DESIGN AND SIMULATIONS OF FRACTAL HIGH-IMPEDANCE SURFACES FOR MODERN WIRELESS COMMUNICATION SYSTEMS

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Abstract: *Unlike the conventional conductive surfaces, high-impedance surfaces (HIS) exhibit reflection coefficient $\Gamma \approx +1$, i.e. they do not change the phase of the reflected wave. Such structures are used in modern wireless communication systems, especially in the antenna design. HIS comprises of a great number of unit cells with sub-wavelength dimensions. Due to this fact, the concept of artificial effective media can be applied and HIS can be described using one parameter, the effective surface impedance. Unit cells are basically resonant LC circuits, whose parameters determine the operating frequency of HIS. Conventional HIS geometries, such as so called mushroom structures do not offer wide range of values of the inductance and the capacitance of the unit cell. This can be overcome by the application of fractal geometries, which allow much greater freedom in the choice of the unit cell parameters. In this paper, HIS that uses Hilbert fractal curves are analyzed. Advanced simulation techniques of HIS are presented, based on the usage of modern commercially available EM simulation tools.*

Keywords: *High impedance surface, mushroom structure, fractal curves, Hilbert curve.*

1. INTRODUCTION

Conductive surfaces are useful as reflectors, but they reverse the phase of reflected waves, [1]. A flat metal sheet, which is used in many antennas as a reflector or ground plane, redirects half of the radiation into the opposite direction, improving the antenna gain. However, if the antenna is too close to the conductive surface, the phase of the impinging wave is reversed upon reflection, resulting in destructive interference with the wave emitted in the other direction, shown in Figure 1.

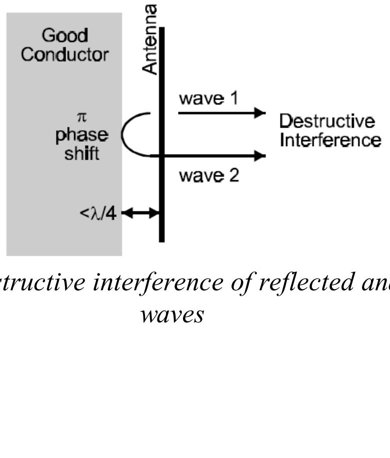


Figure 1: *Destructive interference of reflected and emitted waves*

Another property of metals is that they support surface waves that are nothing more than AC currents at microwave frequencies. By applying special structures these problems could be efficiently solved.

2. HIGH IMPEDANCE SURFACES

High-impedance surfaces (HIS), also known as artificial magnetic conductors, are structures which exhibit reflection coefficient $\Gamma \approx +1$ (expression 1), i.e. they do not change the phase of the reflected wave, [2]. Such structure is comprised of a great number of unit cells with sub-wavelength dimensions. Due to this fact, the concept of artificial effective media can be applied and HIS can be described using one parameter, the effective surface impedance. Unit cells are basically resonant LC circuits, whose parameters determine the operating frequency of HIS. In the vicinity of the resonant frequency, HIS is characterized by having very high impedance, shown in Figure 2, which results in reflection coefficient of $\Gamma \approx +1$ and zero degree reflection phase, depicted in Figure 3. Also, in a forbidden frequency band, HIS does not support freely propagating surface currents.

$$\Gamma = \frac{Z_2 - Z_1}{Z_2 + Z_1} \qquad (1)$$

Since materials that exhibit very high impedance do not exist in nature, HIS has been realized artificially and there are different design approaches of them.

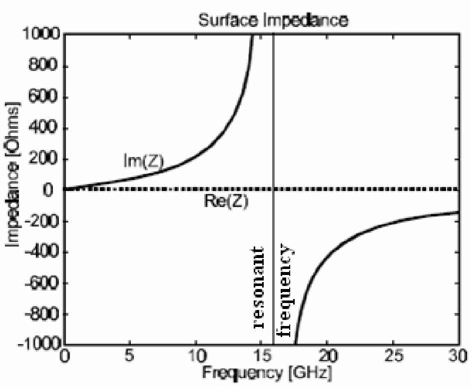


Figure 2: *Impedance of HIS*

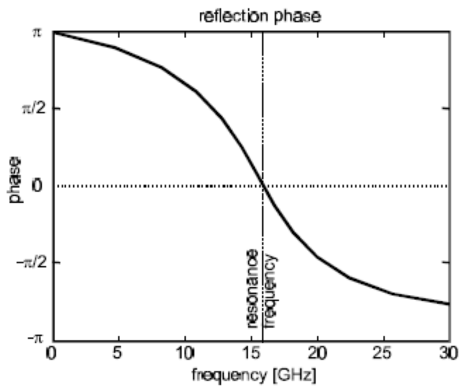


Figure 3: *Reflection phase*

3. HIGH IMPEDANCE SURFACES WITH MUSHROOM-TYPE UNIT CELLS

So-called mushroom structure, described and analyzed in [1], is based on mushroom-type unit cells and nowadays it presents conventional structure of HIS. Mushroom-type unit cell consists of metal patch connected to the ground plane by a via through a dielectric slab. Figure 4 shows an example of a mushroom structure in which metal patches have hexagonal shape.

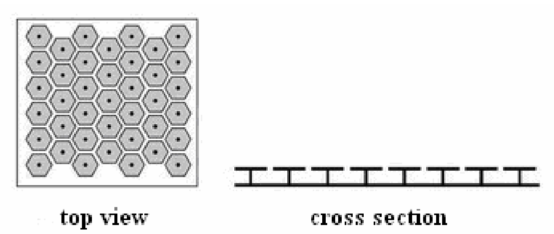


Figure 4: *A mushroom structure with hexagonal metal plates*

When the structure interacts with electromagnetic waves, currents are induced in the metal plates. Associated with these currents is a magnetic field, and thus an inductance. Also, charge is built up on the ends of the plates which can be described as a capacitance. Therefore, every unit cell represent resonant circuit and the behavior of the structure can be reduced to parallel LC circuit, where L and C stands for total inductance and capacitance, respectively, of the structure.

The edge capacitance between two plates, which are surrounded by ε_1 on one side and ε_2 on the other, could be expressed as

$$C = \frac{w(\varepsilon_1 + \varepsilon_2)}{\pi} \cosh^{-1}\left(\frac{a}{g}\right), \tag{2}$$

where w is plate width, g is separation of the plates and a is separation between their vias.

Sheet inductance is given by inductance of solenoid whose length to width ratio is taken as unity, thus it depends only on the thickness of the structure and the permeability.

$$L_s = \mu t. \tag{3}$$

Resonant frequency is given by the following expression:

$$\omega_0 = \frac{1}{\sqrt{LC}}. \tag{4}$$

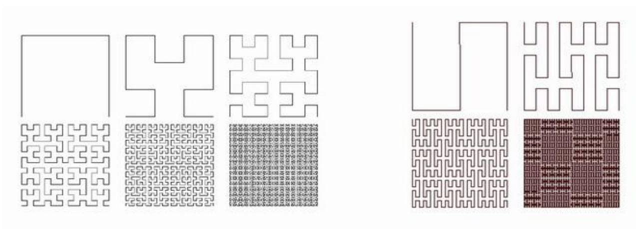
It can be seen from (4) that the resonant frequency can be lowered by increasing either the inductance or the capacitance. Since high-permeability materials do not currently exist at microwave frequencies, the inductance cannot be significantly increased without significant change in the dimensions of the structure. As the capacitance depends on the dimensions of the unit cell, value cannot either be particularly increased since it would undermine the concept of this structure, that is much smaller period of the surface texture than the wavelength of the propagating waves.

We can conclude that the drawback of the mushroom structure is that it does not offer a wide range of values of the inductance and the capacitance of the unit cell, and thus it does not offer a wide range of operating frequency.

In [1] the roles of the ground plane and conducting vias in HIS were also reviewed. If there were not the vias and the ground plane, currents that are responsible for existence of inductance would not propagate. Hence, there would not be the impedance which corresponds to parallel resonant circuit.

4. UNIT CELLS WITH FRACTAL CURVE GEOMETRY

Fractal curves are infinitely long lines which, at the same time, fit into the finite area, [3]. That means that width of a fractal line has to be infinitely small. Since it is not possible to physically realize such a line, in practice we use pre-fractals – fractal curves that are built with finite number of iterations (that are obtained after finite number of iterations), i.e. fractal curves of finite order. Such lines do not occupy the whole area and their width is not infinite. Figure 5 shows several first iterations of some of well-known fractals.



First six fractal iterations for the Hilbert-curve geometry | First four fractal iterations for the Peano-curve geometry

Figure 5: *Hilbert and Peano fractal curves*

In comparison with homogenous metal plates, the main advantage of unit cells that have pre-fractal geometry lies in the fact that finite order fractal curve which has the same footprint size as metal plate has a considerable higher inductance, while its capacitance to ground plane remains practically unchanged. As the iteration order of these curves increases, they maintain their footprint size which implies that the length of fractal curve can vary within the same area. The higher the order of a fractal curve is, the greater the length of the fractal curve is as well as its inductance. By increasing the order of a fractal curve it becomes more and more similar to a homogenous metal plate, and thus has greater capacitance.

It can be concluded that by varying the length of a fractal curve we can change the unit cell parameters and preserve the area that it occupies.

5. HIGH IMPEDANCE SURFACES WITH THE THIRD ORDER HILBERT FRACTAL CURVES

In [4] the structure which is based on the third order Hilbert fractal curves, is described and analyzed, shown in Figure 6. The structure consists of Hilbert curve inclusions which are arranged in a 2D periodic array whose dimensions are 7 x 3. Dimensions of the Hilbert curve footprint are 12 x 12 mm. 2D periodic arrangement is designed on FR-4 substrate with $\varepsilon_r = 4.4$, $h = 1.575$ mm and $tg\delta = 0.02$.

Figure 6: *The high impedance surface with the third order Hilbert curve inclusions*

In order to analyze this structure, electromagnetic simulations were performed and for that purpose the structure was placed in the waveguide WR-430, 5 mm from the short circuited end of the waveguide, as Figure 7 depicts. Since the high impedance surface is placed on substrate whose thickness is 1.575 mm, the 2D periodic arrangement is 6.575 mm from the short circuited end.

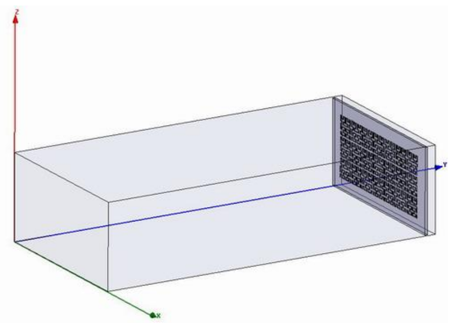


Figure 7: *The simulation model of the high-impedance surface with the third order Hilbert curve inclusion*

Figure 8 shows the magnitude and phase of the reflection coefficient as a function of the frequency, for this structure.

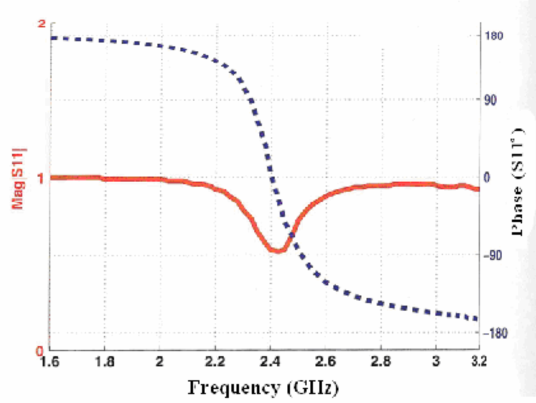


Figure 8: *Simulated results of the structure from [4]*

We can see from the simulation results that the value of the frequency at which the reflection phase crosses through zero is 2.4 GHz. At the same frequency attenuation of the magnitude of the reflection coefficient occurs. In [4] the attenuation is considered to be due to the losses in the substrate.

Apart from the results, it should be noted that the structure from [4], unlike the structure from [1], does not have a ground layer nor vias that would connect the unit cells with the ground plane. Furthermore, in [4] it is not discussed whether vias and a ground layer are necessary in HIS, nor why the structure comprised of the lattice of the unit cells and the dielectric substrate only was chosen to analyze. However, it is important to notice that although the structure itself does not have a ground layer, there is such layer in the analyzed model – the short circuited end of the waveguide.

6. SIMULATION RESULTS

The structure described in the previous section was used as a basis for the research carried out in this paper.

In order to prove the results from [4] and analyze influences of different parameters, electromagnetic simulations were performed by using HFSS (High Frequency Structure Simulator). Also, the same dimensions as those from [4] were used.

The basic model, which is shown in Figure 7, is comprised of: a two-dimensional lattice of unit cells, the substrate on which the lattice is designed, and a waveguide. The shape of the unit cell is the third order Hilbert fractal curve and the dimensions of the unit cell footprint are 12 x 12 mm. The line width is 0.55 mm, and the separation between lines is twice as wide as the line width. In the simulations the boundary condition “*perfect E*” was applied to the unit cells, i.e. the unit cells were assumed to be made of perfect conductor. The two-dimensional lattice of unit cells consists of Hilbert curve inclusions which are arranged in a 2D periodic array whose dimensions are 7 x 3. The separation between the unit cells is 1 mm and they are not galvanic coupled. Dimensions of the substrate are 108.22 x 53.61 x 1.575 mm, where 1.575 mm presents the substrate thickness. Dielectric constant and loss tangent of substrate are 4.4 and 0.02, respectively. The dimensions of the waveguide are 109.22 x 54.61 mm, while its length is 220 mm. The substrate with the lattice is positioned 5 mm from the short circuited end of the waveguide, and 0.5 mm from the each side of the waveguide, which means that the lattice is placed 6.575 mm from the end of the waveguide.

The frequency range from 1.6 GHz to 3.2 GHz was analyzed. Figure 9 shows the magnitude of the reflection coefficient as a function of the frequency.

It can be seen that the magnitude of the reflection coefficient dependence is very similar to those from [4] – in the vicinity of 2.5 GHz the magnitude of the reflection coefficient is evidently smaller than maximum.

The aim of the next step was to analyze the influence of the position of the substrate in the waveguide on the reflection coefficient.

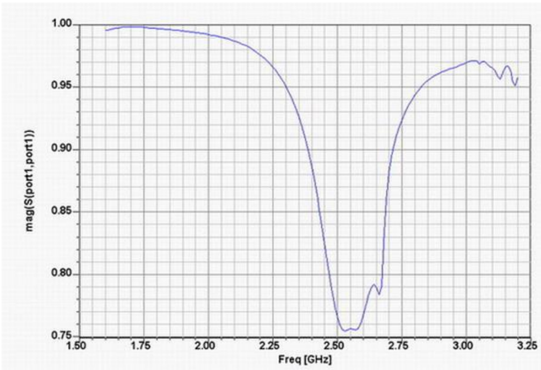


Figure 9: *Magnitude of the reflection coefficient*

Three models which differ in the distance of the substrate from the short circuited end of the waveguide were simulated. In the first case the distance was 5 mm, in the second 2 mm, while in the third case the substrate coincides with the end of the waveguide. The magnitude of the reflection coefficient dependences on frequency for all three cases are depicted in Figures 10, 11 and 12.

In the first case the magnitude is slightly different from the magnitude of the basic model. However, when the separation between the substrate and the short circuited end is 2 mm, the frequency band in which the magnitude attenuates becomes narrower. At the same time, that attenuation is significant, even twice greater than in the first case. Also, the resonant frequency does not change. In the third case, when the lattice and the short circuited end of the waveguide are separated only by the substrate, the resonant frequency shifts to lower frequencies. The frequency band in which the magnitude attenuates, is narrower than in the first case, while attenuation is greater althoug not as much as in the second situation.

In the first case, space between the Hilbert curve inclusions and the short circuited end of the waveguide consists of the dielectric layer and the part between the substrate and the short circuited end of the waveguide which is filled with air, and which length is 5 mm. Effective permittivity of the space between the unit cells and the ground layer is less than permittivity of substrate. In the second case the layer filed with air is smaller and effective permittivity is slightly greater than it is in the previous case. This model exhibit significant increasing in attenuation in the stopband. In the third case, effective permitivitty is equal to permitivitty of the substrate, and thus greatly differs from those in the previous two cases, which explains the variation in the resonant frequency.

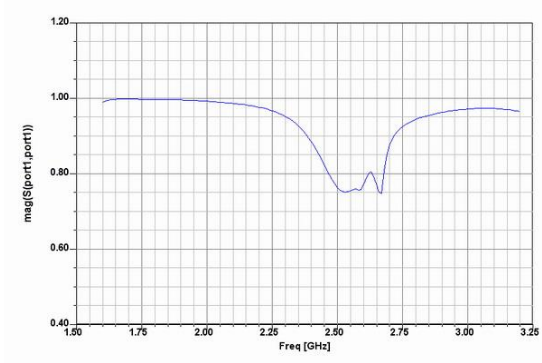


Figure 10: *Magnitude of the refl. coeff. in case the separation between the substrate and the end of the waveguide is 5 mm*

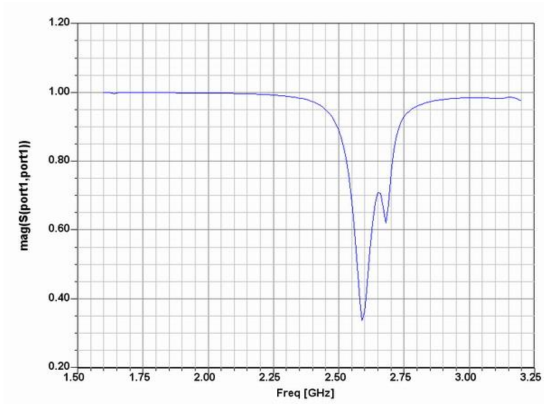


Figure 11: *Magnitude of the refl. coeff. in case the separation between the substrate and the end of the waveguide is 2 mm*

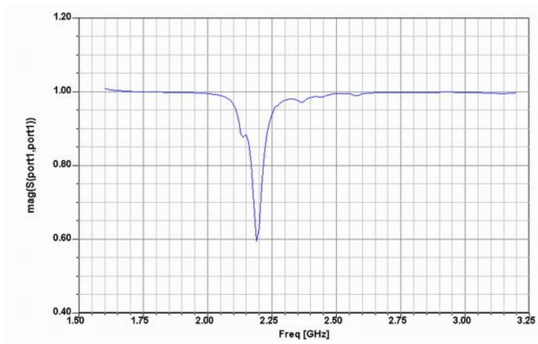


Figure 12: *Magnitude of the refl. coeff. when there is no distance between the substrate and the end of the waveguide*

7. INFLUENCE OF THE GROUNDING OF THE UNIT CELLS

For the purpose of the analysis of the influence of adding vias between the unit cells and the ground layer, the third model from previous section with vias between the Hilbert curve inclusions and the ground plane, was simulated. Figure 13 shows this structure, while Figure 14 depicts the simulation results for it.

One can see that adding vias does not change the nature of the circuit in essence, that is the reflection coefficient still has minimum at the resonant frequency. Though, due to change in total inductance and capacitance, the resonant frequency has shifted, and it has value of 2.75 GHz. By the grounding of the unit cell, parallel inductance in the equivalent circuit of the structure occurs. By suitable choice of the values of circuit elements the structure can perform *left-handed* behavior.

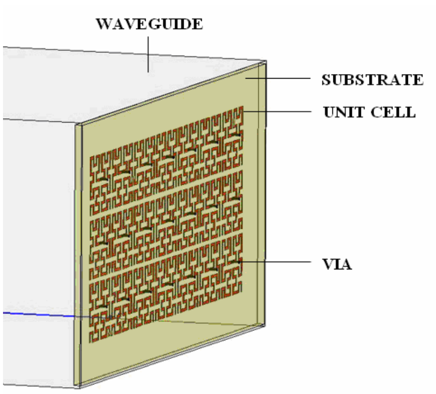


Figure 13: *The structure with vias between the unit cells and the ground layer*

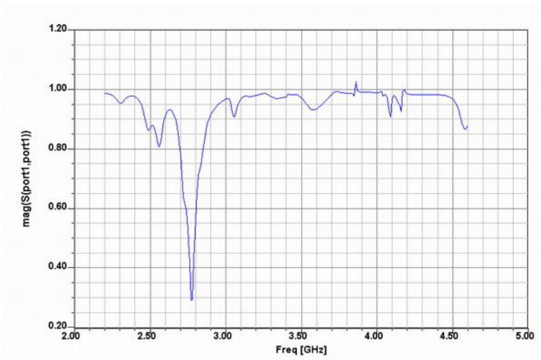


Figure 14: *Simulated results of the structure with vias between the unit cells and the ground layer*

8. CONCLUSION

In this work, high impedance surfaces with conventional and Hilbert fractal unit cells have been analyzed. Owing to its specific features HIS can offer interesting applications in the compact antenna with high directivity design.

It has been shown that changes in position of the substrate with 2D lattice of unit cells in relation to short circuited end of the waveguide, causes significant attenuation of the magnitude of the reflection coefficient in the vicinity of the resonant frequency as well as change in resonant frequency, which contradicts the statement from [4] that these structures can operate without ground layer.

Also, it has been shown that adding vias between unit cells and short circuited end does not change the nature of the circuit in essence, i.e. the reflection coefficient still has minimum at the resonant frequency. Though, due to change of total inductance and capacitance, the resonant frequency has shifted. By suitable choice of the values of circuit elements the structure which would perform *left-handed* behavior can be designed.

REFERENCES

[1] Daniel Frederic Sievenpiper, “High-Impedance Electromagnetic Surfaces”, *PhD Thesis in Electrical Engineering, University of California*, Los Angeles, 1999.

[2] John McVay, Nader Engheta, Ahmad Hoorfar, "High-impedance metamaterial surfaces using Hilbert-curve inclusions," *IEEE Microwave and Wireless Components Letters*, Vol. 14, pp. 130-132, March 2004

[3] Vesna Crnojević-Bengin, “Novel configurations of fractal and LH microstrip resonators“, *PhD Thesis, Faculty of Technical Sciences*, Novi Sad, february 2006

[4] Nader Engheta, Richard W Ziolkowski, “Metamaterials: Physics and Engineering Explorations,” IEEE Press, Wiley-Interscience, 2006.