Experimental Demonstration of Metamaterial Flat Lens at F-band

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***Abstract*—We experimentally demonstrate a metamaterial flat lens based on split-ring resonators at 120 GHz based on the gradient index optics theory. The gap of the SRRs that were used as a unit cell of the lens was varied to obtain desired reflective index at a specific place in the lens. In this work, a far-field radiation pattern of an open-ended waveguide antenna was measured with and without the metamaterial flat lens, and we experimentally determined the improvement in the beam directivity on the antenna gain to be approximately 11 dB, with a 3-dB relative bandwidth of 15% or more.**

I. Introduction

Terahertz waves, which are located in the spectral region between infrared light and microwaves, typically are defined between 0.1 and 10 THz [1], provide several interesting features, and have been receiving great attention for use in various fields such as spectroscopy, imaging, security, and wireless communications. However, transmission loss in a conventional circuit, such as conductive and dielectric loss, is high at these frequencies, and that makes manipulation of terahertz signals difficult. To avoid the transmission loss, methods involving metamaterials composed of subwavelength-sized dielectric or metal structures were used to manipulate terahertz signals in not the circuit but in free space [2]. Using gradient-refractive-index lenses, in which the spatial profile of the refractive index is varied, instead of executing precise control of the surface topography has been reported for various frequency regions as part of efforts to reshape the wavefront of the transmissive waves [3, 4]. These lenses have significant potential advantages in that one can reduce the size, especially the thickness, and reduce the fabrication cost or productivity of common printed circuit boards or semiconductor fabrication technologies. In addition, they can be made flat and can be easily integrated with electric devices or a plane antenna.

In this study, we designed and fabricated a metamaterial flat lens based on split-ring resonators (SRRs) that can collimate incident waves at around 120 GHz the frequency at which split gaps were spatially modulated to make index profiles and to preserve the polarization of the incident waves. We experimentally tested the operation of the SRRs flat lens and found improvement in the beam directivity.

II. Results

SRRs used as a base material in this work were designed to be symmetrical with respect to the electric-field plane of linearly polarized incident waves to cancel out the magnetic responses and to preserve the polarization of the incoming waves. The reflective index of the SRRs was controlled by varying the split gap. A larger gap causes a lower reflective index.

In this work, we used commercial multilayer printed circuit board technologies with Teflon substrates. The substrates have a permittivity of 2.2, a loss tangent of 0.0009 at 10 GHz, and ½ oz Copper metal. For a multilayer structure, 38-μm thick bonding film was inserted between layers as well. A flat lens with a focal length of 20 mm was designed with these physical parameters; the transmission phase shift distribution ϕ(x,y) meets the following equation,

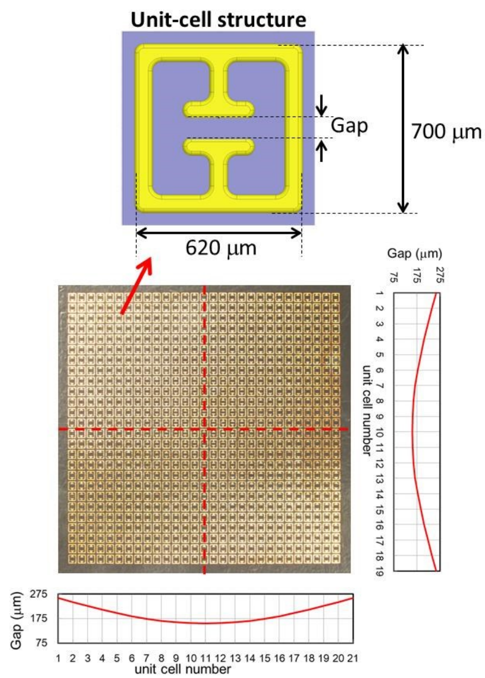

Fig. 1. Photo of fabricated flat lens. All metal patterns were embedded in Teflon substrates.

$$\varphi(x, y) = \frac{2\pi\left(f_0 - \sqrt{f_0^2 + x^2 + y^2}\right)}{\lambda},$$

where x and y represent the positions in the lens in x- and y-directions and where the center of the lens is at x = 0 and y = 0. f_0 and λ are the focal length of the focusing lens and the wavelength of the operating frequency, 120 GHz in this work, respectively. Therefore, small gap SRRs were located in the middle of the lens while large gap ones were located at the edge. Figure 1a shows the photo of the fabricated lens. The aperture of the lens is square, 15 mm or 6λ at 120 GHz on the side. To obtain the 20-mm focal length, 5-metamaterial layers were stacked in the lens because the single layer SRRs did not provide a large enough phase shift.

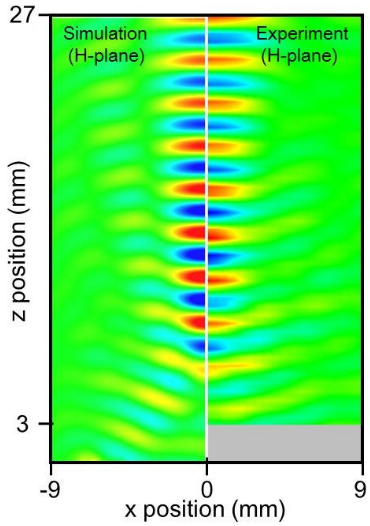

Fig. 2. Simulated and measured near-field distributions in H plane using standard-gain horn antenna with metamaterial lens. Measurement plane was 3-mm above the surface of the lens.

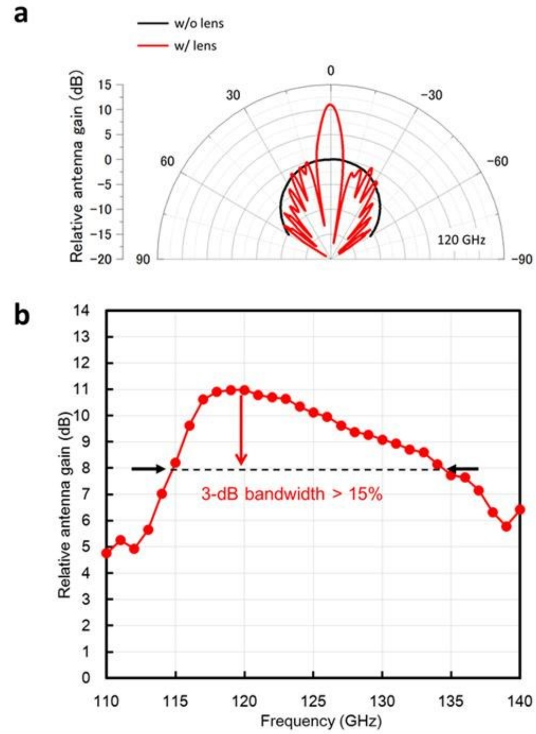

Fig. 3. (a) Measured far-field beam pattern in H-plane with and without metamaterial lens. The antenna gain was normalized to the gain of the wave-guide antenna. (b) Relative gain dependency on frequency for the lens.

To test the operation of the flat lens, we measured near-field distributions and far-field radiation patterns in the H-plane at 120 GHz. The electric fields of the incident wave were aligned in these measurements so that they were across the gap of the SRRs. Figure 2 shows the near-field distributions using a standard-gain horn antenna for Tx and an open-ended waveguide antenna for Rx. For comparison, field distributions simulated by a full-wave electromagnetic (EM) simulation, Ansys HFSS, are also depicted. A relatively high electric-field density at around $z = 20$ mm with a designed focal length was observed, showing a good match with the results of the simulation.

Considering the use case of the lens in improving the antenna gain, we used the open-ended waveguide antenna in a far-field beam pattern measurement. Under the assumption that spherical waves are emitted from the waveguide antenna, we located the source antenna at the focal point of the lens to maximize the effect in improving the antenna directivity. Figure 3a shows the measured far-field beam pattern in the H-plane. The antenna gain was normalized to the gain of the source waveguide-antenna that has a gain of approximately 9 dBi at 120 GHz. As shown in Figure 1b, we can clearly see that the metamaterial flat lens collimates the incident spherical beam and increases the beam directivity in terms of antenna gain by approximately 11 dB. We also conducted a measurement in the E-plane, and similar results with those in the H-plane were achieved. These results demonstrate the proper operation of the lens.

Basically, when the SRRs were used as a unit cell, the frequency region around a resonance was used to achieve negative permeability, resulting in narrow bandwidth and high loss characteristics, thereby limiting the performance. In our lens, a negative refractive index is not necessary; therefore, we can use the frequency region moderately far from the resonance. As a result, our lens should provide low loss and moderate bandwidth characteristics. In the full-wave EM simulation, a 1-layer SRRs array with a split gap of 155 μm, which involves the SRRs being patterned around the center of the lens, exhibited an extremely low transmission loss of close to 0 dB. To estimate the bandwidth of our lens, the frequency characteristic was measured with a far-field measurement at the F-band. Figure 3b shows the relative gain on the frequency. We can see that our lens achieves a 3-dB bandwidth of 20 GHz, which is 15% or more, indicating the lens should be applicable for not only imaging or radar but also communication systems.

III. Summary

In this report, we described how an SRR-based metamaterial flat lens designed based on the gradient reflective index optics theory was experimentally demonstrated at the F-band. The lens was fabricated with commercial printed circuit board technologies. From the near- and far-field measurements, proper operation of the lens was possible at 120 GHz, and an 11-dB improvement in the antenna gain of the open-ended waveguide antenna was obtained. In addition, the lens exhibited a moderate relative 3-dB bandwidth of 15% or more, showing potential for applications including wireless communications.

References

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