wave vector of the photonic lattice of a period a. Four Gaussian lobes at these positions are predicted by two-dimensional (2D) numerical simulations.[4] At larger angles there are distinct, but weaker, diffraction features at wave vectors $(\pm lG/2 \pm mG/2)$ with indices $(lm) = (\pm1,\pm3), (\pm1,\pm5) \ldots$ and $(\pm3,\pm1), (\pm5,\pm1) \ldots$. These weaker diffraction features are double lobes, and the lobe splitting is directed along the axis having the higher index. This splitting cannot be explained with simple diffraction theory. It can be explained by Bloch waves with wave vectors $k_B = [\pm G/2, \pm(G/2 - \delta)]$ and $[\pm(G/2 - \delta), \pm G/2]$ where δ is a small fraction of G. The Bloch waves exhibit the translation symmetry of the Bloch wave vector which modulates the local symmetry of the cells. The observed Bloch wave vectors, emitted photon transverse wave vectors, and reciprocal lattice points are shown in Fig. 2(b).

The radiation patterns correspond to the electric-field intensity in each unit cell being 180° out of phase with its neighbor cells. To measure the phase relationship of the unit cells, we have used a shearing polarization interferometer[5] to record the sheared images in Fig. 3. Images are shown for shears of 6, 0, and 1 period. With a shear of 6 periods, the images are completely separated and have nearly equal intensities. With a shear of 0, the two images recombine constructively to produce a single bright image. With a shear of one period, the resultant image is very dark. These data give direct confirmation that the nearest neighbor unit cells are indeed 180° out of phase.

1. E. Yablonovitch, T. J. Gmitter, K. M. Leung, Phys. Rev. Lett. **67**, 2295 (1991).
2. A. Yariv, P. Yeh, in *Optical Waves in Crystals* (Wiley, New York, 1984), Chap. 4.
3. P. L. Gourley, M. E. Warren, G. R. Hadley, G. A. Vawter, T. M. Brennan, B. E. Hammons, Appl. Phys. Lett. **58**, 890 (1991).
4. G. R. Hadley, Opt. Lett. **15**, 1215 (1990).
5. M. Francon, S. Mallick in *Polarization Interferometers* (John Wiley and Sons, New York, 1971), Chap. 6.

3:30 pm

QWE4 Exploration of photonic band structure in ordered dielectric arrays using picosecond transient spectroscopy

W. M. Robertson, G. Arjavalingam, R. D. Meade,[*] A. M. Rappe,[*] K. D. Brommer,[*] J. D. Joannopoulos[*]

IBM Watson Research Center, Yorktown Heights, New York 10598

The coherent scattering of radiation in a period dielectric structure leads to an electromagnetic dispersion relation that exhibits photonic band gaps, i.e., frequency intervals in which there are no allowed photonic states.[1,2] There is considerable interest in the modification of the electromagnetic dispersion relation and the opening of photonic band gaps in such structures for fundamental as well as practical reasons. Although theoretical calculations of photonic band structure have become somewhat sophisticated, it has not been possible to experimentally measure the photon dispersion relation. Traditional microwave techniques have measured the frequencies that define photonic band gaps.[3] However, propagation characteristics away from the gaps have not been measured. Here, we present the experimentally measured photonic band structure, including the dispersion properties, of a two-dimensional (2D) array of dielectric rods, and we compare the results to theoretical calculations. The measurements were performed using coherent microwave transient spectroscopy (COMITS)[4] in which electro-optically generated and measured electromagnetic transients are used to characterize the complex dielectric properties of materials over a broad bandwidth (15–140 GHz).

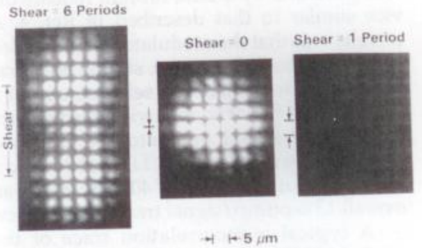
The configuration for COMITS experiments is shown in Fig. 1. The transmitter and receiver are exponentially tapered coplanar stripline antennas photolithographically fabricated on silicon-on-sapphire. The silicon epilayer is ion implanted to reduce the carrier lifetime to less than 1 ps. Picosecond-duration current pulses are photoconductively generated on the transmitter by 1.5-ps wide, 527-nm wavelength optical pulses from a mode-locked, pulse-compressed, and frequency-doubled Nd:YLF laser. The electrical pulse propagates along the stripline and is radiated by the exponentially tapered antenna. Hemispherical fused-silica lenses are used to collimate the freely propagating transient from the transmitter and to focus the transmitted signal onto the receiver. The optical pulses are arranged in a pump–probe configuration such that the transient voltage induced on the receiver is photoconductively sampled as a function of delay between the pump and probe.

In the study described here, we analyzed a 2D dielectric array consisting of alumina ceramic cylinders 0.74-mm diameter arranged in a square lattice of spacing 1.85 mm. The sample can be arranged with the rod axis parallel or perpendicular to the E-field, and results were obtained with both configurations. Time-domain wave forms are recorded with and without the array in the beam path. The wave forms are numerically Fourier transformed and the corresponding spectra divided to obtain the frequency-dependent complex (amplitude and phase) transmission function of the sample. Gaps in the amplitude spectrum reveal the frequencies at which propagation is not allowed, in a fashion similar to previous traditional microwave techniques.[3] In addition, using the known thickness of the dielectric array and the net phase at each frequency point, an effective dielectric constant of the array was derived. Hence, the dispersion relation, f vs k, is established. The experimentally determined dispersion relation for propagation along the <10> direction, with the rods parallel to the E-field, is shown in Fig. 2. The lines in the figure are theoretical predictions for the dispersion relation, calculated using a plane-wave expansion. The agreement between theory and experiment is excellent except for an additional mode that is predicted but not observed experimentally. Results for othe polarizations, propagation directions, an sample configurations are presented.

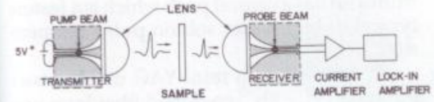
In summary, we have measured the di persion relation of electromagnetic waves i periodic dielectric arrays using electro-opti cally generated transient radiation.

[*] *Department of Physics, Massachusetts Institute of Technology, Cambridge, Massachusetts 02139*

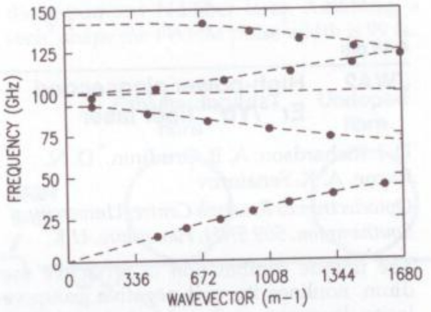
1. E. Yablonovitch, Phys. Rev. Lett. 58, 2059 (1987).
2. S. John, Phys. Rev. **58**, 2486 (1987).
3. E. Yablonovitch, T. J. Gmitter, Phys. Rev. Lett. **63**, 1950 (1989).
4. Y. Pastol *et. al.*, Appl. Phys. Lett. 54, 3 (1989).



QWE3 Fig. 3. Images of lattice and unit cells obtained with a shearing interferometer for shears of (a) 6 lattice periods, (b) 0 lattice periods, (c) 1 lattice period.



QWE4 Fig. 1. Experimental configuration for COMITS measurements.



QWE4 Fig. 2. Photonic band structure of a two-dimensional array of alumina cylinders with the electric field parallel to the rod axes. Dots are the experimental points; lines are theoretical prediction.