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An Artificial Dielectric Material to Enhance Patch Antenna Gain

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Abstract—Artificial material has the feature to realize a controllable effective permittivity, which leads to many potential applications in the RF and optical fields. In this study, an artificial material is proposed for a Resonant Cavity Antenna (RCA) to enhance the gain of patch antenna. The artificial material is made of a lot of circular conducting patches in a uniform size hosted in an FR-4 substrate. The fabricated artificial material is in a square shape with a length and width of 52 mm × 52 mm and a thickness of 1.2 mm. The artificial material is set in front of a patch antenna to construct an RCA, and the gain property of the proposed RCA is evaluated with the simulation and measurement methods. The results by both the simulation and measurement methods prove that the gain is enhanced by the proposed artificial material. The maximum gains are 14.5 dBi in simulation and 12.8 dBi in measurement at 15 GHz for the RCA with one slab of the artificial material. The gain is improved compared to the gain of a patch antenna without the artificial material.

1. INTRODUCTION

Dielectric property of a natural material is based on the displacing of its molecules, atoms, or irons which act as electric charges with respect to an external applied electric field. Displacement and movement of electric charges cause polarization effect to compensate the external fields. The dielectric property is a measure of such a polarization. A similar polarization is present when metal particles shorter than the wavelength are placed in an external electric field. Therefore, artificial material with dielectric property is possibly realized when a large number of small conducting particles are arranged in a regular three-dimensional pattern [1, 2].

Artificial material has a history of more than 60 years. One of the earliest studies utilizing an artificial material is the metallic delay lens proposed by Kock in 1948 [3]. Kock suggested the use of artificial material to overcome the disadvantages of the excessive bulk and weight caused by the natural dielectric material used in a conventional lens. Recently, artificial materials have received increasing attention in the RF and optical fields because of the advancement in electromagnetic knowledges and the available high-speed EM computing technologies. For example, artificial materials have been used for miniaturized filters [2], wave absorber, radomes [4, 5], THz spectroscopy, coating [6, 7], etc. The basic principles and some potential applications are summarized in a recent paper [8].

Our group has proposed a very thin flat lens antenna utilizing an artificial material [9, 10]. The proposed artificial material has a controllable dielectric constant, which varies from 4 to 136. The thin thickness of the lens is realized by using large effective permittivity of artificial material, while the flat profile instead of a convex profile is obtained by using an arbitrary location control of permittivity. The lens antenna is made in a disk shape with a diameter of 50 mm and a thickness of 2.29 mm. Based on the flat lens, we also proposed an anti-reflection (AR) lens which has a matching layer made of artificial material to present the reflection effect from the lens surfaces [11]. Gain enhancement based on the lenses effect has been proved in these previous studies. Additionally, the proposed lens and antireflection

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lens have been applied to microwave free-space methods to realize compact and low-cost measurement setups [11, 12]. However, the proposed lenses have the disadvantage of complicated structure [9–11]. The flat lens is implemented on a multilayers board with 10 conducting layers, and the effective permittivity needs to be controlled in a radial direction. The anti-reflection lens has much more layers and needs a more complicated permittivity disturbance [11].

This paper proposes an artificial material used for Resonant Cavity Antenna (RCA). Directional antennas with high gain property are required in the fields of 5G communication system, wireless power transformer system, and microwave measurement setup. Resonator cavity antenna (RCA) is a convenient method to enhance antenna gain since it has a planar feature that can be easily constructed in an antenna structure. In an RCA, one or multiple dielectric slabs are placed over a patch antenna [13–15]. The gain of antenna can be improved when the dielectric parameters of the slabs and their distance and thickness satisfy some conditions. An artificial material is a good coordinate for RCA because the controllable permittivity of artificial material provides a flexible design for an RCA structure. Furthermore, a very thin dielectric slab can be realized by using an artificial material with a high value permittivity.

The artificial material proposed in this paper is implemented on a multilayer board with 6 conducting layers separated by FR-4 material. The conducting layer is made of a large number of circular metal particles in a uniform size. The effective permittivity is controlled by adjusting the radius of the circular particles. Uniform particles and fewer layers make the artificial material have a simple structure. The multilayer board has a length and width of 52 mm × 52 mm and a total thickness of 1.2 mm. One or multiple slabs of the proposed artificial material are set in front of a 15 GHz patch antenna, to construct resonant cavity antennas. The gain properties of RCAs are evaluated using simulation and measurement methods, and the results are given.

2. ANALYTICAL CALCULATION OF ARTIFICIAL MATERIAL

An artificial material realizes effective permittivity by arranging many conducting particles or conducting lines that are shorter than the wavelength in some ways. Figure 1(a) shows a model of artificial material made of many metal particles within a host material. The structure has n cells in the z direction and an infinite periodic structure in the transverse (xy) plane. When a plane wave incident in the positive z direction, the metal particles are polarized due to the applied electromagnetic field, and the dielectric property presents.

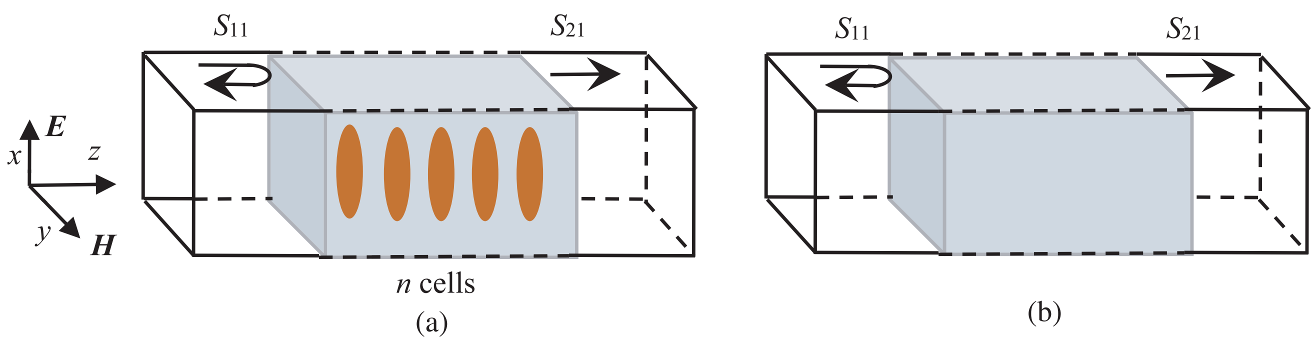


Figure 1. Structures for analytical calculation. (a) Circular metal particles in a host dielectric material. (b) Equivalent uniform medium.

The artificial material is analyzed as a uniform medium with equivalent electromagnetic properties shown in Figure 1(b). When a plane wave in frequency ω propagates through a medium with permittivity ε and permeability μ, the propagating factor γ ($\gamma = j\omega\sqrt{\varepsilon\mu}$) and the normalized characteristic impedance κ ($\kappa = z_0\sqrt{\mu/\varepsilon}$) are obtained from the scatting parameters of S_{11} and S_{21} [2, 16, 17], where z_0 is the characteristic impedance of free space. The effective permittivity ε and permeability μ then can be calculated as,

$$\varepsilon = \frac{\gamma Z_0}{j\omega\kappa} \tag{1}$$

$$\mu = \frac{\gamma\kappa}{j\omega Z_0} \tag{2}$$

The strength of polarization depends on the structure of unit cell, density of metal particles, sizes of the particles, and properties of the host material. Thus, the effective permittivity of artificial material can be controlled by adjusting these parameters. This is the most important feature of the artificial material compared to a natural material because the dielectric constant of a natural material is usually unchangeable.

One structure of artificial material that we studied is face-centered square (FCS) lattice structure [10, 11]. Figure 2(a) shows one cell of FCS, in which circular metals are arranged at a certain distance. Figure 2(b) shows its quarter structure with a periodic boundary condition used in an electromagnetic simulation software. The scatting parameters of S_{11} and S_{21} change as the radius of metal disk r changes, and then the equivalent effective permittivity can be controlled. Our simulated calculation shows that the effective permittivity increases monotonously as the disk radius r increases [9–11]. For instance, the effective permittivity of the artificial material with 6 conducting layers in FR-4 substrate increases from 4.2 to 178 when the radius r of metal disks increases from 0.2 to 1.4 mm, as shown in Figure 2(c).

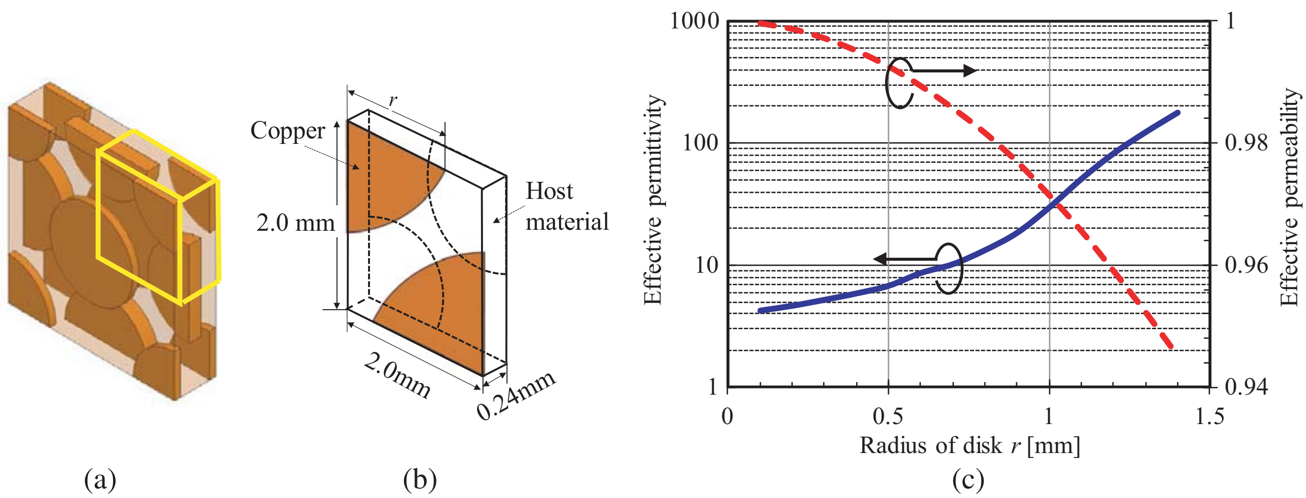


Figure 2. Analytical calculated result of an artificial material with the face-centered square (FCS) lattice structure. (a) A unit cell of FCS. (b) A quarter structure using a periodic boundary condition for simulation. (c) Calculated effective permittivity and permeability with respect to the radius r of a metal circular piece (6 conducting layers separated by FR-4 material, total thickness is 1.2 mm).

3. ARTIFICIAL MATERIAL FOR RCA

In this section, an artificial material with FCS structure is proposed to enhance the gain of a patch antenna based on the principle of RCA [13–15]. The construction of RCA is shown in Figure 3, where a dielectric slab with the thickness of integer multiple of a half effective wavelength is set with distance d above a patch ground. The distance d should be an integer multiple of a half wavelength in free space [13–15]. The key part of RCA is the high-reflective dielectric slab. Usually, high reflection coefficient, i.e., high permittivity of the slab is required to maintain resonance in an RCA structure at the working frequency. The expressions for estimating directivity derived in [13, 18, 19] have shown that a high reflection coefficient leads to a high gain.

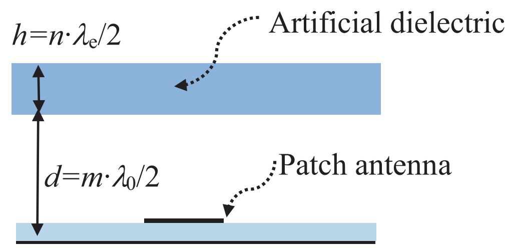


Figure 3. Structure of Resonant Cavity Antenna (RCA).

If an RCA uses a natural dielectric material, the thickness of dielectric slab is fixed because the thickness is determined by its dielectric constant. Additionally, a low value of dielectric constant results in a thick dielectric slab. The results given in Figure 2 show that our proposed artificial material is able to obtain a selected value of permittivity. Using this artificial material, much more selections on the thickness of the dielectric slab can be realized. Furthermore, a high value permittivity corresponding to a thinner dielectric slab is available.

The RCA proposed in this paper is an example working on 15 GHz. The patch antenna working at this frequency has been used in our previous studies. The design procedures of the artificial material for RCA are summarized below,

(1) Determine the frequency of RCA. In this study, the patch antenna resonates at 15 GHz, so the frequency is 15 GHz.

(2) Calculate the wavelength λ_0 in free space. In this design example, $\lambda_0 = 20\,\text{mm}$.

(3) Determine the thickness of the artificial material h. In this design, we choose $h = 1.2\,\text{mm}$. The FR-4 multilayer PCB (printed circuit board) in this thickness is low in cost and easily obtained.

(4) Determine the relative dielectric constant of the artificial. The thickness should be an integer multiple of the half of effective wavelength. For the thinnest slab with $n = 1$, we obtain $\varepsilon_r = 69$ according to the following equation.

$$\varepsilon_r = \left(\frac{n \cdot \lambda_0}{2h}\right)^2 \tag{3}$$

(5) Refer to Figure 2(c), and find the dimension of the metal particle required for the artificial material with $\varepsilon_r = 69$. We get $r = 1.2\,\text{mm}$ for $\varepsilon_r = 69$.

Figure 4 shows the structure of the designed artificial material. It consists of 6 conducting layers separated by FR-4 material. The total thickness is 1.2 mm. The designed structure is simple because the particles are in a uniform circular pattern. Figure 5 shows photographs of the fabricated artificial

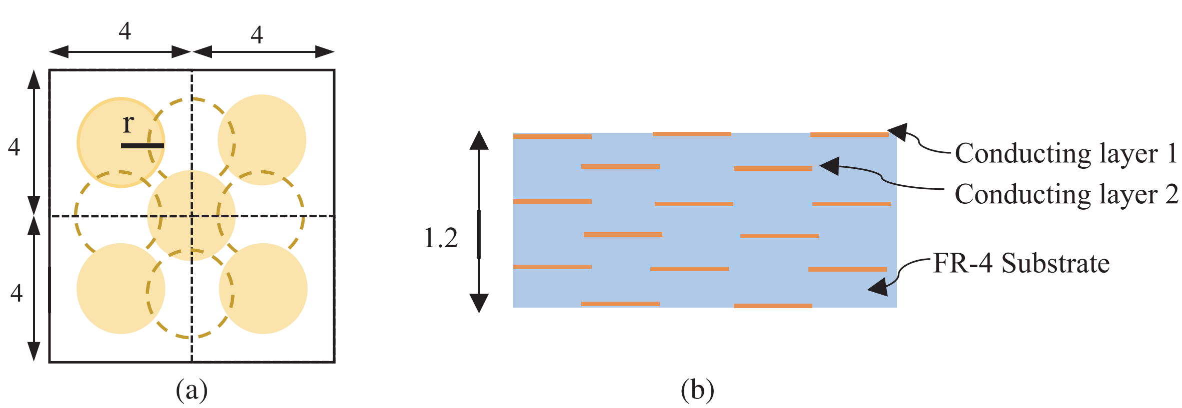
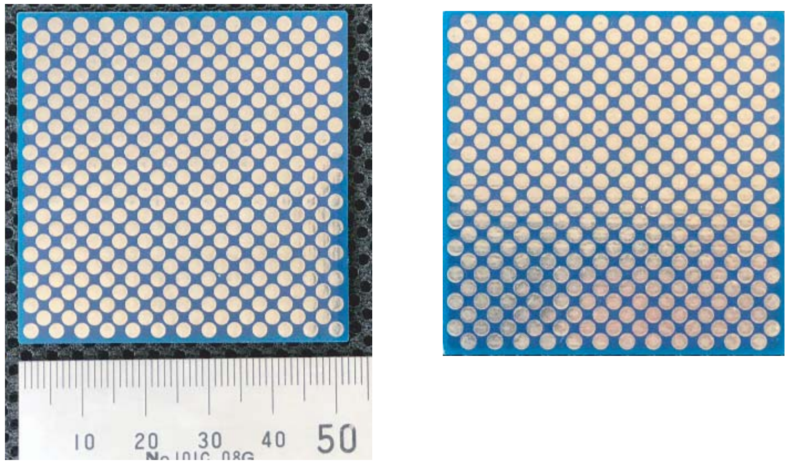


Figure 4. Structure of the proposed artificial material. Circular metal pattern $r = 1.2$, unit: mm. (a) Overview of 4-cells artificial material. The pattern in circle is on odd conducting layer, and the pattern in dot line circle is on even conducting layer. (b) Cross section view of partial artificial material.



(a) (b)

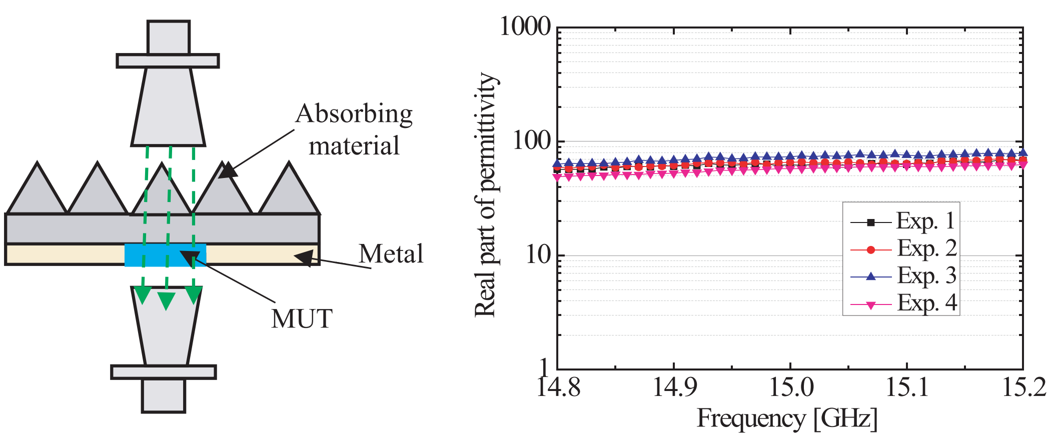
Figure 5. Prototype of the artificial material. The size of the prototype is 52 mm × 52 mm. (a) Pattern of odd conducting layers. (b) Pattern of even conducting layers.

material, which is implemented in a multilayer printed circuit board.

To evaluate the dielectric property of the fabricated artificial material, the dielectric constant of the material was estimated by a microwave free-space measurement method. The real part of permittivity ε' of the material under test (MUT) can be determined according to the phase shift through MUT with the following equation [20–22],

$$\varepsilon' \simeq \left(1 + \frac{\Delta\phi\lambda_0}{360d}\right)^2 \tag{4}$$

where $\Delta\phi$ is the phase shift through MUT, λ_0 the wavelength in the free-space, and d the thickness of MUT. Figure 6(a) shows the measurement setup to estimate ε' for the fabricated artificial material. A calibration of RESPONSE of Network Analyzer was performed in the measurement. The measured real part of the effective permittivity is shown in Figure 6(b). The average value of ε' of four measurements is 65, which is near the designed value of 69, as summarized in Table 1.



(a) (b)

Figure 6. Measurement of permittivity for the fabricated artificial material. (a) Microwave free space measurement setup. (b) The real part of permittivity of the proposed artificial material.

Table 1. Measured result of real part of permittivity @15 GHz.

	Exp.1	Exp.1	Exp.1	Exp.1	Average of Exp. Value	Designed value
ε'	62.8	65.7	73.7	57.7	65	69

4. GAIN PROPERTY OF RCA

The gain properties of RCA using the proposed artificial material are evaluated by the simulation and experimental methods. One or multiple slabs of the proposed artificial material are set in front of the patch antenna, and the gain properties are evaluated. In the simulation, the dielectric material slab is

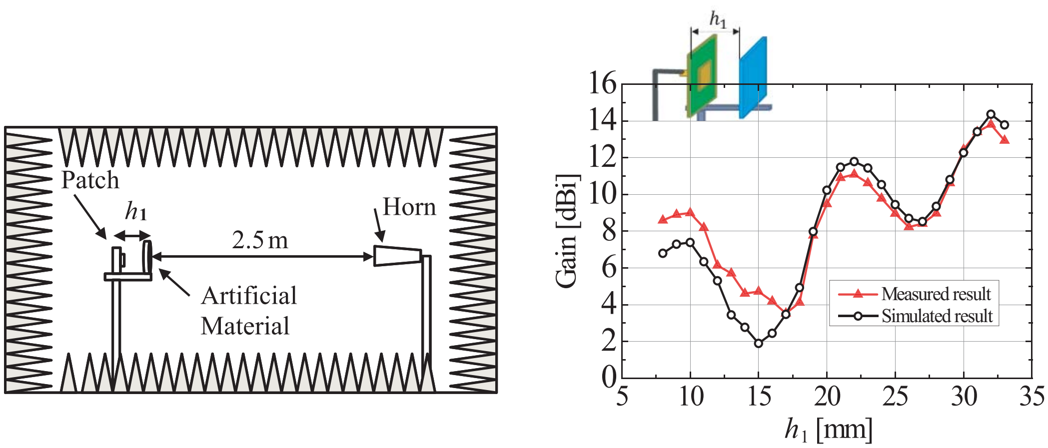


Figure 7. (a) Experimental setup for antenna gain evaluation. (b) The simulated and measured gain with respect to the distance h_1 when one slab of the proposed artificial material is set in front of a patch antenna.

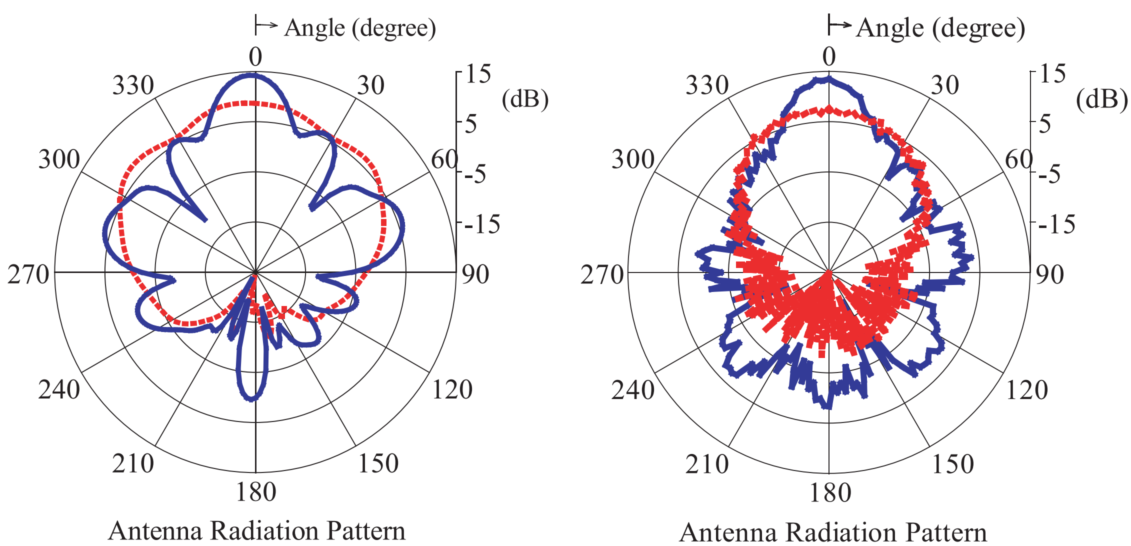


Figure 8. Radiation patterns of patch antenna with and without the artificial material. The artificial slab is set 30 mm in front of the patch antenna when it is used. (a) The simulated results. (b) The measured results.

not the proposed artificial material. It is just a material whose dielectric constant is set as 69 because it is difficult to simulate such a large artificial material with so many metal pieces. In the experiments, the setup shown in Figure 7(a) is used to measure the gain by a HP8720ES network analyzer in an anechoic chamber. The patch antenna resonates at 15 GHz. It is implemented on a Cuflon substrate with a relative permittivity of $\varepsilon_r = 2.2$ and thickness of 0.8 mm. The size of the ground plane is 50 mm × 50 mm. Figure 7(b) shows the gain with respect to the distance between the patch and the dielectric slab h_1 when one slab of the artificial material is set in front of the patch antenna. The measured results agree well with the simulated ones. The value of gain varies much with the distance because of the standing wave between the patch and the artificial material. It can be seen that the gain is enhanced when the distance h_1 is the multiple of the half wavelength. The simulation result shows that the maximum gain is improved to 14.1 dBi, while the gain of the patch antenna without the slab is 8.0 dBi. The experimental result shows that the maximum gain is improved to 13.5 dBi, while the gain of the patch antenna is only 6.7 dBi. Figure 8 shows the simulated and measured radiation patterns for the patch antenna (without the artificial material) and RCA when one slab of the artificial material is set at 30 mm in front of the patch antenna.

Figure 9 shows the gain properties when 2 slabs of the proposed artificial material are set in front of the patch antenna. The measured results agree well with the simulated ones. Unlike the result of the

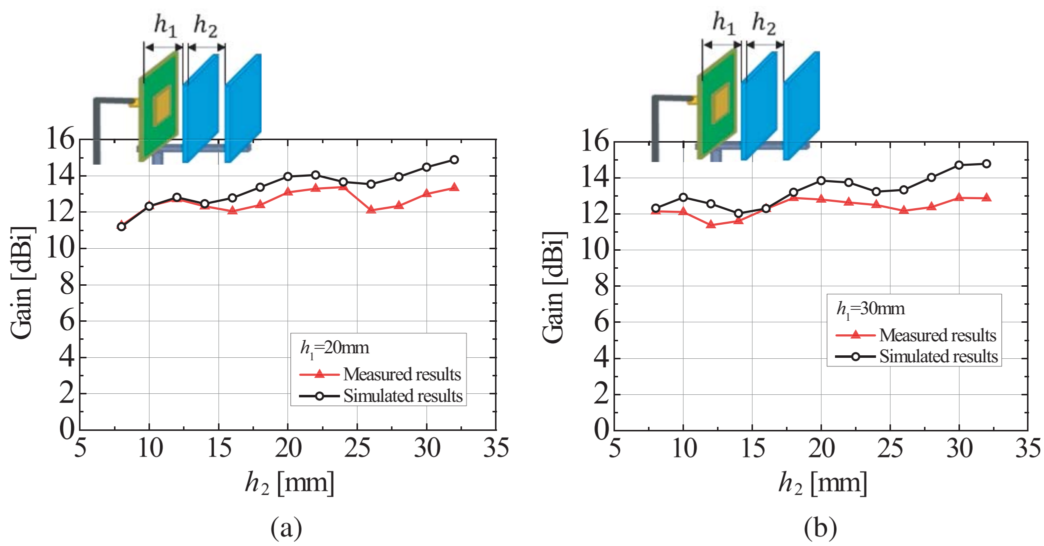


Figure 9. The simulated and measured gain with respect to the distance h_2 when 2 slabs of the proposed artificial material are set in front of a patch antenna. (a) $h_1 = 20$ mm. (b) $h_1 = 30$ mm.

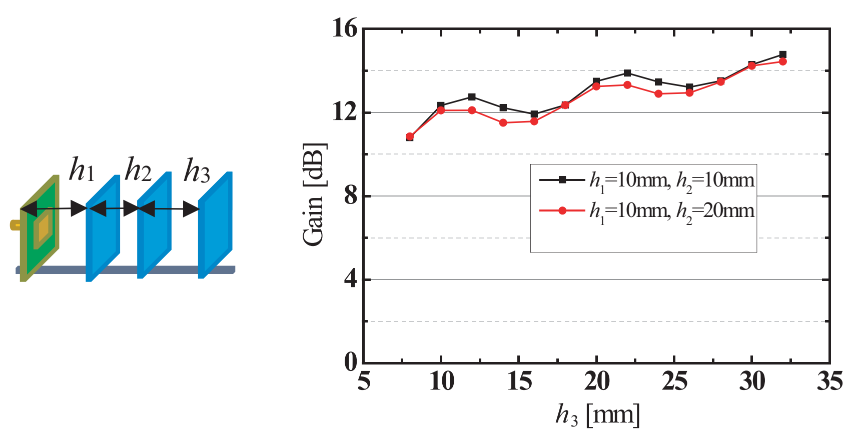


Figure 10. Gain enhancement when multiple slabs of the proposed artificial material are set in front of the patch antenna.

gain of RCA with one slab, the value of gain varies little with respect to the distance between the slabs. The maximum gain is about 14 dBi. Figure 10 shows the gain properties when 3 slabs of the proposed artificial material are set in front of the patch antenna. For an RCA with multiple slabs, it is shown that further enhancement of the gain is not achievable by only increasing the pieces of the dielectric material.

5. CONCLUSIONS

This paper proposes an artificial material for the resonant cavity antenna (RCA). The proposed artificial material has 6 conducting layers separated by FR-4 material. The metal layers are made of a large number of circular conducting particles arranged in FCS. The analytical result shows that the effective permittivity of the artificial material varies from 4 to 178 when the metal disks radius r increases from 0.2 to 1.4 mm. The proposed artificial material is a very good material for RCA because its permittivity can be controlled by selecting the radius. Additionally, a very thin dielectric slab can be realized by using an artificial material with a high-value permittivity.

The fabricated artificial material is 52 mm $\times$ 52 mm, with a total thickness of 1.2 mm. The permittivity of the fabricated artificial material is estimated by a microwave free-space method. The measured real part of the effective permittivity is 65, which is near the designed value of 69. One or multiple slabs of the proposed artificial material are set in front of a 15 GHz patch antenna, to construct resonant cavity antennas. The gain properties of RCAs are evaluated using both simulation and measurement methods. When one slab of the artificial material is used, the maximum gains obtained in simulation and measurement are 14.5 dBi and 12.8 dBi at 15 GHz, respectively. The gain is improved compared to the gain of the patch antenna without the dielectric slab. When multiple slabs are used, the gain enhancement has also been shown. However, a further gain improvement is not obtained by adding additional slabs of the artificial material.

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