Terahertz Wave Applications Using Photonic Technologies

Ho-Jin Song[1], **Katsuhiro Ajito**[1], **Naofumi Shimizu**[1], **Naoya Kukutsu**[1], **and Tadao Nagatsuma**[2]

[1]Microsystem Integration Labs., NTT Corporation, 3-1 Morinosato-Wakamiya, Atsugi, Kanagawa 243-0198, Japan
E-mail: song.hojin@lab.ntt.co.jp

[2]Graduate School of Engineering Science, Osaka University, 1-3 Machikaneyama, Toyonaka, Osaka 560-8531, Japan,

Abstract

We present a potential of photonic technologies originally developed for fiber-optic communications for use in contemporary terahertz-wave applications and demonstrate several examples, including a high-precision time-continuous terahertz-wave signal and terahertz-wave band noise generators, sensing and imaging with CW and noise signals, and wireless communications. In addition, recent progress of uni-travelling photodiodes, key component of this work, is also presented.

1. Introduction

Terahertz (THz) waves, which lie in the frequency range of 0.1 ~ 10 THz, have long been investigated in a few limited fields, such as astronomy, because of a lack of devices for their generation and detection. Several technical breakthroughs made over the last couple of decades now allow us to radiate and detect terahertz waves more easily, which has triggered the search for new uses of THz waves in many fields, such as bio-science, security, and information and communications technology [1]. However, today's THz technologies still rely on complex and bulky equipment, which is not suitable for practical use, especially in outdoor sensing and wireless communications applications.

For compact and reliable THz-wave applications, we have been investigating the possibility of using photonic technologies, which were originally developed for fiber-optic communications and are therefore inexpensive, compact, and reliable. In this report, we will present our recent progress in THz-wave applications using photonic technologies, such as high-precision time-continuous THz-wave signal and THz-wave band noise generators, spectroscopy and imaging systems with the CW and noise signals, noise characterization of electronic devices, and wireless communications.

2. Photonic Generation of Terahertz-Waves

In conventional fiber-optic communications systems, photodiodes (PDs) are used to recover data carried on optical signal. However, because their electrical outputs are, in principle, determined by the autocorrelation function of the input optical field, they can also be used to generate arbitrary radio frequency signals. Figure 1 shows several examples of photonic generation of electrical signals. As shown in Fig. 1(a), when two monochromatic light waves at optical frequencies of ν_1 and ν_2 are input to a PD, electrical currents are induced at DC and radio frequency of $|\nu_1 - \nu_2|$. Therefore, the frequency, phase, and intensity of the output electrical signal can be tuned simply by tuning those of the input optical signals. As can be seen in Figs. 1(b) and (c), a band-limited arbitrary signal can also be generated. Because photonic technologies inherently exhibit very low loss and wide bandwidths, there is no additional loss for tuning optical signals even if one generates THz-waves. Unfortunately, because conventional p-i-n PDs do not provide enough conversion efficiency at THz-wave frequencies, the photonic generation of THz-waves illustrated in Fig. 1 has not been used in practical applications.

In 1997, a new sort of PD, called the uni-traveling-carrier photodiode (UTC-PD), was invented by NTT. The UTC-PD shows superior performance in high frequency applications because of its unique operation principle: the photoresponse of the UTC-PD is dominated by the electron transport in the whole structure, resulting in much shorter transit time and faster photoresponse [2]. In addition to the fast response, the UTC-PD can provide much higher power than the conventional p-i-n PD. This is because the UTC-PD provides higher output saturation current even in high-frequency operation due to the very weak space charge effect in the depletion layer (carrier collection layer), which also results from the high electron velocity in the depletion layer. In general, the output current of a UTC-PD does not saturate until the current density becomes an order of magnitude higher than that for the p-i-n PD. Since the invention of the UTC-PD in 1997, it has been optimized for higher operating frequencies and higher output power. The output power has reached almost 0.5 mW at 350 GHz and 2.3 μW at 1 THz.

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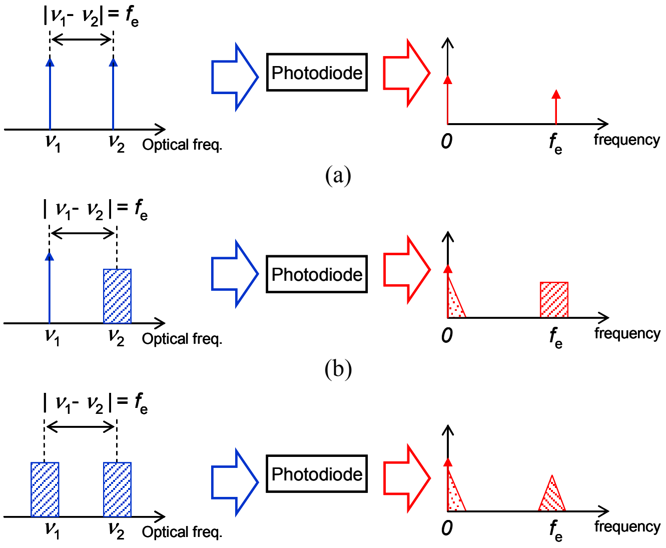


(a)

(b)

(c)

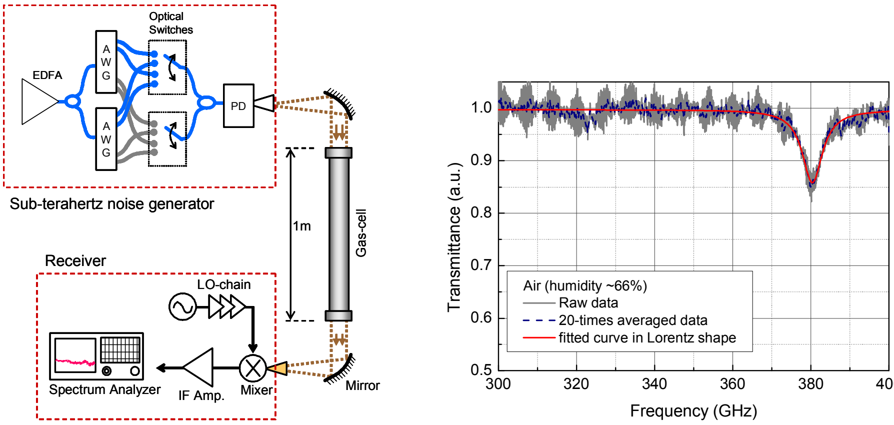
Figure 1. Examples of photonic generation of electrical signals using autocorrelation between optical input and electrical output of PDs.

3. THz-waves Applications Using Photonic Technologies

State-of-the-art UTC-PDs provide reasonable output power for practical applications at up to 1 THz, and various photonic components, such as optical filters, switches, non-linear fibers, and optical amplifiers, allow us to handle or generate THz-waves more easily and effectively. Using these photonic technologies, we have presented several types of signal generators based on the concepts in Fig. 1 and used them to several THz-wave applications, including spectroscopy, imaging, and communications operating below 1 THz. Though the output power from a UTC-PD at THz-wave frequencies is not too low, the signal-to-noise ratio (SNR) is still the most important parameter for practical THz-wave systems and therefore should be kept as high as possible. From this viewpoint, time-continuous signal, which has just a single frequency component or occupies a relatively narrow frequency band, is superior to a pulsed signal, whose energy is spread over a very large bandwidth so that the power spectral density is lower than that of the CW signal. Obviously, however, for spectroscopy or related applications, large frequency coverage, or tunability, over a wide frequency range is also essential.

For spectroscopy applications, we first developed a THz-wave signal generator consisting of a UTC-PD and other optical components, such as arrayed waveguide gratings (AWGs), optical switches, and an optical comb signal generator with non-linear fibers [3-4]. The optical comb generator exhibits excellent coherency between modes, enabling a very narrow linewidth of the output signal of around a few hertz at 300 GHz. The phase noise is expected to be as low as that of instrument-grade microwave signal sources. Another key feature is wide frequency tunability in the range of 100 GHz to 1 THz. Using the THz-wave signal generator, we have demonstrated a simple spectroscopy system for identifying a gas. We've also demonstrated THz-wave spectroscopy measurement with a band-limited time-continuous signal source, whose block diagram is shown in Fig. 2 [5]. The system in Fig. 2 is a kind of the Fourier transform spectroscopy (FTS) system, which usually uses a broadband CW source instead of a pulsed or monochromatic signal. In this work, the CW broadband signal was generated by converting amplified spontaneous emission (ASE) noise from an EDFA into the electrical domain with a UTC-PD. In order to improve the power density at THz-wave frequencies for a better SNR, the ASE noise was sliced with an AWG in the optical domain. Because of the autocorrelation property of the UTC-PD, the sliced optical noise allows us to generate a band-limited CW signal at THz-wave frequencies, as shown in Figs 1(b) and (c), which results in a great increase of power density in the desired band. In addition, a tunable optical filter, consisting of AWGs and optical switches, enables us to tune the occupying band of the band-limited CW source and therefore perform the spectroscopy measurement over a wide frequency band. Figure 2(b) shows the measured and simulated spectroscopy characteristics of air in a gas cell. Note that, in this experiment, the harmonic mixer used as a part of the receiver limited the measurable frequency span to 300 ~ 400 GHz.

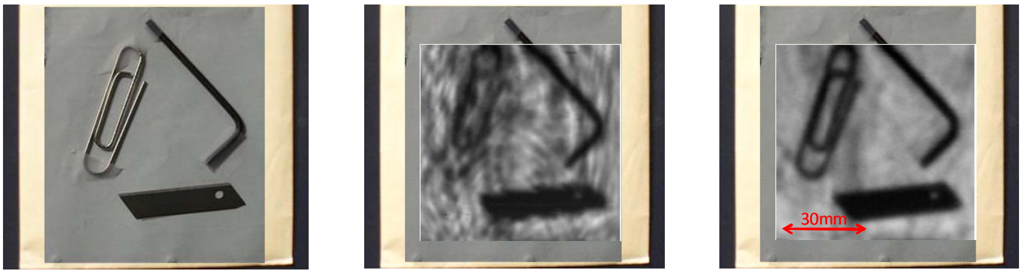
A unique feature of the band-limited CW signal used for the spectroscopy measurement is its incoherency, which results from the use of ASE noise for generation. This feature leads to interesting results in THz-wave imaging systems. Though time-continuous signals provide better power spectral density, resulting in a better SNR of the system, it is quite difficult to avoid interference with signals reflected at the surfaces of samples and at the antenna in the receiver and other components on or around the probe beam path. The interference causes some patterns in the resultant images and obscures objects or parts that need to be identified from the images. When highly coherent monochromatic signal is used, the problem will be more serious. On the other hand, incoherent signal can be said to be free from the interference. This idea was experimentally demonstrated [6]. Using highly coherent monochromatic signal and band-limited incoherent signal at 300 GHz, we took images of a blade, paper clip, and wrench concealed in envelop as shown in Fig. 3. As can be seen, it is quite difficult to distinguish the edges of objects, especially of the metal wire of the clip, and even in the spaces between objects, where one would not expect to see anything, wave-like patters are observed. However, as shown in Fig. 3(c), incoherent signal provides very clean images and allow us to identify all the objects clearly.



(a) (b)

Figure 2. (a) Experimental setup of THz spectroscopy system using a broadband CW signal and (b) the measured and simulated spectroscopy characteristics of air in a gas cell.

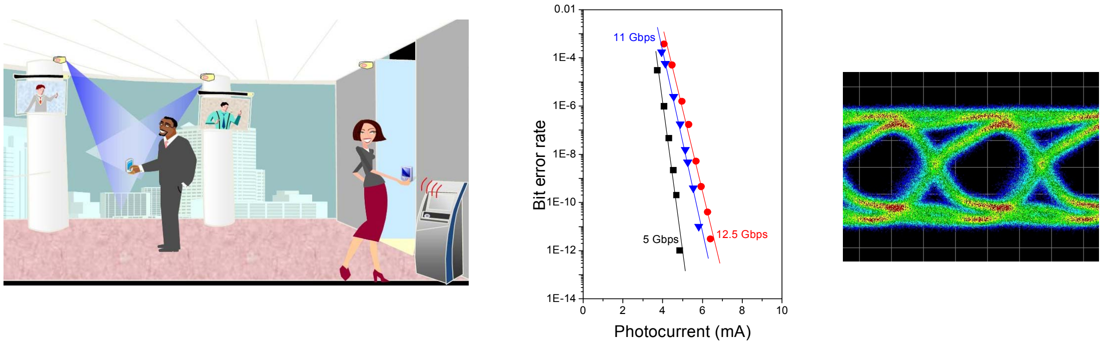
The incoherent signal source can be used as a noise source for characterizing the noise performance of devices, and circuits or an entire system operating in sub-THz- and THz-wave, where conventional solid-state noise source is not available [7]. This THz-wave noise source using photonic technique provides two significant advantages over a conventional solid-state noise source. First, we can produce a noise signal at up to 1 THz because of advances in the speed and output power of UTC-PDs. Second, by simply controlling the optical noise, we can control and predict the power level, occupied frequency band, and the spectral density of the generated noise pretty accurately. Thus, even if accurate calibration data for this photonic noise source is not available in the high-frequency band, noise figure measurement with reasonable error is possible with the predicted output noise power. Using the photonic noise source, we've measured the noise figures of commercial devices in the frequency ranges of 0.1 ~ 20 GHz and 293 ~ 357 GHz. The results showed excellent agreement with the conventional techniques. Measured noise figure differences between conventional and the proposed approach were less than 1 and 2 dB in microwave and THz-wave bands, respectively. Taking into account that we used the predicted noise power, not calibrated noise power, we can say that the errors are acceptable, especially in THz-wave bands. Of course, careful calibration of the noise power must improve the accuracy of the measurement as it does in conventional techniques.



(a) (b) (c)

Figure 3. (a) Sample for THz-wave imaging and resultant images using (b) highly coherent monochromatic CW signal at 300 GHz and (c) band-limited incoherent signal around 300 GHz

In addition to the sensing, imaging, and measurement applications, we have investigated THz waves for wireless communications. Because THz waves offer extremely wide bandwidths (more than 100 times wider than that for the conventional cellular system), data capacities of up to 100 Gbps are expected. When the dream of 100-Gbps wireless links is realized, you will be able download a Blu-ray movie (approximately 25 GB) to a memory card embedded in a smart phone in just a second. For this communications application, photonic technologies are advantageous over electronic approaches because of their inherent broadband nature. Photonic technologies can generate not only a high-frequency carrier signal but can also handle extremely broadband data signal. Recently, we performed a preliminary data transmission experiment, in which 12.5-Gbps data was carried on THz waves at 300 GHz and transmitted over a 50-cm-long distance with no error [8]. Measured bit error rates at 12.5 Gbps are shown in Figure. 4. In this work, the UTC-PD was also used as a transmitter and ASK data modulation was performed with a commercial optical intensity modulator. Taking the performance margins of the transmitter and receiver, such as the signal power and receiver bandwidth, into consideration, we believe that data can be transmitted even at up to 20 Gbps.



(a) (b) (c)

Figure 4. (a) Concept of THz-wave communications. (b) Measured bit error rates of the THz-wave wireless link at several data rates (c) and measured eye-diagram at 12.5 Gbps

4. Summary

Photonic technologies developed for telecommunications systems can now play an important role in practical terahertz-wave applications, such as spectroscopy, imaging, device characterization and wireless communications. UTC-PDs can produce a terahertz wave at up to 1 THz, and many other optical components for 1500-nm telecommunications systems allow us to implement a variety of functions easily with low cost.

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6. References

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