V_a . Lower trace: V_b .

Fig. 5. Phase fluctuation intensity.

decrease of detected phase fluctuations is effective enough for our data transmission system based on amplitude-shift keying modulation and heterodyne detection schemes.

3 Wireless link using coherent THz wave

To verify the importance of phase stabilization in the coherent THz wireless link, we conducted a data transmission experiment based on amplitude-shift keying modulation and heterodyne detection schemes at a carrier frequency of 100 GHz. In the transmitter shown in Fig. 3, a single frequency laser was modulated at $f_{\text{RF}} = 25$ GHz to generate OFC. The OFC spacing was 25 GHz, therefore the carrier frequency of the THz wave was $f_5 - f_1 = 100$ GHz. For the data signal, we used a $2^{15} - 1$ pseudo-random pattern bit stream (PRBS) of up to 12.5 Gbit/s from a pulse pattern generator (PPG). The data signal was amplified with a driver amplifier (SHF communication technologies AG: SHF100CP) and applied to MZM2 (COVEGA: Mach-10 056) for THz amplitude-shift keying modulator.

In the receiver shown in Fig. 6, the OFC, which is the same as the one used in the transmitter, was composed of three frequency components, f_2 , f_3 and f_4 , by passing through the wavelength filter in a single pass. An electrical LO signal was generated by photo-mixing the frequency components of the OFC, f_2 and f_4 , at a PD (Discovery Semiconductors, Inc.: DSC10ER). Therefore the LO frequency was $f_4 - f_2 = 50$ GHz. An LO buffer-amplifier (Wright Technologies: ASG60-3010) with a bandwidth from 40 GHz to 60 GHz was used to amplify the LO signal. The LO signal was supplied to a sub-harmonic mixer (SHM, Virginia diode Inc.: WR10R3SHM 2-17) to realize heterodyne detection. The SHM demodulated the THz wave by mixing it with the LO signal, and output the recovered data signal. The data signal was amplified by a low-noise amplifier (LNA, MITEQ: JSMF4-02K180-32-10P) and a limiting amplifier (LIA, MAXIM: MAX3971A).

Fig. 6. Schematic diagram of the coherent receiver using sub-harmonic mixer. SHM: sub-harmonic mixer. LNA: low-noise amplifier. LIA: limiting amplifier.

4 Transmission results and discussion

Firstly, we tried to measure the eye patterns without phase stabilization, but were not able to obtain a stable pattern over a long time (at least 20 sec) due to the uncorrelated phase fluctuations of the two optical signals used for generating the 100-GHz carrier. The stable pattern was observed for a long time using phase stabilization. Fig. 7 (a) and (b) show the eye diagram at 3.0 Gbit/s accumulated for 20 seconds using a sampling oscilloscope without and with phase stabilization, respectively.

Fig. 7. Eye diagrams at 3.0 Gbit/s accumulated for 20 sec.
(a) Without phase stabilization. (b) With phase stabilization.

The maximum bit rate of 12.5 Gbit/s under the error-free condition is successfully achieved for wireless distance at 65 mm, as shown in Fig. 8. Fig. 9 shows BER characteristics at 10, 11 and 12.5 Gbit/s. The BER of 6.6×10^{-12} was obtained at 10 Gbit/s, when the UTC-PD photocurrent was 0.45 mA and the THz output power was about -35 dBm. The BER of 1.2×10^{-11} was also obtained at 12.5 Gbit/s, when the UTC-PD photocurrent was 0.85 mA and the output power was about -21 dBm. The 11 Gbit/s or 12.5 Gbit/s transmission required more UTC-PD photocurrent than the 10 Gbit/s transmission in order to achieve the error-free condition. The main reason is the band-limitation of the MZM2 (electrooptic bandwidth of 10 GHz) used to modulate the amplitude of the coherent THz wave.

Fig. 8. Eye diagram at 12.5 Gbit/s for wireless distance of 65 mm.

Higher THz wave frequency generated with wider OFC promises a higher bit rate. Moreover, the multi-carrier modulation of OFDM can be easily adapted to our system, which also increases the bit rate.

Fig. 9. BER characteristics at 10, 11 and 12.5 Gbit/s.

5 Conclusion

We have described a photonics-based approach to generating a phase-locked THz wave with a new phase stabilization method. We have conducted a data transmission based on amplitude-shift keying modulation and heterodyne detection schemes at a carrier frequency of 100 GHz, and have successfully demonstrated a stable error-free transmission of up to 12.5 Gbit/s only with phase stabilization. Phase stabilization shows great potential as a technique for achieving the error-free condition in coherent wireless links using photonics-based generation of the THz wave.

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