Simulations and experiments on higher resonant modes of cubic high dielectric resonator metamaterial

J. Kim, H.-S. Yoo and A. Gopinath

The metamaterial structure composed of cubic high dielectric resonators periodically arrayed in a low dielectric substrate is analysed and a flat metamaterial lens is used to improve the gain of a rectangular patch antenna. A dielectric slab is also discussed and compared with the metamaterial lens. Experimental results show that the proposed metamaterial flat lens can improve the gain of a patch antenna remarkably at both the first and the third resonant mode.

Introduction: Metamaterials or negative index materials may be realised with purely dielectric resonators as proposed by [1–4]. Holloway et al. [1] have a periodic magnetic spherical-particle array to obtain negative index effects, whereas [2] uses a periodic structure composed of two sets of resonating dielectric spheres with different radii resulting in negative real parts of both permittivity and permeability. Peng et al. [3] show electric and magnetic resonance simultaneously at the second resonant mode in a cylindrical high dielectric resonator, while [4] proposes an array of cubic high dielectric resonators producing a magnetic resonant dipole at the lowest-order resonant mode aided by the photonic bandgap effect. In this Letter, the calculated and measured metamaterial structure is composed of cubic high dielectric resonators (CHDRs) \( (e_r = 30) \) periodically arrayed in a low dielectric substrate \( (e_r = 2.08) \), and a flat metamaterial lens using CHDRs has been implemented to improve the gain of a rectangular patch antenna. A dielectric slab having an average permittivity of CHDRs \( (e_r = 10.35) \) is also analysed to compare with the proposed metamaterial lens. Both numerical simulations and measurements with a rectangular patch antenna at its negative index regions are discussed and results at third resonance are emphasised. There are no previous reports to the best of our knowledge, of analysis of the high dielectric resonator cubic structure at the third resonant mode. The numerical simulation and experimental results confirm that a dielectric metamaterial flat lens improves the gain of a rectangular patch antenna owing to a magnetic dipole at 5.7 GHz (first resonance) and coexisting electric and magnetic dipoles at 9 GHz (third resonance).

Simulated and experimental results: The scattering parameters of this cubic resonator, \( e_r = 30 \), side 8 mm, embedded in a low dielectric \( e_r \) of 2.08 with periodic boundary conditions for a cubic lattice side 12 mm were calculated from simulations using the Ansoft HFSS program. Note that the resonant frequencies and hence the negative \( e_r \) and \( \mu_r \) regions are due to the embedded dielectric and the periodic boundary conditions. The S-parameters and the retrieved relative permittivity and permeability using the equations from [5] are shown in Figs. 1a and b, respectively. The shaded areas in these Figures mean the negative index regions. Fig. 1a shows the first resonant and the third resonant frequencies are around 5.7 and 9 GHz, respectively, whereas the second resonant region around 8 GHz is very narrow to be visualised. Corresponding to various incident angles, the negative refractive index region for the first resonance did not change, but the magnitudes of the effective permittivity and permeability were altered by the different orientations of the incident wave. For the third resonance around 9 GHz, the negative refractive index region was split and altered by different orientations of the incident wave.

**Fig. 1** Simulation results for unit cell of CHDR structure

a S-parameters  
b Constitutive effective parameters

**Fig. 2** Configuration of rectangular patch antennas with dielectric slab and with metamaterial lens

a Rectangular patch antenna (top view)  
b Rectangular patch antenna with dielectric slab  
c Rectangular patch antenna with metamaterial lens

**Fig. 3** Radiation patterns of rectangular patch antenna at 5.7 GHz

a Simulated radiation patterns  
b Measured radiation patterns with and without metamaterial lens

**Fig. 4** Radiation patterns of rectangular patch antenna at 9 GHz

a Simulated radiation patterns  
b Measured radiation patterns with and without metamaterial lens

Antenna simulations were performed using HFSS both with and without the proposed metamaterial lens and the dielectric slab. Three-dimensional models of the rectangular patch antenna without and with the slab and the lens are shown in Fig. 2. The metamaterial lens is a single layer of 400 (20 × 20) cubes, side = 8 mm, and \( e_r = 30 \), from...
Trans-Tech Inc., in a square lattice side 12 mm, embedded in a dielectric substrate, which has $\varepsilon_r = 2.08$. The lens is positioned over the rectangular patch antenna to improve the antenna gain. In Fig. 3a, the radiation patterns of the patch antennas with the dielectric slab and the metamaterial lens are calculated at 5.7 GHz and they show similar results at the first resonance. Fig. 3b shows simulated and measured radiation patterns of the patch antenna with and without the metamaterial lens at 5.7 GHz. The measurements show that the antenna gain increased from 6.1 to 11 dB, when the lens was 25 mm from the antenna, which is approximately a half wavelength. Fig. 4 shows the simulated and measured radiation patterns of the patch antenna at 9 GHz. At 9 GHz, the antenna gain was also improved remarkably both at 0 mm (direct contact) and 18.75 mm (half wavelength) spacing while at 5.7 GHz the antenna gain was improved only at the half wavelength spacing. In addition, there is no gain improvement for the dielectric slab at direct contact due to the poor S11 (~4.95 dB). This may be explained from the fact that both electric and magnetic dipoles coexist at the third resonant mode.

Conclusion: The metamaterial lens using cubic high dielectric resonators has been used to improve the gain of a rectangular patch antenna. Both numerical simulations and antenna measurements at negative index regions are discussed at the first and third resonances. Simulation and experimental results verified that improvements in antenna gain can be achieved at a half-wavelength spacing using either the cubic resonator metamaterial lens or the dielectric slab, but at the third resonance, only the metamaterial lens, which has coexisting electric and magnetic dipoles, can improve the antenna gain regardless of the spacing.

References