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Transmission of single mode ultrathin terahertz photonic crystal slabs

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Silicon photonic crystal slabs (PCSs) were fabricated using a reactive ion etching technique. The PCSs consist of a triangular lattice of holes with a lattice constant $a=64$ μm, radius $r=0.3a$, and a thickness of $0.75a$. An optical bandgap from 1.15 to 1.56 THz for transverse electric modes was measured using Fourier transform infrared spectroscopy. The optical bandgap is in good agreement with the finite difference time domain and frequency domain predictions. © *2007 American Institute of Physics*. [DOI: 10.1063/1.2806227]

Terahertz radiation lies in the gap between optical and electronic frequencies.[1] Terahertz technology has been fueled the past few years by potential applications ranging from earth based terahertz telescopes to security, biological systems, and quantum information processing.[2–5] These applications often require producing and manipulating electromagnetic radiation on chip. A lot of work has been done on producing terahertz radiation[6] and many techniques have been developed to work at these frequencies.[7]

Photonic crystals (PCs) emerge as a natural way to manipulate radiation within a device. A PC is an artificial crystal which consists of a periodic distribution of two or more media with different dielectric constants. The dielectric periodicity produces a vectorial potential for photons inside the crystal. Under appropriate crystal structure and polarization the dispersion relation for photons exhibits an optical bandgap. The optical bandgaps of PCs have been exploited to fabricate waveguides and cavities with high-Q value.[8] These simple structures allow transport and storage electromagnetic radiation through different regions of a single device. The large dimension of terahertz PC and the negligible terahertz absorption of silicon and GaAs make this area attractive to the PC community, because the fabricated structure can be made with high precision which directly impacts the performance of the structure.

The use of PCs in the visible and infrared regions of the spectrum has been well documented[8,9] and they are beginning to be applied to the terahertz regime.[10] Terahertz photonic crystals slabs (PCSs) have been studied using Fourier transform infrared (FTIR) measurements[11] and time domain techniques.[12] In the previous reported works the thickness of the slab was several times the lattice constant, and therefore the PCS supported multiple slab waveguide modes. Such thick PCSs are not suitable for fabricating PC waveguides and high-Q resonators. In this letter we report fabrication, transmission measurement, and modeling of a PCS which supports only a single slab waveguide mode.

The fabrication process was done at Nanotech UCSB Nanofabrication Facility. The process starts by using ultraviolet lithography to transfer a designed pattern to a high resistivity silicon wafer with nominal thickness of 50 μm. The pattern consist of a triangular lattice of holes with lattice constant $a=64$ μm and five rows of holes along the ΓJ orientation of the lattice. The size of the holes were nominally $r=0.3a$. The etching of the holes in the pattern was done using deep reactive ion etching (RIE) with a Plasma-Therm 770 SLR. RIE allows etching holes with smooth vertical sidewalls and with the desired aspect ratio, as shown in Fig. 1.

To have more precise values of the parameters of the PCS we measured the size of the holes and the thickness of the slab. Optical microscopy measurements found a value of $r/a=0.3075\pm0.003$ for the size of the hole. This value is slightly larger that the nominal 0.3 because of an overetch during the fabrication process. The thickness of the slab was calculated from the transmittance of the slab normal to the planes of the PCS measured with FTIR.[13] Over the frequency range of 35–65 THz, clearly resolved Fabry-Pérot oscillation is observed. The slab thickness d is given by $d=c/2n\delta=48.56\pm0.03$ μm, where $n=3.416$ is the index of refraction at 1 THz (Ref. 14) and $\delta=0.9043$ THz is the period of the Fabry-Pérot oscillations.

Terahertz transmission measurements with the k vector in the plane of the PCS were done using a FTIR with a Hg arc lamp. The edge of the sample was placed in a 500 μm wide gap in a two-dimensional (2D) parabolic mirror. This

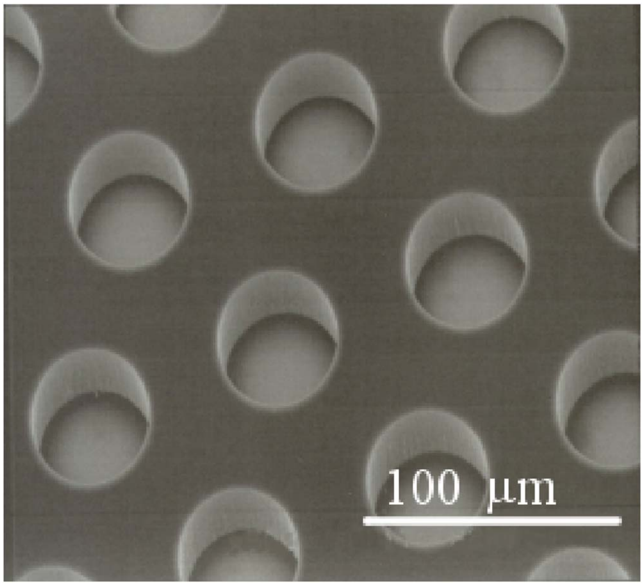

FIG. 1. (Color online) Scanning electron microscopy picture of a slab with a triangular array of holes with lattice constant of $a=64$ μm. The nominal thickness of the slab and the radius of the hole are $0.75a$ and $0.30a$, respectively.

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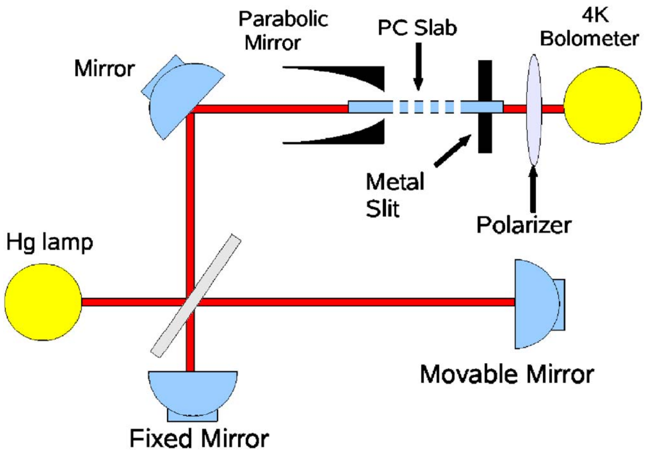

FIG. 2. (Color online) FTIR transmission experimental setup.

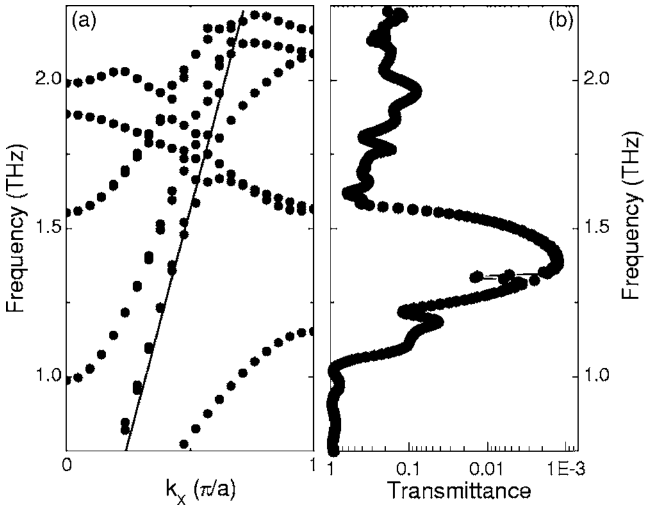

FIG. 4. (a) Frequency domain calculations of the band diagram for TE modes of the PCS; here the PCS is considered to be infinite large on the plane of the slab. (b) Finite diference time domain calculation of the transmittance for TE modes of the PCS. The PCS simulations show a bandgap from 1.2 to 1.6 THz along the ΓJ direction.

gap was cut trough the latus rectum of a parabola with a 500 μm focus. It was found that transmittance is not affected by the length of the PCS inside the 2D parabolic mirror, provided that the beginning of the photonic crystal is not inside of the parabolic mirrors. The transmitted beam was polarized to select between modes with the electric field polarized in the plane of the slab (TE modes) and normal to the plane (TM modes). The signal was then measured by a silicon composite bolometer at 4 K. The experimental setup is shown in Fig. 2. The PCS was explicitly designed to have a bandgap in the peak of the response of the Mylar beam splitter (1.35 THz).

Figure 3 compares the transmission of the PCS and the reference, a blank 50 μm silicon wafer. The PCS shows a very low transmission from 1.2 to 1.6 THz.

To have a better understanding of the PCS we first employed a frequency domain (FD) simulation.[15] The frequency domain simulation allows precise calculation of the band structure diagram. Figure 4(a) shows the band diagram of the PCS considering that is infite large on the plane of the slab: it shows an optical bangap with frequency region that matches the region of low transmission found experimentally. However, in our FD simulations the finite size of the crystal along the ΓJ is not considered so direct comparison with data is not possible.

In order to have a direct comparison with the experiment we realized finite difference time domain[16] (FDTD) calculations of the transmission of the PCS, using a freely available software package with subpixel smoothing for increased accuracy.[17] Figure 4(b) shows the FDTD calculations using the nominal parameters of the structure under study. Experimental [Fig. 3], FD [Fig. 4(a)], and FDTD [Fig. 4(b)] all show a bandgap from 1.2 to 1.6 THz.

Figure 5 shows a detailed comparison of the experimen-

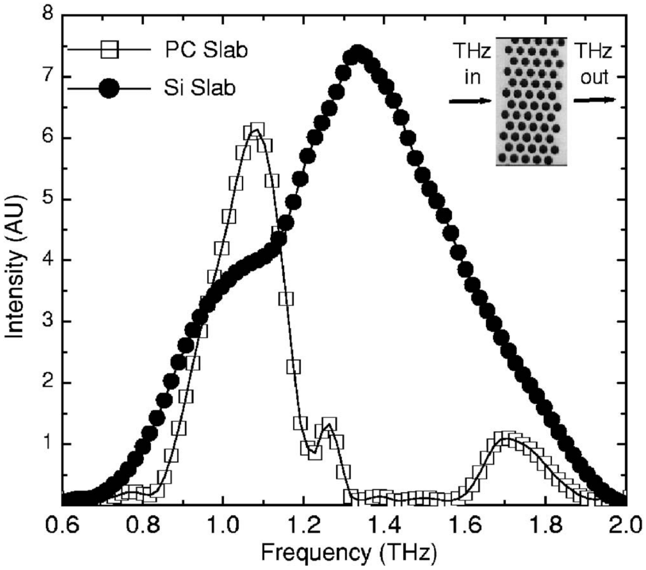

FIG. 3. FTIR transmission spectrum of a PCS along the ΓJ direction. A blank 50 μm silicon wafer employed as a reference. The spectrum shows a bandgap for TE modes from 1.16 to 1.65 THz. Near 1 THz the maximum intensity transmitted through the PCS is larger than through the Si slab because the face of the PCS on which the terahertz beam was incident was wider than the face of the Si slab.

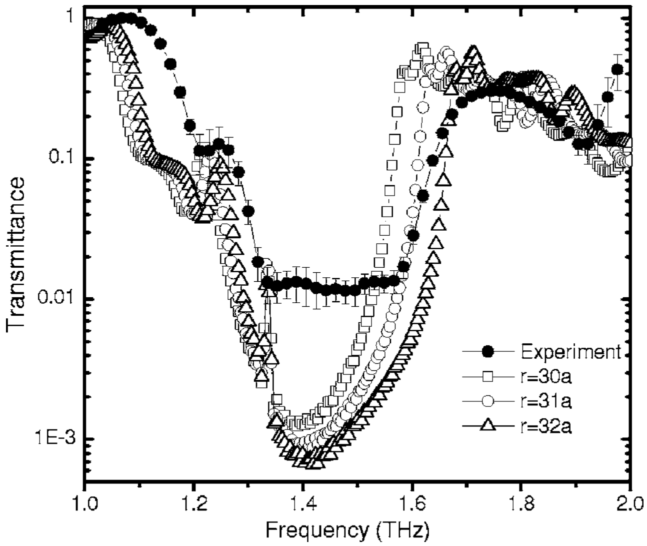

FIG. 5. Experimental spectrum compared with theoretical transmission calculations for different radius sizes. The maximum transmittance is normalized to 1. A hole radius $r=0.31a$ is the best fit for the experimental measurements. The edges of the bandgap are directly observed. The minimum transmittance is higher than predicted due to light leakage in the experimental setup.

tal transmittance and the FDTD calculation for the ΓJ orientation for different values of the hole radius. The FDTD calculations agree with one another and the experiment at the lower frequency part of the bandgap (dielectric band). The higher frequency part (air band), however, is extremely sensitive to changes in the parameters of the PCS. For the measured parameters of the structure ($r=0.31$) the FDTD shows a region of low transmittance whose width matches the experiment. The experimental transmission floor is limited by leakage around the PCS and thus higher than the calculated value.

We have shown that the transmission spectrum is very sensitive to changes in the parameters of the PCS. Finite difference time domain spectra using the experimental values of the structures simulate appropriately the transmission of our PCS. Single mode PCSs are the foundation for waveguides and resonators. The present work shows that it is possible to have these structures to work at terahertz frequencies, enabling another tool that helps to close the terahertz technology gap.

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