Antenna designs for near field waveguide coupling between $0.6-0.9$ THz

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Abstract—**Dielectric waveguide architectures enable low loss, miniaturized terahertz systems-on-chip with extreme bandwidth. However, transfer of power from active devices to the waveguides presents a severe challenge. In this paper, we present a comparison of two Vivaldi end-fire antenna designs with losses of $2-5$ dB per coupling interface to silicon waveguides over a frequency range as large as $0.6-0.9$ THz. We demonstrate lower losses between $0.63-0.83$ THz as compared to far field in-coupling with silicon lenses, despite being orders of magnitude smaller in size.**

I. INTRODUCTION

Traditional terahertz systems employ free-space propagation of terahertz radiation through multiple bulky optical components such as Polymethylpentene (TPX) lenses and parabolic mirrors. To miniaturize such setups and subsequently design systems-on-chip operational at terahertz frequencies, various waveguide architectures have been proposed in the last decade [1-4]. Dielectric waveguide structures generally allow for large bandwidth and lower losses at higher Terahertz frequencies ($0.1-10$ THz) as opposed to metallic waveguides, which suffer from high losses due Skin effect and surface roughness. However, coupling of power into these waveguides presents a major challenge, particularly when a large bandwidth is concerned. Various coupling techniques using dielectric rod waveguides [5] or near-field coupling using microstrip-coupled antennas [6] have been investigated in the past few years for lower terahertz frequencies. However, for higher terahertz frequencies, free-space coupling using optical components is still the method of choice. This requires typical photonic sources and receivers to be packaged with silicon lenses (diameter ~10 mm) that are about six orders of magnitude larger than the actual photoconductive device with an active area of $10\times10\,\mu\text{m}^2$ [7]. Such oversized terahertz sources and receivers lack miniaturization and integration capabilities.

In this paper we investigate two Vivaldi antenna designs, A and B (shown in Fig. 1), for efficient in- and out-coupling of terahertz power into highly resistive silicon-based waveguides ($n\approx3.41$) between $0.6-0.9$ THz. Vivaldi antennas radiate in the end-fire direction ($\theta=90^\circ,\phi=0$), and feature a practically constant radiation pattern as well as antenna impedance within the design window [8]. This makes these antennas highly broadband and scalable. Additionally, when designed carefully, the radiated terahertz beam from such an antenna can be mode-matched with the fundamental propagating mode of the aforementioned waveguides. The antenna-coupled active devices tested here are $\approx 150\times240$ µm² large and do not require any bulky THz optics. Hence, these types of antennas can be the cornerstone for photonic integrated circuits at terahertz frequencies and broadband integrated THz system-on-chips.

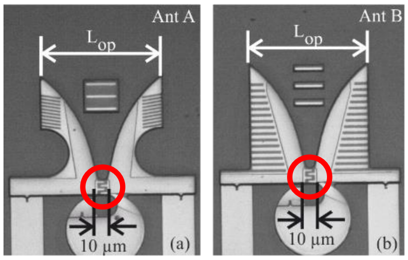

Fig. 1. (a) and (b) show micrographs of antennas A and B, respectively. The photoactive region with 4 finger electrodes is situated at the base of the antennas marked by a red circle.

The antennas characterised in this paper are coupled to ErAs:InGaAs based photoconductive receivers, comprised of $1.6\,\mu$m thick active region supported by an indium phosphide substrate (InP, $n\approx3.46$). The photoactive area is coupled to the antenna using 4 finger electrodes [9], which are $1.5\,\mu$m wide and $7\,\mu$m long. To achieve proper impedance matching in Vivaldi antennas at any wavelength λ_0, the substrate thickness h_{sub} should satisfy $0.005\cdot\lambda_0\leq h_{sub}(\sqrt{\epsilon_r}-1)\leq0.03\cdot\lambda_0$ [10], where ϵ_r is the relative permittivity of the dielectric substrate on which it is placed. However, due to mechanical constraints, the InP substrate could only be thinned down to $32\,\mu$m, which is 5 and 8 times higher than the required thickness at 0.6 and 0.9 THz respectively. This reduces antenna gain in the end-fire direction, however, it can be compensated by maximizing the surface current in the inner edge of the antenna blades [9] by adding different corrugated structures at the outer edge. Antenna A features a circular corrugation near the base of the antenna, where the finger-electrodes are located, with additional uniformly sized rectangular corrugation-slots near its tip. Antenna B, on the other hand, only contains rectangular slotted corrugations with linearly increasing length throughout the outer edge of the antenna blades. Additionally, metallic directors are used in-front of both the designs for an improved performance at higher frequencies. Micrographs of both the antennas are shown in Fig. 1a and 1b.

II. MEASUREMENT AND RESULTS

The simulation schematic in CST microwave studio is shown in Fig 2a. In simulations, the finger electrodes are represented by a discrete port and the fundamental waveguide mode is excited at the waveguide port on the right. Scattering parameters are measured between the waveguide port and the discrete port to obtain simulated coupling efficiency plotted in Fig. 2b. The antenna parameters are subsequently optimised to maximise the power transferred from the waveguide to the discrete port within $0.6-0.9$ THz. Antenna A is $112.5\,\mu$m long with $L_{op}=112.5\,\mu$m, whereas antenna B is $135\,\mu$m in length with $L_{op}=150\,\mu$m. Simulated coupling losses for

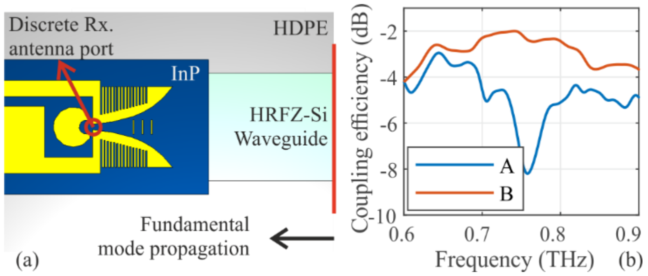

Fig. 2. (a) shows the simulation schematic for Vivaldi antennas. The red vertical line on the right shows a waveguide port. (b) Simulated coupling efficiencies (S21) of A and B to a silicon waveguide.

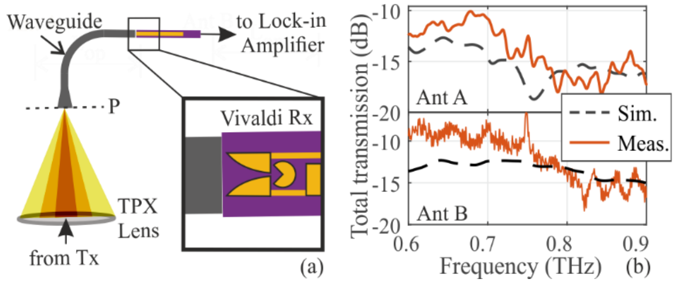

Fig. 3. (a) shows the measurement setup for the Vivaldi antennas. (b) Total power transmission from the PIN-diode source to antennas A and B through the silicon waveguide.

antenna A in Fig. 2b is < 5 dB between $0.6 - 0.9$ THz except a resonance peak at 0.76 THz. Antenna B shows < 4 dB coupling losses in the same frequency range, with < 3 dB losses between $0.63 - 0.83$ THz.

Antenna A and B are subsequently measured using a continuous wave THz system from Toptica Photonics AG, consisting of a silicon lens-coupled terahertz transmitter. The Vivaldi antenna coupled photomixers are used as detectors. Firstly, a reference measurement of the detected terahertz current (I_{ref}) is taken in the free-space setup, with a log-periodic antenna-coupled photomixer, fabricated from same wafer in the same fabrication run. Then, both antennas A and B are positioned directly in contact of a silicon waveguide of length 19 mm, comprising a $90°$ bend with 4 mm radius as shown in Fig. 3a. The other end of the waveguide is tapered out to facilitate in-coupling from free-space terahertz beams and is placed at the focus of a TPX lens. Total transmission losses (T) in this setup is calculated as

$$T = 20 \cdot \log_{10} \frac{I_{meas}}{I_{ref}} \qquad (1)$$

where $I_{meas} \propto E_{THz}^{meas}$ is the detector current measured with Vivaldi antennas. The measured transmission losses are plotted in Fig. 3b. The losses can be broadly categorised into three types, namely, in-coupling losses from free-space into the waveguide occurring at point P, transmission losses in the waveguides, which is negligible in comparison with the other two loss types at these frequencies [4], and the coupling losses between the waveguides and the Vivaldi antennas. The free-space coupling losses accounts for $\approx 10 - 13$ dB losses, which primarily occur as the incident THz- beam spot size is 2 orders of magnitude larger than the waveguide aperture, which consequently results in mode-mismatch [11]. When the simulated antenna coupling losses are taken into account, the total transmission losses increase to ~ 15 dB, as shown in Fig. 3b, which is in excellent agreement with the measured values. Considering the reciprocity theorem for antennas, it can be argued that replacing the free-space in-coupling with a Vivaldi antenna coupled transmitter will further reduce the total transmission losses by another $8 - 10$ dB.

III. CONCLUSION AND OUTLOOK

Vivaldi antennas are well suited for broadband near-field coupling to dielectric waveguides. Both designs A and B provide $8 - 10$ dB better coupling efficiency to silicon waveguides than free-space coupling using TPX lenses. Antenna B provides a coupling efficiency of better than 3 dB between $0.63 - 0.83$ THz. For comparison, the reflection losses in a silicon lens at silicon-air interface is ≈ 1.5 dB, despite being orders of magnitude larger in dimension than that of the Vivaldi antennas. Simulations show that thinning down the antenna substrate up to $\sim 10\ \mu$m will further improve the coupling efficiency, however it will also reduce the mechanical stability and robustness of the Vivaldi antennas. Furthermore, these antennas can be used for highly broadband terahertz applications for frequencies between $0.5 - 1.6$ THz with $3 - 4$ dB higher losses for frequencies > 1 THz [4].

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