A BRIEF REVIEW OF MICROWAVE PHOTONIC BAND-GAP (PBG) STRUCTURES

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INTRODUCTION

Photonic band-gap (PBG) structures are periodic structures with ability to control the propagation of electromagnetic waves [1,2]. They are inspired by the geometry of the crystals, specially semiconductor crystals. In semiconductor, energy gaps are explained by periodicity of atoms in the crystal. According to the quantum mechanics electrons in the crystal behave like the waves in the periodic structure. In the same way, if we construct the periodic structure that can control electromagnetic waves, we can have similar results as for electrons in the semiconductor. The equivalence of the semiconductor energy-gap in the case of the electromagnetic waves is the photonic band-gap (forbidden frequency band). Essential parameter for the formation of the band-gap is the periodic variation of the characteristic impedance $Z_C=(\varepsilon/\mu)^{-1/2}$ [3,4], common for all electromagnetic waves.

Periodic structure that can influence on the electromagnetic waves was given different names: photonic crystals (PC), photonic band-gap (PBG), electromagnetic band-gap (EBG), microwave band-gap (MBG) or (simply) periodic structure. It can be one- dimensional (1-D), two-dimensional (2-D) or three- dimensional (3-D). 3-D PBGs are the closest to the 3-D case of the semiconductor. but are pretty complicated for both simulation and construction.

One of the specific property of the PBGs are defects [5,6]. A defect is defined as a disturbing of the periodicity of the structure. In the aspect of propagation of the electromagnetic waves, defect can be treated as a resonant cavity. In the transmission response it forms free frequency mode inside the forbidden band-gap.

Periodic structures can have two topological forms: discrete (cermet topology) and continual (network topology). Discrete form is more common: response has higher order band-gaps (harmonics) and defects can be easily defined with clear interpretation in the response. Continual periodicity is a specific case of the discrete forms. They were studied in the past, but now, continual periodicity is used to obtain structures with the specific response [7].

Application of the PBGs can be in the whole electromagnetic range: from radio frequency (RF) to X-rays. However, the leading are optics and microwaves and they have the most applicable results. They both have their specific problems according to the nature of the medium and its interaction with the electromagnetic waves. In this paper photonic band-gap in the microwaves will be discussed.

Microwave PBGs have their own specifics that is different from optics. The main are:

- The longer wavelength (around 10^5 times) means bigger absolute tolerances than in optics. Relaxed tolerances are better for technology (photolitography line is wider) but sometimes the big dimension can become a problem for integration.
- Capacity (C) and inductivity (L) are specific properties, not directly seen in optics. They can very successfully shape characteristic impedance, $Z_C=(L/C)^{1/2}$, and make influence on the formation of the band-gaps [3,4].

In the next sections some applications will be briefly discussed.

3-D AND 2-D MICROWAVE PBGs

3-D PBG is complicated for both simulation and realization. In general case, parameters depend on the angle of incidence and on polarization. . They can be used as angle and polarization dependant filters. 3-D PBG is the closest to the 3-D case of the semiconductor but can be complicated for both simulation and construction [8–10].

More successful are quasi-3-D and 2-D structures. They have interesting applications like: photonic crystal based waveguide, isolation and improving characteristics of antennas.

Photonic crystal based waveguides

Photonic crystal based waveguide [11–15] is a waveguide in the PBG structure. It is a line defect

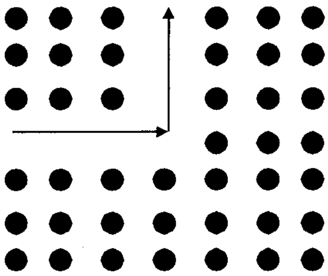

Fig.1 - Line defect inside PBG structure and bending of the electromagnetic waves

introduced in a 3-D (in practice quai-3-D) PBG, Fig.1. Once the electromagnetic wave is coupled inside the guide, the trapped wave is guided through the opening inside the structure. Experimental bending of the microwaves is presented in [14,15].

Improving isolation by PBG

Isolation can be treated as the special case of photonic crystal based waveguide One example is isolation between microelectronic circuits using vias [16]. Next is eliminating current in metal joints using photonic crystal based waveguide on joint (photonic crystal joint - PCJ) [17].

Improving characteristics of antennas by PBG

PBG application to antennas improves directivity. It incorporates mainly: suppression of the surface waves, reflectors and covers, and suppression of harmonics. Suppression of the surface waves is one of the most important task. In fact, it is the first big application of PBG in the microwaves. The surface waves radiate from the roughness of the substrate surface and from the substrate edges and can make harm to the radiation pattern. 2-D PBG is constructed on the antenna substrate to suppress surface wave propagation. Constructions can be of different types: special metal conductor surface, Fig.2 [18], drilled holes in the dielectric substrate, Fig.3 [19–23] or etched metal pattern around antenna [24]. Option without 2-D PBG is removing as much as possible of the dielectric substrate and that can cause a problem with the mechanical strength.

Fig.2 - Special metal conductor surface (cross section)

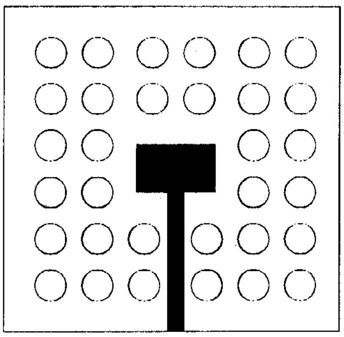

Fig.3 - Drilled holes in the dielectric substrate

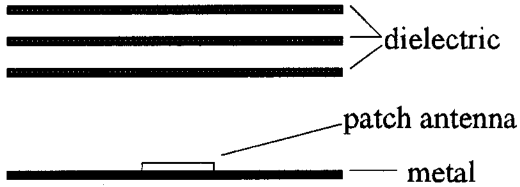

Fig.4 - Patch antenna is inside the defect of the 1-D PBG formed by 6 dielectric planes (metal plane acts as a perfect mirror for 3 upper dielectric planes)

Reflectors and covers of various types of PBGs are used [9,25,26,27]. Authors in [26] sophistically use defect mode inside the 1-D PBG structure, Fig.4. Using both PBG substrate and PBG cover is presented in [27].

Also, suppression of harmonics with PBG acts like a filter for higher radiation frequencies. In [28] PBG structure is etched in the ground plane.

1-D PLANAR PBGs

Brief about technological reason

3-D and 2-D PBGs are consisted of micromachined holes or vias into dielectric material. These structures require nonplanar fabrication processes which are not easy for integration. To overcome this problem planar process must be incorporated as much as possible. The best solution is using 1-D planar printed transmission lines like microstrip and coplanar waveguide (CPW). Some configurations can, also, be treated as quaşi-planar. They use drilled holes [29,30], Fig.5, metal vias [31,32] or dielectric (alumina) rods [33] into microstrip substrate. However vias and rods always make technological problems even if they can give very good results [32].

One of the better solutions was etching in the ground plane of the microstrip Fig.6 [34–37]. Etching (pattering) in the ground plane are still very common in eliminating need for holes or vias. Despite eliminated holes and vias, these structures have one big problem: they must be suspended. The etched ground plane must be far enough from any conductor surface. It makes a problem in packaging (appropriate space, cooling and mechanical strength).

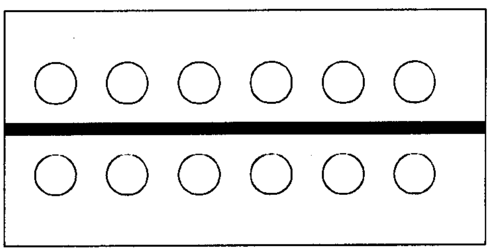

Fig.5 - Microstrip with drilled periodic holes in the substrate

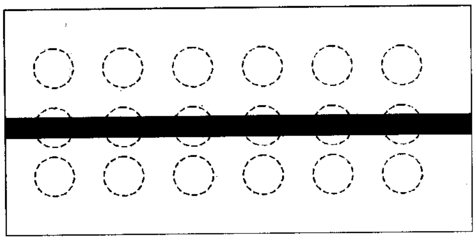

Fig.6 - Microstrip with etched periodic pattern in the ground plane (circles are only an example)

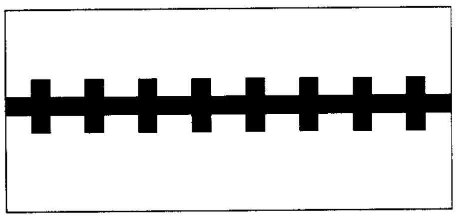

Fig.7 - Microstrip with modification of the microstrip line (without etching in the ground plane)

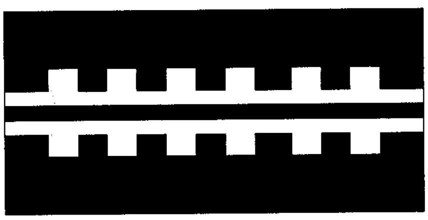

Fig.8 - CPW with modification of the ground plane. Conductor line can also be modified

The solution is a planar structure with a compact back (lower) ground plane like in ordinary microstrip Fig.7 [3,4,7,38]. CPW Fig.8 [39,40] and other uniplanar structures [41] are also used. Comparing with microstrip, CPW has an advantage of the structure only on the upper side that fits planar technology. Disadvantage is "open" lower side. Improvement was done introducing lower ground plane and finite width upper ground planes (FWCB-CPW) [42].

Connected structures

Like all PBGs in general, microwave PBGs control propagation of electromagnetic waves by creating frequency band-gap i.e. band-stop. All other applications are combination or modification of the band-gap concept. Wide band-stop can act as a low-pass filter. A serial connection of two or three band-stops can form low-pass [30,36,43] or band-pass filter [35,43]. Connection can, also, be parallel [36].

Delay and phase shifting

One of the specific of the PBGs is the slow-wave effect [44–46]. At the edge of the band-pass the value of the propagation constant (β) is almost double that of a normal line. Delay is, also, proportional to the number of cells. It is useful for delay lines, phase shifters and shaping the signal. Interesting is using PBG structures for making phase shifting in antenna array and producing beam-steering [46]. Delay of the each antenna of the array can be change by varying the number of cells of the PBG feeding line.

Effect of coupling and leaky-wave antennas

Leaky-wave radiation and coupling are also characteristics of the PBGs. For some applications they can cause problems and must be as low as possible. In simulation, coupling effect between periodic cells demands using full-wave analysis. Useful applications are functional coupling and leaky-wave antennas. Coupling effect in PBGs can be used for efficient forward coupling between lines. It reduces line lengths and relaxes the spacing between lines [47].

Leaky-wave antennas are based on the periodical structure in or close to the dielectric waveguide [48]. Periodicity forms grating structure with specific radiation pattern. Radiation pattern can be shaped by controlling grating profile. Very interesting applications are: photoexcited periodicity in Si waveguide [49] and moveable grating over dielectric line [50].

Using defects

Periodic structure can contain one or more defects Fig.9. Their application is forming band-pass and resonant filters inside forbidden band-gap [33,41,51,52]. Many defects can make complicated structures and are treated mainly theoretically. It is interesting to mention controlling defect [8,51,52].

Integration on Si

One of the main goals for microwave PBGs is integration on semiconductors. Si-substrate is one of the main steps. The first main problems are losses. Good solution needs pure Si (>2 kΩcm). The second is compatibility to the planar application: both input and output need to be on the upper side. In that context, CPW is better than microstrip. In fact, it is FWCB-CPW type of CPW that is promising [42].

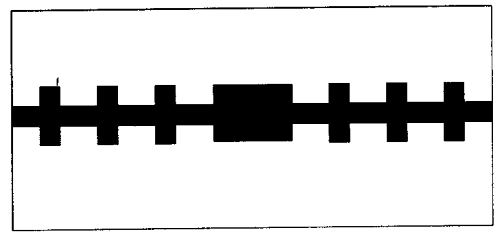

Fig.9 - An example of defect on the microstrip PBG

On of the main advantage of the Si-based PBGs is ability of voltage and optical control [53–56]: optically created plasma effect can change effective ε_r of the substrate and so Z_C.

The light can easily influence the parameters of the Si-substrate. In CPW, the most "active" part of the substrate is close to the "unprotected" upper surface between central line and upper ground plane. However, a great part of the field is in the air above the waveguide (effective ε_r is small). The light can easily influence on the upper surface of the substrate but the influence on the waveguide itself is not so big. There are, also, examples of the optically created PBG on CPW [55–56]. In microstrip, more "active" part is under the microstrip line and light need to come from the side.

Controlled PBG

Controlling of PBGs is, also, one of the main goals (also called "active PBGs"). The control is done by external influence on the Z_C of the structure. One of the ways of the influence can be forming the periodicity on the uniform waveguide [54–56]. Another control can be creating or modifying defects [8,51,52].

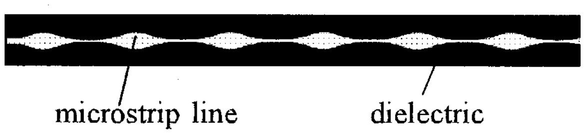

Fig.10 - Layout of microstrip PBG with sinusoidal variation of the characteristic impedance Z_C along the microstrip line and without etching in the ground plane

Fig.11 - One of the realized microstrip PBG band-pass filters (white is the microstrip line)

Fig.12 - Realized microstrip PBG low-pass filter (white is the microstrip line)

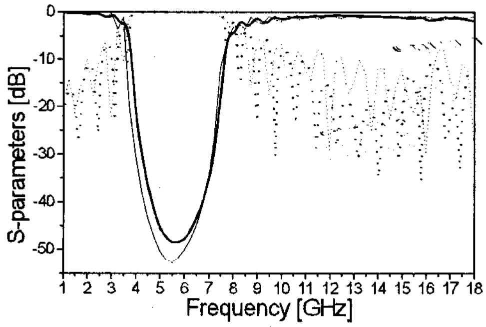

Fig.13. - Band-stop filter with six cells
S_{21} - solid lines; S_{11} - dotted lines
Simulated (thin lines) and measured (thick lines)

The influence on the substrate is possible in the case of the semiconductor substrate. The influence can be done by voltage and light [54–56].

The influence on non-semiconductor PBGs can be done by changing capacity using external objects: devices (i.e. varactor diode [51]) or by small plate (melal or dielectric) above the waveguide [52]. In both cases, changing the capacity of the defect shifts the defect mode inside the band-gap.

Continual PBG

Continual periodicity were studied in the past [57,58] but mainly without direct application. Now, continual periodical structure is used to obtain specific response. One of the examined goals is obtaining only one band-gap (without harmonic response) [7,43,59].

In [7,43] authors introduced the structures with a sinusoidal variation of the characteristic impedance Z_C according to the variation of the width of the microstrip line. The variation of Z_C is between Z_{min} and Z_{max}, (Z_{min} , Z_{max}), and satisfied $(Z_{min} Z_{max})^{1/2} = 50\ \Omega$. They are, also, without etching in the ground plane. Its transmission for only one type of cells, Fig.10, gives only one (first order) band-gap, without harmonic response, Fig.13.

The serial connection of two filters of the different cell lengths, Fig.11, gives a band-pass filter, Fig.14. The serial connection of three filters of the different cell lengths, Fig.12, gives a low-pass filter, Fig.15.

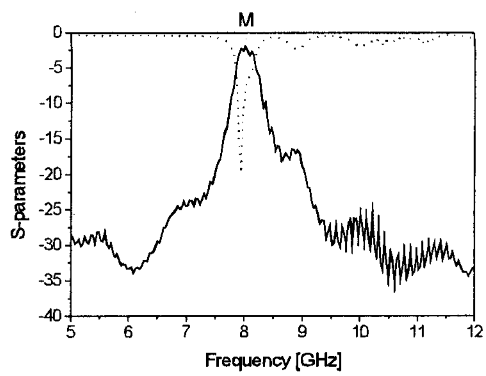

Fig.14 - Measurement for band-pass filter around 8 GHz S_{11}-dotted lines; S_{21}-solid lines

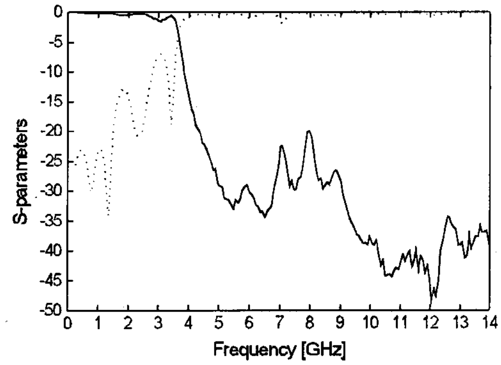

Fig.15 - Measurement for law-pass filter S_{11}-dotted line; S_{21}-solid line

CONCLUSION

In this paper microwave photonic band-gap (PBG) structures were briefly discussed. Overview includes brief introduction to the nature of the PBG and discussion of the specific types and applications of the microwave PBG structures. Intention was to say as much as possible in 6 pages including useful literature. Microwave PBG is a broad and still a new field. A lot of things are not even theoretically and practically clear. Application is still in the beginning but offers wide range of use.

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