Photonic Generation of Millimeter/ Terahertz Waves and Its Applications

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Abstract

This article describes recent advances in the generation of millimeter and terahertz waves based on optical heterodyning techniques. For many applications, the main targets are low-phase noise, wide frequency tunability, and high output power. We present basic component technologies, such as an optical frequency comb generator, photonic light-wave circuits for signal processing, and antenna-integrated photodiode modules, and their applications to high-performance measurement and communications.

1. Introduction

Millimeter-waves (MMWs) at frequencies of over 100 GHz have been intensively used for communications [1] and sensing applications [2], [3]. For the generation of MMWs and/or terahertz (THz) waves, photonic techniques are considered to be superior to conventional techniques based on electronic devices in terms of wide bandwidth, tunability, and stability. In addition, the use of optical fiber cables to transmit high-frequency signals provides us with unique system solutions. For example, we can separate the signal generation or processing unit from the emitter via optical fiber cables, making the antenna site very simple and compact, as shown in **Fig. 1**.

Typical methods for generating continuous MMW/THz-waves are compared in **Fig. 2** in terms of frequency bandwidth, tunability, and stability or noise. Optical heterodyning using two laser diodes is the simplest way to generate MMW signals with great frequency tunability in the range from gigahertz to terahertz [4]. However, frequency stability is generally poor; for instance, the phase noise is –75 dBc/Hz even at an offset frequency of 100 MHz, and the frequency drift is more than 10 MHz/hour when two distributed feedback lasers are used [5]. Thus, a special phase-locking technique is necessary for practical instrumentations.

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The combination of a continuous-wave (CW) laser and an external modulator such as a $LiNbO_3$ modulator or electroabsorption (EA) modulator [6] also offers wide frequency tunability, and the phase noise of the generated signal is as low as that of the synthesizer driving the modulators. However, the bandwidth of the generator is finally limited by that of the driver electronics, and the maximum frequency for the state of the art is 110 GHz [7].

Mode-locked lasers based on semiconductor laser diodes [8], [9] can generate optical pulses or quasi-sinusoidal signals at high repetition frequencies of more than 200 GHz for active mode-locking and over 1 THz for passive mode-locking. Passively mode-locked lasers can output MMW signals with only the application of DC current to the laser diode. Moreover, the frequency stability is relatively high: the linewidth and frequency drift are typically less than 200 kHz and 200 kHz/hour, respectively [5]. The phase noise of MMW signals generated by an actively mode-locked laser is much lower, <–75 dBc/Hz at an offset frequency of 100 Hz. However, the frequency of MMW signals generated by both passively and actively mode-locked lasers is determined by the cavity length of the laser diode, and the frequency tunability is typically from 100 MHz to 1 GHz.

Heterodyning two modes filtered from a multifrequency (wavelength) optical source or optical frequency comb generator (OFCG) satisfies all the requirements of bandwidth, tunability and stability [4], [10]. In this article, we present low-phase-noise and frequency-tunable MMW/THz-wave generators

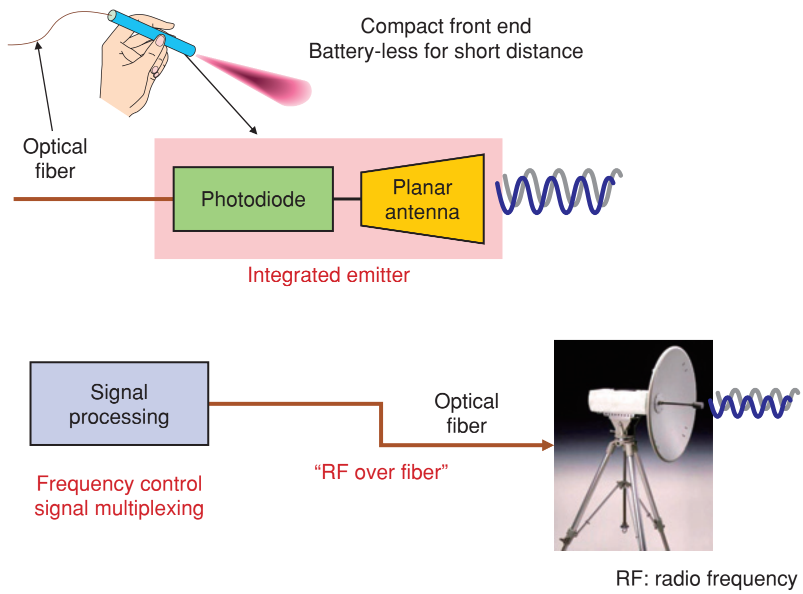

Fig. 1. Conceptual illustration of photonic MMW/THz-wave generators.

Method	Frequency	Tunability	Stability/ noise
Heterodyning two laser diodes	Excellent >10 THz	Excellent >10 THz	Bad Frequency drift Large linewidth
CW laser diode + external modulator	Fair <100 GHz	Fair <100 GHz	Excellent Determined by electronics
Mode-locked laser diode (passive/active)	Good Passive >1 THz Active 240 GHz	Bad <1 GHz	Excellent Only for active
Optical comb (OFCG) + filter	Excellent > 1 THz	Excellent > 1 THz	Excellent Determined by electronics

Fig. 2. Comparison of MMW/THz-wave generation methods based on photonics.

based on optical heterodyning achieved using an OFCG. Basic component technologies, such as the OFCG, photonic light-wave circuits for signal processing, and antenna-integrated photodiode modules, and their applications to high-performance measurement and communications are described.

2. Basic component technologies

2.1 Optical frequency comb generators

A block diagram of the continuous-wave MMW/THz generator is shown in **Fig. 3**. The key components are the OFCG, which generates multifrequency optical signals, the optical filter, which selects two of them, and the optical-to-electrical (O-E) converter, or photomixer, which converts optical signals to electrical signals.

The OFCG consists of an optical intensity modulator, a phase modulator, and an oscillator, which provides stable and "power-flattened" sideband signals with variable frequency spacing determined by the electrical oscillator [11]. Flattened sidebands were obtained by optimizing the driving voltages of the modulators. This is essential to keep the power of the

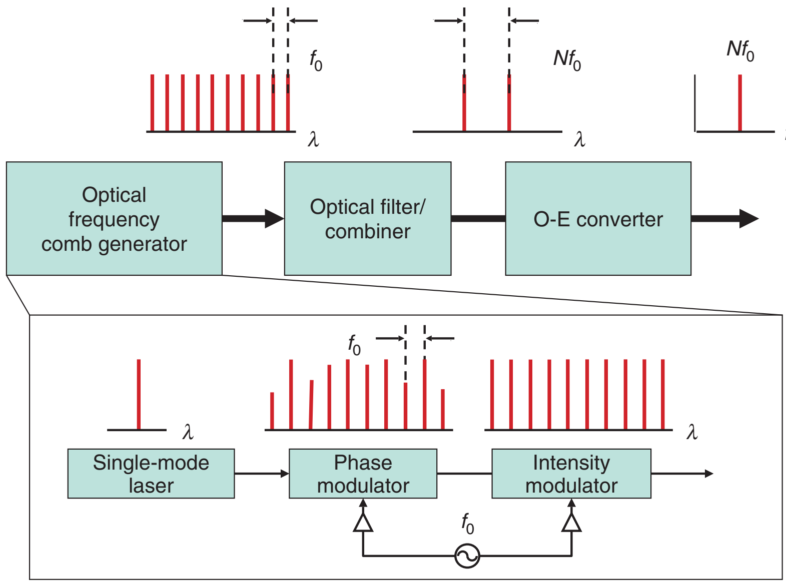

Fig. 3. Block diagram of the MMW/THz-wave generator based on optical heterodyning using optical frequency comb generator.

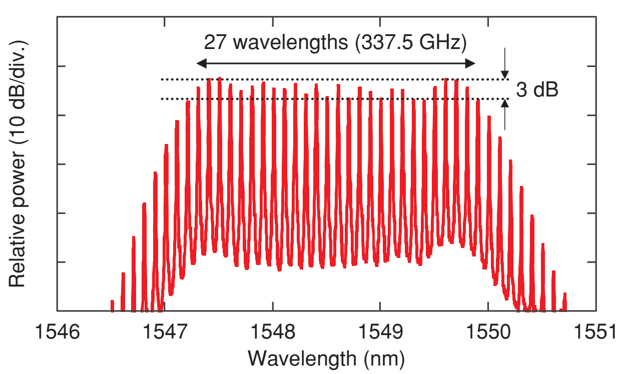

Fig. 4. Optical spectrum of the OFCG. The driving frequency for modulators was 12.5 GHz.

generated MMW signals constant even when the frequency is changed. A typical output spectrum obtained with the phase and amplitude modulators with a half-wave voltage of about 4 V is shown in **Fig. 4**. Here, 27 wavelengths were generated with a power deviation of 3 dB at a fundamental frequency of 12.5 GHz. Decreasing the half-wave voltage of the optical phase modulators is the most effective way to further expand the sideband spectrum.

2.2 Integrated filters and combiners

To achieve extremely low-phase-noise signals, we have to consider how to extract only two sidebands using optical filters and couplers. Conventionally, optical filters and couplers are based on optical fibers and also connected with optical fibers. The phase fluctuations between the two sidebands at low frequencies occur because the optical path length difference between the filter and the coupler changes due to temperature fluctuations and other external effects such as vibrations, which lead to an increase in the phase noise of the generated MMW signals.

To solve this problem, we integrated arrayed optical waveguide grating (AWG) filters and combiners on a silica-based planar light-wave circuit (PLC), as shown in **Fig. 5(a)** [12]. **Figure 5(b)** compares RF spectra of the 120-GHz signal obtained from a PLC combiner and from a conventional technique that uses filters and couplers connected via optical fibers. When optical fibers were used, the phase noise at low frequencies was 10–20 dB higher. The single-sideband phase noise values of the MMW signal with the PLC combiner were less than –75 and –85 dBc/Hz at offset frequencies of 100 Hz and 1 kHz, respectively.

2.3 O-E converters

An O-E converter is a key device in the system. Since optical amplifiers with a high gain of over 30 dB and a large bandwidth of over 1 THz are now readily available, we need a high-power O-E converter to boost the signal generator performance. We used an ultrafast photodiode called a uni-traveling-carrier photodiode (UTC-PD) [13]. It has a photoabsorption layer and a photocarrier collection layer (**Fig. 6**). In this structure, only electrons are used as active carriers. This provides both a large bandwidth and a high saturation output current at a wavelength of 1.55 µm.

Figure 7 shows a comparison of reported MMW/THz-wave output (detected) power against operating frequency for UTC-PDs, pin-PDs, and low-temperature-grown (LT)-GaAs photomixers. The output power of UTC-PDs is about two orders of magnitude higher than those of pin-PDs, mostly due to high saturation output current.

To enhance the output power of UTC-PDs even further, we have examined three approaches. The first is to use resonant matching circuits or antennas integrated with the UTC-PD to compensate for the influence of the CR time constant of the PD and boost the output power by a factor of two or more [14]. A UTC-PD integrated with a twin-dipole planar antenna has generated >10 µW at 1 THz [15] (**Fig. 8(a)**).

The second approach is to use a power-combining scheme by using an array of antennas integrated with UTC-PDs. A 3 × 3 patch antenna array with PDs was fabricated and tested at 300 GHz to raise the output power to the milliwatt level [16] (**Fig. 8(b)**).

The third one is to add an electrical power amplifier. At frequencies around 100–200 GHz, MMW power amplifiers have recently been developed with the advent of high-frequency transistors such as InP-HEMT and HBT. We have integrated the UTC-PD with an InP-HEMT amplifier, which outputs >10 dBm at 125 GHz [17] (**Fig. 9**).

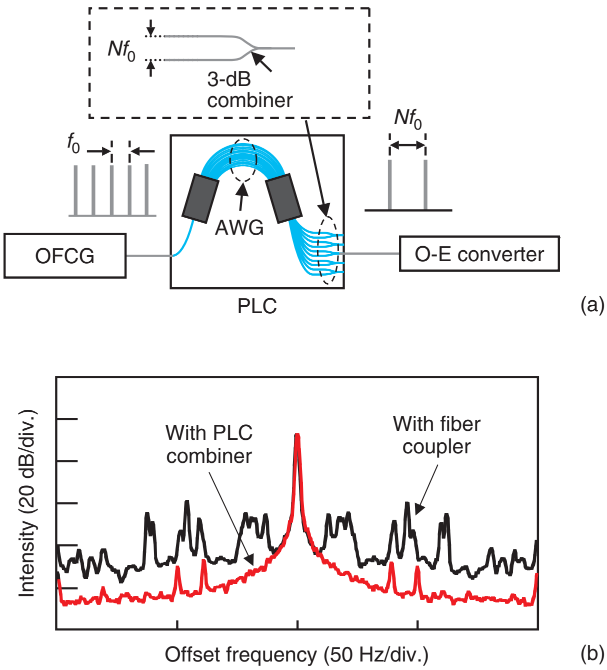

Fig. 5. (a) Role of PLC in photonic MMW generator. (b) RF spectra.

3. System applications

3.1 Wireless communications

A block diagram of a 120-GHz-band wireless link system with 10-Gbit/s transmission capability is shown in **Fig. 10** [1], [18], [19]. A photonic MMW generator is used in the transmitter. An optical MMW source generates optical subcarrier signals whose intensity is modulated at 125 GHz. An optical intensity (ASK) modulator modulates the optical subcarrier signal using data signals. The modulated subcarri-

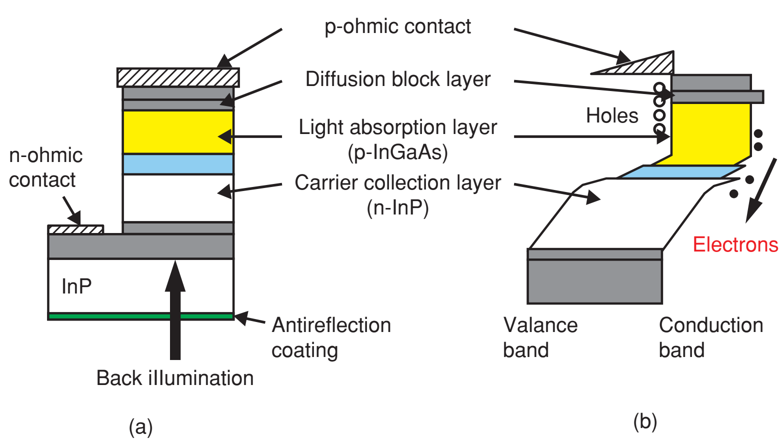

Fig. 6. Structure of UTC-PD. (a) Layer structure and (b) band diagram.

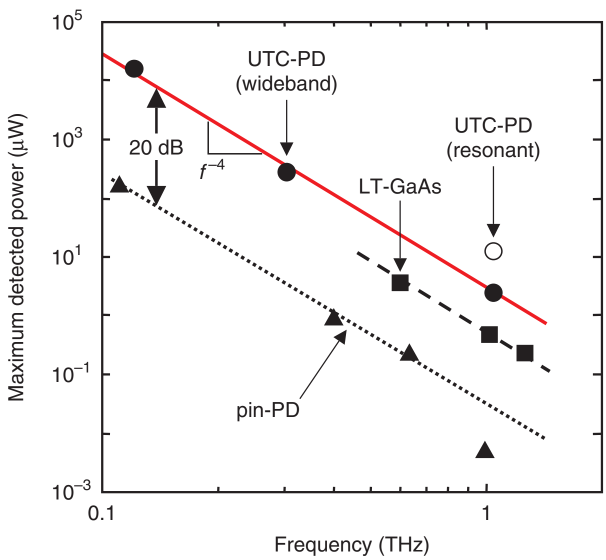

Fig. 7. Comparison of CW output power (average power).

er signal is amplified by an optical amplifier and input to the high-power photodiode. The photodiode converts the optical signals into MMW signals, which are amplified and radiated toward the receiver via an antenna. The received MMW signals are amplified and demodulated by a simple envelope detection scheme, for example. We used the optical MMW signal generator and O-E converter shown in Figs. 3 and 6, respectively. The MMW receiver is composed of all-electronic devices using InP-HEMT technology.

A photograph of the photonics-based MMW transmitter for a long-distance (>1 km) link using a high-gain Cassegrain antenna is shown in **Fig. 11**. This wireless link can support the optical network standards of both 10 GbE (10.3 Gbit/s) and OC-192 (9.95 Gbit/s) with a bit error rate of 10^{-12}. We have also been successful in the wireless transmission of 6-channel uncompressed high-definition television (HDTV) signals using the link.

In addition, a heterodyne receiver for the 120-GHz-band wireless link has been examined using our photonic MMW generator as a local oscillator (LO), and sufficient stability of the photonic LO has been confirmed [12].

3.2 Measurement systems

The ultralow-noise characteristics of the photonically generated MMW/THz-wave signal have been verified through their application to the LO for superconducting mixers in receivers used for radio astronomy. Radioastronomical signals from the universe

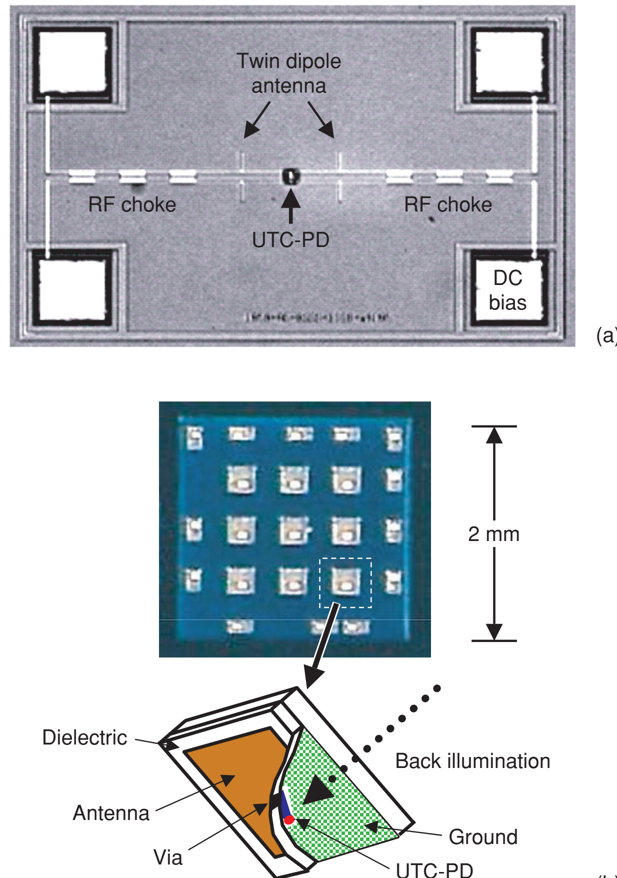

Fig. 8. (a) THz UTC-PD with twin-dipole antenna and (b) microstrip antenna array integrated with UTC-PD.

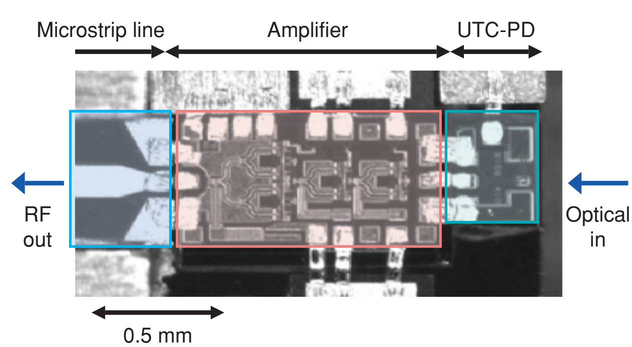

Fig. 9. UTC-PD integrated with power amplifier.

have been successfully observed using a 97.98-GHz photonic LO [2].

A great advantage of photonic LOs in spectroscopic measurement systems is their wide tunability. For this purpose, a wideband receiver has been tested with the same combination of superconducting mix-

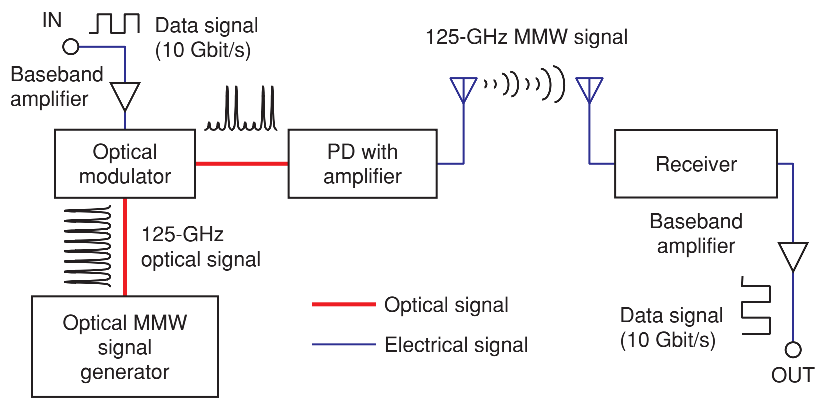

Fig. 10. 120-GHz-band wireless link system using photonic MMW transmitter.

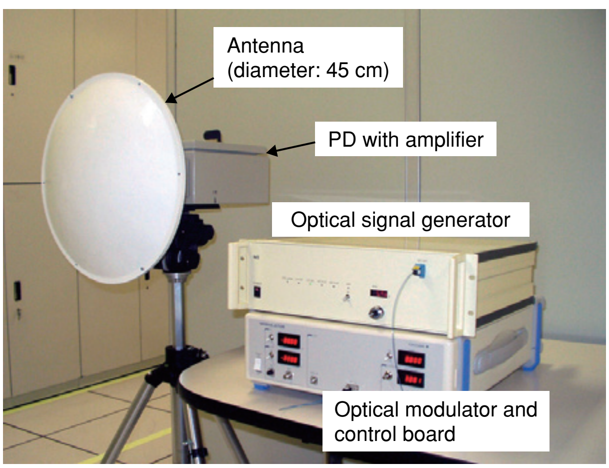

Fig. 11. MMW transmitter for long-distance wireless link.

ers and a photonic LO at frequencies from 260 to 340 GHz [20].

4. Conclusion

We described MMW/THz-wave generation based on optical heterodyning. Frequency-tunable power-flattened optical frequency combs, high output power O-E converters, and integrated optical filter/combiner circuits are key devices for high-performance signal generators. A bandwidth of more than one octave, a frequency resolution of less than 1 Hz, and an output power of more than 100 μW at frequencies up to 1 THz should be feasible in the near future. Such a generator will be useful for exploring MMW/THz electromagnetic waves for basic measurement and communications.

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