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 be very thick, heavy and costly to implement for real applications.

With the advent of metamaterials [2], [3], scientists have been equipped with alternative disruptive approaches to address problems like the aforementioned. For instance, we tackle here 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 [4]-[8]. Alternative solutions are based on gradient index lenses whose design and implementation is cumbersome [9]. The ENZ lens can be considered as an evolution of Kock's metallic lenses [10]. 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 is 1.1 mm × 0.05 mm (along x- and y- axis, respectively), 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 value of 55.5 mm. The fabricated prototype is shown in Fig. 1.

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^{TM} to assess the measurements. In the simulations, the lens model follows the fabrication dimensions (according to confocal 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.

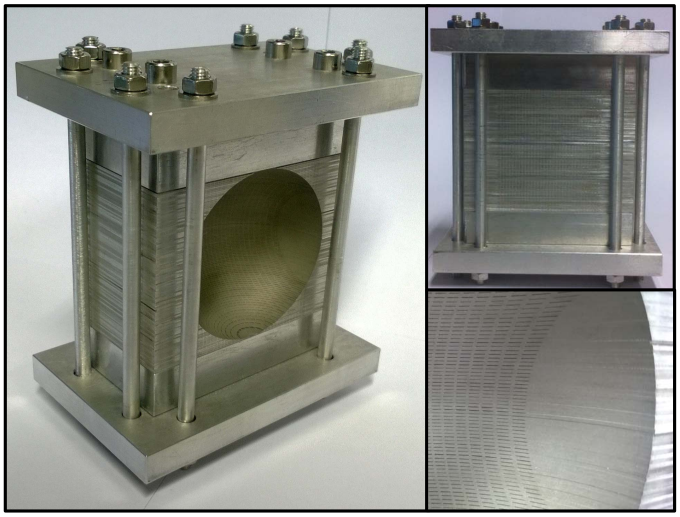

Fig. 1. Photographs of the plano-concave ENZ metallic lens: perspective view (left), back (top right) and detail of the front profiled profile (bottom right).

The experimental focal length estimated with both setups is ~40 mm, which is in agreement with the simulation (~39 mm). The full width at half-maximum (FWHM) along x is ~4.6 mm and ~2.4 mm for the ABmm and Agilent setup, respectively. The FWHM along y is ~3.5 mm and 3 mm, respectively. Both results are shown in Fig. 2(a). The discrepancy between 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. A detailed description of the setup can be found in Ref. 8. The maximum directivity measured is 17.6 dBi, which is ~8 dB below the simulations. The overall performance is worse than that predicted by the simulation and it could be arguably assigned to experimental misalignments and degradation arisen from the waveguide roughness [11] (i.e., large propagation loss could forbid transmission through the longer lateral waveguides, reducing therefore the output radiating area) that was not been considered. The measured co-polar radiation patterns on the E- and H-plane are shown in Fig. 2(b). We also studied the steering of the beam by moving mechanically the feeder (a flange-ended WR-6.5 waveguide) [7]. The gain of 11 dB at 144 GHz drops more than 3 dB for angles larger than 15 deg. Experiments agree well with analytical and numerical calculations.

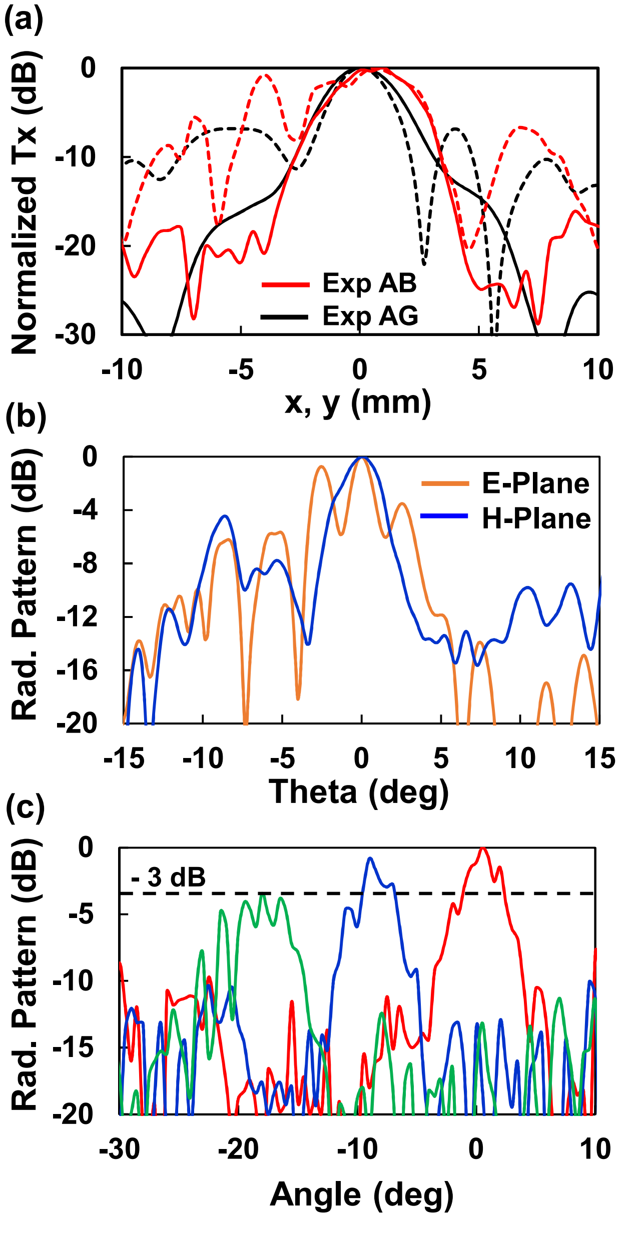

Fig. 2. (a) Normalized transmission along the x-axis (dashed lines) and along the *y*-axis (continuous lines) at the focal length. Exp AB and Exp AG represent experimental results obtained with the AB Millimetre and Agilent VNA setup, respectively. (b) Measured co-polar radiation pattern on the E-plane and H-plane. (c) Measured normalized radiation pattern for the output angles: 0 deg (red line), 9 deg (blue line) and 18 deg (green line).

III. CONCLUSIONS

The performance of a metallic ENZ lens with a plano-concave profile working at 144 GHz has been demonstrated experimentally and compared with 3D full-wave numerical simulations. Experimental measurements with two different setups show a clear focus in both E- and H-planes with a minimum FWHM of $1.46\lambda_0$ and $1.13\lambda_0$, respectively. Moreover, a directivity of 17.6 dBi is also measured with very low values of cross-polar components on the E- and H-plane. The mechanical beam steering performance has also been demonstrated with a gain scan loss below 3 dB for angles up to ±15 deg. This work shows the possibilities of waveguide-based ENZ metamaterial lenses for applications in antenna systems that require steerable performance of the output beam with high gain and low losses.

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