Ultra-Broadband Photonic THz Transceiver IC for High Range Resolution FMCW RADAR

Nabanita Sengupta* [(1)], Marcel Grzeslo [(1)], Shuya Iwamatsu[(1)], Jonas Tebart[(1)], Thomas Haddad[(1)] and Andreas Stöhr[(1)]
(1) Department of Optoelectronics, Universität Duisburg-Essen, Duisburg, Germany

Abstract

High range resolution radars are essential for a great variety of applications, including 3D imaging, target detection, spectroscopy, and defense [1]. In this paper, we report the first experimental validation of a real-time high range resolution frequency modulated continuous-wave (FMCW) THz radar that is based upon a photonic integrated circuit (PIC). The ultra-broadband THz transceiver PIC consists of a uni-traveling-carrier photodiode (UTC-PD) THz transmitter monolithically integrated with a Fermi level managed barrier diode (FMBD) THz receiver. In a first experiment, the FMCW PIC based THz radar is demonstrated of being capable of detecting objects up to distances *d* of 62.5 cm with a theoretically determined range resolution of 1.36 mm. This is achieved by using a THz transceiver PIC operating between 220–330 GHz. It should be noted that in the experiment the operational bandwidth is limited by the applied horn antenna and the probe. In principle, the THz transceiver PIC would be suitable for FMCW radar with a resolution below 1 mm.

1. Introduction

Real-time and high-resolution target detection and imaging is of great significance in civil and security applications such as capturing and tracking fast moving targets. It requires a FMCW radar to be operated at a high frequency and a wide bandwidth with real-time signal processing capability. This obligation creates great challenges to the state-of-the-art electronics. On the other hand, the accuracy of analog-to-digital converters (ADCs) in the receiver drops rapidly as the input bandwidth and sampling rate increase, which severely restricts the resolution as well as the processing speed [1].

Radar applications take advantage of the large attainable bandwidths in the THz frequency range, generating a range resolution in the sub–millimeter range. Conventionally, THz frequencies have been investigated with III-V compound semiconductor. Though these designs realize the highest performance in terms of noise figure and output power, the comprehensive system size and scalability for low-cost commercial deployment in a compact demonstrator is challenging. Currently, state-of-the-art FMCW radar transceivers in silicon-integrated technologies have been shown at 220–320 GHz in 65-nm CMOS [2] and at 460–520 GHz [3] in 90-nm SiGe BiCMOS. Again, an FMCW radar demonstrator was introduced at 0.45–0.49 THz in a monostatic configuration [4]. In best case, state-of-the-art electronic THz radars using THz CMOS integrated circuits (ICs) are reported to offer bandwidths up to 150 GHz with range resolutions as low as 1-3 mm [5]. However, further increasing the bandwidth of electronic components is challenging and thus generation, detection, and post-processing of high-frequency RF signals with the help of photonic radars have attracted a significant interest recently. This is because it utilizes the advantage of the high-frequency and broadband operation potential provided by photonically-driven components.

In this work, we report on an InP-based photonic integrated circuit (PIC) with a theoretical bandwidth of 400 GHz and demonstrate a FMCW THz radar incorporating optical waveform generation. As a result, radar detection with a very high range resolution of 0.375 mm can be realized. The center frequency and $f_{\max}$ of the technology is 400 GHz and 600 GHz, respectively.

2. Theory

The range resolution of a radar system is its ability to distinguish between targets that are adjacent to each other. The smallest measurable distance is determined by the bandwidth available within the system. Range resolution is given by equation 1

$$Res = \frac{c}{2\,B} \qquad (1).$$

Where c is velocity of light at free space and B is the bandwidth of the system [6]. Due to the large available bandwidth of 400 GHz, the expected range resolution is 0.375 mm. As radar identifies the objects by their difference in distance, objects that are positioned at the same bearing with respect to the radar are reliably kept apart by the radar via the distance detection.

3. Conceptual System Design

Figure 1 shows block diagram of THz FMCW radar system. The proposed system employs InP-based photonic THz radar ICs, where monolithically integrated UTC-PDs for transmitting and FMBDs for receiving are implemented together with a high pass filter [7].

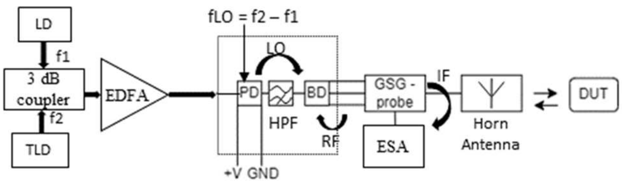

Figure 1. Block diagram of THz FMCW radar measurement setup. (LD: Laser diode, TLD: Tunable laser diode, EDFA: Erbium- doped fiber amplifier, PD: Photodiode, HPF: High pass filter, BD: Barrier diode, ESA: Electrical spectrum analyzer, DUT: Device-under-test)

For generating the FMCW THz signal, a highly stable wavelength-fixed laser (NKT Koheras BASIK X15) and an externally wavelength-tunable laser (Santec TSL-570) are used. The outputs of the lasers are coupled with the aid of a 3-dB coupler. The coupler output is amplified by Erbium- doped fiber amplifier (EDFA) before reaching the photodiode. The photodiode output extracted by ground-signal-ground (GSG) on-chip probe is transmitted through horn antenna. A high pass filter is integrated to segregate transmitter and receiver. After receiving the signal with the same antenna, the signal is mixed in FMBD and intermediate-frequency (IF) output can be seen in electrical spectrum analyzer (ESA). IF is a replica of a received signal but with frequency that is shifted usually below radio receiver frequency. It is created by mixing the carrier signal with a local oscillator signal in a process called heterodyning, deriving a signal at the difference or beat frequency.

4. Set up & Results

Figure 2 presents the setup for measurement. For detecting the object, one corner reflector is placed at about 0.42 m distance from the antenna head. This distance can be changed by moving the object on a rail. The separation between chip and the antenna head is around 0.2 m. The UTC-PD is DC biased and optical signal is transmitted via optical fiber coupling. A high pass filter prevents undesired biasing and irreversible damage in the FMBD from to the generated photocurrent in the UTC-PD. The GSG probe contacting the coplanar waveguide pad on in Figure 3 is for transmitting and receiving.

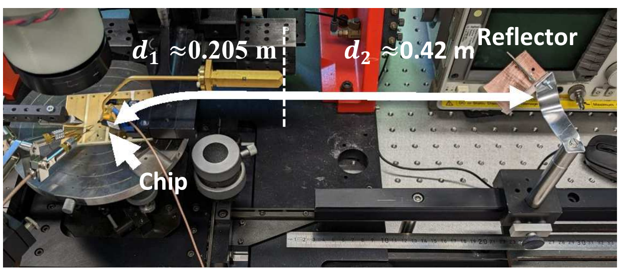

Figure 2. THz FMCW radar measurement set up (distance from chip to center of object is $d_1 + d_2 = 0.625$ m).

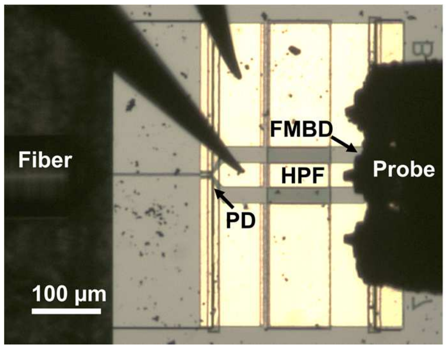

Figure 3. Closeup of the THz transceiver chip contacted by probes and coupled with a lensed fiber. (PD: Photodiode, HPF: High pass filter, FMBD: Fermi level managed barrier diode)

To demonstrate the broadband capabilities of the components, CPW integrated UTC-PDs and FMBDs have been characterized regarding their frequency behavior. Figure 4 shows the normalized response of the UTC-PD using heterodyne photomixing until 330 GHz in a) and the responsivity of the FMBD until 65 GHz using a network analyzer ZNA67 from Rohde & Schwarz in b). The dashed curves were calculated based on the first (RC time) and second order (RC time & transit time) roll-off. Furthermore, broadband capability for the transceiver segment of high-resolution RADAR has been demonstrated regarding both the UTC-PD response and conversion loss of the FMBD [7].

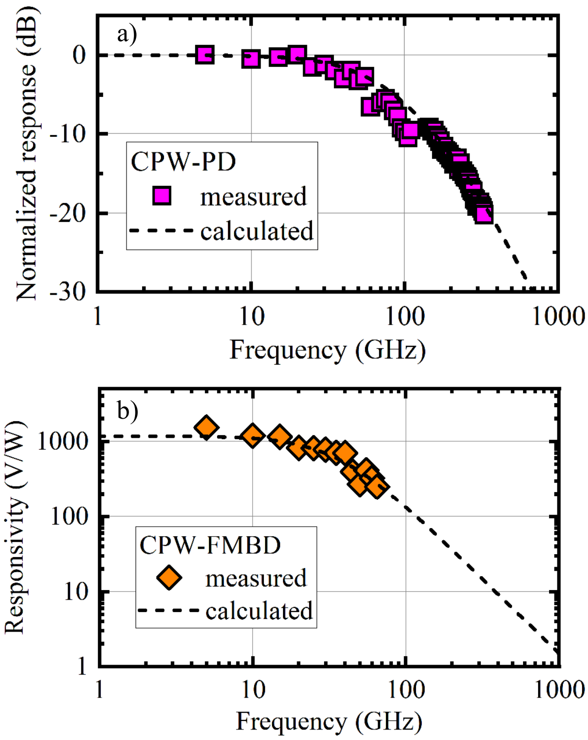

Figure 4. Measured normalized frequency response of the broadband CPW UTC-PD used as the LO source in a) and responsivity of the FMBD in b). The dashed curves correspond to the calculated roll-off respectively.

The distance estimation is based on the IF and can be calculated with equation 2:

$$f_{\mathrm{IF}} = \frac{2d \cdot \left(\frac{\mathrm{d}f}{\mathrm{d}t}\right)}{c} \quad (2).$$

For the FMCW a saw-tooth modulation of the tunable laser with slope 1.24 THz/s is applied, generating beat frequencies between 220-330 GHz. Antenna length and probe length are 11.5 cm and 9 cm respectively. The separation of the target from the end of antenna d_2 is around 42 cm. With a total distance d of 62.5 cm the IF is calculated to be around 4.3 kHz. As shown in Figure 5, the object is detected at several distances like 42.5 cm, 52.5 cm and 62.5 cm.

Figure 6 conveys the effect of bandwidth in order to precisely detect target which is also associated with range resolution. The target placed at 0.425 m is measured with both frequency ranges 220–330 GHz and 270–280 GHz. It can be seen that in case of wider bandwidth, the curve is more pronounced, which indicates an increased range resolution. A dominant limitation of the resolution is contributed to the frequency fluctuations of the tunable laser. Other factors are the frequency limitations of the UTC-PD and the conversion loss of the FMBD, which lead to high power losses towards THz frequencies.

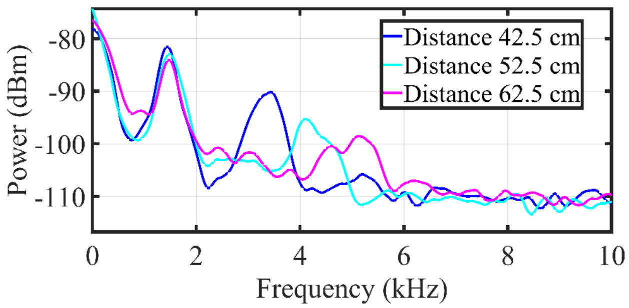

Figure 5. Measured signal mixed-down by FMBD receiver at IF of ~3.5 kHz (blue), ~4.3 Hz (turquoise), and ~5 kHz (pink) after object detection with the RADAR.

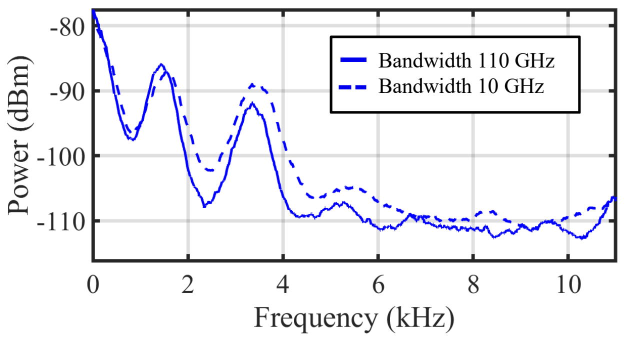

Figure 6. Target detection with different bandwidths. The continuous line represents the measurement over the full WR3.4. The dashed curve was measured with a bandwidth of 10 GHz centered at 275 GHz.

Mechanical instability of the fiber is also causing amplitude fluctuation affecting the measurement. Generally, the contribution of noise is quite high in the current setup, including 1/f noise, white noise and so on. To achieve better results, it is necessary to stabilize the measurement setup, which includes reducing the frequency noise contributions of the laser sources.

5. Conclusion & Outlook

The first THz FMCW radar using integrated THz mixer consisting of UTC-PD transmitter and FMBD receiver is reported. The measured results demonstrate high range resolution THz FMCW radar. Some problems are faced during measurements as they are stated earlier. We are still in the process of reducing noise and providing more stable equipment. For detecting range resolution, an additional target can be placed as close as the peaks are possible to be distinguished. This RADAR will have a great advantage in compact integrated circuits of future because of its size. In terms of cost also it has an upper hand because of its bulk production possibility.

The 2nd generation THz radar PICs will feature on-chip bow-tie antennas operating within frequency range 200 GHz–600 GHz and an antenna gain of about 7 dBi at the center frequency. The antennas will be integrated on chip, removing the otherwise required lossy and unfeasible chip-to-board or chip-to-package interface.

6. Acknowledgements

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