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Authors

Campione, S
Hosseini, SA
Guclu, C
[et al.](#)

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A Comparison of Metalayers Based on Arrayed Pairs of Planar Conductors

Salvatore Campione, S. Ali Hosseini, Caner Guclu,
Shiji Pan, and Filippo Capolino
Department of Electrical Engineering and Computer
Science
University of California Irvine
Irvine, CA, USA
{scampion, sahossei, cguclu, shijip, fcapolino}@uci.edu

Alexander G. Schuchinsky
Institute of Electronics, Communications and Information
Technology, Titanic Quarter
Queen's University Belfast
Belfast, UK
a.schuchinsky@ee.qub.ac.uk

Abstract—In this work we compare the performance of metamaterials based on layers of planar pair conductors with various shapes: dogbone with rectangular and triangular lattice, square loop and gangbuster. We first show the characteristics of transmission, reflection and absorption, and then we compare the absorption coefficient for the four considered structures. We inspect the dependence of the absorption coefficient on unit cell metal density in the case of triangular lattice dogbone pair and gangbuster pair. Last, we analyze the behavior of artificial magnetic conductors above a grounded substrate.

Keywords—metalayers; miniaturization; transmission; reflection; absorption; dogbones; squares; gangbusters; artificial magnetic conductor (AMC)

I. INTRODUCTION

Recently, arrayed periodic pairs of planar conductors have been adopted to engineer both the magnetic and electric resonances to obtain DNG effective behavior. A review on metalayer structures adopted for this purpose has been presented in [1] for both microwave and optical frequencies. In [2,3], properties of pairs of layers of dogbone-shaped conductors have been investigated by forming a 2D isotropic negative refractive index metamaterial for planar technology. These studies have been followed by [4], which analyzed the same effect in pairs of conductors forming a Jerusalem cross. Same investigation has been carried out for pairs of tripoles in [5] and for pairs of metalized patterns made of patches and thin strips in [6]. The properties of a square loop pair have been investigated in [7], in order to obtain negative refractive index at THz frequencies. Pairs of layers of gangbusters have been analyzed in [8].

In this paper we have performed a comparative study of the doubly periodic arrays of planar conductors of different shapes. The considered unit cells are made of pairs of gangbusters, square loops and dogbones in rectangular lattice, and we propose here dogbone pairs in triangular lattice with increased coupling between the elements.

Figure 1. Metalayer unit cells made of pairs of copper conductors. Only the top metal is shown: (a) rectangular lattice of dogbone pairs, (b) triangular lattice of dogbone pairs, (c) square loop pairs, and (d) gangbuster pairs.

II. METAMATERIAL UNIT CELLS

Figure 1 shows the metalayer structures (periodic in x and y directions) based on planar copper conductor pairs (stacked along the z direction) analyzed in this paper.

We will consider unit cells of all the arrangements having the same area of 49 mm^2 as common parameter. We then set $A = B = 7 \text{ mm}$ for the geometries in Fig. 1(a-c), whereas $A = 12 \text{ mm}$ and $B = (49/12) \text{ mm}$ for the layout in Fig. 1(d). It is noteworthy that in the case of gangbuster pairs, the magnetic (antisymmetric) resonance frequency is primarily controlled by the substrate thickness and the length of the each conductor in the unit cell. Indeed, longer gangbuster elements are needed to resonate at lower frequencies. This is the reason why the unit cell cannot be square in this case.

Our objective is to identify the metalayer structure that allows for the lowest working frequency (i.e., the one that achieves the highest miniaturization level in terms of wavelength). In all the cases analyzed in the following sections, we will assume that the substrate is TLY-5 material with

permittivity $\epsilon_r = 2.2$ and $\tan \delta = 0.0009$, and that the thicknesses of the copper conductors and substrate are $t = 30 \mu\text{m}$ and $H = 0.5 \text{ mm}$, respectively. The metalayers are illuminated by a plane wave with the reference plane placed at a distance $C = 7 \text{ mm}$ and $C = 12 \text{ mm}$ from the top metal layer in cases of the unit cells in Fig. 1(a-c) and Fig. 1(d), respectively.

III. TRANSMISSION, REFLECTION AND ABSORPTION

Transmission (T), reflection (R) and absorption (A) coefficients have been simulated for the metalayer arrangements of Fig. 1. Remember that these three parameters are related by the following formula

$$A = 1 - |T|^2 - |R|^2. \quad (1)$$

These three coefficients are shown in Fig. 2 for the dogbone pair metalayers (triangular lattice) in dB scale ($10 \log A$ for the absorption). The unit cell parameters, according to Fig. 1(b), are $A_1 = B_2 = 1.4 \text{ mm}$, $A_2 = 6.5 \text{ mm}$, $B_1 = 5 \text{ mm}$.

Figure 2. Transmission, reflection and absorption for metalayers with a triangular lattice of dogbone pairs.

The transmission peak $T = -1.0 \text{ dB}$ is attained at about 8.7 GHz, as shown in Fig. 2, and the absorption coefficient is about -7.1 dB at the same frequency.

IV. COMPARISON OF THE ABSORPTION COEFFICIENT OF DIFFERENT METALAYERS

In this section, we consider conductors having the same width, i.e. $A_1 = B_2 = 1.4 \text{ mm}$, $B_1 = 5 \text{ mm}$, and $A_2 = 6.5 \text{ mm}$ for the unit cells in Fig. 1(a-c), whereas $A_2 = 11.5 \text{ mm}$ for the unit cell in Fig. 1(d), in order to keep the same gap in the x direction between two contiguous elements of different unit cells. Notice that in the case of pairs of dogbones and square loops, the unit cell contains one element, whereas in the case of pairs of dogbones in triangular lattice and gangbusters, the unit cell comprises two complete elements, as can be inferred from Fig. 1.

Figure 3. Comparison of the absorption coefficient for the metalayers in Fig. 1, keeping the area of the unit cell and the metal width equal for different conductor shapes.

We compare the absorption coefficient for the four discussed layouts in Fig. 3. The square loop pair gives comparable absorption $A = -8.0 \text{ dB}$ (with respect to the gangbuster and dogbone in triangular lattice) at about 10.8 GHz. This structure appears to be the least suitable for miniaturization purposes since it also resonates at higher frequency than the other analyzed layouts. Similarly, the dogbone pair in rectangular lattice gives $A = -5.4 \text{ dB}$ at about 9.2 GHz. Notice that also in this case the metalayer resonates at higher frequency with respect to the gangbuster and dogbone in triangular lattice; moreover, the absorption coefficient is decreased. This limitation can be improved by using triangular lattices, as in the gangbuster and dogbone cases. Notice that the best absorption coefficient profile is obtained by using the gangbuster pairs, for which the peak is $A = -8.8 \text{ dB}$ at about 8.3 GHz. Remarkably, this structure resulted to be the most suitable for miniaturization with respect to the wavelength (remember that we consider different unit cells with the same area) in comparison to the other considered structures. However, the second design for miniaturization is the dogbone pairs in triangular lattice, that presents $A = -7.0 \text{ dB}$ at about 8.7 GHz. We want to emphasize that dogbones in triangular lattice considerably reduce the size for expense of small increase of absorption with respect to the gangbuster pair. However, at the same time, they provide more flexibility in controlling mutual positions of the electric and magnetic resonances as compared with gangbusters (for which they are mostly controlled by the length of the conductors).

V. PARAMETRIC STUDY

In this section we demonstrate how the density of the copper conductor pattern in the unit cell affects the overall performance of the metalayer in terms of resonance frequency and absorption coefficient. We analyze here the dogbone in triangular lattice and gangbuster pairs.

A. Metalayer with dogbone pairs in triangular lattice

The frequency dependence of the absorption coefficient is investigated for metalayers of dogbone pairs in triangular lattice at low, medium and high pattern density. The

dimensions of the three analyzed designs are given in Table I. Results are provided in Fig. 4.

TABLE I. TRIANGULAR LATTICE DOGBONE PAIRS OF METALAYERS PARAMETRIC ANALYSIS BY VARYING THE UNIT CELL PATTERN DENSITY

Dimension	Unit cell metal density		
	Low [mm]	Medium [mm]	High [mm]
A_1	0.4	0.9	1.4
B_1	5.0	5.0	5.0
A_2	6.5	6.5	6.5
B_2	0.4	0.9	1.4

It can be observed in Fig. 4 that increasing the unit cell pattern density affects the maximum of the absorption coefficient as well as its frequency. As such, in the case of low pattern density, the absorption peak is $A = -4.2$ dB at 7.8 GHz, whereas it becomes $A = -5.9$ dB at 8.3 GHz for medium pattern density, and $A = -7.0$ dB at 8.7 GHz for high pattern density.

Figure 4. Comparison of the absorption coefficient in the case of low, medium and high pattern density for the triangular lattice dogbone pairs of metalayers.

This result allows us to state that once the structure has been designed to work at a particular frequency, fine tuning can be realized by modifying the pattern density within the same unit cell, as previously described.

B. Gangbuster pairs of metalayers

Similarly to the previous section, the frequency dependence of the absorption coefficient is investigated for metalayers with the gangbuster pairs of low, medium and high filling density. The simulation results are presented in Fig. 5 for the dimensions of the three designs specified in Table II.

Figure 5 shows that, increasing the unit cell pattern density, the peak of the absorption coefficient shifts to lower frequencies (in opposition to what happens in case of dogbone pairs in triangular lattice) and slightly changes its height. As such, in the case of low pattern density, the absorption coefficient is $A = -8.8$ dB at 8.3 GHz, whereas it becomes

$A = -9.0$ dB at 7.5 GHz for high pattern density.

TABLE II. GANGBUSTER PAIRS OF METALAYERS PARAMETRIC ANALYSIS BY VARYING THE UNIT CELL PATTERN DENSITY

Dimension	Unit cell metal density		
	Low [mm]	Medium [mm]	High [mm]
A_1	0.8	1.4	1.9
A_2	11.5	11.5	11.5

Figure 5. Comparison of the absorption coefficient in the case of low, medium and high pattern density for the gangbuster pairs of metalayers.

The obtained results show again that once designed for a particular frequency, this structure allows fine tuning to the working frequency by modifying the pattern density within the same unit cell, without deteriorating the absorption coefficient.

Figure 6. Comparison of the absorption coefficient in the two best designs in Sec. V, corresponding to the high density patterns designs in the unit cell.

VI. COMPARISON

We compare here the best two designs in terms of the absorption coefficient discussed in Sec. V by modifying the conductor pattern density in the unit cell. As such, the best results have been achieved with the high density pattern configuration for both dogbones in triangular lattice and gangbuster pairs.

We observe in Fig. 6 that the gangbuster seems to provide better performance in terms of miniaturization with respect to the wavelength as well as in terms of absorption frequency profile.

VII. ARTIFICIAL MAGNETIC CONDUCTOR BEHAVIOR

In this section, the four differently shaped conductor geometries in Fig. 1 are evaluated in terms of their applicability as artificial magnetic conductors (AMC). AMC behavior has been related to the zero phase of the reflection coefficient for AMC made by single layers of shaped copper conductors as in Fig. 1 over a perfect electric conductor (PEC) ground plane [9,10].

Figure 7. Comparison of the (a) magnitude and (b) phase of the reflection coefficient (computed at the top metal layer surface) for AMC made by single layers of shaped conductors as in Fig. 1 over a PEC ground plane, with the dimension proposed in Sec. IV.

To analyze such a behavior, Fig. 7 shows the magnitude and the phase of the reflection coefficient (computed at the top metal layer surface) of an AMC made by a single layer of shaped copper conductors (to account for metallic losses) as in Fig. 1 on the top of a substrate above a PEC ground plane. In our preliminary results, it can be observed that the AMC made

by a single layer gangbuster presents smaller losses than all the other geometries.

VIII. CONCLUSION

In this paper we compared the performance of arrayed pairs of planar copper conductors. We analyzed four different unit cells: dogbones in rectangular and triangular lattices, square loops and gangbusters. We have observed that more design flexibility in the working frequency is provided by dogbones in triangular lattice in comparison to all the other cases. However, gangbuster topology has demonstrated the best performance in terms of absorption, miniaturization rates, and losses while keeping the unit cell area fixed between different geometries.

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