Photonic-based beamforming system for sub-THz wireless communications

Photonic-Based Beamforming System for Sub-THz Wireless Communications

Alvaro Morales[#1], Serguei Smirnov[*], Dmitri V. Lioubtchenko[*], Joachim Oberhammer[*], Chigo Okonkwo[#], Idelfonso Tafur Monroy[#]

[#]Inst. for Photonic Integration, Eindhoven University of Technology, Eindhoven, the Netherlands
[*]Dept. of Micro and Nanosystems, KTH Royal Institute of Technology, Stockholm, Sweden
[1]a.morales.vicente@tue.nl

***Abstract*— This work presents a sub-THz transmitter scheme for wireless communications with beam steering capabilities based on photonics means. A true time delay 1x4 beamforming photonic chip is designed in Si_3N_4 technology to continuously tune the progressive time delay between consecutive antenna elements. Simulation results show a progressive delay up to 15 ps with a bandwidth of 1.3 GHz, enabling broadband operation at frequencies above 75 GHz. The sub-THz signals are generated on photoconductive antennas on chip by photonic heterodyning. The design of a dielectric rod antenna array is also presented to efficiently radiate the generated wave.**

***Keywords*— Antenna arrays, microwave photonics, photonic integrated circuits, millimeter wave communication.**

I. Introduction

The continuous increase in bandwidth demands of new wireless communication standards requires new frequency allocations in the millimeter wave and sub-terahertz (sub-THz) range [1]. However, signals at this region of the electromagnetic spectrum suffer from higher attenuation due to increasing free space path loss, atmospheric absorption and diffraction, among other factors [2]. High-gain directive antenna arrays with beam steering capabilities are used to compensate the propagation losses. In order to fully exploit the available spectral resources, all the components in the transceiver chain must ensure the broadband operation of the overall system. One of the major drawbacks of conventional electronics components (e.g. phase shifters) is that they are bandwidth limited, producing distortion in the beam pointing when transmitting broadband signals [3]. Purely electronic approaches are therefore not well suited for sub-THz wireless communications.

Alternatively, optical means offer several advantages when setting up the phase configuration of a phased antenna array (PAA). The low loss, broadband nature and beam-squint immunity of optical true time delay (TTD) beamforming makes this technique particularly suitable for sub-THz wireless communications [3], [4]. Additionally, photonic integration provides extra benefits like small size, lightweight and the fine tuning capabilities. A wide range of integrated microwave photonic functionalities, including optical beamforming, have already been demonstrated in different technologies, such as silicon, indium phosphide and silicon nitride [5]. The development of a full system, based on optical TTD beamforming on chip integrated with an antenna array, is still an open issue to be addressed.

The optical time delay configuration can be directly translated into the electrical domain by photonic heterodyning [4]. The so-called photomixing process is defined as the mixing of two optical sources with a frequency difference equal to the intended sub-THz wave on appropriate semiconductor material [6]. This is one of the most commonly used methods for sub-THz and THz generation and it is fully compatible with the aforementioned optical beamforming technique. A printed antenna can be directly connected to the photomixer electrodes to radiate the wave into the substrate.

The main limitation of this approach is the conversion efficiency, leading to low radiation power compared to electronic approaches [6]. An antenna array can partially sort out this problem by increasing the number of radiating elements. A dielectric structure must be designed to efficiently radiate the generated wave into the air, avoiding the reflections produced in the interface between chip substrate and air. The traditional solution to this problem is to use a hyper-hemispherical lens with similar permittivity, typically in silicon. However, due to its shape, the lenses are expensive, require custom fabrication, and are difficult to integrate with traditional electronic and photonic processes. This solution is also not suitable for an antenna array because of its big size that prevents the antenna elements from being located close together. Instead, rectangular dielectric rod waveguides (DRWs) can be used to guide and radiate the THz signal from the photomixers into the free space [7]. DRWs can be mass-produced in a planar configuration with standard micromachining techniques, enabling a low-cost alternative

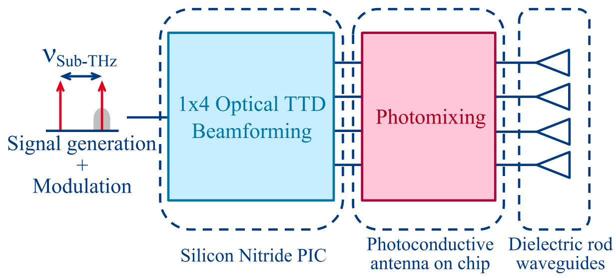

Fig. 1. Proposed system scheme to implement a sub-THz transmitter with beamforming capabilities, composed of three blocks: beamforming photonic integrated chip, photoconductive antennas and dielectric rod waveguide array.

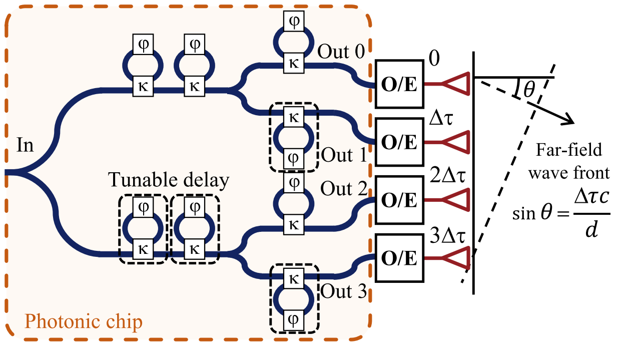

Fig. 2. Four-element linear PAA with optical TTD beamforming implemented by a photonic integrated chip based on a micro ring resonator tree structure.

to lenses. Moreover, their small dimensions allow to design high-density antenna arrays, while optimizing the footprint and radiation pattern.

Figure 1 shows the three building blocks of the proposed system. The spectrum of the optical input is composed of two optical carriers, one of them transporting the modulation. This signal feeds a silicon nitride photonic integrated chip (PIC) with a ring resonator-based tree structure. The tree configuration equally splits the signal into four symmetric paths to the four outputs, each of them containing ring resonator structures that modify the group delay of the optical signals. Consequently, the targeted TTD configuration of the sub-THz signals emerges after photomixing. The domain conversion is done by photoconductive antennas on chip which are glued to an array of DRWs. These components are explained in further detail in the following sections.

II. Optical Beamforming Chip

The PIC technology used in this work is TriPleX and consists of two layers of Si_3N_4 with a core of SiO_2 [8]. The platform was selected for the low loss at telecom wavelengths ($\leq$ 0.5 dB/cm) and high modal birefringence.

The 1x4 optical tree beamforming network on chip is depicted in Fig. 2. The basic element of this architecture is the optical ring resonator (ORR). An ORR is formed by two optical waveguides located close together: a straight one and a circular one (i.e. ring). A fraction of the light travelling through the straight waveguide couples to the ring, and after propagating around the circular structure, it couples back to the straight waveguide. As a result, a resonant behavior is produced at specific wavelengths. At these resonance points, a minimum in the transfer function and a maximum in the group delay appear. The group delay is defined by the amount of light which is coupled to the ring (described by the coefficient κ) and the wavelength resonance can be fixed by controlling the phase of the wave coupled back after the ring (described by coefficient φ). Both κ and φ can be tuned by using thermo-optic modulators in order to set the proper delay configuration at the desired wavelength [4].

The input wave is split into four symmetric paths following a tree arrangement. In the route between the input and each of the outputs the optical signal goes through three ORRs. The configuration of some of these rings is fixed to the minimum group delay for symmetry purposes and others are tunable, providing an additional group delay of Δτ. Therefore, the tunable ORRs are arranged in such a way that a progressive delay configuration is achieved at the output ports, with a delay difference between consecutive outputs of Δτ, as it can be seen in Fig. 2.

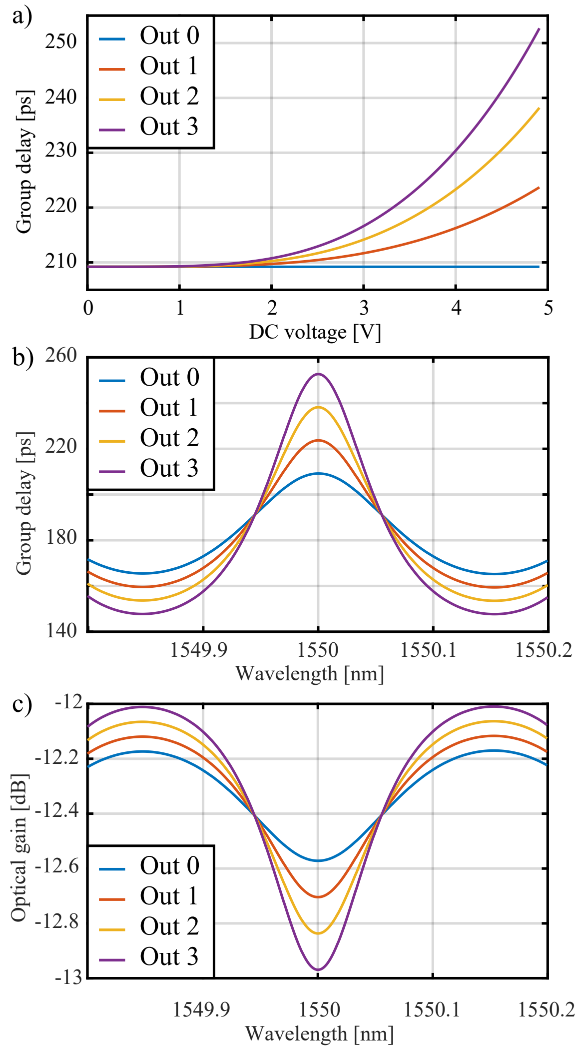

Fig. 3. Simulation results of integrated optical tree beamforming network: a) Maximum group delay at each output with respect to the DC voltage applied to the thermo-optic modulator, b) group delay with respect the optical wavelength for an applied voltage of 4.9 V and c) optical gain with respect the wavelength for an applied voltage of 4.9 V.

The output signals of the chip are converted into the RF domain by photomixing as explained in section III. The group delay in the optical domain is translated into TTD between the sub-THz signals which feed the PAA. The propagation direction of the formed far-field wave is determined by Δτ and the spacing between radiation elements (d), which in general is fixed to half of the wireless wavelength to avoid grating lobes. The steering angle, θ, follows the equation:

$$\sin\theta = \frac{c\Delta\tau}{d} = \frac{\lambda\Delta\Phi}{2\pi d} = \frac{f_c\Delta\tau}{k}, \tag{1}$$

where ΔΦ represent the equivalent phase difference between successive antennas, c is the light velocity in vacuum, λ

represents the wireless wavelength, f_c is the mm-wave carrier frequency and k is defined as $k = d/\lambda$. It can be inferred from Eq. 1 that the required progressive delay $\Delta\tau$ is smaller as the carrier frequency increases. In order to operate at W-band (75 GHz – 110 GHz) the maximum required delay is in the order of 15 ps.

Figure 3 shows the simulated behavior of the described chip. The progressive delay configuration between outputs with respect to the required voltage to modify the thermo-optic modulator controlling κ is shown in Fig. 3a. The time delay difference, $\Delta\tau$, can be continuously tuned from 0 ps (0 V) to 15 ps (4.9 V), corresponding to an overall delay in the range of 210 ps to 255 ps. The resonant characteristics with respect the wavelength in the group delay and transfer function can be seen in Figs. 3 b-c for an applied voltage of 4.9 V. The delay resonance peaks are bandwidth limited. However, the delay can be maintained with a maximum deviation of 1 ps within 1.3 GHz, which ensures broadband operation.

III. Photoconductive Antenna

The different techniques to generate sub-terahertz signals have been considerably improved over the last years, including electronic and photonic approaches [9]. In this work, we have selected photomixing because of the compatibility with the proposed beamforming approach. The fundamental principle is the mixing of two optical lines with a frequency difference equal to the carrier of the targeted wireless wave. In general, the optical frequencies can be defined as $\nu_+ = \nu_o + \nu_{Sub-THz}/2$ and $\nu_- = \nu_o - \nu_{Sub-THz}/2$, resulting in a sub-terahertz signal of $\nu_{Sub-THz}$ [6]. This photonic approach offers broadband operation for wireless communications and potential to cover the full sub-THz and THz gap by simply tuning the frequency separation between the laser sources. However, the power efficiency is low. This challenge can be partially fulfilled with a large number of antenna elements in an array configuration.

Figure 4 shows the operating principle of a photoconductive antenna (PCA), which is one of the most widely used THz photomixers. The optical beam, containing the two frequencies with the modulation, is focused onto a semiconductor area where the electron-hole pairs are generated and separated by an external bias (V_{bias}). A metallic antenna is connected to the electrodes to emit the THz radiation. Different semiconductor materials have

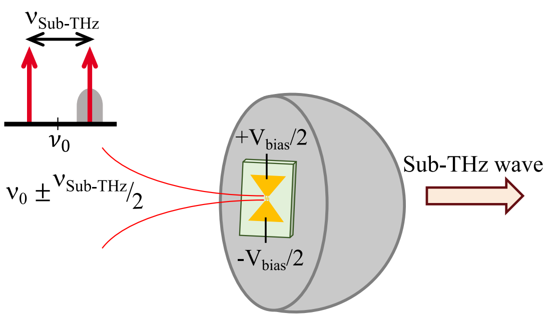

Fig. 4. Operating principle of bow tie photoconductive antenna with silicon lens for sub-terahertz communications.

been studied to develop photoconductive devices working at telecom wavelengths (1550 nm) [10]. This requirement is necessary to make the proposed solution feasible. Different antenna topologies are also available. In this case, a bow tie antenna is selected because of its broadband operation.

The THz wave is mostly radiated into the chip substrate. However, due to the medium transition between substrate-air, part of the radiation is reflected, reducing drastically the emission efficiency. A hyper-hemispherical silicon lens is in general used to avoid internal reflections and collimate the THz wave. This solution is not well suited for a PAA because of two reasons: First, the lens is large, several times the operating wireless wavelength, meaning that grating lobes will appear if individual lenses are used for each PCA. Second, in case of using the same silicon lens for several PCAs, the formed wave will be collimated, changing the desired beam pointing. Consequently, a different structure must be adopted to efficiently adapt the THz wave into the air alongside the beamforming capabilities are not affected.

IV. Dielectric Rod Waveguide Antenna Array

Rectangular dielectric rod waveguides have been proposed as a low-cost alternative to silicon lenses for focusing THz radiation from photoconductive antennas [7]. Their upper cut-off frequency is limited by how sharp the tip of the antenna can be fabricated, and DRWs are thus suited for operation at millimeter wave and terahertz frequencies [11]. A schematic

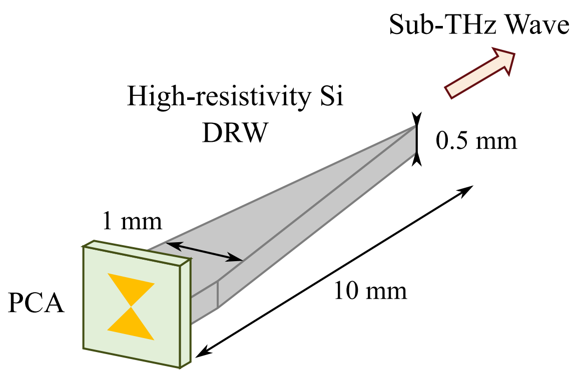

Fig. 5. Schematic drawing of a dielectric rod waveguide (DRW) integrated with a photoconductive antenna (PCA).

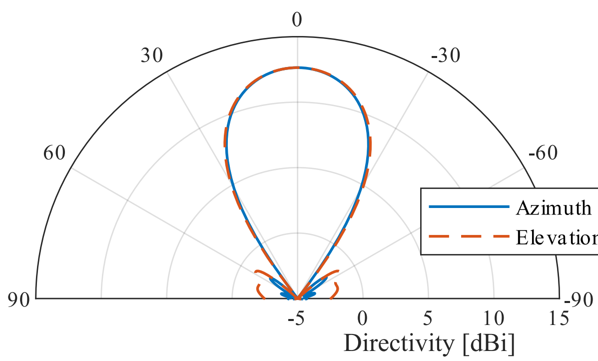

Fig. 6. Simulated radiation pattern at 85 GHz of a single DRW coupled to a photoconductive antenna.

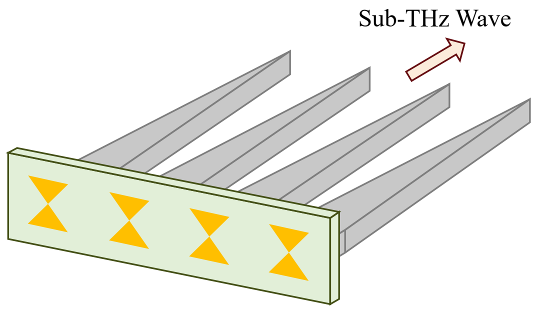

Fig. 7. Schematic drawing of a DRW antenna array integrated with four photomixers for sub-THz beam steering.

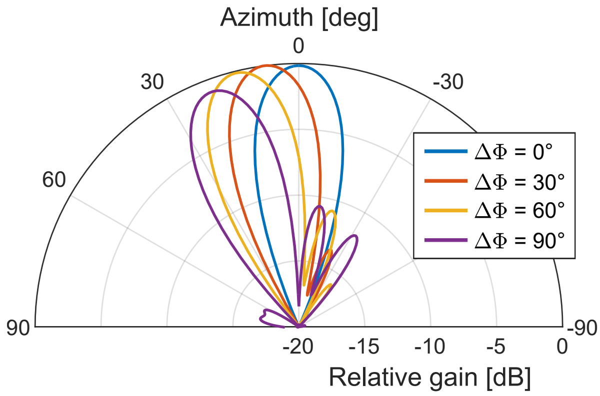

Fig. 8. Simulated beam steering in the horizontal plane at 85 GHz with the DRW antenna array, for increasing phase difference $\Delta\Phi$ between adjacent antenna elements.

drawing of a DRW integrated with a PCA is shown in Fig. 5. A high-resistivity silicon rod is glued on the back-side of the photomixer substrate instead of a lens. The cross-section dimensions of 1 mm $\times$ 0.5 mm were chosen for optimal operation in the W-band [12]. The length of the rod was set to 10 mm as a compromise between mechanical robustness versus high directivity and broadband performance, simulated with CST Microwave Studio 2018. The simulated radiation pattern of the device at 85 GHz is given in Fig. 6. The antenna displays a symmetric main lobe with a directivity of 12.6 dBi, a 3-dB angular width of 40 degrees, and a side-lobe level of -15 dB.

In order to increase the radiated power and to enable beam steering, an array is designed with four elements. A schematic drawing of the antenna array is shown in Fig. 7, where four DRWs are spaced by $\lambda/2$ and coupled to four PCAs, one for each output of the PIC. The simulated radiation pattern at 85 GHz is given in Fig. 8 for varying phase difference $\Delta\Phi$ between adjacent antenna elements. A spatial beam steering up to 25 degrees in the horizontal plane is obtained for a $\Delta\Phi$ of 90 degrees. The results demonstrate the potential of integrating the true time delay photonic chip with photomixers and a DRW antenna array for sub-THz beam steering.

V. Conclusion

A transmitter system to enable broadband sub-THz wireless communications has been presented. This approach exploits the advantages of the optical domain to overcome inherent bandwidth limitations of traditional electronic approaches at this frequency range. The simulation results for an optical tree beamforming network on a silicon nitride photonic chip prove the potential of the proposed solution to operate at frequencies above 75 GHz. The sub-THz signal is radiated by an antenna array composed of bow-tie photoconductive antennas on chip and dielectric rod waveguides. The combination of photonic TTD and DRW antenna array are shown to enable beam steering at sub-THz frequencies for wireless communications. The proposed system represents a first step towards the realization of a fully-integrated photonic-based sub-terahertz transponder. All the components involved in the described system will be manufactured and assembled as part of a laboratory demonstrator.

Acknowledgment

This work was founded by H2020 ITN CELTA under grant number 675683 of call: H2020-MSCA-ITN-2015 and by the European Research Council (ERC) under the European Union's Horizon 2020 research and innovation programme (grant agreement No 616846).

References

[1] T. Nagatsuma, G. Ducournau, and C. C. Renaud, "Advances in terahertz communications accelerated by photonics," *Nat. Photonics*, vol. 10, no. 6, p. 371, 2016.

[2] A. Morales, I. T. Monroy, F. Nordwall, and T. Sørensen, "50 ghz optical true time delay beamforming in hybrid optical/mm-wave access networks with multi-core optical fiber distribution," *Chin. Opt. Lett.*, vol. 16, no. 4, p. 040603, 2018.

[3] Z. Cao *et al.*, "38-ghz millimeter wave beam steered fiber wireless systems for 5g indoor coverage: Architectures, devices, and links," *IEEE J. Quantum Electron.*, vol. 53, no. 1, pp. 1–9, 2017.

[4] A. Morales and I. T. Monroy, "Silicon nitride integrated optical beamforming network for millimeter wave photonics systems," in *Proc. 48th European Microwave Conference (EuMC)*, Sep. 2018, pp. 785–788.

[5] D. Marpaung *et al.*, "Integrated microwave photonics," *Laser Photonics Rev.*, vol. 7, no. 4, pp. 506–538, 2013.

[6] S. Preu *et al.*, "Tunable, continuous-wave terahertz photomixer sources and applications," *J. Appl. Phys.*, vol. 109, no. 6, p. 4, 2011.

[7] A. Rivera-Lavado *et al.*, "Dielectric rod waveguide antenna as THz emitter for photomixing devices," *IEEE Trans. Antennas Propag.*, vol. 63, no. 3, pp. 882–890, Mar. 2015.

[8] K. Wörhoff, R. G. Heideman, A. Leinse, and M. Hoekman, "Triplex: a versatile dielectric photonic platform," *Adv. Opt. Technol.*, vol. 4, no. 2, pp. 189–207, 2015.

[9] M. Tonouchi, "Cutting-edge terahertz technology," *Nat. photonics*, vol. 1, no. 2, p. 97, 2007.

[10] A. d. J. Fernandez Olvera, H. Lu, A. C. Gossard, and S. Preu, "Continuous-wave 1550 nm operated terahertz system using eras: In (al) gaas photo-conductors with 52 db dynamic range at 1 thz," *Opt. Express*, vol. 25, no. 23, pp. 29 492–29 500, 2017.

[11] A. A. Generalov, J. A. Haimakainen, D. V. Lioubtchenko, and A. V. Räisänen, "Wide band mm- and sub-mm-wave dielectric rod waveguide antenna," *IEEE Trans. THz Sci. Technol.*, vol. 4, no. 5, pp. 568–574, Sep. 2014.

[12] D. Lioubtchenko, S. Tretyakov, and S. Dudorov, *Millimeter-wave waveguides*. New York: Springer Science & Business Media, 2003.