FINITE ELEMENT METHOD FOR RIGOROUS DESIGN OF MICROWAVE DEVICES USING PHOTONIC BAND GAP STRUCTURES

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ABSTRACT

In this paper, we present theoretical and experimental analysis of microwave devices using photonic band gap materials. These analysis are applied to design volumic or planar microwave filters. The experiments were conducted at 9-14 GHz to valid the concept which could be applied to millimeter frequency band (60 GHz) filters.

INTRODUCTION

In recent years photonic crystals which are artificial materials made of two or three dimensional periodic dielectrics [1], have been proved to have interesting characteristics, not yet available with the ordinary materials. They may act on electromagnetic waves in a similar way as natural crystals act on electron waves. These artificial materials, commonly called photonic band gap (PBG) materials can significantly changes electromagnetic wave propagation to provide forbidden frequency bands. PBG materials can be applicable to a wide range of frequencies and recently there is increasing interest in microwave and millimeter wave domains to design circuits, broadband absorbers, antennas substrates... [2].

Some theoretical methods have been recently proposed in several papers, to analyze structures using PBG materials. These methods permit to define the frequency band gap, but doesn't establish rigorously the coupling between excitation systems and PBG materials, and then their global microwave devices responses.

The objective of this paper is double : one to present rigorous design of microwave devices using PBG materials, and second to prove the faisability of microwave waveguide and microstrip line filters. The three dimensional Finite Element Method (3D FEM), is applied to rigorously establish the [S] parameters of these structures, taking into account dielectric and metallic losses.

We first analyze the simple waveguide structure described in figure 1 to establish variation laws of the frequency band gap as a function of the device dimensions and electrical characteristics, applying the FEM.

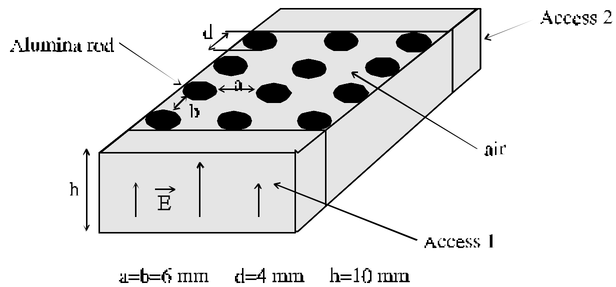


Fig.1. Design of PBG structure in a waveguide

Then this parametric study permits to design rigorously a new topology of waveguide two pole filter using PBG materials and acting around 13 GHz. The [S] parameters obtained applying the FEM compared to the experimental ones show a good agreement between them.

At last, a global analysis applying the FEM is performed to characterize planar structures as microstrip lines or striplines on PBG substrates. Finally, these studies permit to design a new topology for a microwave planar filter.

I - NUMERICAL ANALYSIS

The theoretical analysis is performed applying the free or forced oscillations 3D FEM between the access ports of the device. The FEM is well known to be useful for solving Maxwell's equations. This method has already been explained in several papers [3] and our purpose is not to describe it. Using this electromagnetic software, we can analyze complex volumic or planar devices, taking into account both dielectric and metallic losses. The structure can be open introducing perfectly matched layer absorbing boundary conditions, or closed by introducing perfect electrical conditions and/or distributed access.

II - PARAMETRIC ANALYSIS OF THE FREQUENCY BAND GAP STRUCTURE

Two types of structures have been developed in precedent papers [4] : one is composed of parallel air holes in dielectric material and called connected structure. The other one is composed of parallel dielectric rods in air and called disconnected structure.

The main difference between this two structures is their excitation [4]. To obtain frequency band gap, disconnected structures are excited by an E polarization in which the electric field vector is parallel to the symetrical axis of the rods, and connected structures are excited by an H polarization in which the magnetic field vector is parallel to the symetrical axis of the rods.

In this paper, we consider only disconnected structures, but all the presented results can be applied for connected structures.

Figure 1 presents the first studied structure which is composed of periodic arrays of dielectric rods inserted into a metallic waveguide. The 2D photonic lattice consists of cylindrical rods arranged parallel to one another in a square lattice structure with lattice constant a=b=6 mm and rod diameter d=4 mm. The values of a and b are chosen to yield a frequency band gap between [11-15] GHz. The waveguide is excited at its access ports on its TE_{10} fundamental mode.

In this part, a parametric analysis is performed to characterize the rod permittivity, the number of rods along the propagation axis and the distance between rods to obtain significant frequency band gap.

Figure 2 presents the S_{21} parameter analysis of the previous structure as a function of the dielectric rods permittivity ε_r ($3<\varepsilon_r<11$). This figure shows that for $9<\varepsilon_r<11$, a significant depth band gap is obtained. So, the dielectric rods will be defined in alumina with $\varepsilon_r = 9.7$. The second parametric analysis for which the dielectric constant of the rod has been choosen equal to 9.7 (alumina) permit to define minimal number of four arrays of rods along the propagation axis to have interesting band gap depth as shown in figure 3.

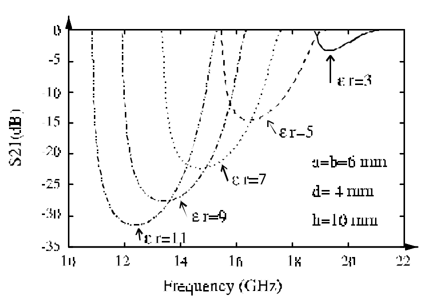


Fig.2. Frequency band gap as a function of permittivity

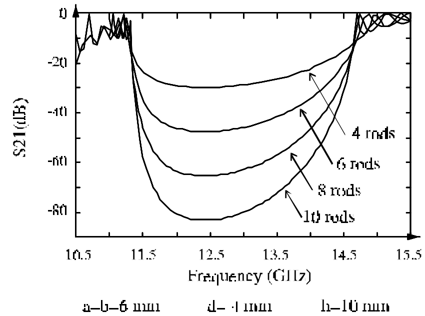


Fig.3. Depth band gap as a function of number of rods along propagation axis

Figures 4 and 5 present transmission responses obtained with 4 mm<b<7,5 mm when a=6 mm, and with 5 mm<a<9 mm when b=6 mm. We can see that b has a real effect on band gap width, whereas a variation provides slightly modification. Finally, we observe same responses whatever height of rods, because the boundary conditions imposed by the waveguide dimensions satisfy the field distributions of the propagative excited mode.

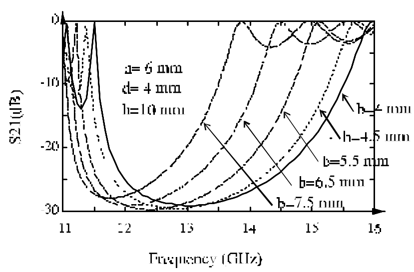


Fig.4. Band gap width as a function of b value

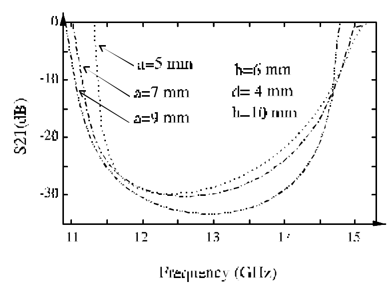


Fig.5. Band gap width as a function of a value

III - RIGOROUS DESIGN AND REALIZATION OF A WAVEGUIDE TWO POLE FILTER USING PBG MATERIALS

Using the precedent parametric analysis, we now design a two pole filter. Actually, for PBG structures, we can obtain defect or cavity resonant modes by locally disturbing the periodicity of the photonic structure [5].

The parametric analysis presented previously, permit to define the new structure described in figure 6. It is composed of six arrays of rods along the propagation axis where we take out two rods to create a defect resonant mode. S_{21} parameter has been computed, and a and b values have been adjusted. Then, the resonant frequency was 12.64 GHz (figure 7).

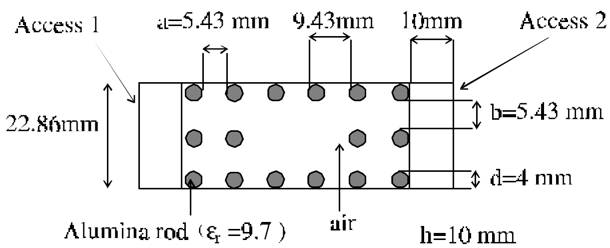


Fig.6. Description of PBG structure with one default

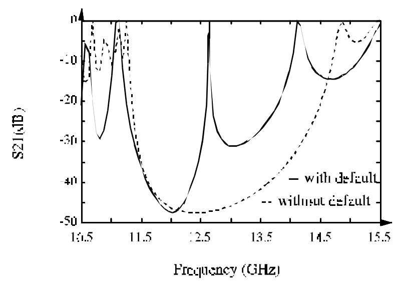
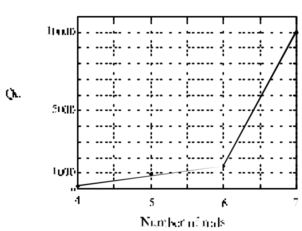


Fig.7. S_{21} parameter of PBG structure with one default

Since our objective is to design a two pole filter with PBG materials, we have to compute external Q_e factor which defines the input/output coupling and the k coupling coefficients which characterize coupling between the two resonant elements. Figure 8 proves that the external Q_e factor is lied to the number of the rod localized along the propagation axis, forward and backward the resonant cavity. So, we can define the input/output coupling coefficient lied to the external Q_e factor between the excitation system and the resonant element.



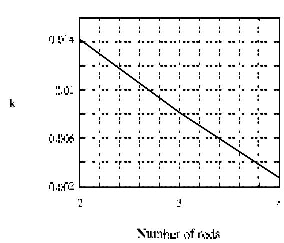


Fig.8 External Qe factor as a function of number of rods forward and backward the resonant cavity along propagation axis

Fig.9. Coupling coefficient k as a function of rods between the two resonant cavities

Figure 9 presents the coupling coefficient k as a function of the number of rods between the two resonant elements. This number of rods act like a classical coupling iris. At last to confine the energy in the propagation axis and to minimize the metallic losses, we define input and output PBG waveguide . In that case only three rods are necessary to guide the propagative field.

The number of arrays between the two resonant cavities and the input/output coupling coefficient have been optimized to have less oscillation and less losses in bandpass. The two pole filter using PBG materials is shown on figure 10.

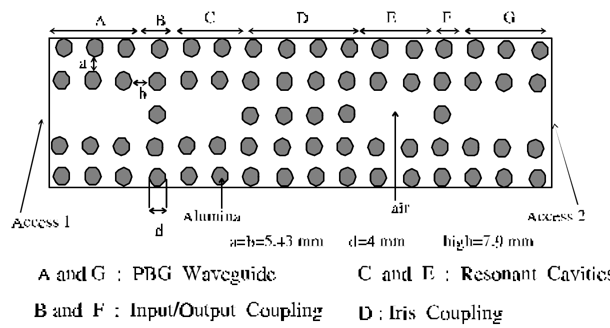


Fig.10. Waveguide two pole filter using PBG material

Figure 11 presents the filter response obtained applying the FEM. In that case the dielectric and metallic losses are taken into account. The central frequency of this response is equal to 13.44 GHz and the bandpass at -3 dB is equal to 85 MHz.

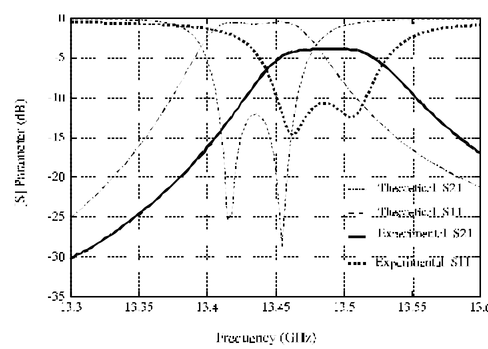


Fig.11. Theoretical and experimental [S] parameters of the waveguide two pole filter

An experimental waveguide structure (WR 62) has been built and tested. An HP 8510C network analyzer is used to measure both the transmitted and reflected waves. Theoretical and experimental results are presented on figure 11. We have nearly the same results concerning the central frequency (0,003 % of error) and the bandwidth at -3 dB (10 % of error). However experimental losses are more important (-3.9 dB instead of -0.8 dB). Some rods are out of lines each other in the two pole structures and create losses. Another mechanical problem is that the axis rod must be perfectly parallel to the electric field. This two reasons explain losses in the two pole structure.

IV - RIGOROUS DESIGN OF A PLANAR TWO POLE FILTER USING PBG MATERIALS

In this part, we present PBG structures realized by using microstrip lines substrate.

Such structure presents a 1D periodic PBG structure under the microstrip line. The line is excited on its TEM mode. To create a localized resonance, we increased the width between two rods (figure 12).

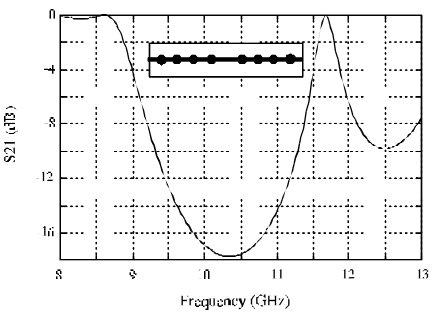


Fig.12. S_{21} parameter of microstrip line on PBG substrate with one defect mode

As the width between the two rods increase, the resonance frequency shifts through the band gap. Coupling between lines and PBG structure is define as a function of distance between lines and the top of alumina rods. A good arrangement is obtained when the distance between lines and the top of rods is equal to 0.28 mm (gap1= 0.28 mm).

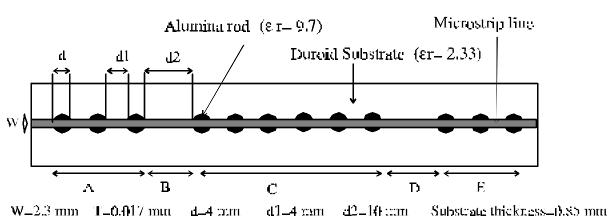


Fig.13. Design of a two pole filter using microstrip line on a PBG substrate

To obtain the two pole filter we used the same step that in part III. We consider on figure 13 the two pole planar structure using a PBG substrate. As in part III, A and E present input/output coupling coefficient, B and D the resonant cavities and C the iris coupling. Figure 14 presents theoretical and experimental results of the two pole filter with gap1, with a 550 MHz bandpass at -3 dB, 10.95 GHz central frequency, and -2.2 dB losses. This result can be improved by the optimization of all the coupling parameters. Then, with gap2= 0.1 we obtain a 200 MHz bandpass at -3 dB, with a good selectivity, and the central frequency is equal to 10.1 GHz.

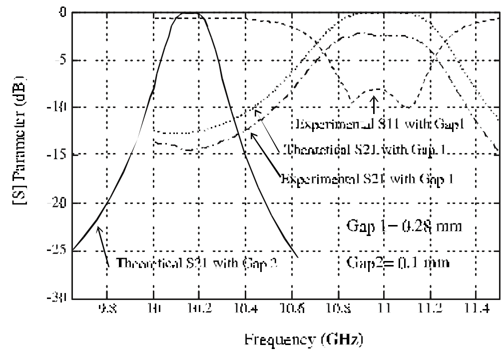


Fig.14. Theoretical and experimental [S] parameters of the planar two pole filter

CONCLUSION

Our purpose was to concept filters with artificial material. We have proved the realization of planar or waveguide two pole filter with PBG material at microwaves frequencies. Results show good agreement between experimental and theoretical results. We can specify that we had realized the same investigation with a stripline and had obtained a two pole filter with nearly same result. Indeed, for these structures, the mechanical problems seem to be less important than those appeared with the disconnected ones.

At last, these experiments realized around 12 GHz, prove that the concept of PBG could be applied to millimeter frequency band (60 GHz) filters.

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