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Photonic Generation of Millimeter and Terahertz Waves and Its Applications

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Original scientific paper

This paper describes recent advances in the generation of millimeter and terahertz waves based on photonic techniques, which provides low-phase noise, wide frequency tunability, and high output power. 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 are presented.

Key words: millimeter wave, terahertz, photonics, wireless communication, spectroscopy

1 INTRODUCTION

Millimeter-waves (MMWs) and/or terahertz (THz) waves at frequencies of over 100 GHz have been intensively used for communications [1] and measurement applications [2, 3]. For the generation of such high frequency signals, 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 Figure 1.

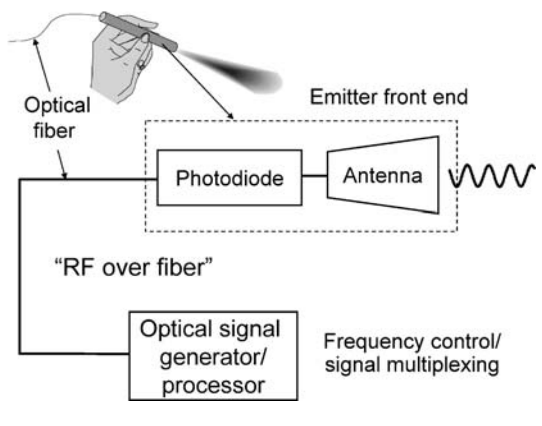

Fig. 1 Conceptual illustration of photonic MMW/THz-wave generators

Typical methods for generating continuous MMW/THz-waves are summarized in Figure 2, and compared in Table 1 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.

The combination of a continuous-wave (CW) laser and an external modulator such as a $LiNbO_3$ modulator or electro-absorption (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 those of modulators and driver amplifiers, 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

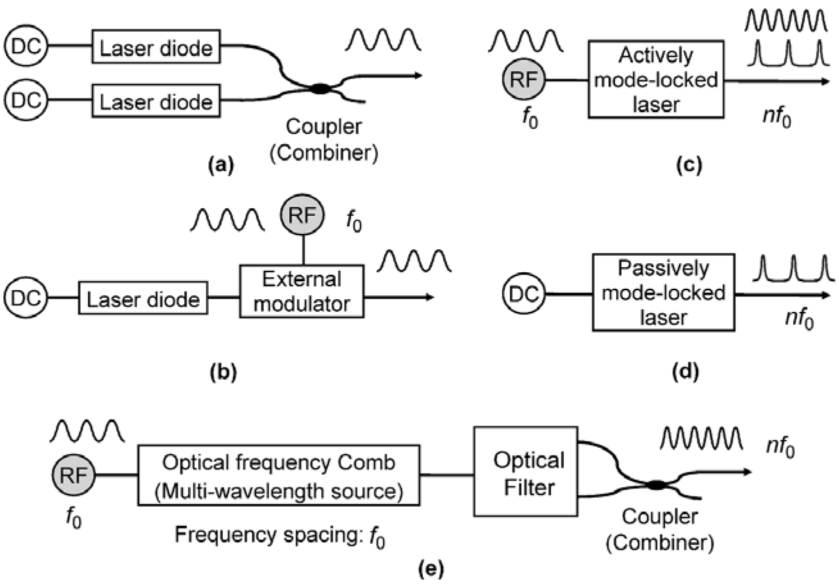

Fig. 2 Schemes for optical MMW/THz-wave generation. DC: direct current source, RF: radio frequency signal source

Table 1 **Comparison of MMW/THz-wave generation methods based on photonics**

Method	Frequency	Tunability	Stability/noise
Heterodyning two LDs	Excellent >10 THz	Excellent >10 THz	Bad *Frequency drift* *Large linewidth*
CW LD + 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*

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 multi-wavelength (frequency) optical source or optical frequency comb generator (OFCG) satisfies all the requirements of bandwidth, tunability and stability [4, 10].

In this paper, we present low-phase-noise and frequency-tunable MMW/THz-wave generators 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 CW MMW/THz-wave generator is shown in Figure 3. The key components are the OFCG, which generates multi-frequency optical sideband signals, the optical filter,

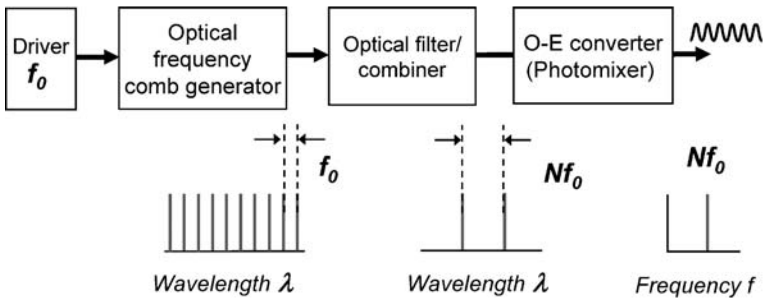

Fig. 3 Block diagram of the MMW/THz-wave generator using optical heterodyning technique

which selects two of them, and the optical-to-electrical (O-E) converter, or photomixer, which converts optical signals to electrical signals. In the OFCG, the frequency spacing of the optical sideband is variable and determined by the frequency of electrical drivers.

In the OFCG, generation of »power-flattened« sideband signals is necessary to keep the power of the generated MMW/THz signals constant even when the frequency is changed. There are many approaches for such an OFCG, one of which is to use an optical intensity modulator and a phase modulator [11]. Use of nonlinear optical fiber is effective to further expand the comb frequency band to THz regions [10].

2.2 Optical Filters and Combiners

To select only two sidebands, narrow-band optical filters such as fiber Bragg grating filters are used [10]. To perform automatically controlled optical filtering, arrayed optical waveguide grating (AWG) filters and optical switches can be used as shown in Figure 4(a). When the frequency spacing changes, however, the unwanted neighboring modes are not suppressed well by the AWG filter with a fixed channel spacing. The unwanted neighboring modes generate spurious signals after the O-E conversion. This problem can be solved by introducing one more identical AWG filter, as shown in Figure 4(b), whose center wavelength is shifted by as much as half of the channel spacing of AWG filters [12]. In this scheme, the combination of two AWG filters and an optical switch works as a tunable optical filter, and when the spacing of a sideband signal is not smaller than the passband bandwidth of AWG filters, any optical mode at any position can be selected without unwanted neighboring modes. The optical side-mode suppression ratio of higher than 25 dB was experimentally confirmed with two AWGs in the mode-spacing range of 200 ~ 550 GHz [12]. It is expected that spurious suppression ratio of generated signal would be higher than 50 dB because of the square-law detection of O-E converters.

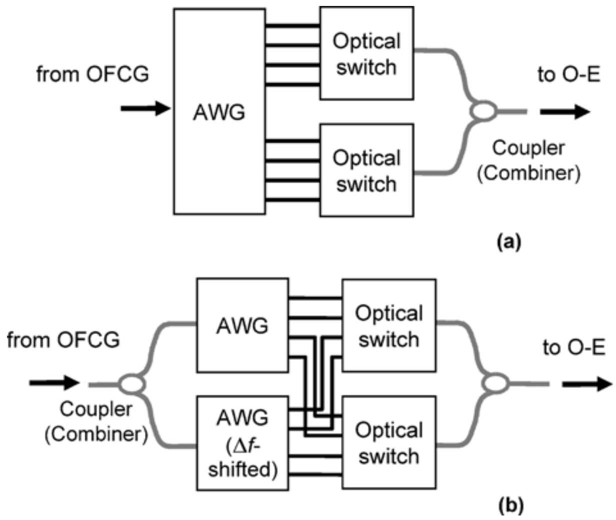

Fig. 4 Schematic diagram of the tunable optical filter block with AWGs and optical switches. (a) use of single AWG, (b) use of two AWGs to suppress spurious signals

To achieve extremely low-phase-noise signals, integration of the AWG filters and combiners on a silica-based planar light-wave circuit (PLC) was examined [13]. This eliminates the low-frequency phase fluctuations between the two sidebands, which occur in optical fiber cables because the optical path length difference between the filter and the coupler changes due to temperature fluctuations and other external effects such as vibrations.

2.3 Optical-to-Electrical 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 perfor-

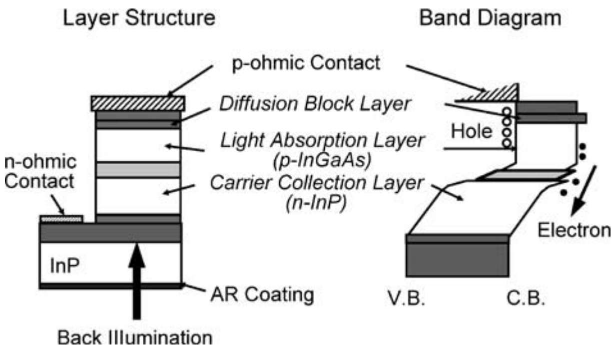

Fig. 5 Layer structure and band diagram of the UTC-PD

mance. We used an ultrafast photodiode called a uni-traveling-carrier photodiode (UTC-PD) [14]. It has a neutral p-type photoabsorption layer and a wide-gap electron collection layer (Figure 5). 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 6 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.

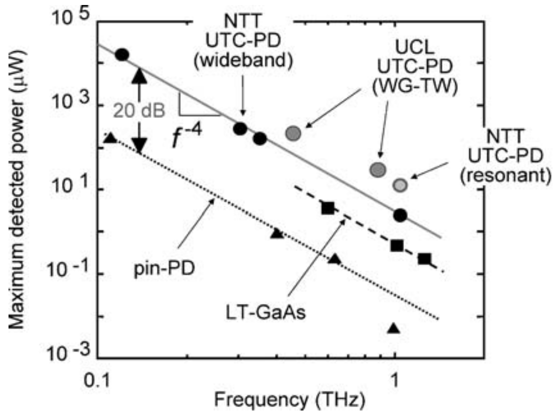

Fig. 6 Comparison of CW output power (average power) obtained with conventional PDs and UTC-PDs

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 [15]. This technique compensates for the internal capacitance of the PD, thus eliminating the constraint of CR time constant at a specific frequency. Addition of the matching element such as a short-stub to the PD was proven to increase the output power by 2–3 dB at the resonant frequency. Figures 7 (a) and (b) show the UTC-PDs integrated with the matching circuits at F-band (90–140 GHz) and J-band (220–325 GHz) [16] operations, respectively. Integration of a resonant planar antenna with the UTC-PD is also effective in particular for THz regions [17] (Figure 8). It must be added that besides the power enhancement with »lumped PDs« as described above the UTC-PD with an evanescently coupled traveling-wave (TW) waveguide structure has recently been shown to offer both the high efficiency and large bandwidth [18, 19].

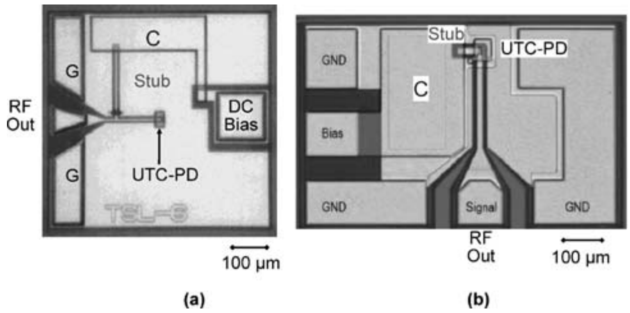

Fig. 7 Photographs of the UTC-PD chips integrated with matching circuits for (a) F band and (b) J band

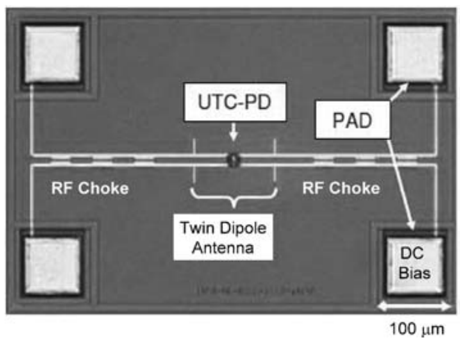

Fig. 8 Photograph of THz UTC-PD chip integrated with twin--dipole antenna

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 [20].

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 [21].

3 SYSTEM APPLICATIONS

3.1 High-speed Wireless Communications

One of common concerns when we use >100--GHz radio waves for wireless communications is a large propagation loss in the air. Figure 9 shows the atmospheric attenuation of radio waves at frequencies from 10 to 1000 GHz. From 100 to 300 GHz, there are three valleys, where the attenuation is a local minimum, our initial choice is the 120-GHz band centered at 125 GHz.

A block diagram of a 120-GHz-band wireless link system with 10-Gbit/s transmission capability is shown in Figure 10 [1, 22, 23]. 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 subcarrier 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. The MMW receiver is composed of all-electronic devices using InP-HEMT technology.

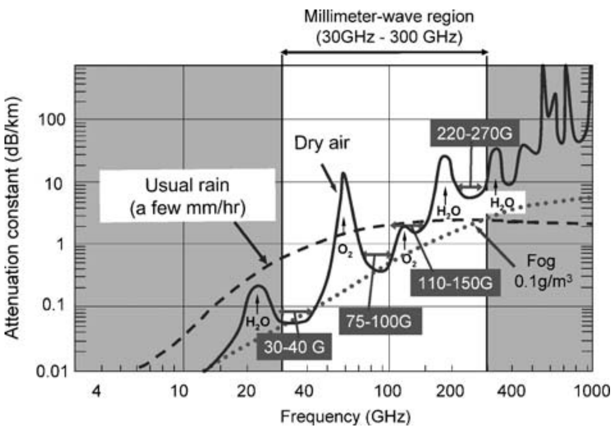

Fig. 9 Atmospheric attenuation of electromagnetic waves

The promising application of the above 10-Gbit/s wireless link is found in the broadcasting industry. A wireless link system that can transmit »uncompressed« high-definition television (HDTV) signals has been strongly desired, because TV program production based on the HDTV standard is spreading rapidly in TV stations due to the launch of digital TV broadcasting all over the world. An uncompressed HDTV signal (HD-SDI: high definition serial digital interface) requires a data rate of 1.5 Gbit/s per channel. Conventionally, for wireless transmission of broadcast materials, a 7- or 10-GHz-band microwave field pick-up unit (FPU) is used. The data rate of the state-of-the-art FPUs is as low as 3–80 Mbit/s, which cannot handle the full bandwidth of real-time HD-SDI signals. Therefore, current microwave wireless link compresses the HD-SDI signals with MPEG or JPEG2000 encoders. This compression always causes a time delay, which makes it difficult to edit programs or switch cameras in a live broadcast, and sometimes

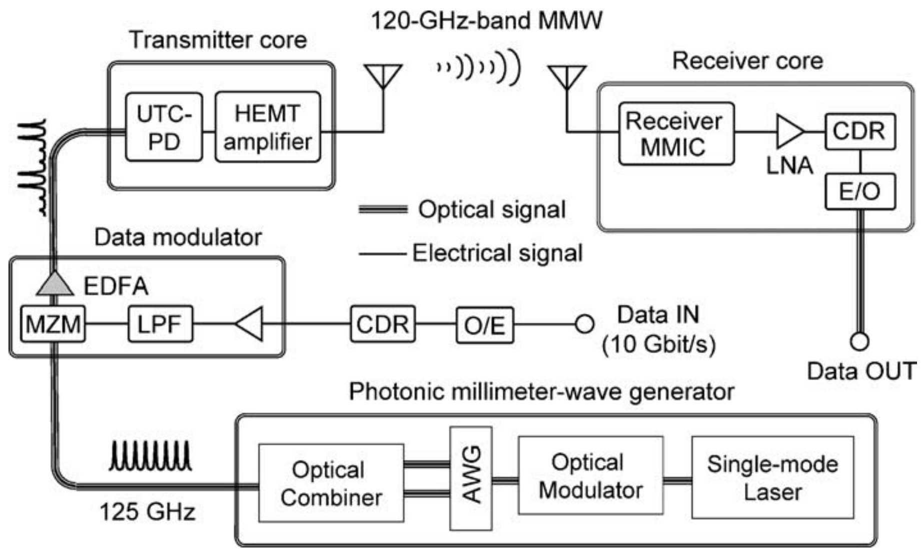

Fig. 10 Block diagram of 120-GHz-band wireless link system using photonic MMW transmitter

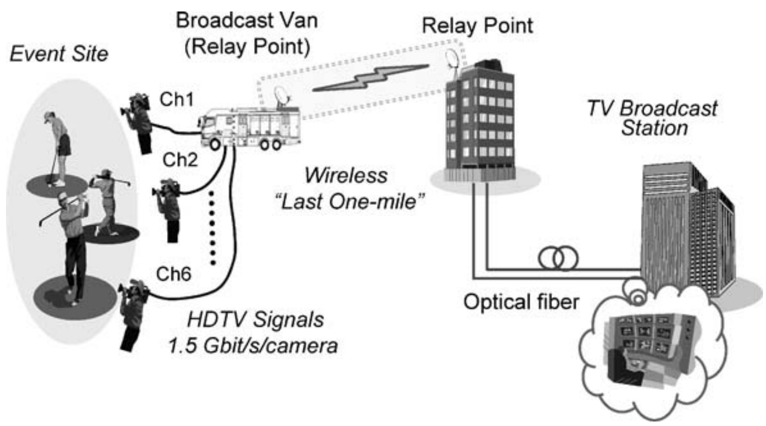

Fig. 11 Targeted application scene of the 10-Gbit/s wireless link system

causes deterioration of HD-SDI signal quality. MMWs are suitable for increasing the data rate of wireless communications systems, because the data rate generally increases with the carrier frequency. Commercial wireless links using 60-GHz-band MMWs have a data rate of over 1.5 Gbit/s and thus a capability of transmitting one channel of uncompressed HD-SDI signals. However, large-scale live relay broadcasts, such as golf tournaments and music concerts, requires multiple channels of uncompressed HD-SDI signals. The 120-GHz-band system allows up to 6 channels of HDTV material to be sent over a wireless link with no latency.

For such a purpose, this link uses a high-gain (~ 50 dBi) Cassegrain antenna, and 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. The 120-GHz-band wireless link will be used in the last-one-mile between a relay van and a broadcast station, where optical fibers cannot be installed easily, as shown in Figure 11.

One of the advantages of the photonically-assisted MMW transmitter is to make the transmitter core (Figure 10) very compact and light-weight, so we can bring and place the antenna unit anywhere in the field. The photonic MMW transmitter can be expanded to the multi-band system as shown in Figure 12. By using the WDM technology, we can select one of three carrier-frequency-bands where the atmospheric attenuation becomes minimum (30 GHz band, 90 GHz band, and 120-GHz band) as shown in Figure 9, in order to ensure the transmission quality depending on the weather, and to perform a frequency hopping for security reason.

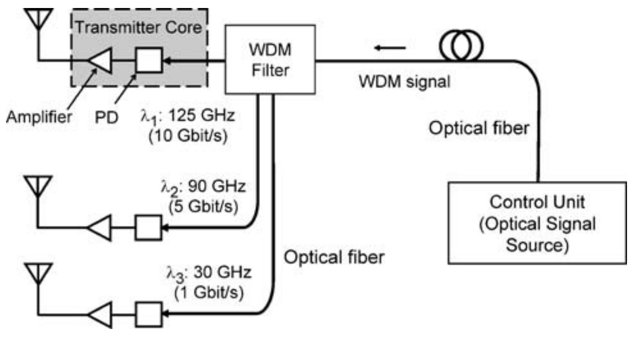

Fig. 12 Schematic diagram of the multi-band wireless link systems using photonic MMW transmitters

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 [23].

3.2 Spectroscopic 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 (SIS: superconductor-insulator-superconductor) mixers in heterodyne receivers used for radio astronomy. Radio-astronomical signals from the universe have been successfully observed using a 98-GHz photonic LO [2]. Use of the photonic LO in the SIS mixer system is the best combination, since the SIS mixer requires an LO power as low as a few 10 nW, that has been already achieved with the use of UTC-PDs. Another advantage of the photonic LO in spectroscopic measurement systems is their wide tunability. For this purpose, a wideband receiver has been tested with the same combination of the SIS mixers and the photonic

LO at frequencies from 260 to 340 GHz [24]. Low--temperature (2.6 K) operation of the UTC-PD has also been confirmed, and it makes the photonic LO more attractive for integration with the SIS mixer [25].

Using the photonic MMW/THz-wave generator, simple spectroscopic measurements has successfully been demonstrated in the frequency range between 240 and 360 GHz [26]. The sample under the test was a mixture of N2O and N2 in the ratio of 3:1 (75 %), and filled in a 1 m long gas cell with atmospheric pressure. The experiment setup is shown in Figure 13. The MMW/THz signal generator was computer controlled to sweep the frequency and the optical MMW/THz signal before the UTC-PD was intensity modulated at a frequency of 10 kHz. Then, the generated signal was radiated and collimated with a diagonal horn antenna and a gold-coated off-axis parabolic mirror, respectively. The transmitted signal through the gas cell was received with a Schottky barrier diode, and detected with a lock-in amplifier tuned at 10 kHz.

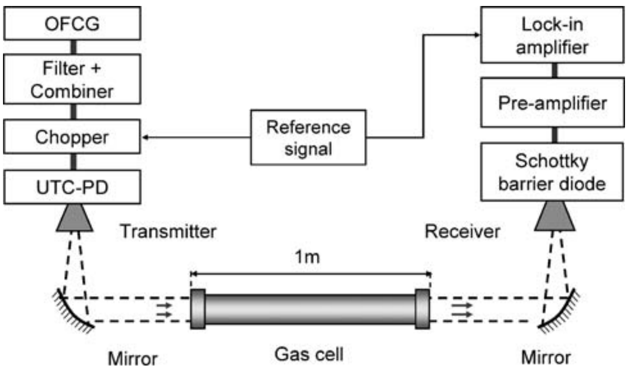

Fig. 13 Experiment setup for spectroscopic measurement system using photonic MMW/THz signal generators

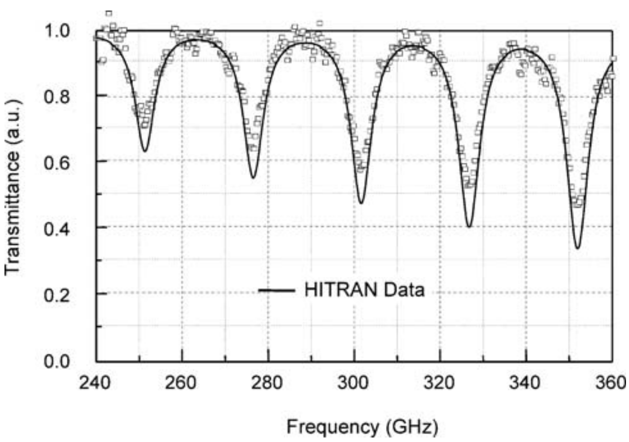

Fig. 14 Measured and simulated spectroscopic results for N_2O concentration of 75 %

The measured transmittance for the gas is plotted in Figure 14 with simulated results based on the HITRAN database [27]. As can be seen, the positions, tendency of the magnitude and the shape of absorption peaks from the measurement coincide well with those of HITRAN.

In the future, this system will be extended to the standoff sensing system for toxic and/or dangerous gasses such as CO, CO_2, HCN, HCl, SOx, NOx, etc. in case of disaster or fire (Figure 15). In this system, highly-sensitive receiver is required, and the SIS mixer mentioned above is one of the candidates.

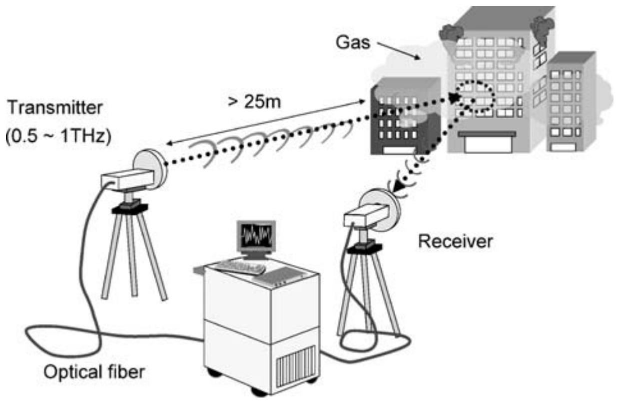

Fig. 15 Targeted application scene of the sub-THz standoff gas sensing system

4 CONCLUSION

We described MMW/THz-wave generation based on the optical heterodyning. Frequency-tunable optical frequency combs, high output power O-E converters, and optical filter/combiners 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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REFERENCES

[1] A. Hirata, M. Harada, T. Nagatsuma, **120-GHz Wireless Link using Photonic Techniques for Generation, Modulation, and Emission of Millimeter-wave Signals.** IEEE J. Lightwave Technology, vol. 21, no. 10, pp. 2145–2153, 2003.

[2] S. Takano, A. Ueda, T. Yamamoto, S. Asayama, Y. Sekimoto, T. Noguchi, M. Ishiguro, H. Takara, S. Kawanishi, H. Ito, A. Hirata, T. Nagatsuma, **The First Radioastronomical Observation with Photonic Local Oscillator.** Publ. Astron. Soc. Japan, vol. 55, pp. L53–L56, 2003.

[3] T. Nagatsuma, **Photonic Measurement Technologies for High-speed Electronics.** Meas. Sci. and Technol., vol. 13, no. 11, pp. 1655–1663, 2002.

[4] Z. F. Fan, N. Dagenais, **Optical Generation of a Megahertz-linewidth Microwave Signal Using Semiconductor Lasers and a Discriminator-aided Phase-locked Loop.** IEEE Trans. Microwave Theory and Tech., vol. 45, no. 8, pp. 1296–1300, 1997.

[5] A. Hirata, M. Harada, K. Sato, T. Nagatsuma. **Low-Cost Millimeter-Wave Photonic Techniques for Gigabit/s Wireless Link.** IEICE Trans. Electron., vol. E86-C, no.7, pp. 1123–1128, 2003.

[6] T. Kuri, K. Kitayama, K. Murashima, **Error-free DWDM Transmission of 60-GHz-band Fiber Radio Signals with Square-like Response Fiber Bragg Grating.** Tech. Dig. of Microwave Photonics 2001, pp. 69–72, Long Beach, 2001.

[7] D. Chen, H. R. Fetterman, A. Chen, W. H. Steier, L. R. Dalton, W. Wang, Y. Shi, **Demonstration of 110 GHz Electro-optic Polymer Modulators.** Appl. Phys. Lett., vol. 70, no. 25, pp. 3335–3337, 1997.

[8] K. Sato, **100 GHz Optical Pulse Generation Using Fabry-Perot Laser Under Continuous Wave Operation.** Electron. Lett., vol. 37, no. 12, pp. 763–764, 2001.

[9] T. Ohno, F. Nakajima, T. Furuta, H. Ito, **240 GHz Active Modelocked Laser Diode.** Electron. Lett., vol. 41, no. 19, pp. 1057–1059, 2005.

[10] T. Yamamoto, S. Kawanishi, **Generation of Low-noise Optical Frequency Comb and Optical Beat Signal Using Phase Modulator.** Tech. Dig. Japan-Korea Workshop on Microwave and Millimeter-Wave Photonics 2004, pp. 15–19, 2004.

[11] M. Fujiwara, M. Teshima, J. Kani, H. Suzuki, N. Takachio, K. Iwatsuki, **Optical Carrier Supply Module Using Flattened Optical Multicarrier Generation Based on Sinusoidal Amplitude and Phase Hybrid Modulation.** IEEE J. Lightwave Technology, vol. 21, no. 11, pp. 2705–2714, 2003.

[12] H.-J. Song, N. Shimizu, T. Nagatsuma, **Generation of Two-mode Optical Signals with Broadband Frequency Tunability and Low Spurious Signal Level.** Opt. Express, vol. 15, no. 22, pp. 14901–14906, 2007.

[13] A. Hirata, H. Togo, N. Shimizu, H. Takahashi, K. Okamoto, T. Nagatsuma, **Low-Phase Noise Photonic Millimeter-Wave Generator Using an AWG Integrated with a 3-dB Combiner.** IEICE Trans. Electron., vol. E88-C, no. 7, pp. 1458–1464, 2005.

[14] H. Ito, T. Furuta, F. Nakajima, K. Yoshino, T. Ishibashi, **Photonic Generation of Continuous THz Wave Using Uni-traveling-carrier Photodiode.** IEEE J. Lightwave Technology, vol. 23, no. 12, pp. 4016–4021, 2005.

[15] H. Ito, T. Nagatsuma, A. Hirata, T. Minotani, A. Sasaki, Y. Hirota, T. Ishibashi, **High-power Photonic Millimetre Wave Generation at 100 GHz Using Matching-circuit-integrated Uni-travelling-carrier Photodiodes.** IEE Proc. Optoelectron., vol. 150, no. 2, pp. 138–142, 2003.

[16] H. Ito, T. Furuta, Y. Muramoto, T. Ito, T. Ishibashi, **Photonic Millimetre- and Sub-millimetre-wave Generation Using J-band Rectangular-waveguide-output Uni-travelling-carrier Photodiode Module.** Electron. Lett., vol. 42, no. 24, pp. 1424–1425, 2006.

[17] F. Nakajima, T. Furuta, H. Ito, **High-power Continuous-terahertz-wave Generation Using Resonant--antenna-integrated Uni-travelling-carrier Photodiode.** Electron. Lett., vol. 40, no. 20, pp. 1297–1299, 2004.

[18] C. C. Renaud, M. Robertson, D. Rogers, R. Firth, P. J. Cannard, R. Moore, A. J. Seeds, **A High Responsivity, Broadband Waveguide Uni-travelling Carrier Photodiode.** Proc. SPIE 6194 (Photonics Europe 2006), Apr., 2006.

[19] K. J. Williams, D. A. Tulchinsky, J. C. Campbell, **High--Power Photodiodes.** Tech. Dig. Microwave Photonics, pp. 9–13, Oct. 2007.

[20] N. Shimizu, T. Nagatsuma, **Photodiode-integrated Microstrip Antenna Array for Subterahertz Radiation.** IEEE Photon. Technol. Lett., vol. 18, no. 6, pp. 743–745, 2006.

[21] H. Ito, T. Furuta, T. Kosugi, A. Hirata, H. Takahashi, Y. Muramoto, M. Tokumitsu, Y. Sato, T. Nagatsuma, T. Ishibashi, **Over-10-dBm Output Uni-traveling--carrier Photodiode Module Integrating a Power Amplifier for Wireless Transmissions in the 125--GHz Band.** IEICE Electronics Express, vol. 2, no. 16, pp. 446–450, 2005.

[22] H. Suzuki, M. Fujiwara, K. Iwatsuki, A. Hirata, T. Nagatsuma, **Photonic Millimetre-wave Generator Using Intensity and Phase Modulators for 10 Gbit/s Wireless Link.** Electron. Lett., vol. 41, no. 6, pp. 355–356, 2005.

[23] A. Hirata, T. Kosugi, H. Takahashi, R. Yamaguchi, F. Nakajima, T. Furuta, H. Ito, H. Sugahara, Y. Sato, T. Nagatsuma, **120-GHz-band Millimeter-wave Photonic Wireless Link for 10-Gb/s Data Transmission.** IEEE Trans. Microwave Theory Tech., vol. 54, no. 5, pp. 1937–1944, 2006.

[24] S. Kohjiro, Y. Uzawa, J. Inatani, T. Nagatsuma, H. Ito, Z. Wang, A. Shoji, **Quasi-optical Superconducting Heterodyne Receiver Using a Photonic Local Oscillator in the Submillimeter-wave Region.** Tech. Digest of Intern. Workshop on Terahertz Technology, 18B-6, Osaka, pp. 119–120, 2005.

[25] H. Ito, T. Furuta, S. Kodama, K. Yoshino, T. Nagatsuma, Z. Wang, **10-Gbit/s Operation of a Uni-travelling-carrier Photodiode Module at 2.6 K.** Electron. Lett., vol. 44, no. 2, pp. 149–150, 2008.

[26] H.-J. Song, N. Shimizu, T. Furuta, K. Suizu, H. Ito, T. Nagatsuma, **Broadband Frequency Tunable Photonic Sub-terahertz Wave Generation for Spectroscopic Applications.** Tech. Digest, 20th Annual Meeting of the IEEE Lasers and Electro-Optics Society, ThF2, pp. 733–734, 2007.

[27] ..., HITRAN homepage, **http://cfa-www.harvard.edu/hitran/welcometop.html**

Fotonički izvori milimetarskih i terahercnih valova i njihova primjena. U radu su opisani rezultati najnovijih istraživanja izvora milimetarskih i teraherc valova, zasnovanih na fotoničkim rješenjima, koji generiraju signale velike izlazne snage s niskim faznim šumom u širokom frekvencijskom području. Prikazana je tehnologija izrade osnovnih komponenata kao što su optički frekvencijski češljasti generator, fotonički valni krugovi za procesiranje signala, integrirani antenski moduli koji sadrže fotodiodu, kao i njihova primjena u mjernim sustavima visoke preciznosti i komunikacijskim sustavima.

Ključne riječi: milimetarski valovi, teraherc, fotonika, bežične komunikacije, spektroskopija

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