Epsilon-Near-Zero Lens for Beamshaping of Sub-Terahertz Waves

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***Abstract*—The focal properties and radiation characteristics of an epsilon-near-zero metamaterial lens are investigated numerically and experimentally in the D-band. The experimental focusing enhancement of the lens is ~16 dB. The directivity of the lens antenna configuration at 144 GHz is ~18 dBi and the corresponding gain scan loss below 3 dB is achieved for angles up to ±15 deg.**

I. INTRODUCTION

STANDARD dielectric lenses operating at millimeter-waves suffer from significant Fresnel reflection loss [1]. At optics this can be easily reduced with anti-reflective coatings. However, at millimeter-waves the required anti-reflective coatings would relatively be very thick, heavy and costly to implement for real applications.

With the advent of metamaterials [2], scientists have been equipped with alternative disruptive approaches to address problems like the aforementioned. Hence, we tackle the problem of impedance mismatch by implementing an epsilon-near-zero (ENZ) lens operating in the energy squeezing and tunneling realm where reflection is minimized [3,4]. This lens can be considered as an evolution of Kock's metallic lenses [5]. The focal properties of the lens as well as its radiation characteristics are studied analytically, numerically and experimentally in the D-band of the millimeter-wave regime.

II. RESULTS

The ENZ lens is implemented via a two-dimensional arrangement of narrow rectangular aluminum waveguides operating near cut-off (for the fundamental TE_{10} mode), which is carved to produce a plano-concave profile. The hollow region in each waveguide is 1.1 mm × 0.05 mm, whereas the in-plane periodicities are d_x = 1.4 mm and d_y = 0.5 mm. The diameter of the spherical profile has a diameter of 55.5 mm.

After a fast prototyping based on 2D Huygens-Fresnel principle, full-wave simulations of the 3D fabricated lens are carried out with CST Microwave Studio™ to assess the measurements. In the simulations, the lens model follows the fabrication dimensions (according to conformal microscope pictures) and aluminum is modelled with conductivity $\sigma_{Al} = 3.56\times10^7$ S/m.

Initially, the focal properties of the lens are measured with two independent setups. The first setup uses as a feeder a corrugated horn antenna placed 1.3 m away from the flat face of the lens along with a flanged-ended WR-6.5 waveguide working as a detector. Both elements are connected to an ABmm vector network analyzer. The second setup uses the same corrugated horn antenna, but placed closer to the lens (160 mm away), together with a near-field probe with sharpened edges. Both elements are connected in this case to an Agilent Technologies N5242A PNA-X network analyzer.

The maximum transmission is measured at 144 GHz and the experimental focal length estimated with both setups is ~40 mm, which is in agreement with the simulation (~39 mm). The FWHM along x is ~4.6 mm ($2.2\lambda_0$) and ~2.4 mm ($1.1\lambda_0$) for the ABmm and Agilent setup, respectively. The FWHM along y is meanwhile ~3.5 mm ($1.7\lambda_0$) and ~3 mm ($1.4\lambda_0$), respectively. The discrepancy between the setups stems from the different invasiveness and collection of each detector.

In our next experiment, we characterize the radiation properties of the lens antenna configuration. The maximum directivity is measured to be 17.6 dBi, which is ~8 dB below the simulations. The drop can be arguably assigned to experimental misalignments and additional losses arisen from the narrow hollow waveguide roughness [6] that has not been modelled. We also study the steering of the beam by moving mechanically the feeder (a flange ended WR-6.5 waveguide). The gain of 11 dB at 144 GHz drops further than 3 dB for angles larger than 15 deg. Experiments agree well with analytical and numerical calculations.

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