

Broad-Angle Beam-Steering Using a Silicon-Based Flattened Luneburg Lens for THz Band

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Abstract: We present a silicon-based flattened Luneburg lens for terahertz beam-steering, utilizing quasi-conformal transformation optics and effective medium theory. This device achieves broad-angle steering, supporting high-speed, on-chip THz communication. © 2022 The Author(s)

1. Introduction

Terahertz (THz) communication systems have gained significant attention due to their potential to enable high-speed data transfer rates. A key challenge in THz communication is overcoming free-space path loss, which requires the use of highly directional THz signals. As a result, beam steering devices have become increasingly important. One such device is the flattened Luneburg lens (FLL) [1], which can steer the beam over a broad angle. The development of integrated and efficient beam steering solutions for high-speed, on-chip communication [2] is also crucial for advancing THz-frequency technologies. However, current on-chip beamformers face several challenges, including significant loss, limited bandwidth, constrained spatial coverage, and poor integration with on-chip THz circuits. The proposed device offers a robust solution to bridge the gap between beam steering and on-chip integration.

We use transformation optics to modify the cylindrically symmetric Luneburg lens. This flattens a portion of the lens, such that the initially curved edge becomes planar. This device is a gradient-index (GRIN) [3] device based on air holes in high-resistivity Si used as a base material. This makes it well-suited for an all-silicon platform, and the high permittivity of Si (11.68) makes it advantageous to increase maximum permittivity of the FLL. This can be achieved by increasing the arc of the device that we plan to flatten. To minimize material anisotropy, we apply quasi-conformal transformation optics (QCTO) [1] to modify the geometry of the Luneburg lens. This QCTO calculation allows us to determine the desired permittivity distribution for the FLL. The desired permittivity distribution is predicted using effective medium theory (EMT), which introduces the air holes as subwavelength structures into the Si base material. The permittivity of the composite material is determined by the volume fraction of air and silicon, allowing precise control of the effective permittivity by adjusting the size and spacing of the air holes.

2. Experiment

First, we flatten 160° section of the arc of a normal Luneburg lens (Fig 1(a)) using QCTO [1]. The resultant permittivity profile is shown in Fig. 1 (b). Then we use a high resistivity Si slab as our platform to create a FLL using EMT. The effective permittivity of the Si slab can be controlled by putting subwavelength through-holes. The volumetric fill factor (ζ) of the air in the silicon slab is given by

$$\zeta = \frac{(1 + \epsilon_{Si})(\epsilon_L - \epsilon_{Si})}{(1 - \epsilon_{Si})(\epsilon_L + \epsilon_{Si})} \quad (1)$$

Where ϵ_{Si} is the permittivity of the Si slab and ϵ_L is the permittivity of the FLL.

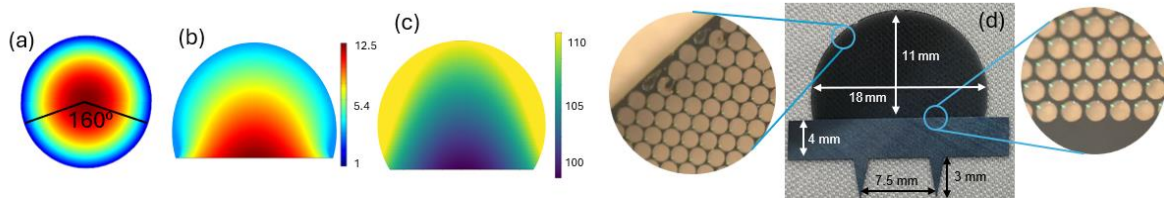


Fig. 1. (a) Permittivity profile of a normal Luneburg lens. (b) Permittivity profile of the FLL. (c) Hole density profile of the device (μm). (d) Fabricated lens with zoomed in images of circular parts.

These through holes can be employed in a triangular lattice with lattice constant of a with a value of $120\text{ }\mu\text{m}$ and then the fill factor (ζ) can be controlled by the hole diameter D with the relationship of $\zeta = \pi D^2 / 2\sqrt{3}a^2$. The resultant hole density profile for the corresponding FLL permittivity profile (Fig. 1(b)) is shown in Fig. 1(c). Then we put through holes according to the equation 1 using deep reactive ion etching of high resistivity Si and backgrinding to $200\text{ }\mu\text{m}$ thickness. The fabricated device is shown in Fig. 1 (d) with zoomed-in views of the edge and center, clearly illustrating the variation in hole diameters at different places for different permittivity distributions. There are two tapered ports on the flattened part to increase the coupling efficiency to the antenna shown in Fig 2(a).

The dimensions of the fabricated device are shown in Fig. 1 (d). Next, we experimentally characterize the fabricated device using a communication system operating at a carrier frequency of 300 GHz, employing Quadrature Phase Shift Keying (QPSK) at a data rate of 10 Gbit per second. The experimental setup is shown in Fig. 2 (a). The fabricated device is placed in front of the transmitter with one port inserted into the horn antenna to increase the coupling efficiency. The THz electric field polarization is horizontal i.e. parallel to the fabricated device. The receiver and the transmitter are 7 cm apart from each other. First, we measure the received power without the device by rotating the receiver antenna with respect to the device at the center with 0.5° step size spanning a total angle of 130° . Then we repeat the same experiment with both ports (P1 and P2) inserted into the transmitter antenna to demonstrate the beam steering capabilities in both directions as shown in Fig. 2 (b).

The received power as a function of the receiver angle is shown in Fig. 2(b), with 0° corresponding to the alignment of the receiver and transmitter along the same optical axis. We can observe a clear reduction of power of 10 dB at the center when the fabricated device is inserted to the antenna, which can be attributed to the scattering effects of the device and its beam-steering capabilities. Secondary lobes appear around $\pm 30^\circ$, with a width of 20° which are present on both sides but are less prominent when the device is absent. When P1 inserted into the antenna we clearly see a peak at $+50^\circ$ and when P2 inserted we see a peak at -50° . These two peak as the opposite sides of the optical axis clearly show the beam steering capabilities of the device. Both of these signals have a peak of 20 dB. Then we also observe the eye diagram (inset, Fig.2) of the signal at that peak of this signal ($+50^\circ$) and see a clear eye diagram which confirms that the fabricated device cannot only steer THz signals but can carry high speed data. We also performed this experiment at different frequencies (50 GHz bandwidth with the center frequency as 300GHz) and observed similar results which prove the broadband capacity.

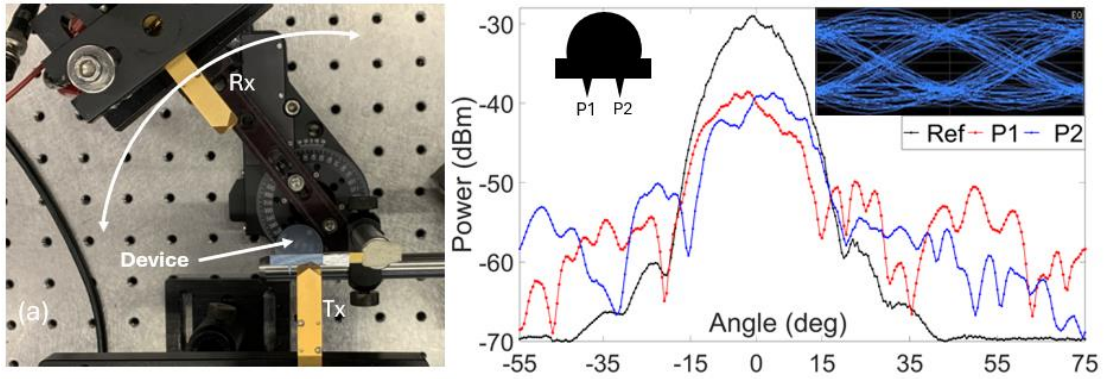


Fig. 2. (a) Experimental Setup. (b) Received power vs angle. (inset) eye diagram of the received signal at 50° with the device.

3. Summary

We have demonstrated a broad-angle beam-steering solution using a FLL in a Si slab, designed for operation at THz frequencies. By applying QCTO and EMT, we achieved the desired permittivity profile through a patterned Si slab with subwavelength through-holes. The experimental results confirm the device's capability to steer THz beams effectively, showing a strong, directionally selective response. This novel FLL design in Si addresses key challenges in on-chip THz communication, paving the way for high-performance, integrated beam-steering applications essential for next-generation wireless systems.

4. References

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