Laser-machined layer-by-layer metallic photonic band-gap structures

N. Katsarakis,[a] E. Chatzitheodoridis, and G. Kiriakidis
Materials Group, Institute of Electronic Structure and Laser (IESL), Foundation for Research and Technology-Hellas (FO.R.T.H.), Heraklion 711 10, Greece

M. M. Sigalas, C. M. Soukoulis, W. Y. Leung, and G. Tuttle
Ames Laboratory and Microelectronics Research Center, Iowa State University, Ames, Iowa 50011

(Received 23 November 1998; accepted for publication 7 April 1999)

Metallic photonic band-gap crystals operating in the microwave frequency range were fabricated by laser precision machining. 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. The experimental measurements are in good agreement with theoretical calculations. [S0003-6951(99)03822-X]

Photonic band-gap (PBG) crystals are periodic dielectric structures, which can suppress the transmission of electromagnetic (EM) waves at certain frequency ranges.[1] 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.[2–9] These include reduced size and weight, easier fabrication, and lower costs.

In this letter, inexpensive and simple metallic PBG (MPBG) structures operating in the microwave range of frequencies, and especially between 8 and 18 GHz, are described. The structures were fabricated by laser precision machining according to the layer-by-layer model.[10] Both periodic and defect MPBG structures were studied. It is pointed out that both the cutoff frequency of the MPBG structures and the introduced defect modes can be easily tuned.

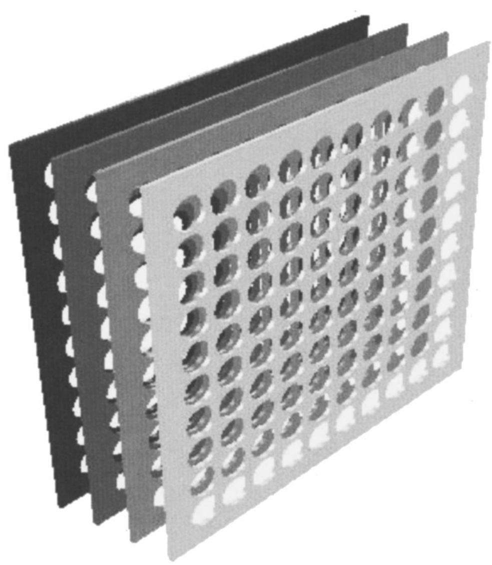

FIG. 1. A three-dimensional image of a layer-by-layer metallic photonic band-gap structure.

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 was 600 mm/min. Holes with diameters of 8, 10, 12, and 14 mm were drilled on each plate in a square arrangement with a center-to-center distance of 15 mm (10×10 array). Four layers of each specific structure were fabricated. Consequently, periodic structures of up to four layers, as shown in Fig. 1, could be built and measured, while combinations of layers with different hole diameters could also be used to study defects.

Transmission properties of the metallic structures were measured using a Hewlett–Packard 8510C network analyzer. The measurements were performed in an enclosure with special isolation to reduce reflections. Two pairs of microwave

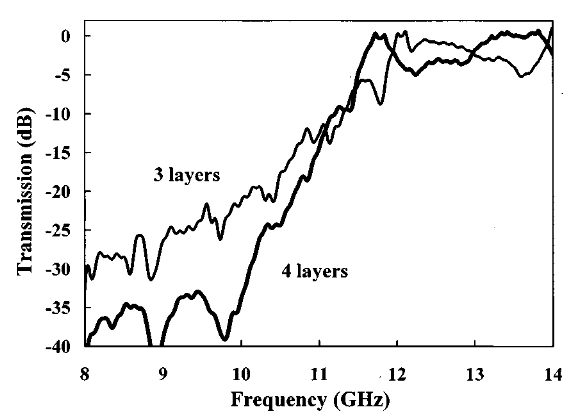

FIG. 2. Transmission profile for a periodic structure with three or four layers. The lattice constant (within one layer) is 15 mm, the diameter of the holes is 12 mm, and the distance between the layers is 7 mm.

[a]Electronic mail: katsan@esperia.iesl.forth.gr

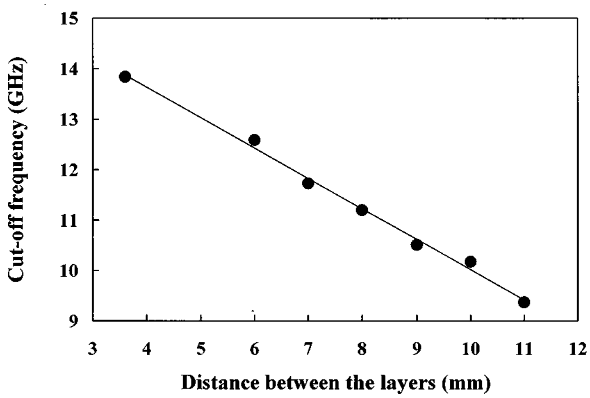

FIG. 3. Cutoff frequency as a function of the interlayer distance for a periodic structure similar with the one described in Fig. 2.

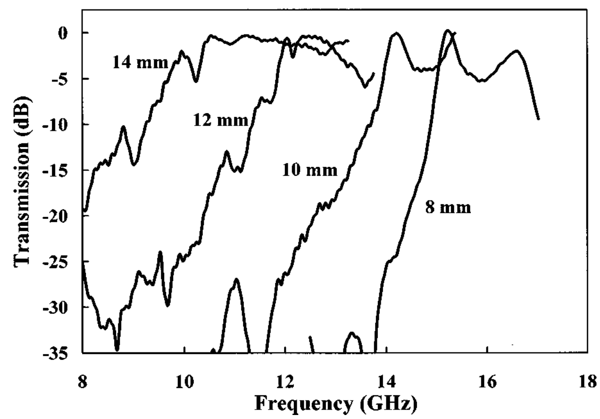

FIG. 5. Cutoff frequency as a function of the hole diameter.

standard-gain horn antennas were used to cover the frequency range of 8–18 GHz. The analyzer was first calibrated without the structures and then, the calibration was saved and used to normalize the transmission measurements of the structures. In all cases the field was incident normal to the metallic plates (001 direction) and the electric field polarization vector **e** was parallel to the surface of the plates (either along the 100 or 010 directions; both directions give the same results).

All periodic structures behave, as it was expected for MPBG structures, 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-diam holes at a distance of 7 mm are presented in Fig. 2. 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. 3 it is demonstrated that the cutoff frequency is linearly related to the interlayer distance. These results are in good agreement with the theoretical calculations that are shown in Fig. 4. 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 behavior is shown in Fig. 5, where it can be seen that 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. 6, 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. 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 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

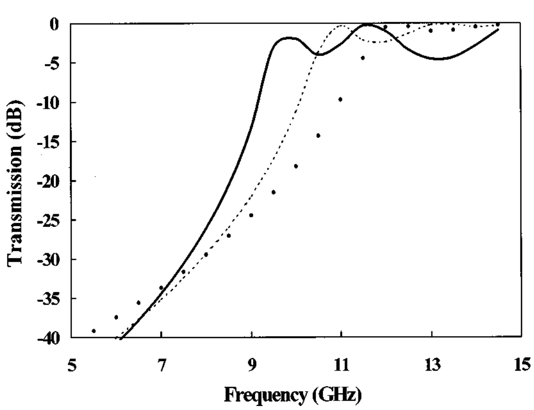

FIG. 4. Calculated transmission profiles for periodic structures consisting of three layers with hole diameters of 12-12-12 mm at a distance of 11, 9, and 7 mm (solid, dashed and dotted line, respectively). The lattice constant within one layer is 15 mm for all structures.

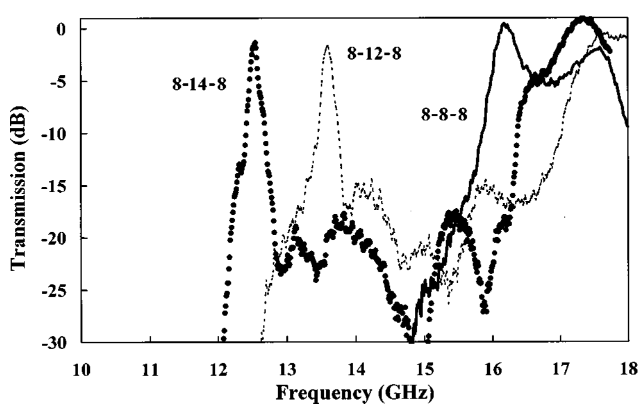

FIG. 6. Transmission profiles for defect structures consisting of three layers with hole diameters of 8-12-8 and 8-14-8 mm (dashed and dotted line, respectively), as well as for the periodic structure with hole diameters 8-8-8 mm (solid line). In all cases, the lattice constant within one layer is 15 mm and the interlayer distance is 7 mm.

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.

In summary, three layers are, in general, enough to show the high-pass effect but, depending on the application, four or more layers might be more appropriate. The cutoff frequency can be tuned by varying two different parameters, either the interlayer distance or the hole diameter. Defect structures produce clear and high-Q (about 70) defect peaks. The cutoff is shifted to higher frequencies relative to the periodic counterparts. The frequency of the defect mode can be tuned by varying the amount of the removed metal. However, this does not affect the observed cutoff frequency. All measurements are in good agreement with theoretical calculations.

The authors are indebted to Laser Innovation Center (LIC) and especially to E. Hontzopoulos for his contribution to the laser-machining process. They would also like to thank K. M. Ho for some helpful discussions. This work is supported by NATO Grant No. 940647, PENED, and the CEC ''MICROSYNC'' TMR Project No. FMRX-CT97-0140. Ames Laboratory is operated for the U.S. Department of Energy by Iowa State University under Contract No. W-7405-Eng-82.

[1] For a review, see the articles in *Photonic Band Gap Materials*, edited by C. M. Soukoulis (Plenum, New York, 1996).
[2] D. R. Smith, S. Schultz, N. Kroll, M. Sigalas, K. M. Ho, and C. M. Soukoulis, Appl. Phys. Lett. **65**, 645 (1994).
[3] E. R. Brown and O. B. McMahon, Appl. Phys. Lett. **67**, 2138 (1995).
[4] A. R. McGurn and A. A. Maradudin, Phys. Rev. B **48**, 17576 (1993).
[5] M. M. Sigalas, C. T. Chan, K. M. Ho, and C. M. Soukoulis, Phys. Rev. B **52**, 11744 (1995).
[6] S. Gupta, G. Tuttle, M. Sigalas, and K. M. Ho, Appl. Phys. Lett. **71**, 2412 (1997).
[7] D. F. Sievenpiper, M. E. Sickmiller, and E. Yablonovitch, Phys. Rev. Lett. **76**, 2480 (1996).
[8] E. Ozbay, B Temelkuran, M. Sigalas, G. Tuttle, C. M. Soukoulis, and K. M. Ho, Appl. Phys. Lett. **69**, 3797 (1996).
[9] B. Temelkuran, E. Ozbay, M. Sigalas, G. Tuttle, C. M. Soukoulis, and K. M. Ho, Appl. Phys. A: Mater. Sci. Process. **66**, 363 (1998).
[10] J. S. McCalmont, M. M. Sigalas, G. Tuttle, K. M. Ho, and C. M. Soukoulis, Appl. Phys. Lett. **68**, 2759 (1996).