Photonic Integrated Circuits with an Optical Phased Array for THz Generating and Beamforming

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Abstract

Photonic integrated circuits (PICs) are crucial in terahertz (THz) technology due to their compact, integrated, efficient, and controllable design. They consolidate multiple active or passive components on a single chip, facilitating lightweight construction and high-speed communication, imaging, and sensing applications. The generic foundry platform using indium phosphide (InP) offers a universal integration platform for THz systems. Optical arrays for THz beamforming can precisely adjust the beam length and integrate both passive and active components, enhancing the THz beamforming performance. Indium phosphide-based photonic integrated circuits (PICs) offer an ideal solution for achieving precise, high-speed, compact, and integrated terahertz (THz) beamforming, addressing a broad spectrum of application needs. This study employs an InP-based multi-project wafer (MPW) platform for designing a 4-channel optical phase array (OPA) aimed at THz beamforming. The platform offers a range of validated optical components that can be utilized to construct intricate circuits, thereby enhancing the reliability of the system implementation. Moreover, the hybrid integration technology developed by Smart Photonics and Fraunhofer HHI allows for quick prototyping, short iteration cycles, and reduced development time and costs.

Keywords— Generic Foundry Platform, Multi-Project Wafer (MPW), Photonic Integrated Circuits (PICs), Terahertz (THz), Optoelectronic Beamforming, Beam Steering

1 Introduction

Photonic integrated circuits (PICs) are essential in advancing photonic terahertz (THz) technology due to their compact, integrated, efficient, and controllable features. By employing multi-project wafer (MPW) services, which enable the sharing of semiconductor fabrication among multiple projects, PICs become even more cost-effective and accessible for research and development. Through the integration of multiple active or passive elements onto a single InP chip within these MPW runs, PICs simplify the design and construction of THz systems, making them more lightweight. This integration not only enhances compactness but also leverages the MPW platform’s ability to prototype diverse designs, allowing PICs to excel in applications such as high-speed communication, imaging, and sensing. The use of indium phosphide (InP) in a generic foundry platform, which offers MPW services, has created a versatile and easily accessible integrated platform [1, 2, 3]. This platform employs the butt-joint active-passive interface technique, enabling seamless connections between different components while maintaining their individual performance. The incorporation of MPW approaches within the universal integration platform is an optimal choice for developing sophisticated THz systems, thereby promoting the commercialization and broad adoption of THz technology.

An optical phased array (OPA) that manipulates the optical path length or optical phase shift is intended for THz beamforming [4, 5]. It can effectively meet the varied beam adjustment requirements in different THz application scenarios [6, 7]. In contrast to THz phased arrays implemented using electronic devices, this method demonstrates a broader response bandwidth. Moreover, the optical array enables the incorporation of both passive and active elements, such as integration with active sources like lasers, thereby enhancing the performance and versatility of THz beamforming systems [8]. Through the utilization of the same photolithography techniques, passive components like THz transmission lines and antennas can be integrated onto a single chip simultaneously. In summary, InP-based photonic integrated circuits provide an optimal solution for achieving precise, high-speed, compact, and integrated THz beamforming, catering to a wide range of application requirements.
This study used cost-effective InP-based MPW technology to design a four-channel OPA chip specifically for THz beamforming. The MPW platform facilitates the concurrent fabrication of multiple design projects on a single wafer, providing an array of validated optical components that enhance the reliability of intricate PIC system assemblies. Using this platform, the study successfully incorporated a dual-wavelength light source essential for THz signal generation, along with the requisite optical modulators, onto the prototype chip. A comprehensive theoretical analysis paired with meticulous circuit design underpinned the development of the PICs, ensuring both the fidelity and functionality of the envisioned THz applications.

2 Concept and Schematic

The concept of optoelectronic THz generation and beamforming is illustrated in Figure 1. Two laser diodes (LD1 and LD2) generate continuous light waves (E₁ and E₂) with frequencies f₁ and f₂, and phases ϕ₁ and ϕ₂, respectively. The electric fields of these light waves are denoted by

\[
\begin{align*}
E_1(t) & = A_1 \exp (2\pi f_1 t + \phi_1) \\
E_2(t) & = A_2 \exp (2\pi f_2 t + \phi_2)
\end{align*}
\]  

(1)

where A₁ and A₂ denote the amplitudes of the electric field. One optical wave E₁ utilizes an optical modulator (OM) to transmit data streams, while the other optical wave is utilized to adjust the phase difference between channels. Each optical wave is evenly distributed among the N channels, and then a gradual optical phase shift \((k\Delta\phi, k = 0, 1, \ldots, N-1)\) is imposed on the optical wave E₂ in each channel. Consequently, each split optical wave E₁ is combined with the split optical wave E₂ to achieve a specified phase difference in each channel. Each channel incorporates a semiconductor optical amplifier (SOA) to modulate the intensity of THz optical beat linked to the corresponding UTC-PD. The resulting AC photocurrents from UTC-PDs can be expressed mathematically as

\[
i \propto r A_1 A_2 \cos[2\pi(f_1 - f_2)t + (\phi_1 - k\Delta\phi - \phi_2)]
\]

(2)

where r denotes the responsivity of UTC-PD [9, 10]. The phase of the produced THz wave is determined by the phase discrepancy of the interconnected optical wave, as specified by the equation.

Figure 1: The block diagram of schematic for optoelectronic THz generating and beamforming. PIC: Photonic Integrated Circuit; OPA: Optical Phased Array; LDs: Laser diodes; OM: Optical Modulator; OSs: Optical Splitters; OPSs: Optical Phase Shifters; OCs: Optical Couplers; SOAs: Semiconductor Optical Amplifiers; UTC-PDs: Uni-Traveling-Carrier Photodiodes.

The method suggested mainly utilizes optical couplers and waveguide intersections to build the OPA, enabling the combination and division of signals at varying wavelengths. Figure 2 illustrates a more efficient strategy that utilizes arrayed waveguide gratings (AWGs) to merge and separate dual-wavelength signals within the PIC. This approach not only streamlines the PIC design and decreases loss but also restricts the bandwidth for wavelength adjustability.
Assuming that the antenna positions are evenly distributed in a linear array, the array consists of $N$ horizontal elements with each element spaced at a uniform distance $d$. The radiation pattern of a complete array antenna is a composite of two components. First, the radiation pattern of each individual element in our array is determined by the element factor ($G_E$). Secondly, the impact of beamforming arrays can be applied through the array factor ($G_A$). The array factor $G_A$ is computed on the basis of the geometry of the array and the weights of the beam (both amplitude and phase). The normalized array factor of a uniformly spaced linear antenna array can be represented as

$$AF[\theta, \Delta \phi] = \frac{\sin(N \left( \frac{\pi d}{\lambda} \sin(\theta) - \frac{\Delta \phi}{2} \right))}{N \sin(\frac{\pi d}{\lambda} \sin(\theta) - \frac{\Delta \phi}{2})}$$  (3)

Hence, by modifying the phase of the radiation unit of the antenna array with a tailored OPA, it is possible to estimate the direction of the THz beam as.

$$\Delta \phi = \frac{2\pi}{\lambda} \cdot d \cdot \sin(\theta).$$  (4)

Here, $\lambda$ represents the wavelength of the emitted THz wave. The beam angle $\theta$ has previously been established as a function of the phase difference $\Delta \phi$ between the elements. Therefore, when the optical phase shift ($\Delta \phi$) of light waves is synchronized across adjacent channels, it allows the determination of a beam steering angle ($\theta$) for the THz wave.

### 3 Design and Fabrication

Figure 3 illustrates the block diagram of our PIC chip, conceptualized using Smart Photonics technology [11, 12, 13, 14]. The chip integrates four distributed Bragg reflector (DBR) lasers with three electrodes that interface with the gain section. The gain section is composed of a semiconductor optical amplifier (SOA) and two DBR grating sections. These sections function as reflective mirrors to establish standing waves within the laser cavity. The operation of the DBR laser is modulated by varying the current injected into these electrodes, while electrical isolation regions demarcate the gratings from the SOA. The PIC employs an electro-absorption modulator (EAM) to dynamically adjust the amplitude of the optical signal by altering the device’s bandgap energy. This is possible because of the Franz-Keldysh effect or the quantum-confined Stark effect, which allows for tuning of the absorption spectrum. For low-frequency or DC applications, the DC phase modulator (DCPM) independently manages the phase shift across each channel. This design integrates four DCPMs and multiple $1 \times 2$ multimode interference (MMI) couplers to cascade and manipulate signal pathways. Waveguide crossings facilitate signal routing and isolation. Additionally, the SOAs, with a semiconductor gain medium, amplify light signals and are structurally similar to laser diodes, but they differ in having an antireflective coating instead of an end reflector. This optimizes the gain when the photon energy marginally exceeds the bandgap energy.
The layout of our custom PIC chip based on Smart Photonics is illustrated in Figure 4. Smart Photonics utilizes their InP MPW technology to provide a wide range of building blocks for constructing intricate PICs for various applications. These building blocks consist of active components such as DBR lasers, SOAs, phase shifters, and EAMs, as well as passive components including waveguides, MMI devices, couplers, and splitters. With a standardized set of pre-validated components, Smart Photonics’ MPW InP platform enables quick prototyping and development, allowing designers to focus on system-level innovations rather than component-level fabrication details. The wafers used in the MPW are n-doped substrates, and the chip layout size for an arrayed dual-wavelength output with an OPA application is 4.6 × 4 mm.
Following the same design principles, we have utilized HHI’s MPW technology [3, 15, 16, 17] to seamlessly integrate optoelectronic technologies on a single chip for the generation and modulation of THz optical beats, as shown in Figure 5. In this setup, a distributed feedback (DFB) laser acts as a precise optical source for the THz frequencies. DFB lasers are preferred for their outstanding wavelength selectivity and extremely narrow linewidth, which is a result of their feedback structure spreading throughout the entire gain medium. On the other hand, DBR lasers, although also known for their high spectral purity, do not achieve the same narrow linewidths as DFB lasers because their feedback mechanism is limited to the ends of the laser. This design combines two DFB grating lasers with RF modulation and thermal tuning capabilities, connecting to E1700 waveguides. Since HHI’s technology does not include an inherent waveguide crossing design, a directional coupler is employed in this project to ensure signal isolation. By using a directional coupler, the lightwave can be split into two paths at a customizable ratio, depending on the length of the coupler.

Figure 5: The schematic of the designed PIC chip based on Fraunhofer HHI. DFB: Distributed Feedback Grating Laser; MMI Coupler: Multi Mode Interferometer Coupler; EAM: Electro-Absorption Modulator; SOA: Semiconductor Optical Amplifier; WT: Waveguide Transition; DC: Directional Coupler; TO-PS: Thermo-Optic Phase Shifter; SSC: Spot Size Converter.

Figure 6 presents the layout of our Fraunhofer HHI-based PIC chip designed with a size of 8 × 2 mm, specifically engineered for THz beamforming functions. The circuit incorporates two DDFB lasers, responsible for the emission of coherent optical signals. These signals are then dynamically modulated by an EAM which provides control over the light intensity necessary for THz applications. The modulated light is distributed through an MMI coupler device, which functions as an optical splitter, channeling the light into multiple paths for subsequent processing. Four thermo-optic phase shifters (TO-PSs) are deployed along these paths, which are critical for adjusting the optical phase and achieving directive beamforming. The shortest length of the TO-PS for the phase shift 2π can be determined using the following equation.

$$L_{\text{min}}^{\text{TO-PS}} = \frac{P_{2\pi}/(I_{\text{max}})^2}{R/L_{\text{heater}}} = \frac{164 \text{ mW}/(50 \text{ mA})^2}{185 \Omega/\text{mm}} = 354.595 \mu\text{m}$$

Amplification is performed by a series of SOAs, chosen for their ability to amplify optical signals within the PIC without converting them into electrical signals. This amplification process preserves the integrity and quality of the optical signal. The waveguides, labeled E600 and E1700, specify distinct passive waveguide geometries characterized by their etching depths and the composition of the surrounding medium. Finally, a 2 × 2 directional coupler in the circuit allows controlled coupling and decoupling of optical signals, which act as waveguide crossing. Typically, the spot size converter (SSC) is set at a 7° angle to reduce reflective losses; however, this arrangement was found to impact the coupling efficiency to the array of UTC-PDs in our setup. Therefore, the SSC in our design remains untilted to maximize coupling effectiveness.
4 Conclusion

This research takes advantage of the InP MPW platforms offered by SMART Photonics and Fraunhofer HHI to create two different chip configurations of PICs with an OPA for THz generation and beamforming. By utilizing a well-established modular approach, we achieved the integration of crucial active and passive photonic components. These configurations were produced on a single InP substrate, showcasing precise management of THz beam manipulation, which is essential for high-speed communication and cutting-edge sensing applications. The successful realization and verification of these configurations using the MPW service highlights the feasibility of such a cooperative and cost-effective strategy for swift prototyping in the field of advanced integrated photonics.

Acknowledgments

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References


