Photonic Integrated Terahertz System-on-Chip for Enhanced Precision Agrifood Applications

Chen Gong, Bruno Cimoli, Simon Rommel, and Idelfonso Tafur Monroy

Eindhoven University of Technology, Dept. of Electrical Engineering, Groene Loper 5, 5612 AE Eindhoven, Netherlands

Precision agriculture leverages digital technologies to monitor and optimize farming, aiming to increase output quality and quantity while using fewer resources (water, labor, fertilizers, energy, pesticides, etc.), thereby reduces costs and minimizes environmental impact. A key challenge is balancing cost and benefit, as farmers seek clear returns on investment but face budget constraints. Additionally, sensor technology should be easy to use and well-integrated into farming workflows. Cost-effective, reliable, and robust sensor systems are essential. Integrated photonics, particularly system-on-chip solutions, address these challenges. We are developing a photonic integrated continues wave terahertz system-on-chip for sensing and spectroscopy, offering coherent detection, broad bandwidth, and continuous tunability. This system will enhance smart sensor deployment on robots and drones, supporting precision agriculture and autonomous farming. Unlike traditional free-space terahertz systems, the on-chip approach prioritizes compactness and affordability, presenting unique technical challenges. This article outlines the system design and future development directions.

Introduction

Agriculture, a $3.7 trillion global industry, employs roughly 26.6% of the global workforce as of 2021, creating an immense demand for resources [1]. This heavy reliance is unsustainable; for example, agricultural irrigation accounts for 70% of water use worldwide, nitrogen deposition reduces biodiversity, and overusing fertilizers depletes phosphorus supplies [2]. To address these concerns, precision agriculture employs digital tools to optimize farming by enhancing output quality and quantity while reducing resources waste and environmental impact. However, the variable rate technology, which allows farmers to apply fertilizer, water, chemicals, and seed at different rates across a field, is adopted by fewer than 20% of farms [3]. The cost-benefit ratio is crucial for adoption, as smaller farms often operate within tight budgets, and user-friendly, integrated sensor technology remains essential for practical use. Meanwhile food processing 4.0 aims to cut production costs and resource consumption and improve quality and safety through smart sensors, robotics, and data. Low adoption rates of Industry 4.0 in food processing, between 20% and 40%, partly due to limited R&D investment, with food companies allocating only 1.4% of revenues on innovation versus 7~21% in big tech companies [4].

Small, portable smart devices containing multiple sensors for Agrifood applications will be a vibrant and growing market. Global agriculture sensing market is likely to expect a compound annual growth rate (CAGR) of 10.2 % between 2022 and 2030 to reach an estimated $43.37 billion [5]. Photonic integrated circuits (PICs) play a key role in this growth, offering versatile, low-cost technology ideal for optical sensing. Terahertz (THz) technology, operating between microwave and infrared bands, enables non-destructive, non-contact testing due to its unique properties: it can penetrate materials like microwaves, propagate directionally like light beam, and does not cause ionizing

radiation. Many biomolecules have energy transitions in the THz range, allowing THz spectroscopy to identify material components and analyze physical and chemical properties. This dual capability in chemical and physical sensing makes it highly valuable, though development remains challenging and costly due to the complexity of creating tunable sources and sensitive detectors. By using photons instead of electrons, PICs perform complex optical functions on a single chip, making them highly effective for real-time, remote and non-destructive composition monitoring. A recent series of optoelectronic systems operating in the C-band (1532 nm ~ 1568 nm) have enabled the miniaturization of continuous-wave THz systems through photonic integration techniques, realizing on-chip THz systems with high bandwidth and dynamic range. Furthermore, miniaturization and low power consumption make it well-suited to handheld. This article briefly describes how THz spectroscopy can be integrated on-chip and how its design can be optimized for further field applications in agriculture or the food industry.

Concept design of on-chip integrated THz spectroscopy system

Among the various methods for generating and detecting THz radiation, fiber-coupled optoelectronic solutions using InGaAs-based photomixers stand out because they enable bandwidths of several THz, high-frequency resolution, room-temperature operation, and utilize mature, off-the-shelf components from 1550nm telecommunication technology [6]. In sensing applications, pulsed THz technology with femtosecond (fs) laser pulses as optical excitation remains the most common. The radiated THz pulses are broadband and contain frequency components up to more than 10 THz. However, optoelectronic mixers can also convert the optical-beats of two continuous-wave (CW) lasers with a frequency difference in the THz region. This approach provides finer frequency resolution, allows for the use of more compact lasers and other photonic components that could potentially be integrated into handheld devices, and eliminates the need for the mechanical delay-lines required for most pulsed THz systems [7].

Since most components such as lasers and optical amplifiers are readily available in InP based PICs, CW THz systems operating in the C-band are very promising. In order to be able to integrate THz emitters and receivers in PICs, waveguide-integrated devices are required. Another advantage of waveguide integration is the possibility to improve the optical coupling of the optical excitation to the active element. In vertically illuminated photoconductive antennas (PCAs), the absorption of the incoming light is hampered by the metallic contact electrodes placed on top of the photoconductor as well as the reflection at the interface between air and the photoconductor. In waveguide-integrated PCAs, the evanescent coupling from a passive optical waveguide below the PCA to the absorber avoids these drawbacks.

The functional schematic of the photonic integrated THz spectroscopy system architecture considered in this work is shown in Fig. 1. We envision that the device has both THz signal transmission and detection capabilities with reflectance spectroscopy measurement mode. The optical control signal in the 1.5 μm range is generated by one fixed laser source and one swept laser source to generate tunable optical beats of THz frequency. The two laser beams are separated and coupled by a 3 dB coupler and then being interfaced and guided to the transmitter (Tx) and receiver (Rx) modules through

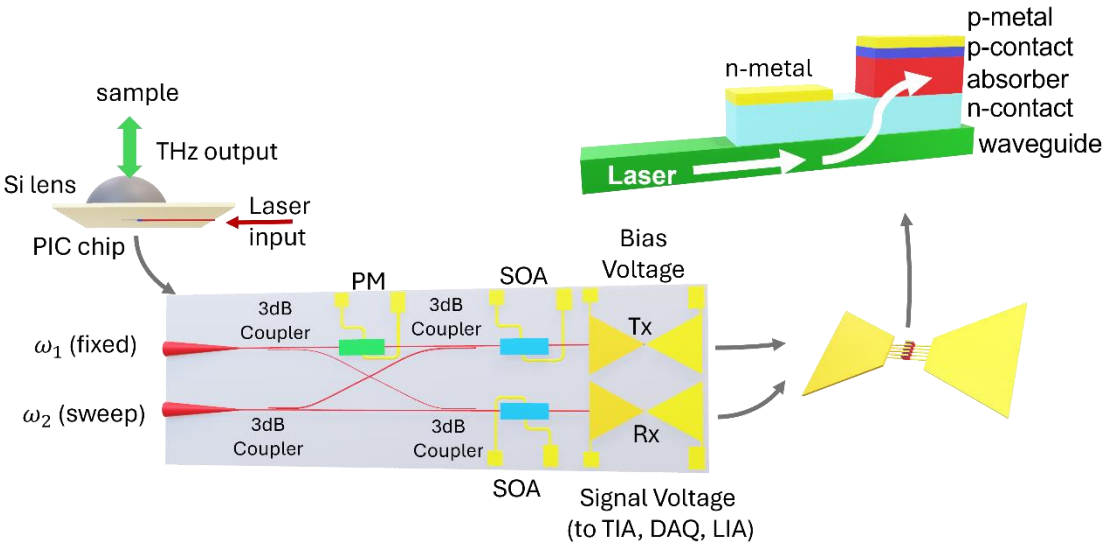

Fig. 1: Schematic of the THz spectroscopy system PIC.

optical waveguides. To enhance the power of the signal, semiconductor optical amplifiers (SOA) are used. The waveguide integrated PCA consists of a photoconductor with an iron-doped InGaAs absorber. The InGaAs absorber is grown on top of an InP-based waveguide stack. In this way, the laser beam is coupled to the edge of the chip and then guided to the PCA, where it evanescently couples into the photoconductor to generate free carriers. In the transmitter, the free carriers are accelerated by an external bias electric field to form a current to radiate THz waves. On the receiver side, the field of the incident THz wave accelerates the free carriers to form a current that is processed by subsequent transimpedance amplifier (TIA), data acquisition (DAQ), and lock-in amplifiers (LIA). Lock-in detection is achieved by phase modulation (PM) of the transmitter laser source. The feasibility of this concept is due to the recent major technological breakthroughs in on-chip waveguide integrated photoconductive THz emitters and detectors. In particular, the improvement of photoconductive materials in the past 10 years has increased the output power and signal-to-noise ratio by several orders of magnitude [8]. Light absorbing material in the emitter side requires high resistivity combined with high electron mobility to effectively accelerate the photogenerated carriers. The key parameter of the detector is an electron lifetime of less than 1 ps in order to achieve sensitive THz waveform sampling.

Transition metal (TM)-doped InGaAs grown by molecular beam epitaxy (MBE) is a promising material system that combines all the desired properties of THz PCAs: ultrashort electron lifetime, high mobility and resistivity, which is benefit by the transition metal acts as a deep acceptor in the middle of InGaAs and acts as a recombination center. Uniform doping in the MBE process is the only method to reproducibly grow TM-doped InGaAs suitable for ultrafast devices. THz emitters and detectors are grown from InGaAs:Fe by gas source molecular beam epitaxy at temperatures around 650 °C. Bandwidth up to 10 THz and a signal-to-noise ratio of 115 dB have been achieved with a commercial all-fiber coupled spectrometer [8][9]. For a CW beat source, bandwidths of 5.5 THz and 4 THz have also been achieved in vertical illumination and optical waveguide coupled systems [10]. These results demonstrate the potential of the material. Performance of the on-chip integrated detector is still not comparable to that of existing

commercial spectrometers. The performance of the on-chip system is still not comparable to that of existing commercial spectrometers with the waveguide-integrated PCA showing slightly lower amplitude at higher frequencies, mainly due to its improved noise level about 3.2 times compared to the top-illuminated PCA [10]. Further improved material and fabrication processes could reduce the dark current and thus the noise level.

Conclusion

In conclusion, progress in precision agriculture and food processing 4.0 requires innovation through technological means to achieve sustainable development goals. The development of PICs based THz sensors offers a promising solutions for real-time, remote, and non-destructive analysis. Innovations in optoelectronic and waveguide-integrated THz spectroscopy have advanced the feasibility of compact, portable devices that can analyze materials at a detailed level, essential for precision in resource usage. Although commercial spectrometers currently outperform on-chip systems, ongoing improvements in materials like TM-doped InGaAs and fabrication techniques could significantly enhance the efficiency of compact devices, offering a sustainable pathway forward for the Agrifood industries.

Acknowledgements

This project has received funding from the PhotonDelta National Growth Fund programme and the EU HORIZON-KDT-JU project HICONNECTS with grant number 101097296.

References

[1] FAO, “World Food and Agriculture – Statistical Yearbook,” Rome, 2023.
[2] K.O. Fuglie et al., “World agricultural production, resource use, and productivity, 1961–2020 (Report No. EIB-268),” U.S. Department of Agriculture, Economic Research Service, 2024.
[3] N. Peraly, “Flexibility, food safety and productivity: Three proven benefits of Industry 4.0 for the food and beverage industry – Tetra Pak,” Oct 9, 2019. https://www.foodnavigator-asia.com/Article/2019/10/09/Flexibility-food-safety-and-productivity-Three-proven-benefits-of-Industry-4.0-for-the-food-and-beverage-industry-Tetra-Pak
[4] A. Fleck, The World’s Biggest R&D Spenders, , April 8, 2022. https://www.statista.com/chart/27214/companies-that-spent-the-most-on-research-and-development-in-2020/
[5] A. Morchid et al., “Applications of internet of things (IoT) and sensors technology to increase food security and agricultural Sustainability: Benefits and challenges”, Ain Shams Engineering Journal, vol 15(3), 102509, 2024.
[6] H.J. Song and N. Lee, "Terahertz Communications: Challenges in the Next Decade," in IEEE Transactions on Terahertz Science and Technology, vol. 12, no. 2, pp. 105-117, March 2022.
[7] L. Liebermeister et al., “Optoelectronic frequency-modulated continuous-wave terahertz spectroscopy with 4 THz bandwidth,” Nat. Commun., vol 12, 1071, 2021.
[8] B. Globisch et al.,“Iron doped InGaAs: Competitive THz emitters and detectors fabricated from the same photoconductor” J. Appl. Phys. 121, 053102, 2017.
[9] R.B. Kohlhaas, et al., “Ultrabroadband terahertz time-domain spectroscopy using III-V photoconductive membranes on silicon,” Optics Express, vol. 30(13), pp. 23896-23908, 2022.
[10] M. Deumer et al., "Waveguide-integrated photoconductive THz receivers", Int. Conf. Infrared Millimeter Terahertz Waves IRMMW-THz, vol. 2022-Augus, pp. 2022-2023, 2022.