Demonstration of Optoelectronic-Phased-Array Driven THz-wave Power Combination and Beam Steering

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Abstract: We developed a THz-wave power-combination and beam-steering system driven by an optoelectronic phased array. The 300-GHz waves from an antenna-coupled InP/InGaAs UTC-PD array are combined with 16-dB gain and steered continuously over a 30° range.

1. Introduction

With the limited output power of photonic THz sources and the high atmospheric attenuation of the THz waves, beam combining and steering are critical requirements for increasing power-efficiency and reliable coverage as well as providing low-profile packaging. This is promising for broadband wireless communications as well as THz applications in radar imaging, time-domain spectroscopy, and security screening. For this reason, a THz beam has been studied to be dynamically steered from an arrayed photomixers by optically changing the phase of coupled lightwaves, without altering the radiating elements or other hardware [1]. In this technology, each optoelectronic element in a number of closely spaced array is fed and radiated separately. Then, through controlling each coupled optical phase and amplitude individually, a desired radiation pattern of constructive and destructive interference in the free space can be established.

Currently, noteworthy solutions for beam steering in the THz range have been demonstrated, including geometric optic lens-loaded antennas, electronic phased array antennas, leaky-wave antennas, mechanically deflected mirrors and reflectors, reconfigurable sub-wavelength metasurfaces, etc. Among them, the phased array antenna based on electronic phase shifters and amplifiers, is implemented to increase the signal strength in a specified direction without physical movement. However, the performance limitations of transistors make it impossible to drive solid-state electrons directly and reliably at higher frequencies. Metasurface-based THz wave manipulation, which produces anomalous phase changes in subwavelength-scale structures, is a powerful THz beam steering technique, but should provide additional breakthroughs to address high losses and low reconfigurability issues [2].

The aim of the present work is to demonstrate an optoelectronic THz beam steering technique. A monolithic InP substrate chip integrating 4×4 planar slot antennas and 8 arrayed InP/InGaAs uni-traveling-carrier photodiodes (UTC-PDs), as well as an 8-channel optical phased array (OPA) based on the thermo-optic effect, was developed for optoelectronic THz waves generation and phase adjustment, respectively. Moreover, 300-GHz beam combining and steering in a specified angle is demonstrated through optoelectronic aligned and gradient phase tuning. This demonstration will be able to achieve high power efficiency through increased directional gain and feeding gain in large-scale planar integration.

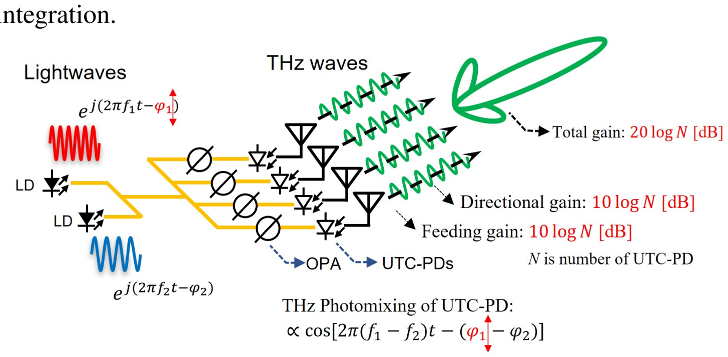

Fig. 1: Schematic of optoelectronic THz beam steering with large-scale planar photonic integration technology.

2. Fabrication of Optoelectronic Phased Array for THz Beam Combining and Steering

Currently, significantly boosting the absolute power of individual UTC-PD remains a tough problem since there is a trade-off between response bandwidth and output power. In this work, we are expected to enhance the relative radiated power or energy efficiency, instead of increasing the absolute power of individual UTC-PD with large-scale planar photonic integration technology, as shown in Fig. 1. Each element phase of the generated THz wave is indirectly controlled by the phase-shifting of an optical carrier wave. An electrical THz beam forming network would be implemented with optical devices, thus yielding the benefits of wide bandwidth, low power-consumption, high integration, etc. With this optoelectronic arraying technique, we can obtain quantitative feeding gain ($10\log N$, N is number of UTC-PD) as well as coherent direction gain ($10\log N$).

Fig. 2(a) shows the schematic of our designed 8-channel OPA chip based on planar lightwave circuits technique. It consists of eight silica-based waveguide optical phase shifters (OPSs) and multiple optical couplers (OCs). The thermo-optic effect is utilized in each silica waveguide OPS. This effect is exploited to change the material's refractive index, where the temperature is adjusted in proportion to the power consumption of the heater. In Fig. 2(b), we measured the phase-shifting efficiency of the OPS which exhibits 0.24 W for π phase shift of lightwave at 1550 nm band. Fig. 2(c) shows the layout of our fabricated eight arrayed InP/InGaAs UTC-PDs with integrated 4×4 one-sided directional slot antennas. Eight UTC-PDs were linearly placed at the edge of the InP substrate chip with 250 µm gap and 4×4 planar slot antennas were located at the other side with an element spacing of 500 µm. Two generated photocurrents were combined and then fed in parallel to 1×4 planar slot antennas by 50 Ω coplanar waveguides. In Fig. 2(d), we measured the relative THz power for one excited UTC-PD with photocurrent of 3 mA and a DC bias voltage of -1.5 V which exhibits a 3-dB down bandwidth of frequency dependency over 40-GHz at 300-GHz band, and the inset shows the simulated pattern of a 1×4 corporate-fed antenna array at 300-GHz.

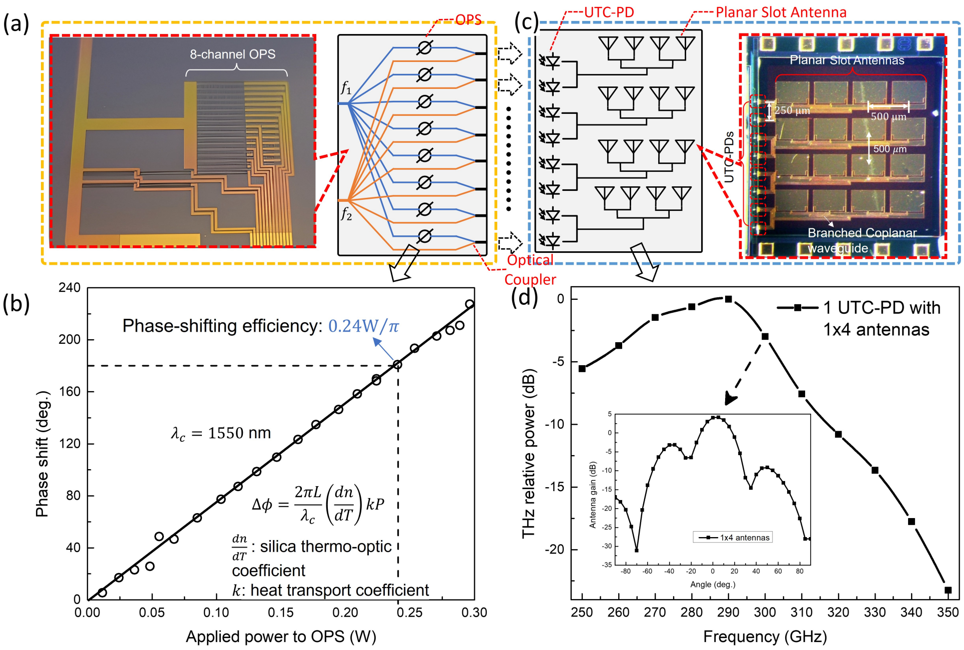

Fig. 2: (a) Schematic and photograph of 8-channel OPA. (b) The OPS phase shift characteristic at 1550 nm. (c)Layout and photo of 8 arrayed UTC-PDs with integrated 4×4 PSA array. (d) Frequency dependency of 1×4 antennas with an excited UTC-PD. The inset is simulated 300-GHz beam pattern.

3. Experiment and Result of 300-GHz Beam Combining and Steering

Fig. 3 shows the experimental setup for 300-GHz beam combining and steering. Two laser diodes (LDs) with different frequencies but identical linear polarization are employed to generate a 300-GHz-wave by heterodyne photomixing. Both lightwaves are amplified by two Erbium-doped optical fiber amplifiers (EDFAs). One of them is modulated with a sinusoidal waveform at 1-MHz by an electro-optic modulator (EOM), and is intended to extract THz wave with a known carrier wave from an extremely noisy environment through a lock-in amplifier (LIA). After the optical phase tuning of the OPA, eight pairs of optical beatnotes are coupled to the corresponding edge-illuminated UTC-PD through a micro-lens array (MLA) for THz waves generation. The spatial coupled 300-GHz wave is detected by an InGaAs Fermi-level managed barrier diode (FMB-D) [3] detector which is mounted on a rotating setup at a distance of 100-mm for radiation pattern measurement.

To achieve a coherently combined 300-GHz power, the phase shift is introduced by applying voltage to each channel of the OPA for compensating the phase difference due to the different fiber lengths. Fig. 4 shows the relative THz power distribution of 8 arrayed UTC-PDs compared with an individual UTC-PD activation at a

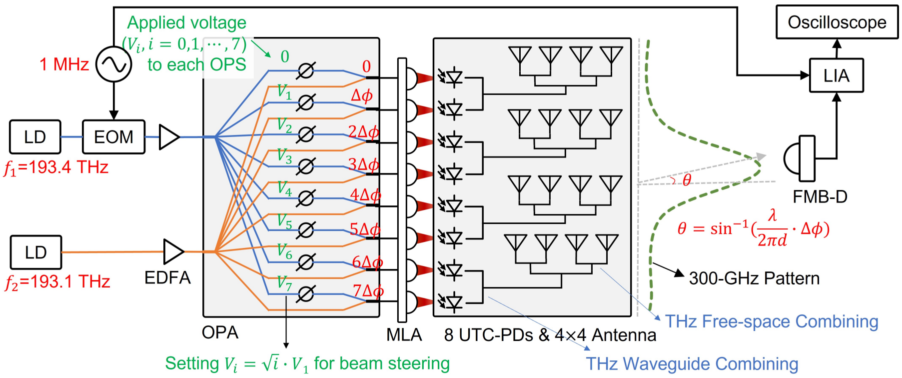

Fig. 3: Experiment setup for 300-GHz beam combining and steering.

photocurrent of 3 mA and a bias voltage of -1.5 V. The result indicates that a directional gain of 16 dB, including coplanar waveguide combining and free-space combing, has been obtained through optical phase alignment by OPA. Through optoelectronic phase-gradient shift by 8 channels of the OPA, a continuous scan angle of -15° to 15° of a 300-GHz beam can be achieved, as shown in Fig. 5. When there is no voltage applied to the OPA, the peak power is not in the broadside direction, since each channel suffers from uncertain optical path length. The results further demonstrate that the relative beam steering angle is not influenced by the initial beam pointing.

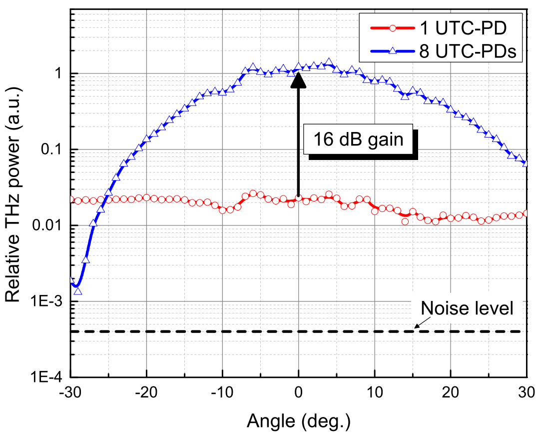

Fig. 4: Radiation pattern of 300-GHz beam combining by aligned optical phase.

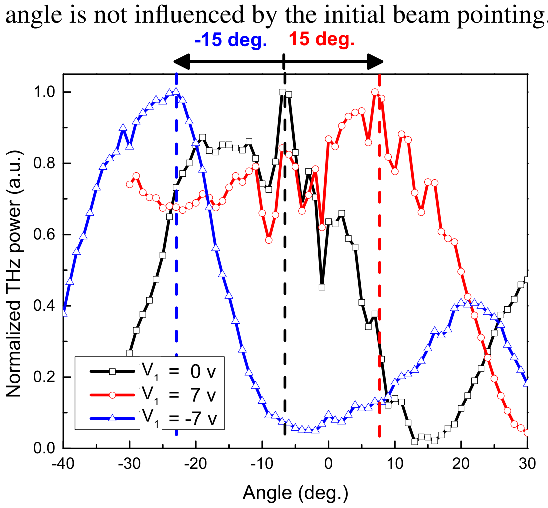

Fig. 5: Radiation pattern of 300-GHz beam steering by gradient optical phase. V_1 is the applied voltage to the OPS of channel 1 and the other applied voltages satisfy $V_i = \sqrt{i} \cdot V_1$ (i is the channel number).

4. Conclusion

In this work, we developed an 8-channel OPA based on the thermo-optic effect for phase tuning of THz waves and a monolithic InP substrate chip integrated with a 4×4 planar slot antenna and 8 UTC-PDs for generating 300-GHz waves. Compared to an individual UTC-PD excitation, the OPA enables 8-channel phase-aligned optical beatnotes to achieve a combined power of 300-GHz wave with a gain of 16-dB. With further optoelectronic gradient-phase control, it is experimentally verified that a 300-GHz beam is steered continuously over a range of 30°.

Acknowledgements

This work was supported by Kyushu University 2022 Research Start Program 202206, the commissioned research by National Institute of Information and Communications Technology (NICT) #02801, #00901, the MIC/SCOPE #195010002, and JSPS KAKENHI Grant Number: JP20H00253.

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