2版

様　式　Ｃ－１９、Ｆ－１９－１、Ｚ－１９　（共通）

科学研究費助成事業　　研究成果報告書

令和　４ 年　 ６ 月 ２２ 日現在

機関番号：１４４０１

研究種目：若手研究

研究期間：2019～2021

課題番号：１９Ｋ１４９９５

研究課題名（和文）Investigation of a practical sparse array terahertz imaging sysytem for real-time 3-dimensional imaging applications

研究課題名（英文）Investigation of a practical sparse array terahertz imaging sysytem for real-time 3-dimensional imaging applications

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交付決定額（研究期間全体）：（直接経費）　　3,300,000円

研究成果の概要（和文）：本研究は主な成果は二つがあります。１、初めて共鳴トンネルダイオード(RTD)の送信受信を同時に行い、単体で低コストなTHzイメージング素子を実現した。これを用いて、スパースアレーでのイメージングをシミュレーションで検証した。ですが、現段階RTD素子の発信周波数制御は完全にできていないため、RTDだけで高分解能の３次元イメージングはまだ困難である。２、そのため、本研究室既存の光技術に基ついて、高速なテラヘルツ波レーダを実現した。また、合成開口レーダ技術の導入によって、およそ２㎜の分解能で三次元イメージングを実現した。将来的には、当システムの低コスト化および更なる高速化を目指している。

研究成果の学術的意義や社会的意義
本研究の着目点は、現在発展しているテラヘルツ波技術をイメージング応用（セキュリティ、生産線の検査、リモートセンシングなど）に開きたいと思います。そのため、システムの低コストの目的で、本研究を展開しました。成果概要で紹介したように、高価な電子逓倍器の代わりに、共鳴トンネルダイオードや、光技術基ついた広帯域レーダシステムなどの手法を導入した。

研究成果の概要（英文）：The imaging techniques with RTD sensors and high-speed photonic radar were mainly investigated through this project. The single RTD transceiver was firstly introduced for THz imaging, which can greatly reduced the cost of THz imaging technique. However, due to the complicity of RTD device introduced in below and the limited cost, the research on realizing the RTD imaging array cannot be fully achieved and it is still undergoing with other project. Alternatively, the high-resolution 3D imaging was enabled with photonic radar technique together with the SAR imaging technique at 300-GHz band. Comparing with the previous system, the data acquisition speed of ~200GHz bandwidth (which can provide millimeter order imaging resolution) reduced to ~1ms, which is crucially important for achieving real-time 3D imaging. Besides, the sparse array technique and algorithm are evaluated with numerical simulation.

研究分野：リモートセンシング

キーワード：テラヘルツ波イメージング　フォトニクレーダ　共鳴トンネルダイオード　合成開口レーダ

様　式　C－１９、F－１９－１、Z－１９（共通）

１．研究開始当初の背景

The terahertz(THz) wave occupies a middle ground between microwaves and infrared light waves. And it is a relatively new technique for sensing purposes and not been practically applied yet due to its high cost. The main purpose of this research work is to develop a practical THz imaging system that combines the sparse array synthetic aperture radar(SAR) idea and resonant tunneling diode(RTD) for real-time 3-dimensional imaging with sub-millimeter resolution (which should operate at more than 300 GHz) and penetrating ability. It is expected to greatly reduce the complicity and high cost of the previous THz sensing systems through this research work, which makes it possible to bring the THz sensing techniques from the laboratory to real applications. This research is potential for popularizing the THz sensing applications to benefit variants of industrial applications in our daily life.

２．研究の目的

As it was summarized in the proposal of this research work, investigation on RTD sensor and real-time 3D imaging THz array with SAR technique are the main topics for this work. Ideally, we aims at combine the RTD sensor with SAR array for realizing a low-cost THz 3D imaging system.

The applicant gained experience on THz imaging techniques throughout this project, and I realized that the THz array technique for 3D imaging is far more difficult than that was expected based on the theoretical study, which are mainly caused by the hardware difficulties at the THz band. In this case, from the second year, the applicants focused on RTD sensors and high-speed photonic radar techniques (early stage of SAR array) due to the limited budget.

３．研究の方法

As it was mentioned in above, the imaging techniques with RTD sensors and high-speed photonic radar were mainly investigated through this project. Besides, the sparse array technique and algorithm are evaluated with numerical simulation. However, due to the complicity of RTD device introduced in below and the limited cost, the research on realizing the RTD imaging array cannot be fully achieved and it is still undergoing with other project.

1. Progresses on RTD imaging sensor:

The applicant proposed a novel way of using the RTD device as a THz transceiver based on its special oscillating property, which can greatly reduce the cost for both THz source and detector. The RTD operation is determined by its current–voltage (I–V) characteristics. In the negative differential conductance (NDC) region, due to the quantum tunneling effect, oscillation occurs if the magnitude of the NDC exceeds the positive conductance of the resonator circuit. Recently, an RTD oscillator exhibits extraordinary sensitivity as a coherent detector when it operates as a self-oscillating mixer. Hence, the RTD device is applied for homodyne wireless communication in the 300-GHz band without using an extra LO source. When the RTD is biased in the NDC region, the RTD can simultaneously provide LO signal while operating as a mixer. Moreover, a single RTD can be employed as both transmitter and receiver simultaneously for imaging applications. When the RTD operates in the NDR region, a small portion of the self-oscillating signal remains within the RTD device as the LO signal, while most of the self-oscillating signal is transmitted and reflected at the target, denoted as the reflected signal.

The reflected signal acquires a constant phase shift of $2\pi f\frac{2d}{c}$ during propagation, where d is the distance to the target, f is the oscillating frequency of the RTD, and c is the speed of light. If the high-frequency components of the detected signal are removed, the remaining detected voltage V_{LPF} can be expressed as (1), and a similar result can also be obtained by considering the mechanism of the external feedback property of the RTD

$$V_{LPF}(t) \propto Acos\left(\frac{4\pi fd}{c}\right) \qquad (1)$$

Equation (1) indicates that when the oscillation frequency is swept or the distance to the target is linearly varied, the detected signal becomes a cosine function that can provide accurate range information.

For confirmation, we performed ranging measurements to demonstrate the capability of the RTD transceiver sensor. The experimental setup of the imaging experiment employing the RTD transceiver module is shown in Fig. 1(a). The applied RTD is integrated within a hollow waveguide with a standard UG-387/UM flange and its concept is shown in Fig. 1(b). The output power was ~50 μW, and the oscillating frequency was ~278 GHz with a bias voltage of 0.71 V. The schematic diagram of the system is shown in Fig. 1(c). The transmitted signal was spatially modulated by an optical chopper with a frequency of 1 kHz and then transmitted to a mirror at a distance of 32.5 cm. The reflected signal was output via the bias tee and a lock-in amplifier, and an analog/digital (A/D) converter was used to digitalize the signals. A mirror reflector mounted on the moving stage was moved toward the RTD module, and the detected phase differences were evaluated. When the mirror reflector shifted 3.5 mm, and a clear periodical signal can be obtained, as shown in Fig. 1(d). The wavelength was 0.54 mm, which corresponds to the oscillation frequency of the RTD. Owing to the low phase noise of such a configuration, a resolution of less than 4 μm can be realized by detecting the voltage variation of the detected signal without using an extra amplifier. Furthermore, a 100-yen coin inside the envelope (the envelope was not included in Fig. 1(a) for recognizing the position target) was imaged at a distance of ~20 cm with the conventional quasi-optic setup shown in Fig. 1(a) and a 2D moving stage. The spatial resolution of ~1 mm was measured experimentally by using knife edge method. The text on the surface of the coin could be imaged clearly as it is shown in Fig. 1(e).

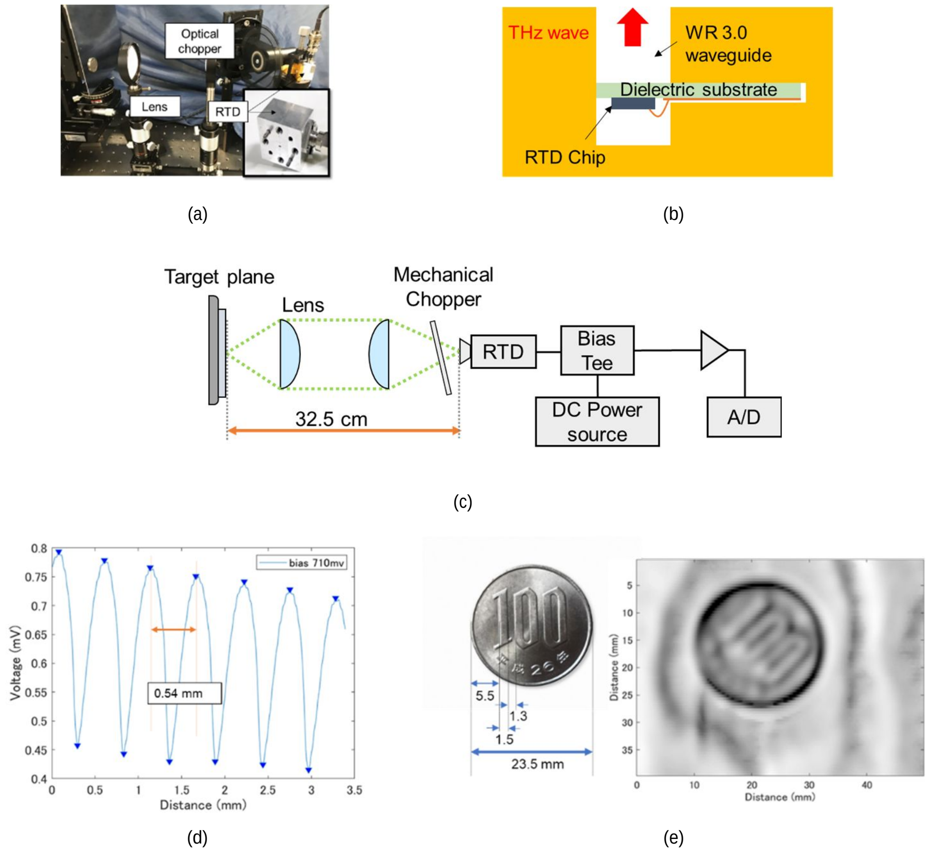


Fig. 1. Demonstration of a single RTD transceiver for imaging application; (a) Experiment setup; (b) concept of the waveguide integrated RTD (b) block diagram of experiment setup; (c) coherence signal obtained by moving the reflector; (d) imaging result of a 100-yen coin, ~ 1 mm spatial resolution can be obtained.

Beside of the 2D imaging application and detection of small displacements, the proposed RTD transceiver was further introduced for fast 2D imaging system with beam scanning. However, due to the complicity of RTD device the RTD oscillating frequency cannot be controlled ideally. The range resolution was low due to the limited bandwidth of ~300MHz. In this case, the RTD transceiver cannot fully replace the conventional multiplier for high-resolution 3D imaging application.

2. Progresses on high-speed 3D imaging with photonic-radar technique:

After a year of research on THz imaging technique, the applicant noticed that there is a huge gap between the mature microwave/millimeter-wave imaging technique and THz imaging technique. Many issues still need to be resolved before the trials on THz imaging array, including the limited output power and antenna aperture. Even for the 3D imaging with a single THz transceiver, the imaging speed becomes the bottleneck since frequency sweep across a wide frequency band is required for achieving high spatial resolution. And conventional electronic devices are extremely expensive for achieving a wide bandwidth of more than a hundred gigahertz. Alternatively, we turned to the photonic imaging technique using UTC-PD instead of an electronic multiplier for achieving fast data acquisition speed.

A frequency-modulated continuous-wave photonic radar system was presented in the 300-GHz band. The proposed system can obtain a 6-dB bandwidth of 120 GHz for achieving a range resolution of ~1.3 mm. To obtain the desired 3D information, the array imaging technique was introduced to the proposed system for achieving 3D imaging, which was not bounded by the fixed focal distance of a focus lens. It can provide a spatial resolution of ~1.5 mm within a 3D imaging range up to ~300 mm. Notably, the data acquisition speed was reduced from second-order to ~1ms, which make it possible for realizing the real-time 3D imaging in the future.

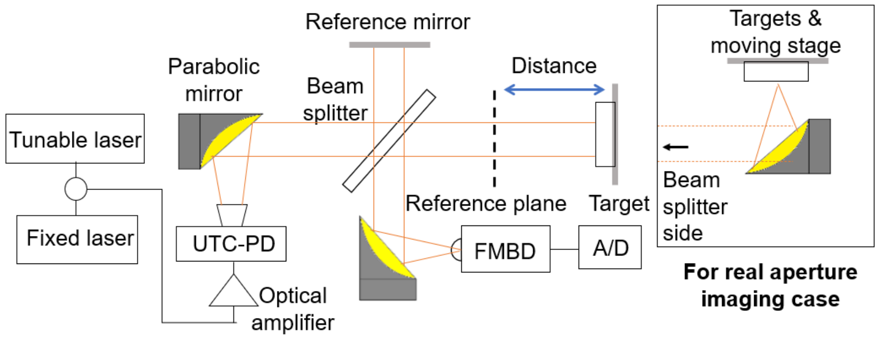


Fig. 2. Experimental setup of the THz FMCW system.

Fig. 2 shows a block diagram of the proposed system. A Michelson interferometer was applied using a beam splitter instead of a mixer, and the photomixing technique was used to generate a fast frequency-swept THz source. To obtain the wide-bandwidth chirp signal, a UTC-PD was applied for its ultra-wide frequency bandwidth and high output power. Notably, the applied UTC-PD was integrated with the metal waveguide of WR-2.8. Although it will limit the bandwidth of UTC-PD, such integration is crucially essential for future system integration with a pre-amplifier for enhancing the output power. The frequency of the transmitted THz beam was determined by the frequency difference between the two lasers. To generate the chirp signal, the frequency of one laser was fixed, whereas the frequency of the other laser was swept for a specific frequency range. In the experiment, the wavelength of the fixed wavelength laser was 1550.00 nm, and that of the tunable laser was swept from 1546.64 nm to 1548.40 nm. Hence, a chirp signal between 200 and 420 GHz can be generated. The tunable laser operated at a speed of 50 nm/s, which resulted in a data acquisition time of ~35 ms. The output power from the PD for a typical measurement was approximately 15 μW. The generated THz beam was emitted from a conventional horn antenna of 26 dB gain connected to the UTC-PD, and collimated by a parabolic mirror. The collimated beam was divided into two paths by a pellicle beam splitter: one to the reference mirror and the other to the object being tested. Finally, both reflected beams were received by a quasi-optic lens integrated FMBD module as a square-low detector with a superiority sensitivity of ~3 MV/W in the 300-GHz band.

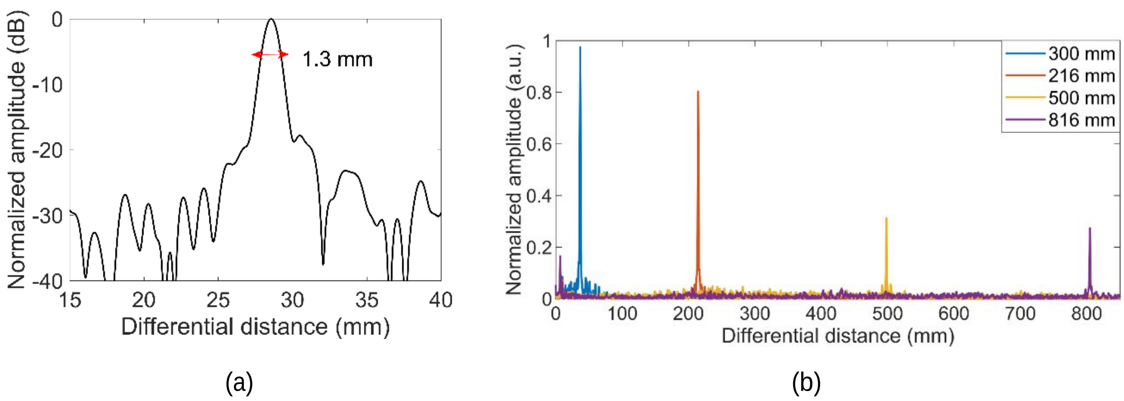
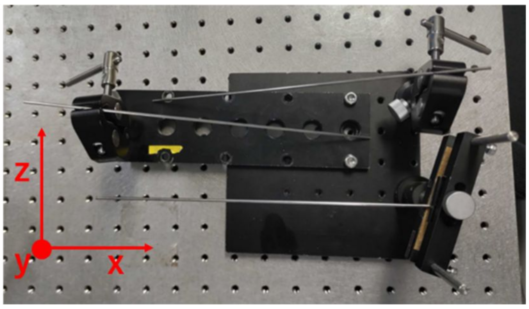


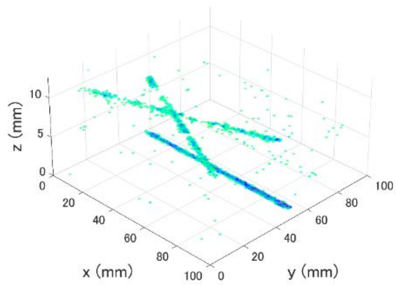
Fig. 3 Signal characteristics of the proposed system: (a) reflected time-domain signal from a mirror at a 28-mm distance; (b) sensing results with a metal reflector placed at different distances.

As a result of the broad RF frequency bandwidth and high sensitivity of FMBD, mixing of the 220-GHz bandwidth could be achieved. To evaluate the performance of the detected signal with the proposed system, the RF spectrum was measured by removing the reference mirror and introducing a 100-kHz modulation signal. The 6-dB bandwidth of ~120 GHz is obtained. The reduced bandwidth at both sides is mainly caused by the integrated metal waveguide of UTC-PD. Finally, the beat signal was obtained using (3), and the reflected pulse signal obtained after the FFT is shown in Fig. 3(a), which indicates a distance of 28 mm. The full-width at half-maximum (FWHM) of the reflected signal is ~1.3 mm, which is larger than the theoretical range resolution expressed with (4). It is caused by the metal waveguide as it is addressed in above. Notably, the pulse response obtained with FFT indicates that the distance between the transmitter and the reference mirror was excluded. For example, the distance between the UTC-PD and the reference mirror was ~160 mm, and the reflector mirror was positioned ~188 mm away from the UTC-PD along the propagation path of the THz beam. The collimated beam can detect the reflection at ~800 mm distance even with such small amount of output power. Based on the photonic technique, it was demonstrated that the high-resolution ranging data can be obtained with much faster than conventional electronic devices.

The configuration of the proposed photonic radar system for SAR imaging is shown in Fig. 2. The operating frequency ranged from 200 to 420 GHz, which provided a range resolution of ~1.3 mm, as shown in Fig. 3(a). Beam collimation is not required, whereas a beam splitter operates as a mixer for generating the beat signal. The transmitter and the receiver are installed at the same distance from the beam splitter, and such a zero-offset configuration is known as a monostatic system for the SAR system. In order to present the 3D imaging ability of the proposed system, three metal rods with a 2-mm diameter are distributed in different angles within a 100-mm range, as shown in Fig. 4(b). The distances between the three rods are 60 and 40 mm. The model was mounted on a two-axis moving stage with an imaging distance of ~50 mm for obtaining a scanning region of 100 mm × 100 mm, with a spatial interval of 0.5 mm. The time required for data acquisition was approximately 1 h, limited by the acquisition speed bottleneck. The 3D imaging results at different angles are shown in Fig. 4(b). It can be observed that the spatial resolution did not reduce with the increasing imaging distance and all the rods were imaged clearly. However, due to the increasing imaging distance, the rods at further distances become weak due to the un-collimated beam.



(a)



(b)

Fig. 4 SAR imaging result of the 3D distributed rods: (a) imaging model; (b) top-view of the 3D-imaging result.

4．研究成果

a. The RTD transceiver was proposed for imaging application for the first time. Comparing with the other THz imaging technique, the propsoed technique can greatly reduce the high cost of THz imaging devices. It was considered as the potential technique instead of the existing radar module for self-driving vehincles. However, currently the proposed technique was only avalidated with single frequency, which was not suitable for obtaining the 3D information. Theoritically, the RTD sensor is possible for genearing a frequency band of ~30 GHz, while obtaining such bandiwdith is still difficult due to the uncertainty of the mechanism. The applicant will continue the research work on extending the bandwidth of RTD transceiver.
b. The data acquisition speed of photonics-based 3D THz imaging system has been improved from second-order to less than one mili-second by introducing the FMCW technique at microwave band. Fuethermore, the SAR imaging approach has been firstly demonstrated with photonics-based THz system. It delighted the potential of introducing THz band for remote sensing applications.
Due to the limited budget the high speed 3D imaging system was only avalidated with the rented equipment. The imaging distance and the range resolution was reduced due to the non-linearity of the laser source. It can be expected that the new sweeping laser technique or equipment is required for further improving the current results.

５．主な発表論文等

〔雑誌論文〕　計1件（うち査読付論文　1件／うち国際共著　1件／うちオープンアクセス　1件）

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掲載論文のDOI（デジタルオブジェクト識別子） 10.1109/JLT.2021.3092779	査読の有無 有
オープンアクセス オープンアクセスとしている（また、その予定である）	国際共著 該当する

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〔図書〕　計0件

〔産業財産権〕

〔その他〕

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6．研究組織

	氏名 （ローマ字氏名） （研究者番号）	所属研究機関・部局・職 （機関番号）	備考

7．科研費を使用して開催した国際研究集会

〔国際研究集会〕　計0件

８．本研究に関連して実施した国際共同研究の実施状況

共同研究相手国	相手方研究機関