Analysis of the effect of the variation geometric characteristics the basic cells in a metamaterial

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Abstract. The analysis of the impact of the variation of the substrate and the geometric characteristics of the cells basic that make up a metamaterial, as well as their frequency response, bandwidth and insertion losses level of the bandgap generated, is presented. A metamaterial in microstrip transmission line technology was simulated and manufactured on two dielectric substrates with different relative permittivity index, introducing electromagnetic band gap structures (EBG) in the ground plane. Five geometrical shapes were selected for the cells of the EBG structure. The response of the metamaterial is analyzed on the characteristics of the band gap, varying the lattice constant, the size and the geometry of the cells (defects) and the substrate used. The results obtained show that this type of devices can be used to measure the properties of elements by detecting the change of the refractive index of the metamaterial, with frequency selectivity. The study of these parameters is critical for the applications of metamaterials in filters, sensors and actuators, among others.

1. Introduction

Metamaterials (MTMs) are artificial materials obtained by combining different types of structures or materials; they are capable of simultaneously controlling both permittivity ($\varepsilon_r$) as well as effective ($\mu_r$) permeability. The MTMs also demonstrate desirable properties for a wide range of engineering applications that materials in their natural state do not offer [1]; among these properties is the fact that they have a negative refractive index. According to Engheta and Ziolkowski, there are two major classes of metamaterials: the SNG and DNG metamaterials and the EBG structured metamaterials [2]. During the last two decades, the study of the optical properties of the MTMs has attracted attention, due to its potential applications in various field such a optics and electromagnetic [3] [4], telecommunications for suppression of the surface waves in antennas for example [5] [6], engineering and fundamental physics study [7].

The PBG structures, also known as Photonic Crystal in optics or Electromagnetic Band Gap (EBG) structures in general [8] is originated from two papers published by Yablonovitch and John in 1987 [9] [10]. EBG are periodically structures of dielectrical patches in one, two or three spatial dimensions on dielectric substrates with the capacity of engineering stopbands to selectively control the propagation of electromagnetic waves [8] [11] [12]. These structures prove to be interesting for the development of new components in different technological areas such as communications and sensors systems, as they
offer the possibility of controlling the frequency and amplitude of electromagnetic modes of propagation in a wide range of frequencies [1] [13]. Furthermore, PBG/EBG structures are now included in the MTMs [8].

There are various studies in the application of EBG structures in the range of microwaves, mainly dealing with antennas, filters, amplifiers, and oscillators. It has been shown that the separation between the defects, known as lattice constant, establishes the center frequency \( (f_c) \) of the attenuated frequency band and the defects control the insertion losses level \( (IL) \) [14-17]. As for the effect that the geometrical shape of the defects that form the structure can have, Karbassian analyzed the response of a microstrip line with circular and square defects, obtaining similar responses for both structures, concluding that the characteristics of the rejected frequency band depends of factors such as the number of defects and the relationship between the size and the lattice constant [18]. Similarly, Garde presented the results obtained by varying the sizes of the two geometric shapes [19]. In addition, it is known that the bands are controlled by changing the substrate and geometric characteristics the structure [18-20]; but not specify how each of the physical characteristics of the EBG structure affects the characteristics of the generated bandgap. Rahman present a study on planar EBG structures circular, square and triangular forms applied to microwave filter design [21]. Thus, up until now no comparative study has been found, that fully analyzes the effects the following can have on the response of a periodic device: the geometric shape and the size of the defects that form the EBG structure, as well as the lattice constant and the dielectric substrate on which it is built. Therefore, a study of the effects of varying the geometric parameters of the cells that form the periodic structure EBG is presented, paying special attention to analyze the center \( (f_c) \) response, bandwidth \( (BW) \) and insertion losses level \( (IL) \).

This analysis is performed using two microstrip lines fabricated on substrate with different relative permittivity constants whose values differ significantly: substrate FR4 \( (\varepsilon_r = 4.4) \) and substrate Duroid 6010 \( (\varepsilon_r = 10.2) \) respectively, figure 1a. On the ground place EBG structures formed by five different geometric shapes are generated: squares, circles, hexagons, stars and
diamonds, with the square being selected as the basic geometry with three different sizes: \( L = 6\text{mm}, \ L = 9\text{mm} \) and \( L = 12\text{mm} \); and each of the four remaining figures are assigned the confined characteristic (adjusted) to the sizes specified for the basic geometry, figure 1b. The lattice constant was varied in the range of \( 12\text{mm} \) to \( 42\text{mm} \), for all the developed models. The devices were simulated in High Frequency Structure Simulator (HFSS), and were produced using printed circuit manufacturing techniques.

The results obtained can be used in the design of devices for the diverse application areas of MTMs because they allow for the identification of geometric shape, the size and separation of the cells of the periodic structure according to the specifications and features of the system, and the area where it will be applied. In addition, once identified that the change in the parameters of the generated gap is due to the variation of the refractive index of the homogeneous medium by which signals are transmitted, which is achieved by modifying the geometrical characteristics of the EBG structure, the possibility of modifying the refractive index of the metamaterial using methods that do not involve the physical change of the EBG structure is raised, and so the \( f_c \), the \( BW \), and \( IL \) of the gap can be varied on the same structure.

2. EBG structure

One of the techniques used to fabricate EBG structures is by generating a periodic array of the perforations on the ground plane of a microstrip transmission line, figure 1a. The insertion of EBG structure generates a range of frequencies at which the transmitted signals are attenuated. The EBG terminology is based on the total internal reflection, phenomenon of photonic crystal in optics, which is realized by periodic structures [22]. EBG structures are popularly known as photonic crystals that are artificially synthesized crystals, which control light completely [23].

As posed by Vasco and Posada, the dielectric function of the photonic crystal is periodic in space; therefore, the allowed states (valence and conduction bands) and forbidden states (band gaps) – which in atomic crystals are produced by constructive and destructive interference phenomena of the electronic wave function – turn into photonic crystals as interference phenomena of the electromagnetic waves dispersed in the crystal [7]. When the periodicity of the photonic crystal is broken by the introduction of impurities or defects (either geometric or compositional), the localization of the electromagnetic field around the impurity is induced; consequently, confinement or guidance of high efficiency light modes occurs. The confinement mechanism associated to photonic crystals, known as Distributed Bragg Reflector (DBR), is based on electromagnetic wave constructive and destructive interference phenomena [7]. The photonic crystals prevent light over a small frequency range from passing through the crystal in specific directions by destructive interference [24]. For the wave to be reflected and the existence of destructive interference, Bragg’s law must be fulfilled, \( n\lambda = 2ds\sin\theta \). Where \( n \) is the order of reflection, \( d \) interplanar distance and \( \theta \) the angle of incidence. When comparing photonic crystals with the EBG structure used, the interplanar distance \( d \) corresponds to the separation distance between defects, figure 1a. Signal incidence is normal in relation to the structure, that is \( \theta = \pi \); consequently, the wavelength must be: \( \lambda = 2d \) for destructive interference to occur within the basic cells. Then an approximate calculation of the central frequency of this gap can be made from the frequency definition of a wave and wavelength established. According to Pozzar [25], the frequency of a wave is defined as a function of the phase velocity, and in the case of microstrip line, states that the phase velocity and propagation constant can be expressed as appears in equation (1).

\[
 f = \frac{v_p}{\lambda}, \quad v_p = \frac{c}{\sqrt{\varepsilon_e}}, \quad f = \frac{c}{\lambda\sqrt{\varepsilon_e}} \tag{1}
\]

Where \( v_p \) being phase velocity of wave, and \( \lambda \) wavelength, \( \varepsilon_e \) is the effective dielectric constant of microstrip line and \( c \) the speed of light in the vacuum. When replacing wavelength, \( \lambda = 2d \); necessary for total reflection (law of Bragg), the central frequency of first bandgap is given by:
Central frequency of the gap generated can be validated theoretically and experimentally through equation (2) as shown in the network constant analysis, figure 3a. $f_c$ is a key parameter of the metamaterial gap. The table 1, present technical specifications and characteristics calculated for dielectric substrates selected and microstrip line. The calculation of the width of the microstrip line with characteristic impedance of 50Ω was made with the software tool for the design of transmission lines (TRL) of Ansoft designer. For FR4 substrate a width of 3mm and of 1.17mm for the Duroid 6010. The constant relative permittivity ($\varepsilon_r$) and substrate height it was assumed from the technical specifications. The effective dielectric constant of microstrip line in both substrates, was calculated according to the one proposed by Pozzar [25]; and to calculate the effective permittivity constant in the area affected by the defects, we used the equation proposed by Laso [15] and Fesenco and Tkachenko [26].

**Table 1.** Key features and technical specifications calculated for the substrates used: FR4 and Duroid 6010

| Parameter                                           | FR4   | Duroid 6010 |
|-----------------------------------------------------|-------|-------------|
| Constant relative permittivity, $\varepsilon_r$     | 4.4   | 10.2        |
| Effective permittivity constant $\varepsilon_e$ for widths (w) calculated for lines | 3.33  | 6.83        |
| Effective permittivity constant in the area affected by the defects, $\varepsilon_{eh}$ | 3.30  | 6.72        |
| Substrate height, h (mm)                            | 1.57  | 1.27        |
| Thickness of the cooper layer ($\mu$m)              | 17    | 17          |
| Width of the microstrip line for 50Ω impedance (mm)  | 3     | 1.17        |

The effective permittivity constant for the FR4 substrate was verified experimentally using the methodology proposed by Avella, et al [27]. A $\lambda/4$ resonator was added to the line for a 3.5GHz resonance frequency; a refractive index $n = 1.88$, which is similar to the technical specifications of the substrate, was obtained. Figure 2 shows results obtained in terms of simulation and measurement of the microstrip line analyzed.

**Figure 2.** Simulation and measurement of the refractive index of the FR4 dielectric substrate
3. **Effect of the geometric characteristics of the basic cell**

The analysis of the effects geometric characteristics of defects which make up the EBG structure have was conducted varying the network constant in a $12\,\text{mm}$ to $42\,\text{mm}$ range, the cell geometric shape in the five geometries that were selected and cell size in three dimensions: $L = 6\,\text{mm}$, $= 9\,\text{mm}$ and $L = 12\,\text{mm}$. Two dielectric substrates were used: FR4 and Duroid 6010. 165 models were developed and simulated on substrate FR4 as well as 165 models on substrate Duroid 6010.

3.1. **Lattice constant**

The lattice constant control the center frequency, the $BW$ and the $IL$ of the generated bandgap. Figure 3 shows the results corresponding to the EBG structure comprised of circles introduced into the ground plane of a microstrip line built on substrate FR4; similar results were obtained for all the models developed.

![Figure 3](image)

**Figure 3.** Effects of the variation of lattice constant of EBG structure of microstrip line built on substrate FR4, circles in this case. (a) Effects on the $f_c$. (b) Effect on the $IL$

When the lattice constant is increased the center $f_c$ of the bandgap decreases, reaching similar values for lattice constants greater than $30\,\text{mm}$ ($d > 30\,\text{mm}$) regardless of cell size; however, there are small differences of $0.1\,\text{GHz}$ approximately, in the magnitude of the $f_c$ for frequencies above $4\,\text{GHz}$ that correspond to lattice constants less than $20\,\text{mm}$. The $BW$ varies similarly to the center frequency; but its magnitude differs for each of the three sizes of cells, though the values obtained are similar to each other, for lattice constants greater than $35\,\text{mm}$.

As for the level of losses, figure 3b; the lower the net constant, it is possible to locate a larger number of cells on the EBG structure. For the developed models, we use line microstrip with $100\,\text{mm}$ of length; with lattice constant, less $15\,\text{mm}$ ($d < 15\,\text{mm}$), seven cells can placed ($N = 7$). With lattice constant between $15\,\text{mm}$ and $25\,\text{mm}$ the number of cells that can placed is five; and for $d > 25\,\text{mm}$, three cells. Greater number of cells between Port 1 (input) and port 2 (output), results in a higher level of attenuation of the signal.
3.2. Geometric shape

Figure 4 shows the results obtained for the $f_c$, $BW$ and the $IL$ when varying the geometric shape of the basic cells that form the EBG structure, introduced on a ground plane of a microstrip line built on substrate FR4 for a fixed lattice constant ($d = 21\,mm$). The magnitude of the band gap frequency is not significantly affected by the variation in the geometric shape of the basic cell of the EBG structure. A slight reduction in magnitude is noted for irregular geometric shapes, such as stars and diamonds, when compared to the magnitude of the square, circular or hexagonal geometric shapes.

![Graphs showing effects of varying geometric shape on $f_c$, $BW$, and $IL$.](image)

**Figure 4.** Effects of varying the geometric shape cells EBG structure on FR4 substrate, varying its size in the three dimensions selected; with a fixed lattice constant $d = 21\,mm$. (a). Effect on the $f_c$. (b). Effect on the $BW$. (c). Effect on the $IL$, of the generated bandgap.
Figure 4b shows that the geometric shape of the cells has a large impact on the $BW$. Its magnitude is greater for the more regular three geometric shapes and less for the diamond and star geometric shapes. The geometric shape of the cells also has an effect on the $IL$, figure 4c; it shows a greater magnitude for squares, circles and hexagons, due to there being more space in which the refractive index varies, and less for the diamonds and stars. The behavior is similar to that obtained for $BW$. This allows us to conclude that the geometric shape of the cells has no great effect on the $f_c$, but it does have an effect on the $BW$ and the $IL$ of the generated bandgap.

3.3. Size the basic cell

The results obtained in the electromagnetic simulations, in all geometries and defect sizes, show that the variation of the size of the cells that form the EBG structure, modify the $BW$ of the generated bandgap; figure 5a shows the response in terms of $BW$ of the generated.

![Figure 5a](image1.png)

**Figure 5a.** Response in $BW$ for three sizes selected.

The magnitude of the $BW$ varies in proportion to the size of the cell. In order to further analyze the effect of the size of the cells in the $BW$, using the same microstrip line model, simulations were performed in a wider range by varying the size of the cells; the dimension of the radius of the circles varied from $r = 3mm$ to $r = 10mm$ with steady increases equal to the unit. The results of the simulations are shown in figure 5b; in which it is possible to observe in detail that the size of the cells modifies the $BW$ and the $IL$, this variation being
proportional to the size of the cells. Meanwhile, the $f_c$ of the generated bandgap remains constant ($3 \text{GHz}$). This permits one to conclude that the size of the cell has no effect on the $f_c$ of the generated bandgap, but it does modify the $BW$ and $IL$, these two parameters being proportional to the size of the cells.

3.4. Effect of the substrate

Figure 6 shows that the substrate on which the device is constructed affects the magnitude of the $f_c$ and $BW$, but does not affect the $IL$ of the generated bandgap. Figure 6a shows the $f_c$ response of the generated bandgap for the two microstrip lines, one on substrate FR4 and the other on substrate Duroid 6010, with EBG structures formed by circular cells of size $L = 9 \text{mm}$. A greater magnitude is observed for devices constructed on substrate FR4 (lower refractive index), compared with those constructed on Duroid 6010 (higher refractive index); but the shape of the response is similar for the two substrates. Likewise, the bandwidth is affected by the characteristics of the substrate on which the device is constructed, presenting a lower value for the substrate with a higher refractive, but as with the $f_c$, the two responses are similar, Figure 6a.

The level of $IL$ is independent of the substrate used. Figure 6b shows the response in terms of the magnitude of the $IL$, of the microstrip line built on substrate FR4 and a similar one built on substrate Duroid 6010, with an EBG structure on the ground plane, formed by circles of the three sizes selected. The responses are the same and only the magnitude varies because size of the cell.

![Figure 6](image_url)

**Figure 6.** Effect of the substrate on which the device is constructed (substrate FR4 continuous lines and substrate Duroid 6010 dotted lines) (a). Effect on the $f_c$ and $BW$ (b). Effect on $IL$. 
4. Fabrication and measurement of metamaterial

Geometric shape the circles and stars were selected to produce twelve (12) prototypes of metamaterial; generated by introducing an EBG structure in the ground plane of a microstrip line. These geometries were chosen because in the simulations, the results obtained for the circles, squares and hexagons showed similar responses, while the star was the geometry that presented a different response compared to the other geometric shapes studied. The devices were constructed in the Printed Circuit Manufacturing Laboratory (LFCI) of the University of the Andes - Colombia, using lithography techniques for manufacturing printed circuits, Figure 7.

![Prototype of metamaterial manufactured, with EBG structures in the ground plane of a microstrip line](image)

The lattice constant selected was \( d = 29\,mm \), which corresponds to a \( f_c \) of 2.83GHz for substrate FR4 and of 1.98GHz for substrate Duroid 6010, calculated using the equation (5), and taking into account that the vector network analyzer (VNA) HP8753D would be used for the measurement of the devices, which has a range of measurement up to 6GHz. Thus, six microstrip lines were simulated, fabricated and measured. Three for each of the substrates, with EBG structures formed by circles with radio: \( r = 6.5\,mm \), \( r = 7.25\,mm \) and \( r = 8\,mm \); and six others with EBG structure formed by stars of the sizes \( L = 13\,mm \), \( L = 14.5\,mm \) and \( L = 16\,mm \), corresponding to the selected base geometry, figure 1b.

![S-parameters measured in microstrip line built on substrate FR4, with EBG structure formed by circles of sized \( r = 7.25\,mm \) and another formed by stars sized \( L = 14.5\,mm \), corresponding to the selected base structure.](image)
The figure 8 shows the results corresponding to the microstrip line with EBG structures on the ground plane, formed by circles with a radius of $r = 7.25\, mm$ and stars sized $L = 14.5\, mm$. It was verified that the geometric shape of the cells affects the $IL$ and the $BW$, but does not affect the magnitude of the center frequency, which remains constant at a value around $3\, GHz$.

Meanwhile, figure 9 shows that the substrate characteristics affect the magnitude of the $f_c$ and the $BW$, but not the $IL$, showing the results of measurements taken at two microstrip lines constructed on substrates FR4 and Duroid-6010, respectively, with EBG structures formed by circles sized $r = 7.25\, mm$.

Figure 9. S-parameters measures in two microstrip line on FR4 y Duroid 6010 substrates, with EBG formed by circles of sized $r = 7.25\, mm$.

Finally, figure 10 shows the results obtained by measuring the response of three microstrip lines constructed on substrate FR4, with EBG structures formed by circles of the three sizes selected; showing that the size of the cells affects the $BW$ and the $IL$, but does not affect the $f_c$.

Figure 10. S-parameters measured in three microstrip lines on FR4 substrate with EBG structure formed by circles of the three sizes selected: $r = 6.5\, mm$, $r = 7.25\, mm$ and $r = 8\, mm$. 
5. Conclusions

A detailed analysis was performed to evaluate the effect of the geometric characteristics of basic cell in a metamaterial. The results show that the magnitude of the $f_c$ is affected by the lattice constant and the type of substrate used. $BW$ is affected by both the lattice constant, which directly affects the number of cells that can be placed within the structure, as well as the substrate used, the size and the shape of the cells. The $IL$ is affected by the lattice constant, the shape and the size of the basic cells, but not by the characteristics of the substrate. The Table 2 shows a synthesis of the effect of the geometric characteristics of the EBG structure, in the parameters of the generated bandgap.

| Parameter of the bandgap that is affected | Features of EBG structure |
|------------------------------------------|----------------------------|
| Lattice constant                         | Geometry       | Size | Substrate |
| Central frequency                        | √             | x    | √         |
| Bandwidth                                | √             | √    | √         | √         |
| Insertion losses level                   | √             | √    | √         | x         |

Table 2. Summary of the geometric characteristics of the EBG structure that affect each bandgap parameter. √ means that the geometric feature of the EBG structure does affect the parameter of the bandgap and x means that it does not affect it.

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