Terahertz spectroscopy of three-dimensional photonic band-gap crystals

E. Özbay, E. Michel, G. Tuttle, R. Biswas, and K. M. Ho

Micorelectronics Research Center and Ames Laboratory, Iowa State University, Ames, Iowa 5001

J. Bostak and D. M. Bloom

Edward L. Ginzton Laboratory, Stanford University, Stanford, California 94305

Received February 15, 1994

We have fabricated and built three-dimensional photonic band-gap crystals with band-gap frequencies larger than 500 GHz. We built the crystals by stacking micromachined (110) silicon wafers. The transmission and dispersion characteristics of the structures were measured by an all-electronic terahertz spectroscopy setup. The experimental results were in good agreement with theoretical calculations. To our knowledge, our new crystal has the highest reported photonic band-gap frequency.

In analogy to electrons in a crystal, the propagation of electromagnetic (EM) waves in a three-dimensional dielectric structure can be forbidden for a certain range of frequencies. These three-dimensional structures, which are called photonic band-gap crystals, have recently received both theoretical and experimental attention.[1–3] The early research in the field has concentrated on possible optical frequency range applications that take advantage of reduced spontaneous emission, such as thresholdless semiconductor lasers and single-mode light-emitting diodes. The proposed applications were later extended to the millimeter and submillimeter wave regimes, such as efficient antennas, sources, waveguides, and other components that take advantage of the unique properties of photonic band-gap materials.[4] However, the difficulties associated with the fabrication of smaller-scale structures have restricted the experimental demonstration of the basic photonic band-gap crystals to microwave frequencies (12–15 GHz).[5]

We have recently designed a new three-dimensional structure that may alleviate some of the fabrication problems associated with the earlier photonic band-gap designs.[6] The new structure exhibits a sizable and robust photonic band gap over a range of structural parameters. Using a large-scale model made of cylindrical alumina rods, we have confirmed the existence of a full photonic band gap at *Ku*-band frequencies (12–14 GHz).[7] We have also fabricated smaller-scale structures with 100-GHz photonic band-gap frequencies by using semiconductor micromachining techniques.[8] In this Letter we demonstrate the scalability of the new structure to a band-gap frequency of 500 GHz, which was measured by terahertz spectroscopy techniques. Such a performance offers a readily available structure for the demonstration of the proposed millimeter and submillimeter wave applications.

The new structure, shown in Fig. 1, is constructed of layers of dielectric rods. The stacking sequence is repeated every four layers, corresponding to a single unit cell in the stacking direction. To build the 500-GHz crystal we used fabrication techniques similar to the one used to build 100-GHz crystals.[8] Fabrication consisted of defining stripes that were parallel to (111) planes and subsequently etching the wafers in a KOH etch solution. The well-known anisotropic etching properties of aqueous KOH etch solutions resulted in parallel rods with rectangular cross sections similar to one of the single layers described in Fig. 1. The fabricated stripes were 2.0 cm long and 50 μm wide, separated by 185-μm-wide gaps. A total of 86 parallel stripes were fabricated on each wafer, resulting in a square 2.0 cm × 2.0 cm pattern. We then stacked the individual etched wafers to form the photonic crystal, using a holder with pins that aligned the guide holes that were etched through the wafers. The (110) silicon wafers used in this research were each 2 in. (5.1 cm) in diameter and 100 ± 5 μm thick. Relatively high-resistivity wafers ($>100\ \Omega$ cm) were chosen to minimize absorption losses in the silicon. Dur-

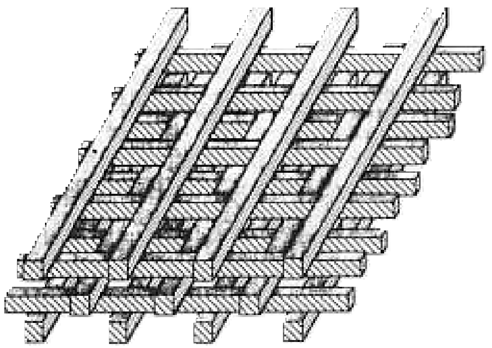

Fig. 1. Schematic illustrating the design of the three-dimensional photonic band-gap crystal. The structure is built by an orderly stacking of dielectric rods and is repeated every four layers in the stacking direction.

0146-9592/94/151155-03$6.00/0

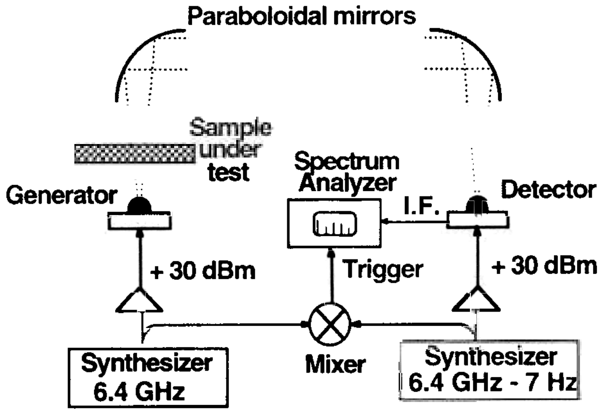

Fig. 2. All-electronic terahertz free-space spectroscopy system: I.F., intermediate frequency.

ing the course of fabrication, we were cautious in handling the thin silicon wafers, which were susceptible to breakage. A layer of oxide that was used to protect the back surface of the silicon wafer during the KOH etch was intentionally kept after the etch. This gave robust support to the relatively long stripes, preventing individual stripes from bending and bonding to the adjacent stripes.

The testing was performed with the terahertz free-space spectroscopy setup shown in Fig. 2.[9,10] EM pulses were generated and detected by an all-electronic approach designed and built around nonlinear transmission line technology along with magnetic dipole (slot) antennas. Two phase-locked microwave synthesizers with an offset frequency of 7 Hz were used to drive the generator and detector circuits. A spectrum analyzer was used to compute directly the Fourier spectra of the detected signals. The dynamic range of the system was ~ 30 dB for frequencies up to 550 GHz. We carried out the free-space spectroscopic measurements of the photonic crystal by placing the structure on the beam path of the radiated signal. By comparing the detected signals with and without the crystal in place, we obtained the phase and magnitude transmission properties of the structure as a function of frequency. Because the pulses were periodic, the frequency domain information was limited to the harmonics of the input signal frequency (6.4 GHz). The setup used high-resistivity silicon lenses to collimate and focus the radiation generated and detected by the antennas. The resulting test beam was highly collimated, with 95% of the output radiation remaining within a 10° radiation cone.

We used a structure that consisted of 16 stacked silicon wafers (corresponding to 4 unit cells) for transmission measurements. We obtained the characteristics along the stacking direction by placing the structure on the beam path so that the transient radiation propagated in a plane perpendicular to the top surface of the structure. For this propagation direction the transmission characteristics were essentially independent of the polarization of the incident radiation, as the structure had a fourfold axis of symmetry along this direction. The only polarization dependence came from the orientation of the first layer rods with respect to the polarization of the incident radiation. Although this resulted in an expected band-gap edge difference between two polarizations, the difference (~ 3 GHz) was smaller than the minimum frequency resolution of the experimental setup. We placed the structure ~ 1 cm away from the generator chip, so that most of the incident radiation remained perpendicular to the surface. Figure 3 shows the transmission characteristics of the propagation along the stacking direction. The lower edge of the photonic gap is at 370 GHz, while the upper edge is at 520 GHz. This is very close to the calculated band-gap edges of 378 and 518 GHz. The average measured attenuation within the band gap was ~ 30 dB, limited by the dynamic range of the experimental setup. Our calculations for the band-gap frequencies predicted the attenuation to be ~ 65 dB.

The dispersion characteristics of the structures were obtained by a method similar to the one used by Robertson *et al.* in which they measured the dispersion characteristics of a 70-GHz two-dimensional photonic band-gap structure.[11] The phase of the detected signal with the crystal was subtracted from the phase of the detected signal without the crystal (calibration measurement). This gave the net phase difference $\Delta\phi$ between the phase of the EM wave propagating through the photonic crystal and the phase of the EM wave propagating in free space for a total crystal thickness of L (which was 1.6 mm for this measurement). This was used to calculate the wave vector k of the crystal at each frequency by

$$k = \frac{\Delta\phi}{L} + 2\pi\frac{f}{c},$$

where f is the frequency of the EM wave and c is the velocity of the light. Figure 4 compares the experimental and the theoretical energy band diagrams. The experimental dispersion characteristics are in excellent agreement with the calculated values.

The transmission characteristics of the structure in other crystal directions could not be measured because of experimental limitations. To measure the transmission from the side surface of the crystal, we

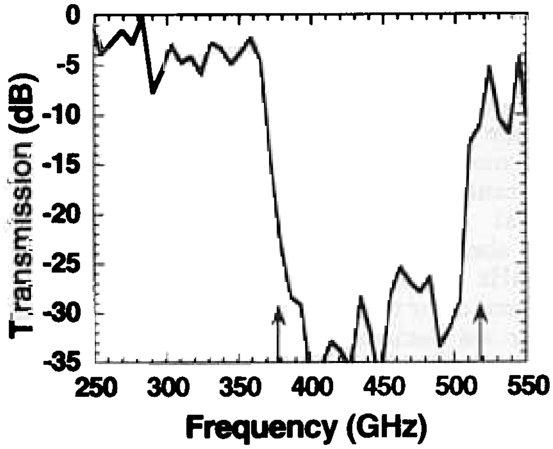

Fig. 3. EM wave transmission through the micromachined crystal in which the wave vector of the incident radiation is normal to the wafer surfaces. The arrows indicate calculated band-edge frequencies.

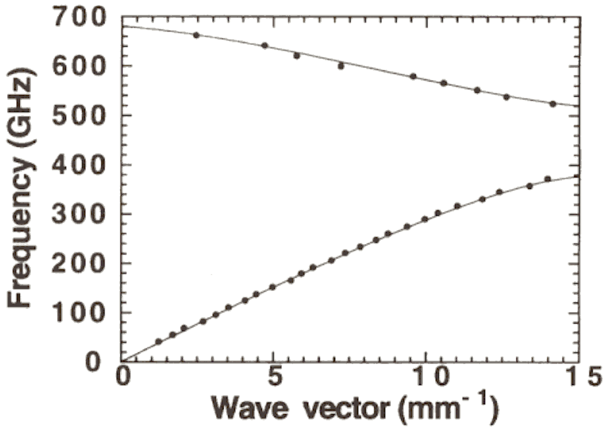

Fig. 4. Frequency versus wave vector dispersion along the stacking direction of the crystal. The solid curves represent the calculations; the filled circles represent the values obtained from the experiments.

needed a crystal that was at least 2 cm thick. This corresponded to a structure with 200 wafers, which would be too expensive to build. Although it was possible to make transmission measurements (along other crystal directions) by rotating the crystal, the refraction at the surface of the crystal resulted in a misalignment of the detected signal by steering the beam away from the original path. This misalignment resulted in uncalibrated measurements when we rotated the crystal from its original orientation. This prevented us from measuring the full band gap of the structure in all propagation directions. Although we were able to measure the properties of the photonic band gap only along the stacking direction, our theoretical calculations predicted a full three-dimensional band gap from 425 GHz (which occurs when the sample is rotated 55°) to 518 GHz (which occurs along the stacking direction).

As explained above, the difficulties associated with the unfeasible three-dimensional structure designs have restricted the experimental demonstration of the basic photonic band-gap crystals to microwave frequencies. Our new structures built with the new fabrication technique bring a feasible solution to this problem. We expect the new design and the fabrication technique to be used to demonstrate most of the suggested applications at the millimeter and submillimeter wave regime. To the best of our knowledge, our new photonic band-gap crystal has the highest reported band-gap frequency.

In this research we used commercially available silicon wafers and did not make any effort to thin our wafers. By using special silicon thinning methods and double etching the wafers on both surfaces, we suspect that the frequency range of this fabrication technology could be extended to build structures with photonic band gaps as high as 3 THz. We also expect the same three-dimensional dielectric design to be useful at even smaller scales for the eventual goal of fabricating photonic gap structures at infrared and optical frequencies.

We thank M. Sigalas, C. M. Soukoulis, and C. T. Chan for helpful discussions. Ames Laboratory is operated for the U.S. Department of Energy by Iowa State University under contract W-7405-Eng-82. This research is supported by the Director for Energy Research, Office of Basic Energy Sciences and Advanced Energy Projects, and the Center for Advanced Technology Development, Iowa State University. The research done at Stanford University is supported by Joint Services Electronics Program under contract N00014-91-J-1050.

References

1. K. M. Ho, C. T. Chan, and C. M. Soukoulis, Phys. Rev. Lett. **65,** 3152 (1990).
2. E. Yablonovitch, T. J. Gmitter, and K. M. Leung, Phys. Rev. Lett. **67,** 2295 (1991).
3. For a recent review, see C. M. Soukoulis, ed., *Photonic Bandgaps and Localization* (Plenum, New York, 1993).
4. See the feature issue on development and applications of materials exhibiting photonic band gaps, J. Opt. Soc. Am. B **10,** 280–413 (1993).
5. E. R. Brown, C. D. Parker, and E. Yablonovitch, J. Opt. Soc. Am. B **10,** 404 (1993).
6. K. M. Ho, C. T. Chan, C. M. Soukoulis, R. Biswas, and M. Sigalas, Solid State Commun. **89,** 413 (1994).
7. E. Ozbay, A. Abeyta, G. Tuttle, M. Tringides, R. Biswas, C. Soukoulis, C. T. Chan, and K. M. Ho, "Measurement of three-dimensional photonic band gap in new crystal structure made of dielectric rods," Phys. Rev. B (to be published).
8. E. Ozbay, E. Michel, G. Tuttle, M. Sigalas, R. Biswas, and K. M. Ho, Appl. Phys. Lett. **64,** 2059 (1994).
9. D. W. Van Der Weide, J. S. Bostak, B. A. Auld, and D. M. Bloom, Appl. Phys. Lett. **62,** 22 (1993).
10. J. S. Bostak, D. W. Van Der Weide, I. Aoki, B. A. Auld, and D. M. Bloom, in *Ultrafast Electronics and Optoelectronics,* J. Shah and U. Mishra, eds., Vol. 14 of OSA Proceedings Series (Optical Society of America, Washington, D.C., 1993), p. 112.
11. W. M. Robertson, G. Arjavalingam, R. D. Meade, K. D. Brommer, A. M. Rappe, and J. D. Joannopoulos, Phys. Rev. Lett. **68,** 2023 (1992).