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Research Article

Designing Wideband Microstrip Reflectarrays for 10 GHz

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Abstract

This paper presents two microstrip reflectarray designs based on variable size unit cells for 10 GHz. One design uses a 3-layer unit cell with polygon shaped patch and the other uses a unit cell with 1-layer square loop patch. Both arrays have a size of 10λ × 10λ at 10 GHz, can reflect the incoming wave as a high gain pencil beam in the desired direction of θ = 30°. Gains at 10 GHz are 23.6 dB and 26.1 dB for the 3-layer and one-layer structures, respectively. The multi-layer structure resulted in a wider gain banwdith. Simulation results show that the 3-dB gain bandwdith is about 22% for the 3-layer structure reflectarray, as compared to 12% for the one-layer structure.

Keywords: Microstrip, Unit cell, Multilayer, Reflectarray, Bandwidth.

10 GHz için Geniş Bant Mikroşerit Yansıtıcı Dizi Tasarımı

Öz

Bu çalışma, 10 GHz için iki mikroşerit yansıtıcı dizi tasarımı sunmaktadır. İstenen yönde yansıtma elde etmek için her iki yansıtıcı yüzeyde değişken boyutlu birim hücreler kullanılmıştır. Yüzeylerden birinde, çokgen biçimli mikroşerit yama ve 3 katmanlı birim hücre, diğerinde kare çevrim biçimli yama ve tek katmanlı yapı kullanılmıştır. Her iki dizi de 10 GHz'de 10λ × 10λ boyutunda olup, gelen dalgayı θ = 30° yönünde yüksek kazançlı kalem ışın olarak yansıtmaktadır. 10 GHz'deki kazanç, 3-katmanlı yapı için 23,6 dB ve tek katmanlı yapı için 26,1 dB'dir. Çok katmanlı yapı ile daha geniş kazanç-bant genişliği elde edilmiştir; 3-dB kazanç bant genişliği 3- katmanlı yapı için yaklaşık %22 iken tek katmanlı yapı için yalnızca %12 olarak bulunmuştur.

Anahtar Kelimeler: Mikroşerit, Birim hücre, Çok katmanlı yapı, Yansıtıcı dizi, Bant genişliği.

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1. Introduction

Reflective surfaces are seen as a promising technology that can improve the quality of wireless communication by reconfiguring the wireless propagation environment in a desirable manner (Dai et al., 2020). Reflective surfaces are two dimensional structures with a large number of programmable passive reflector elements (also known as unit elements or cells) that have the ability to reflect an incoming wave in a specific direction. Reflective surfaces (also known as reflectarrays) can be implemented using microstrip techniques and easily mounted on a wall or ceiling. They can be used for improving coverage at microwave frequencies by illuminating dead zones where line-of-sight path is obstructed, and therefore, can play a major role in improving capacity and boosting the quality of systems without additional power consumption (Rajatheva et al., 2020) (Zhao & Liu, 2019). Furthermore, low weight and ease of deployment make microstrip reflective surfaces ideal for many applications.

The main limitation of microstrip reflective surfaces is their narrow bandwidth owing to two factors; the narrow bandwidth of the unit radiating elements, and the different phase delay from source to each element. The bandwidth of a microstrip patch varies between 3 and 10 % (Huang, 1995). Approaches to increase the bandwidth include use of a thick substrate, but this reduces the phase range that can be obtained from a unit cell (Nayeri, Yang, & Elsherbeni, 2018). Another technique is to use multi-layer structures, which can increase the phase range significantly, and then increase the dielectric thickness of each layer to obtain a smoother and more linear phase variation, and hence a wider bandwidth. For example 16% bandwidth was achieved for a two-layer 40 cm prototype at 12 GHz (Encinar, 2001).

In order to have a directional reflected beam, the spatial phase delay from source to the unit cells needs to be compensated by varying the reflection phase at each unit cell. The phase of the reflected wave can be changed by varying the dimensions of the unit cells or the length of the phase line connected to the unit elements. With these approaches, the reflection phase range is usually limited to a range of 360º, and the reflection phase of unit cells is exactly adjusted at the design frequency, but changing rapidly around the resonant frequency, giving an S-shaped reflection phase versus element size curve. As a result, phase distribution across the aperture will be distorted at frequencies other than the design frequency, hence limiting the operational bandwidth.

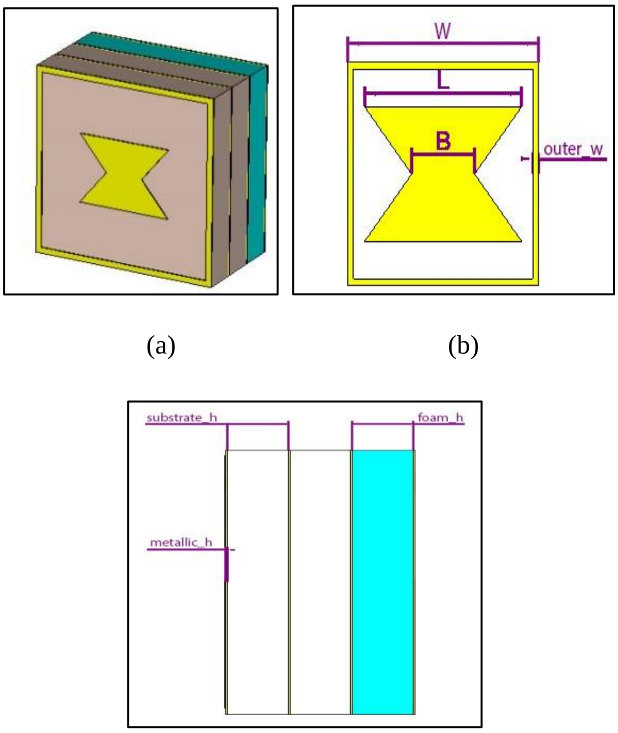
This paper investigates two reflectarray surfaces designed (one with 3-layered and the other with one-layer structure) to reflect incident signals at 10 GHz with high gain, and compares their performance regarding gain and bandwidth. Variable element size approach was used for both surfaces.

2. Design and Simulation of Reflectarray Surfaces

2.1. Unit Cell Designs

There are two main steps in designing reflectarrays; the unit cell (element) design, and the entire surface design. In this work, a variable element size approach was used to control the reflection phase of unit cells. Computer Simulation Technology (CST) (Microwave Studio Suite) was used to design and simulate the unit cells and arrays. MATLAB was used to calculate appropriate reflection phases (i.e. element sizes) for each element of the array aperture, and to transfer the reflection phase versus element location results to CST to enable automated design of reflectarrays. Antenna Magus was used to design a source antenna to illuminate the array in the CST.

Unit cells were first designed and the data for reflection phase versus element size obtained. The unit cells providing phase ranges greater than 310º were used in the array designs. A wide range of reflection phases were necessary to reflect the incident wave as a collimated beam in a desired direction. In this paper, we present results for two unit cell structures; one with three-layers of a polygon shaped patch in a square ring (Fig. 1), the other is a single layer of a square loop patch (Fig. 2). The unit cell with 3 layers of reflecting surfaces is shown in Fig. 1a, and its dimensions are given in Table 1. In this unit cell, two FR-4 substrate layers were used between the three reflecting metallic surfaces, backed by a ground plane separated by a foam layer of thickness 1.5 mm and permittivity of ε_r=1.37 (Fig. 1c). The thickness of each FR-4 substrate is 1.6 mm with relative permittivity ε_r=4.3, and loss tangenttan) δ) 0.025.



(a) (b)

(c)

Fig. 1. 3-layered unit cell with polygon shaped patch: (a) 3D structure; (b) top view; (c) side view

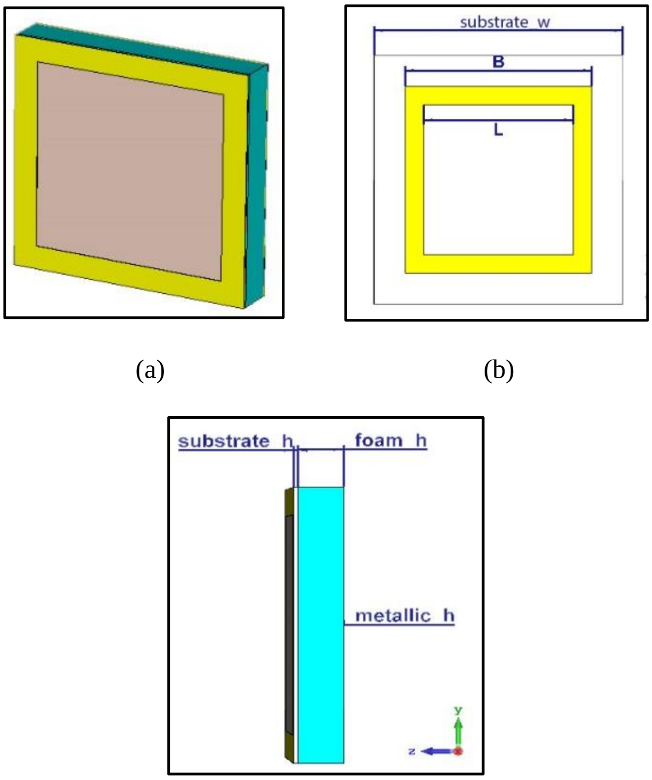
Table 1. The dimensions of the 3-layered unit cell.

Parameter	Value (mm)
W	8
B	0.4L
Outer_w	0.25
Substrate_h	1.6
Foam_h	1.5
metal_h	0.035

The one-layer unit cell consists of a metallic square loop with inner length ‘L’ and outer length ‘1.25*L’ printed on a Roger RT 5880 substrate (with thickness of 1.6 mm, $\varepsilon_r = 2.2$ and $\tan\delta = 0.0009$), and backed by a ground plane separated with a foam layer of thickness 1.5 mm (Table 2) and relative permittivity $\varepsilon_r = 1.37$.

A Floquet port was used to excite and to obtain reflection characteristics (magnitude and phase values) of the unit cells for varying element sizes. The Floquet port was placed at a distance of about half a wavelength at 10 GHz from the top of the unit cells. The edge length, L, of the polygon in the 3-layered unit cell was varied from 2 mm to 7 mm, and the edge length, L, in square loop was varied from 1 mm to 8 mm. The magnitude of the reflection coefficient was greater than 0.75 for the first unit cell and greater than 0.83 for the second. Fig. 3 shows reflection phase versus L for the two unit cells. The variation of the reflection phase is about 320º for the 3-layered unit cell and 330º for the one-layer unit cell. These reflection phase ranges are sufficient to provide the desired reflection phase at each unit element in order to compensate the phase differences due to distances from the source to the array elemets on the reflectarray surface. The change in the phase curve for the 3-layer structure near resonance is less steep than that for the one-layered unit cell, making phase change less sensitive to the unit cell size and frequency. As a result, a wider operational frequency band is expected for the 3-layer structure.

The reflection phase versus element size characteristic is then used in the entire array design to select element sizes. Element sizes on the array surface are chosen so as to obtain compensating phase shifts for a collimated beam in the desired direction.



(a) (b)

(c)

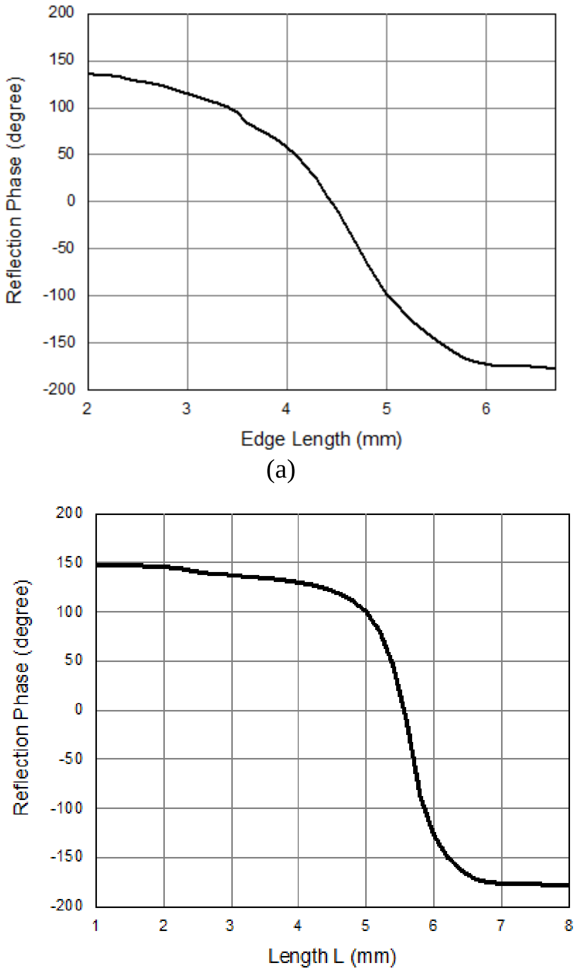
Fig. 2. One-layer square loop unit cell: (a) 3D structure; (b) top view; (c) side view.

Table 2. The dimensions of the one-layered unit cell.

Parameter	Value (mm)
W	10
B	1.25L
Outer_w	0.127
Substrate_h	1.6
Foam_h	1.5
metal_h	0.035

2.2. Reflectarray Design

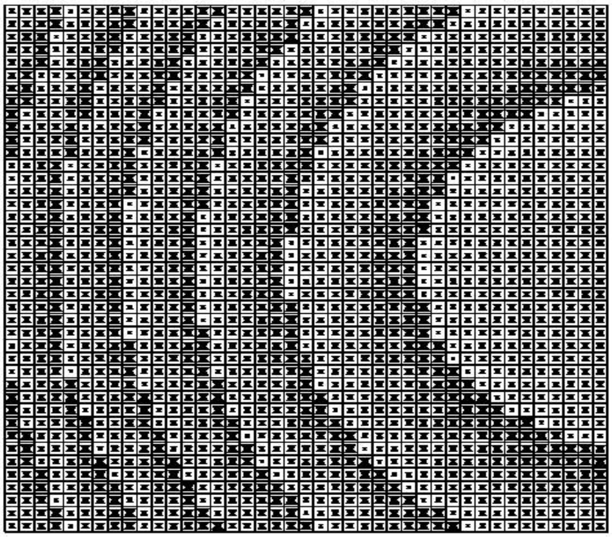
Design of the entire array requires determining the appropriate reflection phase (i.e. appropriate unit cell size) at each unit cell in the aperture in order to compensate for the differences in spatial phase delay in the incoming wave and thus obtain a collimated beam in a specific direction. For the current work, the arrays were designed to be $10\lambda x 10\lambda$ in size and reflect the incoming wave in the direction of θ=30º. The required phase distribution on the array aperture is calculated in MATLAB. The data table for phase shift versus cell size from the unit cell design stage in CST is used to determine appropriate cell dimensions for each element location on the array aperture. Fig. 4 shows the mask plots for the reflection direction of θ=30º (Fig. 4a-b), and for the 3-layered structure (Fig. 4c).



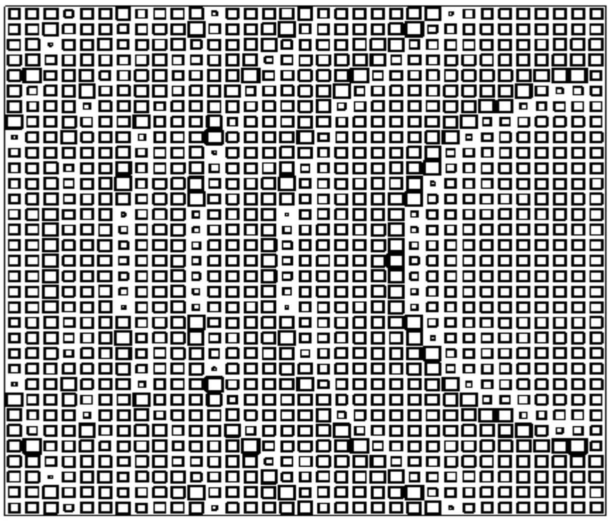
(a)

(b)

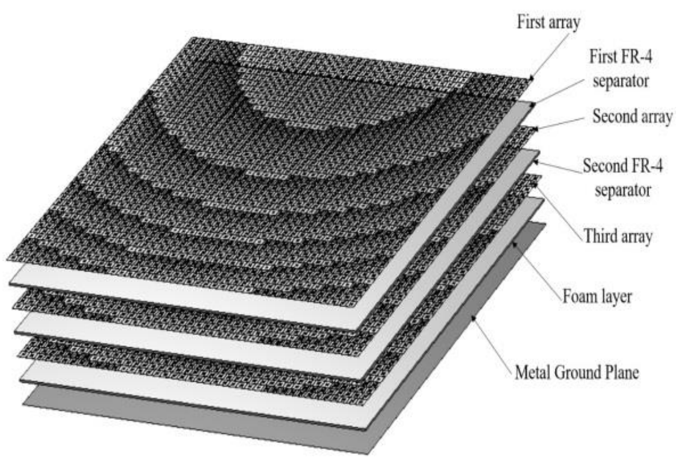
Fig.3. Reflection phase versus unit element size: (a) 3-layer polygon shaped patch; (b) one-layer square loop patch.



(a)



(b)



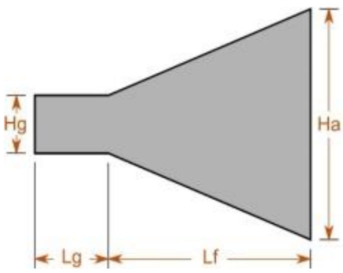
(c)

Fig. 4. Masks of the arrays for reflection in the direction of θ =30°: (a) the array with 3-layer polygon unit cell; (b) the array with one-layer square loop unit cell; (c) the 3-layers of the entire array with polygon unit cells.

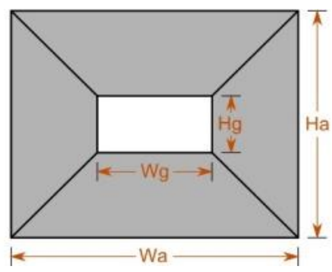
2.3. Far-field Radiation Analysis of the Arrays

A horn antenna was designed using the Antenna Magus, and used as the source antenna in the CST simulations. The geometry of the horn antenna is given in Fig. 5, and the dimensions are shown in the figure caption. The horn antenna was analyzed in CST; s_{11} was below -20dB over 9 GHz to 11 GHz, and the boresight gain was 17.6 dBi at 10 GHz, hence radiating the power in a directive beam. Therefore, the horn can be used for illuminating the reflectarray surfaces.

The 10λ × 10λ reflectarrays are placed at a distance from the source horn according to f/D=1, where D is the dimension of the reflectarray antenna and f is the distance between the source antenna and the surface of the reflectarray.



(a)



(b)

Fig. 5. Dimensions of the horn antenna (in mm): Hg=11.76; Wg=23.53; Lg=29.97; Lf=79.96; Ha=78.19; Wa=102.01.

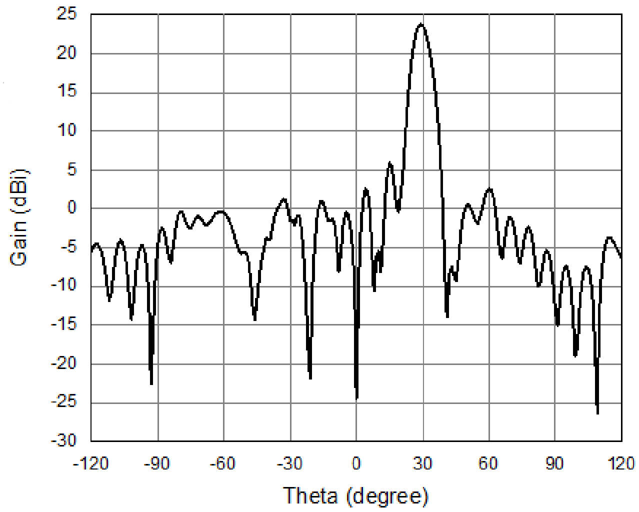
3. Results

3.1. Radiation Patterns

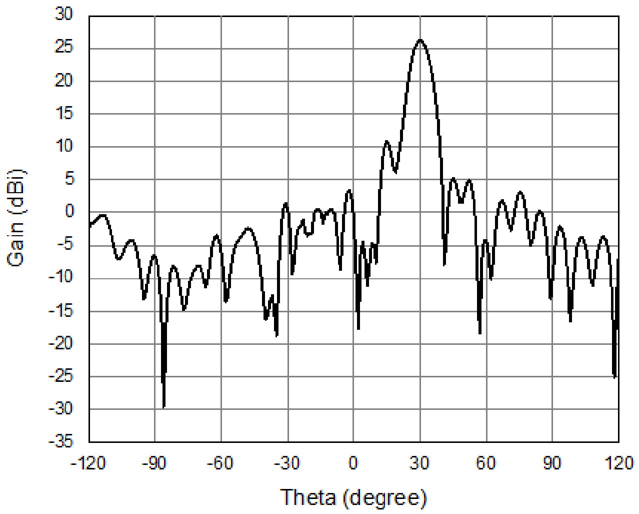
The two-dimensional radiation patterns on the E-plane for 10 GHz are shown in Fig. 6. It can be seen that both arrays reflect the incoming wave as a high gain pencil beam in the desired direction of 30° (θ = 30°). The 3-layered array with polygon-shaped unit cell has a main beam with a gain of 23.6 dBi in the direction of θ ≈ 29° (Fig. 6a), and the one-layer array with square loop unit cells (Fig. 6b) has a gain of 26.1 dBi at θ = 30°; the main beam of the former being slightly narrower than that of the latter. Side lobe level is 18 dB for the 3-layer structure and 16 dB for the one-layer structure.

3.2. Bandwidth

Simulations were performed at different frequencies to determine the gain bandwidth of the proposed arrays. The gain versus frequency plots for the reflectarrays are given in Fig. 7. A peak gain of 23.8 dBi is obtained at 9.8 GHz for the 3-layered structure (Fig. 7a), and 26.5 dBi at 10.2 GHz for the one-layer structure (Fig. 7b). The 3-dB gain bandwidth was about 22% (8.9–11.1 GHz) for the 3-layered structure, and 12% (9.5 – 10.7 GHz) for the one-layer structure.



(a)

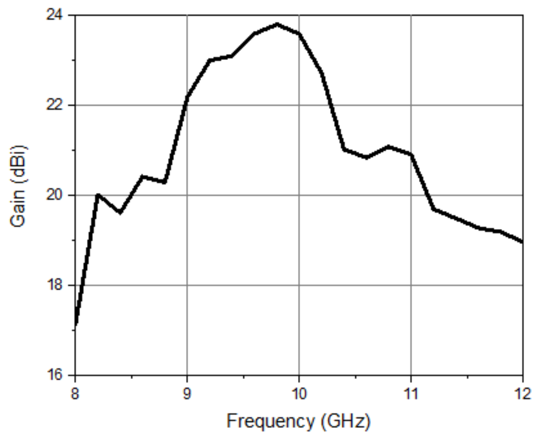


(b)

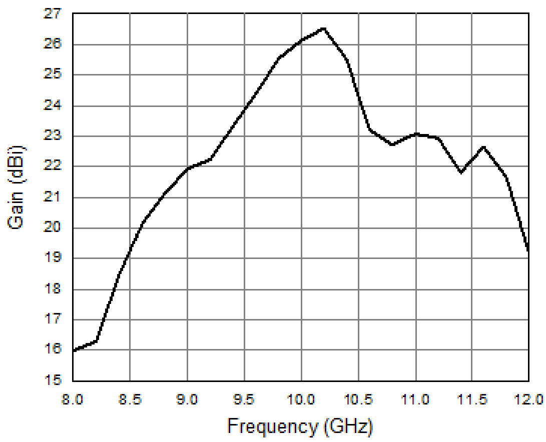
Fig. 6. Radiation patterns; (a) the array with 3-layer polygon unit cell; (b) the array with one-layer square loop unit cell.

4. Conclusions

Two reflectarray structures were designed to reflect incoming wave in the direction of $\theta = 30°$ and simulated; one with 3-layer unit cells of polygon shaped patches and one with one-layer unit cells of square loop patches. Both arrays can reflect the incoming wave as a high gain pencil beam in the desired direction of $\theta = 30°$. The 3-layered structure resulted in 23.6 dB gain at 10 GHz and about 22% 3-dB gain bandwidth. The corresponding values for the one-layer structure were 26.1 dBi and 12%, respectively.



(a)



(b)

Fig. 7. Bandwidths of the arrays: (a) the array with 3-layer polygon unit cell; (b) the array with one-layer square loop unit cell

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