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著者	花泉　修
journal or publication title	Applied Physics Letters
volume	74
number	6
page range	777-779
year	1999
URL	http://hdl.handle.net/10097/46791

doi: 10.1063/1.123364

Propagation of light beams along line defects formed in *a*-Si/SiO_2 three-dimensional photonic crystals: Fabrication and observation

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(Received 14 July 1998; accepted for publication 2 December 1998)

We have fabricated optical waveguides in three-dimensional (3D) photonic crystals and observed propagation of light beams. Light beams with wavelengths of 1.15 μm propagate along the line defects formed in the 3D photonic crystals. The 3D photonic crystals consist of *a*-Si/SiO_2 multilayers laminated alternately by rf bias sputtering on a periodically hollowed silica substrate with a triangular lattice. The pit diameter is 0.2 μm and the pitch of the lattice is 0.5 μm. The thickness of each laminated layer is 0.2 μm. Line defects are formed normal to the surface by laminating *a*-Si/SiO_2 multilayers with ten periods on the substrate in which the corrugation patterns have been omitted in a certain area corresponding to the core. The measurements of transmittance normal to the surface show that the wavelength of 1.15 μm used in observation of propagation is in the passband for the one-dimensional periodic region corresponding to the core and in the stop band for the 3D periodic region corresponding to the cladding, respectively. Measurements show good agreement with finite-difference time-domain calculations. [S0003-6951(99)01106-7]

In order to create a photonic band gap structure[1,2] for the optical wavelength, a three-dimensional (3D) submicrometer periodic structure must be fabricated. Some technologies for fabricating 3D periodic structures have already been reported.[3–8] Three-dimensional submicrometer periodic structures with many layers, however, have not been realized and further progress is needed in conventional technologies.

With respect to photonic crystal waveguides, fabrication of an optical fiber using two-dimensional (2D) confinement[9] and simulation of a highly efficient 90° bend slab waveguide[10] have been reported. 3D photonic crystal waveguides, however, have not been realized because fabrication is very difficult.

Recently, we have successfully obtained *a*-Si/SiO_2 3D submicrometer periodic structures as shown in Fig. 1 by using rf bias sputtering.[11] In our method, the fabrication process is very simple because of the autocloning effect[12,13] of the corrugated pattern produced by rf bias sputtering and their merits are as follows:

(1) The only microprocess required is the formation of periodic pits on the substrate. No alignment processes are required.
(2) There is no limitation as to the number of periods of lamination.

In this study, we have fabricated 3D photonic crystal waveguides normal to the surface for the first trial and observed propagation phenomena of light beams. This is a demonstration of 3D photonic crystal waveguides. To verify our results, we have also measured the transmission spectra of the one-dimensional (1D) and 3D periodic regions, which correspond to the core and the cladding, respectively, and compared the values with calculations.

We herein present an outline of our fabrication process of 3D photonic crystals. Periodic circular pits having a triangular lattice configuration are formed on a fused silica substrate by electron beam (EB) lithography and dry etching. The diameter, depth, and center-to-center distance of pits are 0.2, 0.4, and 0.5 μm, respectively. Alternate multilayers of *a*-Si/SiO_2 are deposited by rf bias sputtering. Circular pits become hexagonal in shape after deposition of a few layers. This honeycomb pattern is conserved during subsequent deposition.

A light beam with a certain wavelength can propagate along the line defect formed in the 3D periodic structure. The line defect is formed normal to the surface by depositing *a*-Si/SiO_2 multilayers on the SiO_2 substrate on which some

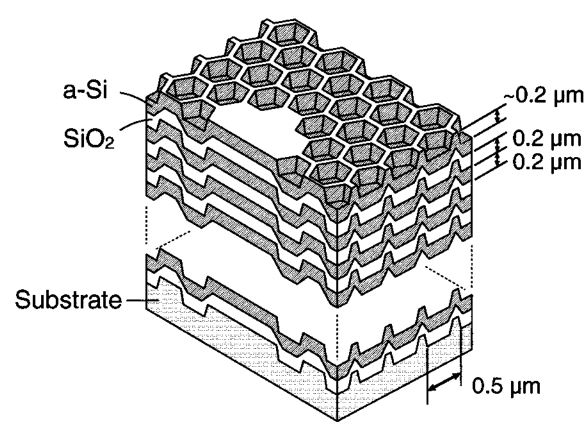

FIG. 1. Illustration of 3D periodic structure composed of *a*-Si/SiO_2 multilayers. Fabrication of this region without corrugation, which corresponds to the core of the waveguides normal to the surface, is the point newly proposed in this letter.

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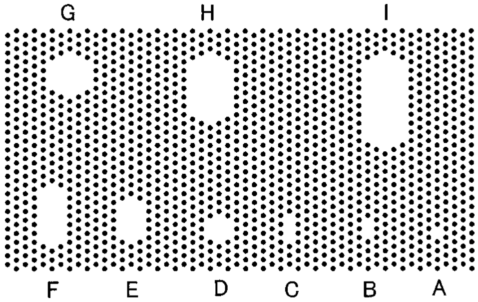

FIG. 2. Schematic patterns of the pits formed on the substrate. The diameter and the pitch of each pit are 0.2 and 0.5 μm, respectively. The pits corresponding to nine cores of A to I are omitted. The numbers of omitted pits are 1, 2, 3, 7, 13, 19, 19, 34, and 49, for the cores of A, B, C, D, E, F, G, H, and I, respectively.

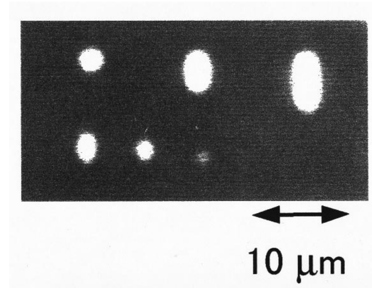

FIG. 4. Observation of propagating light beams. Six spots of the light beams are observed transversing each waveguide with the same number of laminated layers and different sizes of cross section. The wavelength is 1.15 μm as indicated by the arrow in Fig. 5. The third spot from the left in the lower row corresponds to the spot of the core shown in Fig. 3. Light beams propagating through cores smaller than this cannot be observed because such beams radiated from the small cores diffract with a large angle and a sufficient amount of power cannot be detected through an objective lens.

pits have been intentionally omitted. Figure 2 shows schematic patterns of the absence of pits. Figure 3 shows an example of the atomic force microscope (AFM) image of the surface of a sample with line defects formed by depositing multilayers on this substrate. Figure 4 is a photograph of the near field pattern. The light beam is observed propagating normal to the surface. The wavelength is 1.15 μm as indicated by the arrow in Fig. 5, which corresponds to the pass band for the 1D region and the stop band for the 3D region, as shown by both measurements and calculations, as mentioned later.

To verify the results of observation of propagating light beams, the transmission spectrum normal to the surface is measured and compared with finite-difference time-domain (FDTD)[14] calculations as shown in Fig. 5. Measurements by AFM show that the dispersion of the size of the surface pattern is very small.[11] In our calculation model, it is assumed that all surfaces have the same patterns as the top layer. A few layers near the substrate are the transition region where the circular pits become stable, hexagonal pits. Our calculation model considers the configuration of the sample exactly except for this transition region. Measurements and calculations for the 3D periodic region are performed both for the polarization shown in the inset of Fig. 5 and perpendicular to this direction. There is no large difference between these two polarizations in either measurements or calculations, so we show the results for only one polarization.

Transmittance is measured for the wavelengths of 1.0–1.55 μm. Measured pass bands are 1.05–1.45 μm and 1.25–1.45 μm for the 1D and 3D region, respectively. Other wavelengths correspond to the stop bands. Photonic crystal waveguides can be realized by having the core of the 1D region and the cladding of the 3D region for the wavelengths of 1.05–1.2 μm, which are in the pass band for the 1D region and the stop band for the 3D region. Calculations show good agreement with measurements except for the wavelengths near 1.15 μm where the measurements show a shallower and wider stop band than the calculations. The reason for this may be that the transition region of a few layers near

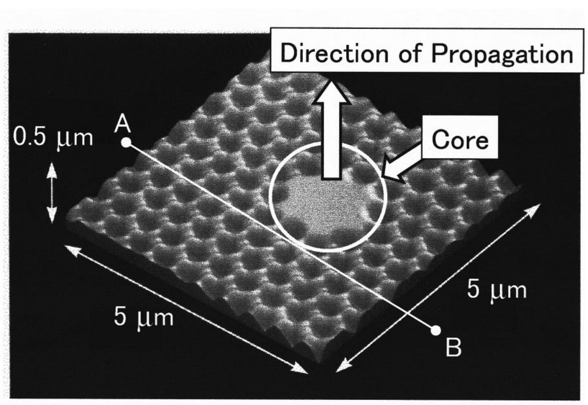

FIG. 3. AFM image of the surface of the waveguide normal to the surface fabricated by depositing Si/SiO_2 multilayers with ten periods on the substrate where seven pits have been omitted, which corresponds to the core of D shown in Fig. 2. The flat region without corrugation corresponds to the cross section of the core. The core region is uniform in the lateral direction but has a 1D periodic structure normal to the surface. The cladding region has a 3D periodic structure. The rows of pits are straight along the line AB, for example, and not disturbed even near the core. This fact shows that the position of the pits does not change during deposition.

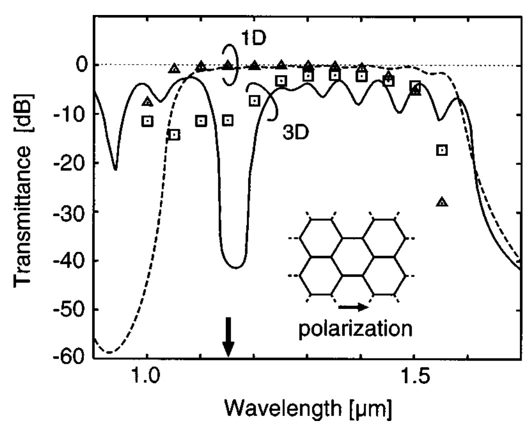

FIG. 5. Measurements [(⊡) 3D, (△) 1D] and calculations [(solid line) 3D, (dashed line) 1D] of the transmittance normal to the surface of the sample with ten-period lamination. 3D means the 3D periodic region laminated on the substrate with periodic pits, corresponding to the cladding, and 1D means the 1D periodic region, corresponding to the core, laminated on the flat substrate without pits. The light sources with broad spectra [a Lambertian lamp for $\lambda<1.5$ μm and a super luminescent diode (SLD) for $\lambda=1.55$ μm] and interference filters are used to select the wavelength. Transmission spectra of the interference filters approximate the Gaussian function having a full width at a half maximum (FWHM) of about 35 nm; this is taken into consideration in the calculations. The arrow on the horizontal axis indicates the wavelength of 1.15 μm used in the experiments of Fig. 4, which is in the pass band for the 1D region (core) and the stop band for the 3D region (cladding).

the substrate is not taken into consideration by our calculation model, although further study is needed to resolve this completely.

In conclusion, we have fabricated 3D photonic crystal waveguides normal to the surface and observed propagation of light beams. The transmission spectra normal to the surface are measured in the 1D and 3D periodic regions and the results of observation of propagating light beams are verified. Measurements show good agreement with FDTD calculations for $\lambda > 1.2$ μm. Our method of fabricating submicrometer 3D periodic structures has good controllability and has no limitation as to the number of laminations, so it is applicable to various new functional devices.

The authors wish to thank Professor J. B. Pendry of the Imperial College for fruitful discussions on numerical analysis. They are also grateful to Dr. T. Meguro for his help in EB lithography and Y. Aizawa and N. Sugiyama for their assistance with fabrication of samples. Part of this study was supported by the Telecommunications Advancement Organization of Japan (TAO) and a Grant-in-Aid for Scientific Research from the Ministry of Education, Science, Sports and Culture of Japan. This work was carried out in the Laboratory for Electric Intelligent Systems, Research Institute of Electrical Communication, Tohoku University.

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