Silicon-Micromachined High-Gain Multi-Beam Beam-Steering THz Graded-Index Lens Antenna Enabled by a Passive Beamforming Interposer

Alireza Madannejad*, Mohammad Mehrabi Gohari*, Joachim Oberhammer*
*School of Electrical Engineering and Computer Science, KTH Royal Institute of Technology, Sweden.
Madann@kth.se

***Abstract*—This paper presents, for the first time, a novel high-gain beam-steering lens antenna operating in the 610 to 645 GHz range. The antenna, fabricated using silicon micromachining, is based on incorporating a Fresnel lens layer in combination with a frequency-dependent graded-index interposer that acts as a passive beamformer. Frequency-dependent narrow beams are generated using an open waveguide feed. The prototype implemented in this paper features the generation of 8 frequency-dependent narrow beams with just two open waveguide feeds. These beams can be steered from -30° to 2° in the azimuth. The prototype achieves a measured realized gain of 32.1 dBi with low beam-steering losses of just 0.8 dB. The antenna also exhibits a high radiation efficiency of -1.25 dB. The lens antenna is very compact, measuring only 15.8 mm × 15.8 mm × 0.526 mm. This beam-steering antenna offers a promising solution for future high-gain, multi-beam THz communication systems.**

***Index Terms*—THz Antenna, Graded Index, silicon micromachining, Multi-beam.**

I. Introduction

The rapid advances in telecommunication, particularly in the context of 5G-Advanced and 6G, have escalated the demand for ultra-high data rates to support emerging applications such as high-resolution imaging, virtual reality, and remote sensing. To meet these requirements, the Terahertz (THz) frequency band is emerging as a key enabler due to the large available bandwidths, which are capable of delivering unprecedented data rates [1]. Thus, the THz band, ranging from 0.1 to 10 THz, holds promise for wireless local area networks (WLAN) and point-to-point communication links, but it comes with inherent challenges, particularly the high path loss, and limited range [2], which can be overcome by high-gain antennas. However, the narrow beamwidth of high-gain antennas results in stringent alignment requirements and may lead to significant directional loss if not properly addressed [3]. To overcome these challenges, active beamforming techniques have been explored, including the use of multiple-input multiple-output (MIMO) and hybrid beamforming, to enhance the angular coverage [4], [5]. However, implementing active beamforming systems at THz frequencies presents difficulties due to a large number of required RF chains, high power consumption, increased hardware complexity, and simply the lack of mature, volume-manufacturable, and power-efficient active components at THz frequencies [6]. A further challenge is the reduction of efficiency when employing beam steering, as conventional frequency-scanning antenna systems often experience significant gain variations when steering across angles [10],[11].

Recently, several concepts have been proposed to mitigate these issues. For instance, frequency-dependent antennas with beam-splitting capabilities have been shown to divide a single THz beam into multiple directional subcarrier beams, each pointing in a different direction, enabling more efficient spatial reuse and spectrum allocation [12]. Additionally, passive beamforming methods, such as transmit arrays and lens-based antennas, have been explored to improve beam steering and coverage [13], [14]. These designs offer wideband, high-gain performance potential, but many still suffer from challenges such as complex mechanical movement, low aperture efficiency, and high losses during beam steering [15].

Recent studies have highlighted the potential of silicon micromachining as a fabrication technique for high-performance THz antennas [16], [17]. Silicon micromachining allows for micrometer-accurate complex three-dimensional structures on silicon wafers, enabling low-loss, high-gain antenna designs at THz frequencies. The authors have recently demonstrated high-gain THz antennas, such as Fresnel lens configurations, utilizing silicon micromachining [18]. However, many existing THz antenna concepts are limited to generating a single beam, which restricts their applicability in multi-user, multi-beam modern communication scenarios. Not much has been demonstrated of high-gain multi-beam antennas, which can generate multiple beams within a wide spatial spread, for future THz communication systems. These antennas enable efficient beam and bandwidth sharing, allowing for optimized resource allocation across users and minimizing interference [19], [20]. In this paper, we address these limitations by proposing a first multi-beam beam steering above 300 GHz high-gain, wideband, lens antenna operating in the 610-645 GHz range, fabricated using silicon micromachining. The proposed antenna employs a graded-index silicon lens for passive beamforming, enabling the generation of 8 orthogonal beams with just two feeds. This design minimizes power consumption, improves beam steering efficiency, and provides a flat gain of 32.1 dBi with an average radiation efficiency of -1.25 dB. The compact, low-cost design is integrated using standard waveguide interfaces, making it suitable for a wide range of THz communication applications.

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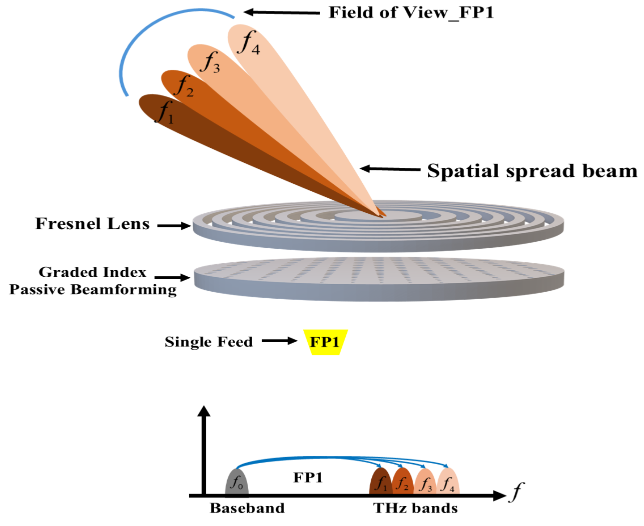
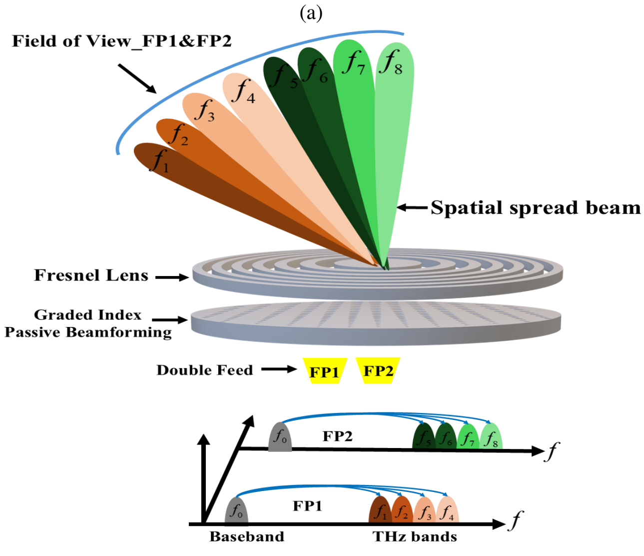


(a)



(b)

Fig. 1: Operating mechanism of the orthogonal multi-beam THz lens antenna featuring spatial beam distribution and frequency multiplexing. (a) Single feed, (b) Double feed.

II. Antenna Design

The multi-beam beam steering is achieved by spatial beam spreading, which divides the very large available bandwidth at THz frequencies (610 GHz to 645 GHz for the device prototype in this paper) into multiple sub-carrier bands of equal bandwidth, with the beams generated for each sub-carrier pointing into a different direction due to the designed frequency-dependent beam-forming geometry of the antenna system. Fig. 1 shows an overview of the concept. The complex geometries of the proposed antenna system are designed to be implemented by utilizing the two silicon layers of a silicon-on-insulator (SOI) wafer. The top layer is used for a Fresnel zone lens with 13 concentric zones, and the bottom layer contains the novel perforated disk interposer, which acts as the passive

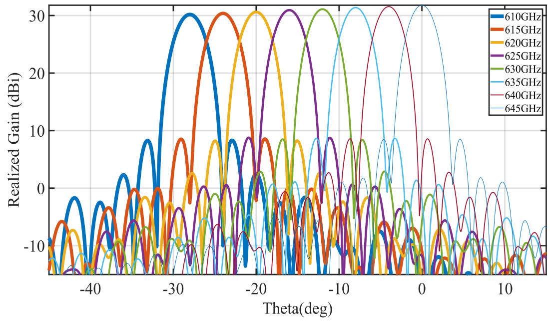


Fig. 2: Simulated E-plane radiation patterns of the multi-beam lens antenna demonstrating 8 frequency-dependent narrow beams generated from two feeding ports.

beamformer. The frequency beam steering in the proposed antenna is achieved using a frequency-dependent graded index interposer. This interposer consists of a perforated disk with varying hole sizes, creating sections with different dielectric constants. As a result, each section introduces a unique delay, enabling the antenna to provide distinct spatial delays at different frequencies. The designed antenna is controlled by two feeding points, both positioned at the same focal distance from the lens but located at different positions in the xy plane. Four distinct beams can be generated per feed, spread over a field of view of -30 to 2 degrees in the azimuth plane, with a 4-degree half-power beamwidth and equivalent angular distance corresponding to a 5 GHz beam separation in the frequency domain. These sub-channels, ranging from 610 to 645 GHz, are assigned distinct beam directions using graded-index silicon lenses, resulting in multiple unique radiation beams. The chosen approach minimizes interference between beams, maximizes resource allocation, and improves the system's overall performance. Simulations in Fig.2 show that the antenna achieves high gain 33dBi with minimal expected beam steering loss predicted by the simulations 0.7, showcasing efficient multi-beam generation and steering capabilities.

III. Fabrication

The fabrication process utilized in this study is based on a silicon-on-insulator (SOI) wafer configuration, consisting of a 96um thick device layer and a 430 um thick handle layer, separated by a 1 µm Buried Oxide (BOX) layer. Both silicon layers have high resistivity (2000 ohm-cm) to minimize dielectric loss. The fabrication follows the process detailed in [18], which was used for fabricating a single fixed-beam lens antenna. A scanning electron microscope picture of the interposer layer is shown in Fig. 3. Silicon micromachining, due to the lithography-defined features, allows for etching of 3-dimensional geometrical features with 1-µm accuracy into the silicon layers, which is the key to the good agreement between simulations and measurements even at these very advanced frequencies beyond 500 GHz. The fabricated lens in

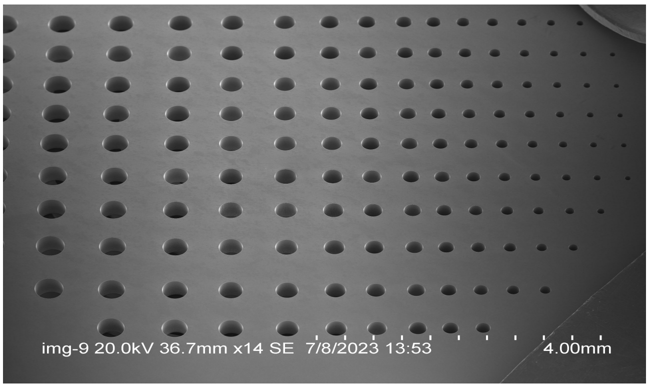


Fig. 3: SEM images of the manufactured Multi-beam lens antenna.

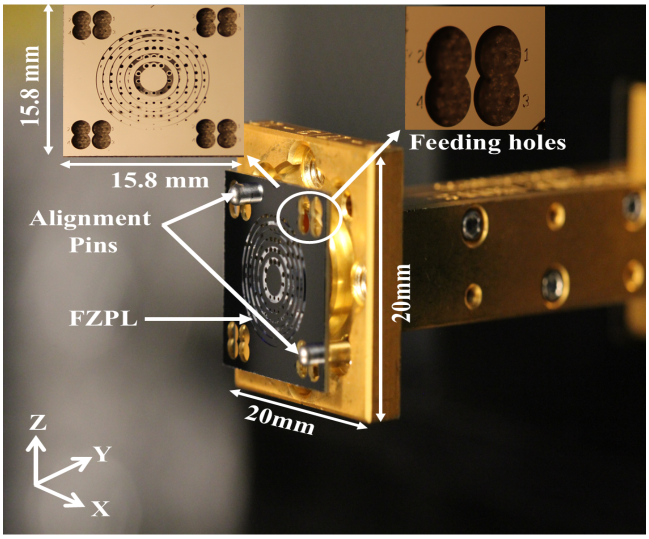


Fig. 4: Picture of fabricated multi-beam lens antenna mounted on waveguide flange and feeding holes arrangement.

Fig.4 is designed for being fed through multiple feeding points, featuring alignment pin holes for the different configurations.

IV. Characterization

The antenna prototype was evaluated in a far-field setup in the THz anechoic chamber at KTH Royal Institute of Technology, Sweden, using a setup for calibrated-gain measurements. As illustrated in Fig. 4, the antenna under test (AUT) was mounted to a WR-1.5 waveguide flange linked to a Virginia Diodes Instrument (VDI) frequency extender operating in the 500-750 GHz range. A fully automated 3D robotic system controlled the antenna's positioning. The return loss of the fabricated lens antenna was measured and compared to the simulated results, as shown in Fig. 5. The measured return loss remained consistently below -10 dB across the 590-730 GHz frequency range, which comprises a fractional bandwidth (FBW) of 21%. Additionally, the radiation patterns of the multi-beam antenna, as depicted in Figs. 6(a) and 6(b) were measured in the E-plane across varying frequencies. The main

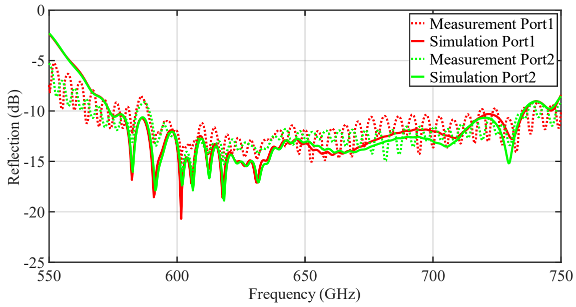
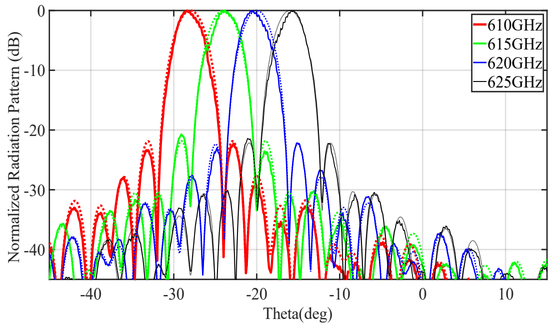
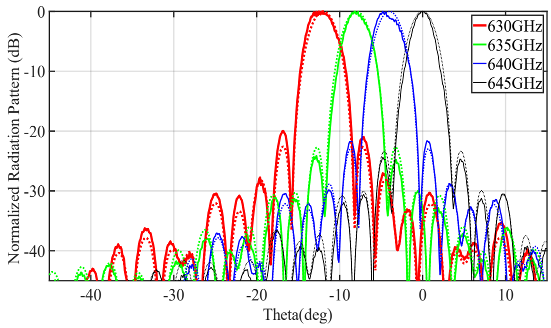


Fig. 5: Comparison of simulated and measured reflection loss for four-port lens antenna.



(a)



(b)

Fig. 6: Normalized E-plane radiation pattern comparison between simulation and measurement for the multi-beam lens antenna. (a) Port 1 results, (b) Port 2 results.

beam could be steered from -30° at 610 GHz to 2° at 645 GHz, with side lobe levels (SLL) below -22 dB, as predicted. The realized gain and the radiation efficiency for antenna prototypes are plotted in Fig. 7. As shown, the realized gain is constant over the frequency with only 0.8dB variation, which means the beam steering loss is very low. Also, the antenna's radiation efficiency was measured to an average of -1.25dB, which emphasizes the advantage of pure-dielectric antenna at

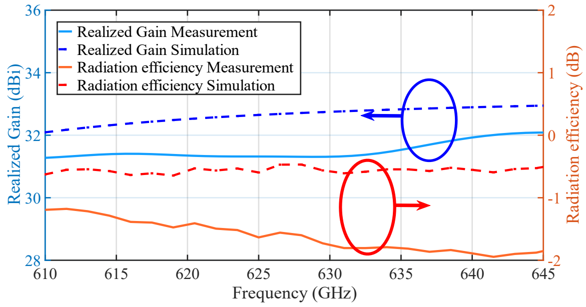


Fig. 7: Simulated and measured maximum realized gain and radiation efficiency of multi-beam lens antenna.

these high frequencies, as compared to metal-coated designs. This very good agreement between measured and simulated return loss results, radiation pattern, realized gain, and beam steering loss demonstrates the fabrication accuracy and the robustness of the antenna design.

V. Conclusion

In conclusion, this work introduces the first multi-beam antenna demonstration above 300 GHz by a compact and high-gain multi-beam, beam steering lens antenna designed for the 610-645 GHz frequency range. Utilizing silicon micromachining for its fabrication, the antenna demonstrates the ability to generate 8 frequency-dependent beams using only two feeds, offering significant efficiency in beamforming and spatial resource allocation. The measured results closely align with simulations, showcasing a flat realized gain of 32.1 dBi and consistent performance across the entire operating bandwidth. The compact size of 15.8 mm × 15.8 mm × 0.526 mm further highlights its suitability for next-generation THz communication systems. This antenna design addresses the challenges of beam steering and interference and paves the way for efficient, multi-beam communication in future high-frequency applications.

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