Mater.Phys.Mech.1 (2000) 20-26

FABRICATION OF 2-D AND 3-D PHOTONIC BAND-GAP CRYSTALS IN THE GHz AND THz REGIONS

G. Kiriakidis and N. Katsarakis

Institute of Electronic Structure and Laser (IESL), Foundation for Research and Technology-Hellas (FO.R.T.H.), P.O. Box 1527, Heraklion 711 10, Greece

Received: October 1999

Abstract. Two- and three-dimensiona1 dielectric and metallic structures exhibiting photonic band-gaps in a broad frequency range were fabricated by deep X-ray lithography and laser micro-machining. These techniques seem promising for mass production of photonic structures with full band-gaps in a spectrum ranging from the millimeter wave up to the far infrared regime. Deep X-ray lithography was applied to produce periodic 3-D photonic band-gap structures based on the "three-cylinder" model with mid-gap frequencies up to 2.4 THz. Metallic 3-D structures with incorporated point and linear defects are currently under development. Layered metallic and metallo-dielectric structures exhibiting a cutoff frequency in the microwave regime were fabricated by laser precision machining. The observed cutoff frequency can be easily tuned by varying the interlayer distance or the filling fraction of the metal. Combinations of layers with different metal filling fractions create defect modes with relatively sharp peaks, which are also tunable. The metallo-dielectric structures are significantly smaller than the simple metallic ones. The experimental measurements seem to be in good agreement with theoretical calculations.

1. INTRODUCTION

Over the last decade, a new brand of artificial structures has raised the excitement of scientists. In analogy to electrons in a crystal, the propagation of electromagnetic waves travelling in periodic dielectric structures can lead to the formation of stop bands [1,2]. When these stop bands are wide enough to overlap for both polarization states along all crystal directions, the material displays a complete Photonic Band-Gap (PBG), that is, a frequency range where the propagation of electromagnetic waves is forbidden, irrespective of the propagation direction. These effects lead to some novel applications in quantum optics in the frequency range from microwave to the optical regime such as low-cost efficient microwave antennas, low-loss cavities and resonators and zero-threshold lasers [3-7]. Photonic crystals represent also a novel and promising improvement on the operating efficiency of either Laser Diodes or Light Emitting Diodes (LEDs). They have already been recognized for their ability to control the flow of light and their capacity to modulate, suppress, concentrate and direct it, in an enhanced light-matter interaction manner.

The potential of these artificial structures has been exploited by theoretical and experimental studies mainly on 2-D and 3-D photonic crystals operating from the microwave to the optical regime utilizing a number of diverse fabrication techniques and materials. It is the purpose of this work to present an inside of two selected fabrication techniques for 2-D and 3-D crystals, namely LIGA [8] and laser machining [9], and explore their potentials, limitations and applications utilizing both dielectric and metallic materials.

2. 2-D PHOTONIC CRYSTALS

The critical factors to control the properties of 2-D photonic crystals are the refractive index contrast, the arrangement of the lattice elements and the fraction of high and low index materials in the lattice. In principle, the higher the refractive index contrast the stronger the expected effects and the larger the band-gap achievable. Fabrication of 2-D structures has flourished due to the fact that they are relatively easy to make utilizing tools and techniques borrowed from the silicon microelectronics industry. The most significant progress so far has been reported with planar structures patterned by standard photolithography or electron-beam lithography, generating patterns in the visible and near-IR ranges [10-12]. More recently, multiple exposure holography, a technique well established for some time, has been applied successfully to fabricate advanced structures [13]. The importance of

Corresponding author: G. Kiriakidis, e-mail:kiriakid@ies1.forth.gr

© 2000 Advanced Study Center Co. Ltd.

producing low dimensionality structures relates to the ease of manipulating for the photonic lattice particularly in as far as interfacing with optical elements such as fibres, light sources, detectors and waveguides are concerned. A typical 2-D photonic lattice consists of holes etched into a semiconductor substrate. One type of lattice is triangular, self-similar upon 60° rotations with two main directions of symmetry in the "honeycomb" configuration [14]. This, along with the "graphite" type have demonstrated the widest band-gaps when regions of semiconductors are surrounded by large regions of air, i.e. when the area fill-factor is low [15]. Under the above configurations the criterion for maximum effect is achieved when the optical path length in both materials is roughly equal. However, an additional important factor that determines the properties of 2-D PBGs is that of light confinement in the third dimension. Most successful structures presented to date utilize some forms of waveguide confinement. In such configurations there are a number of obvious advantages related with the application of epitaxial layer growth techniques and compatibility with established planar optoelectronic elements [16]. Advanced configuration designs have recently demonstrated PBG structures with high transmission, reflection and very sharp filtering characteristics, promising interesting future optoelectronic applications [17,18].

3. 3-D PHOTONIC CRYSTALS

The first experimental evidence of a 3-D photonic crystal was presented by E. Yablonovitch and co-workers [4,5] following the theoretical work of K. M. Ho and co-workers [6] in 1990. This was an array of holes drilled into high refractive index material (since called the "Yablonovite") showing a stop band for the transmission of microwave radiation that extended from 10 to 13 GHz irrespective of the direction of propagation. Furthermore, it was demonstrated that by including a defect either by adding or removing material, localized states in the band-gap were created, in direct analogy to "doping" effects for semiconductors. For the microwave regime the immediate application for such an effect could be related to couple a PBG crystal with an antenna and allowing more flexibility and enhancement of the radiation process in point-to-point communications. The above proof-of-concept demonstration by E. Yablonovitch is known today as the "three-cylinder" model and presents a structure with the symmetry of the diamond. A corresponding diamond structure was also proposed by C. T. Chan and co-workers [19]. Later, the same group from Iowa State University designed a novel three-dimensional "layer-by-layer" structure demonstrating again a full 3-D PBG over a wide range of structural parameters. This structure consisted of layers of one-dimensional dielectric rods of rectangular, circular or elliptical cross section. The band-gap is optimized by controlling the dielectric contrast of the materials been used, the filling factor of the dielectric and, of course, the lattice constant of the PBG structure. Although it was fundamentally important to demonstrate the existence of a full 3-D PBG in the microwave regime, the drive was soon focused towards the fabrication of truly "photonic" 3-D structures that operate in the near IR and eventually the visible regime of the electromagnetic spectrum. The obvious approach was to scale down fabrication techniques successfully employed in the microwave regime. Indeed, a significant improvement was first demonstrated by G. Feiertag and co-workers [8], showing the potential of combining deep X-ray lithography (LIGA technique) with the "three-cylinder" model to produce 3-D structures with lattice constants of 227 and 114 μm, corresponding to mid-gap frequencies of 0.75 and 1.5 THz respectively. Detailed account of the LIGA processing results will be presented in the following section. Since then, the "layer-by-layer" model was matured further to a point of reaching into the far-IR producing structures displaying a stop-band between 1.35 and 1.95 μm [20]. The use of microfabrication techniques to produce structures in the 1.5 μm window has failed to show yet the expected sharp spectral response. However, the technique has been very useful in the fabrication of Metallic Photonic Band-Gap (MPBG) structures and is presented in details in the subsequent chapters. Finally, novel concepts that are based upon the self-organization of structures show the promise of the approach rather than providing a fully convincing demonstration.

4. The LIGA technique for PBG structures in the far infrared frequency range

LIGA is a well established technique for the production of high aspect ratio microstructures [21,22]. It combines deep X-ray lithography (DXRL) with synchrotron radiation, electroforming and ceramic moulding. Deep X-ray lithography with synchrotron radiation is used to transfer an absorber pattern from an X-ray mask into a thick resist material deposited on a substrate. The mask consists of an X-ray transparent membrane (e.g. Be, Si, Ti) with absorber structures made of gold. By shadow printing the mask pattern is transferred into the resist using X-rays. Synchrotron radiation is applied because of its high intensity and small divergence. In this way, extremely precise microstructures with high aspect ratios can be realized. Due to the extremely high depth of focus the lateral

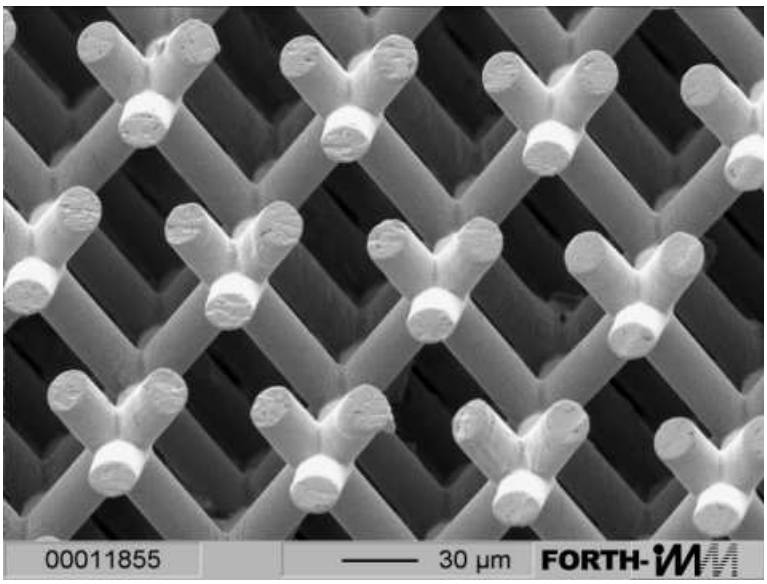

Fig. 1. 3-D photonic band-gap structure fabricated by LIGA according to the "three-cylinder" model.

deviations of the resist walls are as small as 0.05 μm per 100 μm thickness. PMMA is usually applied as resist material. It has very good properties to achieve vertical walls with a roughness of less than 50 nm. Through exposure, the resist undergoes a decrease in molecular weight and becomes soluble in an organic developer, if the deposited dose is above 2 kJ/cm^3. After development of the exposed resist, the gaps of the resist relief are filled with metal via electroforming. The extremely accurate metal form can be used, e.g., for plastic moulding, offering inexpensive microstructure replication. A melted thermoplastic or a casting resin is injected through holes in a conducting gate plate, yielding a corresponding plastic structure which is fixed on by the remaining resin in the holes of the gate plate after cooling and separating the mold from the mold insert. The plastic structure obtained in the moulding process can be used as well as a "lost form" for the fabrication of ceramic microstructures. After filling the plastic form with a ceramic paste, a dense ceramic structure is formed by following conventional drying and firing processing. LIGA is a generic technology and therefore has a wide range of applications in fields such as sensors and actuators, optical engineering (integrated optics, nonlinear optics, fibre optics), electrical connectors, instrumentation for minimal-invasive surgery, biomedical and fluid-dynamical engineering and micro-filtration systems.

The "three-cylinder" model was selected for the fabrication of 3-D PBGs using LIGA. It is easily realized by three tilted irradiations of a PMMA slab using an X-ray mask with a triangular array of holes. Mask and resist are tilted 35° with respect to the synchrotron radiation beam. Between the irradiations, the tilted arrangement of mask and resist must be rotated each time by 120°.

A process that comprises two main steps has been chosen for the fabrication of three-dimensional PBG structures in the far-IR [8]. Deep X-ray lithography is used to produce a mold which is then filled with a ceramic or pre-ceramic material (Fig.1). It was first tried to fill the holes with a ceramic paste but the resist mold could not be filled completely. Therefore, it was decided to use a pre-ceramic polymer (polyvinylsilazane) that can be transformed into a silicon-carbonitride ceramic by a subsequent pyrolysis process.

The transmission characteristics of a structure with a lattice constant of 85 μm and rod diameter of 22 μm have been measured. The filling ratio of the ceramic rods in this structure was 35% and the total thickness of the structure 450 μm. There is a constant drop of the transmission which is attributed to the absorption of the ceramic. The experimental results are in agreement with theoretical calculations (Fig. 2). There is also a well-defined drop of the transmission at around 80 cm^{-1} (2.4 THz) which is related with the first band-gap created due to the periodicity of the structure. The gap over the mid-gap ratio for this stop band is $\Delta\omega/\omega_g$=0.35. Transmission measurements for a similar photonic structure with rods diameter of 31 μm, which corresponds to a filling ratio of 57%, show a gap at around 70 cm^{-1} (2.1 THz) with $\Delta\omega/\omega_g$=0.32.

Recent efforts are targeting the fabrication of metallic 2-D and 3-D structures with different kind of defects in the far-IR range of the electromagnetic spectrum. New photosensitive materials, like SU-8, are applied in order to achieve even higher aspect ratios for both 2-D and 3-D structures.

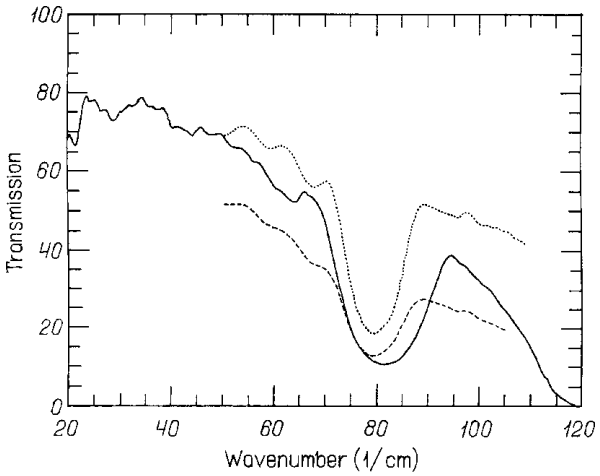

Fig. 2. Measured (solid line) and calculated results for a photonic structure with 85 μm lattice constant and 22 μm rods diameter. In the calculations, a dielectric constant of the rods with real part equal to 3 and imaginary part 0.1 and 0.2 was used (doted and dashed lines respectively).

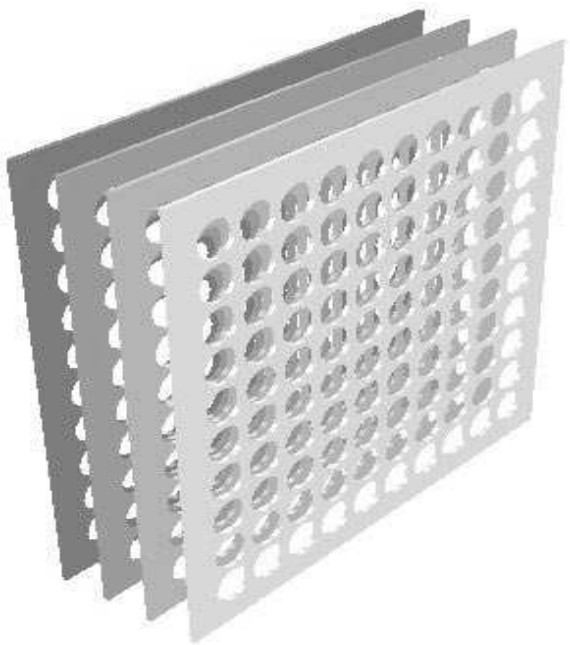

Fig. 3. A three-dimensional image of a layer-by-layer metallic photonic band-gap structure.

5. LASER-MACHINED METALLIC AND METALLO-DIELECTRIC PBG STRUCTURES

Most of the earlier research work was concentrated on the development of PBG crystals built from frequency-independent dielectrics. At lower microwave and millimeter wave frequencies, however, metals act like nearly perfect reflectors, no absorption problems occur, and there are certain advantages of introducing metals to photonic crystals. These include reduced size and weight, easier fabrication and lower costs.

Metallic photonic band-gap crystals (MPBG) operating in the microwave frequency range were fabricated by laser precision machining [9]. They consist of stainless steel plates with a tetragonal lattice of holes and a lattice constant of 15 mm. Transmission measurements show that periodic crystals exhibit a cutoff frequency in the 8-18 GHz range, below which no propagation is allowed. The cutoff frequency can be easily tuned by varying the interlayer distance or the filling fraction of the metal. Combinations of plates with different hole-diameters create defect modes with relatively sharp peaks, which are tunable.

In particular, stainless steel plates of 1 mm thickness were drilled using a Nd:YAG laser with a wavelength of 1064 nm and an output power of 100 W at a CNC working station with four degrees of freedom. The laser was operated in pulsed mode with a repetition rate of 120 Hz. Oxygen flow was necessary to prevent deposition of debris on the metal surface. The distance of the laser focusing system from the sample surface was 0.5 mm and the cutting velocity 600 mm/min. Holes with diameters of 8, 10, 12 and 14 mm were drilled on each plate in a square arrangement with a centre-to-centre distance of 15 mm (10·10 array). Four layers of each specific structure were fabricated. Consequently, periodic structures of up to 4 layers, as shown in Fig. 3, could be built and measured while combinations of layers with different hole-diameters could also be used to study defects.

All periodic structures behave like high-pass filters. They exhibit a cutoff frequency in the 8-18 GHz frequency range, below which there are no propagating modes. Within the band-gap, the rejection rate of the transmitted EM signal ranges between 5 and 10 dB per layer. The transmission characteristics of periodic structures consisting of three or four metallic layers with a tetragonal lattice of 12 mm-diameter holes at a distance of 7 mm are presented in Fig. 4. It can be seen that a structure with three layers exhibits a cutoff frequency at 12 GHz.

The cutoff frequency of the MPBG structures can be easily tuned by varying the distance between the metallic layers. In particular, by increasing the interlayer distance the gap-edge shifts to lower frequencies. In Fig. 5, it is demonstrated that the cutoff frequency is linearly related to the interlayer distance. These results are in good agreement with theoretical calculations that are shown in Fig. 6. The filling fraction of the metal also affects the observed cutoff frequency. A decrease in the hole-diameter, which corresponds to an increase in the filling ratio of the metal, shifts the gap-edge to higher frequencies. This behaviour is shown in Fig. 7, where it can be seen that

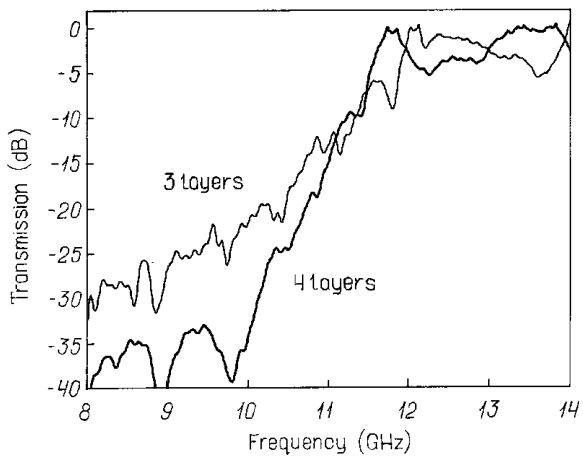

Fig. 4. Transmission profile for a periodic structure with three or four layers. The lattice constant (within one layer) is 15 mm, the diameter of the holes is 12 mm, and the distance between the layers is 7 mm.

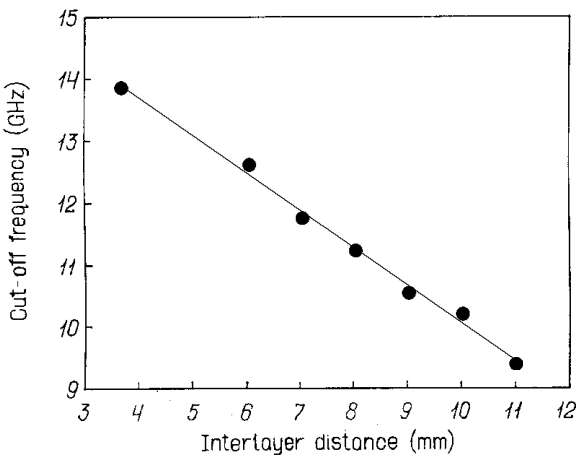

Fig. 5. Cutoff frequency as a function of the interlayer distance for a periodic structure similar with the one described in Fig. 2.

indeed the cutoff frequency increases as the hole-diameter drops.

Defects are created easily by replacing the middle layer of a periodic structure with a layer having larger holes. Thus, in this way, metal deficiency is created in the middle layer. All defect structures show sharp transmitted modes in the prohibited frequencies of the periodic counterparts. The quality factor Q of the defect modes is about 70. Additionally, the introduction of a defect in the MPBG structure shifts the gap-edge to higher frequencies. In Fig. 8, defect structures consisting of three layers with hole-diameters of 8-12-8 mm and 8-14-8 mm are compared to the fully periodic one (8-8-8 mm). The removal of more metal from the middle layer (hole-diameters of 8-14-8 mm instead of 8-12-8 mm) moves the defect mode to lower frequencies while the position of the gap-edge is not affected.

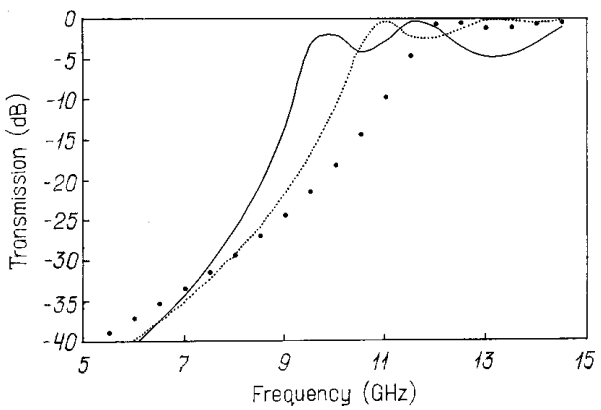

Fig. 6. Calculated transmission profiles for periodic structures consisting of three layers with hole-diameters of 12-12-12 mm at a distance of 11, 9, and 7 mm (solid, dashed and dotted line respectively). The lattice constant within one layer is 15 mm for all structures.

This demonstrates that not only the cutoff frequency but also the frequency of the defect modes can be tuned.

By changing the interlayer distance of the defect structure with hole-diameters of 8-12-8 mm from 7 mm to 9 mm, a shift of the total frequency spectrum to lower frequencies occurs, as has been also observed for the periodic counterparts. It is important to note that this effect does not change the distance between the defect peak and the gap-edge. The above observations have been also demonstrated on different arrangements such as the 12-12-14-12-12 mm structure.

However, the size of the simple metallic PBGs is restrictive for their application in microwave technology. Therefore, it is essential to reduce their size by introducing other dielectrics rather than air. Metallo-dielectric PBG structures operating in the microwave frequency range and especially between 10

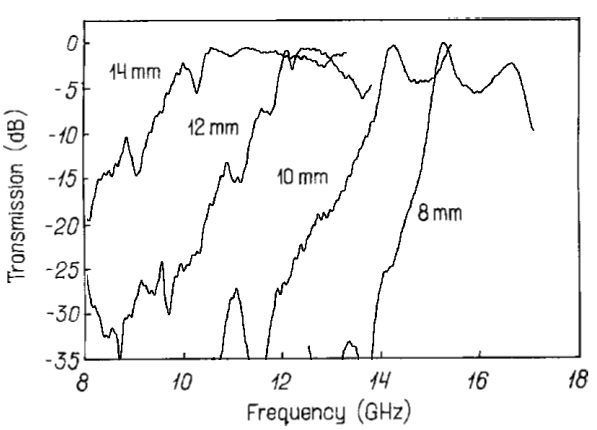

Fig. 7. Cutoff frequency as a function of the hole-diameter.

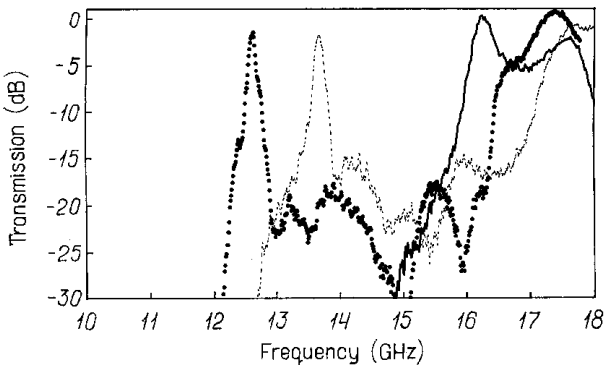

Fig. 8. Transmission profiles for defect structures consisting of three layers with hole-diameters of 8-12-8 mm and 8-14-8 mm (dashed and dotted line respectively) as well as for the periodic structure with hole-diameters 8-8-8 mm (solid line). In all cases, the lattice constant within one layer is 15 mm and the interlayer distance is 7 mm.

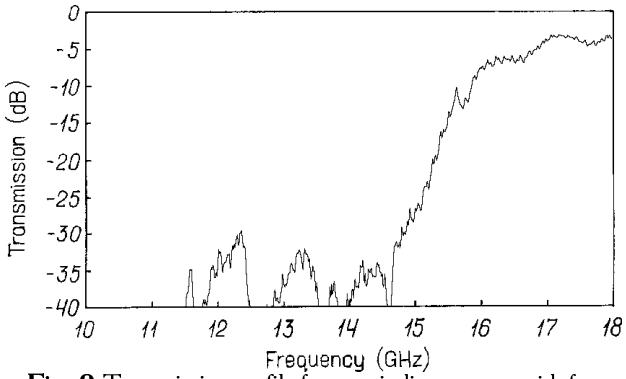

Fig. 9. Transmission profile for a periodic structure with four Al/Al_2O_3 layers. The lattice constant of the structure is 5 mm, and the width of the Al wires is 2 mm.

and 18 GHz were fabricated according to the layer-by-layer model. In particular, a metal (aluminum) pattern was applied onto Al_2O_3 wafers. The pattern consists of a square lattice of metal grids with a lattice constant of 5 mm. Transmission measurements show that periodic structures, consisting of up to four wafers laterally aligned to each other, exhibit a cutoff frequency in the 10-18 GHz frequency range, below which no propagation is allowed (Fig. 9). The cutoff frequency can be easily tuned by varying the interlayer distance or the width of the metallic grids. Combinations of wafers with grids of different width create defect modes with relatively sharp peaks, which are tunable. The size of the PBG structures was strongly reduced compared to the simple metallic meshes, for the same frequency characteristics, by using a supporting dielectric substrate for the metallic grids. The application of Al_2O_3 wafers as a supporting material for a metallic grid pattern leads to a reduction of the size of the simple MPBG structure by a factor of 3. This can be further improved by using high dielectric microwave materials. Dielectric materials with tunable properties may open new perspectives for the application of "clever" PBG structures in microwave technology.

Recent activities are targeting the fabrication of monolithic MPBG structures consisting of microwave dielectrics patterned with metallic grids for applications in microwave technology.

6. CONCLUSIONS

Laser micro-machining and LIGA are two very useful techniques for the fabrication of PBG structures. LIGA has been selected for its ability to produce accurate and reproducible 3-D PBGs up to the THz spectral range, while laser machining has been selected for its versatility to producing effective tuneable 2-D metallic structures in the millimeter wave regime. Results presented have demonstrated the advantages of these two techniques for high quality, reproducible and low-cost PBGs and their potential for immediate application in the production of novel components in quantum optics.

REFERENCES

[1] *Photonic Band Gaps and Localization*, ed. C.M. Soukoulis, (Plenum: New York 1993), Proceedings of the NATO ARW.

[2] *Photonic Band Gap Materials*, ed. C.M. Soukoulis, NATO ASI, Series E, vol. 315.

[3] S. John // Phys. Rev. Lett. **58** (1987) 2486.

[4] E. Yablonovitch, T.J. Gmitter and K.M. Leung // *Phys. Rev. Lett.* **67** (1991) 2295.

[5] E. Yablonovitch and K.M. Leung // *Nature* **351** (1991) 278.

[6] K.M. Ho, C.T. Chan and C.M. Soukoulis // *Phys. Rev. Lett.* **65** (1990) 3152.

[7] W. Robertson, G. Arjavalingan, R.D. Meade, K.D. Brommer, A.M. Rappe and J.D. Joannopoulos // *Phys. Rev. Lett.* **68** (1992) 2023.

[8] G. Feiertag, E. Ehrfeld, H. Freimuth, H. Kolle, H. Lehr, M. Schmidt, M.M. Sigalas, C.M. Soukoulis, G. Kiriakidis, T. Pedersen, J. Kuhl and W. Koenig // *Appl. Phys. Lett.* **71** (1997) 1441.

[9] N. Katsarakis, E. Chatzitheodoridis, G. Kiriakidis, M.M. Sigalas, C.M. Soukoulis, W.Y. Leung and G. Tuttle // *Appl. Phys. Lett.* **74** (1999) 3263.

[10] M.D.B. Charlton, S.W. Roberts and G.J. Parker // *Materials Science and Engineering B-Solid State Materials for Advanced Technology* **49** (1997) 155.

[11] J.M. Gerard, A. Izrael, J.Y. Marzin, R. Padjen and F.R. Ladan // *Solid State Electronics* **37** (1994) 1341.

[12] T. Krauss, Y.P. Song, S. Thoms, C.D.W. Wilkinson and R.M. Delarue // *Electronic Letters* **30** (1994) 1444.
[13] V. Berger, O. Gauthier Lafaye and E. Costard // *Electronic Letters* **33** (1997) 425.
[14] R.D. Meade, K.D. Brommer, A.M. Rappe and J.D. Joannopoulos // *Appl. Phys. Lett.* **61** (1992) 495.
[15] D. Cassagne, C. Jouanin and D. Bertho // *Phys. Rev.* B **53** (1996) 7134.
[16] H.W. Lau, G.J. Parker, R. Greef and M. Hoelling // *Appl. Phys. Lett.* **67** (1995) 1877.
[17] D. Labilloy, H. Benisty, C. Weisbuch, T.F. Krauss, R.M. Delarue, V. Bardinal, R. Houdre, U. Oesterle, D. Cassagne and C. Jouanin // *Phys. Rev. Lett.* **79** (1997) 4147.
[18] T.F. Krauss, B. Vogele, C.R. Stanley and R.M. Delarue // *IEEE Photonics Technology Letters* **9** (1997) 176.
[19] C.T. Chan, K.M. Ho and C.M. Soukoulis // *Europhys. Lett.* **16** (1991) 563.
[20] J.G. Fleming and S.Y. Lin // *Optics Letters* **24** (1999) 49.
[21] W. Ehrfeld and H. Lehr // *Radiat. Phys. Chem.* **45** (1995) 349.
[22] F.J. Pantenburg and J. Mohr // *Nuclear Instruments and Methods in Physics Research* B **97** (1995) 551.