Passive THz Optoelectronic Beamforming Network

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Abstract

This study presents a passive terahertz (THz) optoelectronic beamforming network (OBFN), utilizing optical dispersion components to induce time delays or phase shifts in signals with varying frequency components. Two feasible schemes are compared and analyzed in terms of implementation difficulty. To validate the concept, feasibility experiments are designed and prototype circuits towards photonic integration are proposed. A comparative analysis of THz beamforming schemes was performed, indicating that the proposed OBFN is beneficial for various THz applications with high beam flexibility and energy efficiency.

1 Introduction

Beamforming is a technique used to enhance the performance of communication systems by controlling the directionality of transmitted or received signals. Its function lies in the deliberate adjustment of the phase and amplitude relationships between individual antenna elements in an array. This enables the system to precisely focus signals or transmit and receive them in specific directions. The significance of beamforming lies in its ability to improve the directional characteristics of signals, reducing signal propagation in non-target directions. This, in turn, enhances the reliability, interference resistance, and coverage range of wireless systems. Currently, the expanding applications of terahertz (THz) technology, including high-speed communication, medical imaging, and non-destructive testing, highlight the necessity of applying beamforming techniques to THz sources. In THz communication, this directional beamforming helps reduce signal propagation losses, thereby enhancing communication reliability and increasing the transmission distance. In medical imaging and non-destructive testing, beamforming can optimize the illumination and reception of THz waves, enabling more precise imaging and detection.

The beamforming network and antenna array are two key components that play distinct roles in beamforming technology. An antenna array is a collection composed of multiple antenna elements arranged in specific geometric shapes, such as a linear array or uniform matrix. The antenna array forms the physical basis for beamforming, allowing directional adjustment of signals by manipulating the phase and amplitude of each antenna element. The beamforming network is a circuit or system used to control the phase and amplitude of each antenna element in the antenna array, facilitating the formation and adjustment of the beam. Serving as the control system, the beamforming network ensures that each antenna element in the array works in a coordinated manner to achieve the desired beam direction. The collaborative interaction between the antenna array and the beamforming network is crucial for effective beamforming. While the antenna array provides a physical structure with multiple receiving or transmitting channels, the beamforming network ensures the coordinated operation of these channels to form and adjust the beam according to specific beamforming requirements for various applications. In summary, the antenna array offers a physical structure with multiple channels, and the beamforming network is responsible for orchestrating coordinated operations among these channels to meet the beamforming requirements of specific applications.

In THz beamforming research, as shown in Figure 1, various approaches utilizing diverse technologies have been investigated. Electronic beamforming in the THz domain typically employs electronic components such as phase shifters and amplifiers to modulate the phase and amplitude of signals in an array antenna [1, 2, 3, 4, 5, 6, 7]. However, this approach is constrained by the limited bandwidth of electronic components and higher power consumption. In contrast, optoelectronic beamforming leverages optical modulators and photomixers to manipulate THz signals, incorporating optical components to control phase and amplitude [8, 9, 10, 11]. It is potential for broader bandwidth and lower power consumption due to its optical properties. Metasurfaces are engineered structures with
sub-wavelength features that can control the phase, amplitude, and polarization of incident waves [12, 13, 14, 15, 16]. In THz beamforming, they serve as passive devices for wavefront shaping, offering advantages in compactness, light weight, and flexibility, albeit with frequency range limitations.

Figure 1: Summary and classification based on the position of THz beamforming network in optoelectronic THz wave generation systems.

In this paper, we introduce a novel passive OBFN concept targeted at the THz spectrum. We delve into a thorough analysis and discussion of the implementation methods and performance comparisons of this concept, aiming to provide insights into its efficacy and potential applications in THz wireless systems.

2 Method

In this section, the fundamental principle of this method and two feasible approaches will be first elucidated. Subsequently, we will delve into the specific implementation strategies for realizing this scheme through photonic integrated circuits.

2.1 Principle and Conceptual Schematic

In antenna array-based beamforming techniques, the crucial factor for flexible wavefront manipulation is the independent phase adjustment of each radiating element. Figure 2 highlights a passive OBFN unit as the pivotal component in our proposed system, exploiting dispersion-induced equivalent THz phase shifts. The phase shift in the THz signal output is governed by the frequency of the incoming lightwave. Thus, achieving controllable and deterministic equivalent THz phase shifts involves two approaches: employing an optical beat in multiple dispersive mediums with varying dispersion characteristics, or coupling optical beats of different bands but with identical frequency differences, into multiple dispersive mediums with uniform dispersion properties. These methods enable the attainment of a gradient in THz phase shifts, which is instrumental in directing the THz beam.

Figure 2: Concept of a passive THz OBFN unit by dispersion-induced phase shifting.
A straightforward method to control the wavefront of THz waves involves using multiple optical transmission media with varying dispersion coefficients, including dispersion-varied fibers. As depicted in Figure 3(a), the direction of the THz beam emitted from a uniform linear array antenna can be controlled by injecting an optical beat with a consistent frequency difference into mediums with a dispersion gradient, with beam steering achieved through switching the wavelength of the optical beat. However, designing photonic devices with precisely equal, quantifiable dispersion presents a significant challenge in practical implementation, particularly in extending to multi-channel applications. In a dispersive medium, the dispersion of an optical beat, and consequently the equivalent THz time delay and phase shift, is influenced by the light’s wavelength entering the medium. Thus, effectively employing multiple dispersive devices involves using multi-band optical beats as substitutes. In Figure 3(b), while the frequency differences of the optical beats are constant, their central frequencies vary, resulting in equivalent THz-level dispersion. Consequently, altering the relative wavelengths of these multi-band optical beats enables THz beam steering.

Figure 3: Gradient optical phase shift difference induced by dispersion. (a) multiple optical beats with one dispersive medium, (b) one optical beat with multiple dispersive mediums.

Figure 4 illustrates a feasible experiment for passive THz beam steering through laser wavelength switching, comprising three primary components: electro-optic frequency comb (EOFC) generation, a gradient-dispersion generation network, and THz beam generation. In Figure 5, the process begins with generating an EOFC by modulating a continuous-wave laser diode (CW-LD) using an optical phase modulator (OPM), which is driven by a radiofrequency (RF) sinusoidal signal. This modulation results in the EOFC expanding around the CW-LD’s laser frequency, with comb spacing determined by the external RF source. Subsequently, a passive OBFN is employed to impart gradient dispersion to the optical beats among the optical comb lines. This is achieved by continuously tuning the wavelength of the CW-LD, thereby uniformly adjusting the dispersions of the optical beats. A programmable optical filter (POF) is utilized to facilitate this gradient dispersion among the comb lines [17]. Finally, pairs of comb lines having identical spacings and differing in THz frequency are coupled to uni-traveling-carrier photodiodes (UTC-PDs) to generate THz waves through photomixing. In this experiment, switching the laser wavelength will alter the initial phase of the THz, however, this will not affect the direction of the beam as the relative phase between channels remains constant. The frequency lines of the OFC exhibit excellent coherence, but special attention is required on the phase differences of selectively filtered optical beat signals [18, 19].
Figure 4: Experiment setup configuration for the proof-of-concept of the proposal. (CW-LD: continuous-wave laser diode, OPM: optical phase modulator, PAA: photonic antenna array.)

Figure 5: Operation flow of the proposed passive THz OBFN for beam steering.

2.2 Toward Photonic Integration

The photonics THz source offers high integration capacity, allowing for the fabrication of large-scale monolithic optoelectronic integrated circuits (OEICs), which incorporate both photonic components (such as lasers, modulators, UTC-PDs, etc.) and electronic components (including planar high-frequency transmission lines, antennas, etc.). Integration of the OEICs with the proposed passive THz OBFN not only expands the modulation bandwidth and enhances beam manipulation flexibility but also provides benefits of compactness and energy efficiency. In Figure 6(a), one feasible approach
is based on arrayed waveguide gratings (AWGs) and multiple optical waveguides with gradient optical path lengths (OPLs). The AWG functions as a wavelength demultiplexer for the OFC, where each optical beat with the same frequency difference is coupled into optical waveguides with varying OPL. Consequently, each optical beat with gradient dispersion is introduced into UTC-PDs to generate THz waves. This approach is relatively easy to implement, but its performance is constrained by the wavelength spacing between channels in the AWG. In Figure 6(b), an alternative feasible approach involves the use of AWG, chirped Bragg gratings (CBGs), and optical circulators (CIRs). Unlike the previous method, the frequency-dependent optical dispersion is achieved through CBG rather than optical waveguides. The advantage of this approach is the reduced dependency on AWG, allowing for a more compact photonic integrated circuit implementation. However, it demands a higher level of integration complexity in the devices.

Figure 6: Implementation of a passive THz OBFN utilizing photonic integrated circuits.

3 Discussion

In this study, wavelength switching is employed to maintain a constant optical beat frequency difference, rather than a constant wavelength difference. Within a specific wavelength region, the center wavelength can correspond to the center frequency. While this passive OBFN approach does not explicitly address channel amplitude adjustment, a feasible solution involves using wave interference to alter the excitation amplitude of array elements [20]. However, this method may result in a reduced number of available channels. In addition, due to the nonlinear dispersion characteristics of general optical devices, further research is needed to understand how to evaluate, calculate, and implement the appropriate dispersion values for achieving the desired THz phase shift.

The efficacy of various THz beamforming techniques is demonstrated in Figure 7, focusing on flexibility and power consumption. THz lenses or reflectors ([21], including mechanical rotation, quasi-optical lenses [22, 23], Luneburg lenses [24, 25, 26, 27], Fresnel zone plates [28], and reflectors [29, 30, 31]) offer simplicity but are generally large and lack flexibility. THz dispersive radiators, encompassing leaky-wave antennas [32, 33, 34, 35] and slotted waveguide antennas, feature frequency tunability and low power consumption. THz metasurfaces, while highly flexible, currently face challenges with high losses, leading to considerable cumulative energy consumption across units response control [12, 13, 14, 15, 16]. In contrast, optoelectronic phased array methods [8, 9, 10, 11] typically offer wider bandwidth, greater flexibility, and lower power consumption than conventional electronic phased array approaches [1, 2, 3, 4, 5, 6, 7]. The proposed passive THz OBFN in this study significantly reduces power consumption while maintaining high flexibility.
4 Conclusion

This study presents a passive THz OBFN utilizing optical dispersion components to create time delays and phase shifts in signals of varying frequencies. We explore and evaluate two potential configurations in terms of their implementation complexity. To corroborate this concept, we conducted experiments and proposed prototype circuits for photonic integration. A comparative analysis of THz beamforming methods showed that our proposed OBFN is beneficial for a range of THz applications, offering both high flexibility in beam manipulation and significant energy efficiency.

Acknowledgments

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References


