Microwave measurements of the photonic bandgap
in a two-dimensional photonic crystal slab

J. M. Hickmann,* D. Solli, C. F. McCormick, R. Plambeck,† and R. Y. Chiao

Department of Physics; University of California; Berkeley, CA 94720-7300.

Abstract

We have measured the photonic bandgap in the transmission of microwaves through a two-dimensional photonic crystal slab. The structure was constructed by cementing acrylic rods in a hexagonal closed-packed array to form rectangular stacks. We find a bandgap centered at approximately 11 GHz, whose depth, width and center frequency vary with the number of layers in the slab, angle of incidence and microwave polarization.

*Also at Departamento de Física, Universidade Federal de Alagoas, Cidade Universitária, 57072-970, Maceió, AL, Brazil.
†Also at Astronomy Department; University of California; Berkeley, CA 94720-3411.
There has been much recent interest in photonic bandgap materials [1], especially in two-dimensional (2D) periodic dielectric structures, also known as photonic crystal slabs [2]. These structures offer the possibility of guiding light along their extended (non-periodic) dimension and are much more easily constructed than full three-dimensional (3D) photonic crystals.

Micro-machined photonic bandgap crystals have been both fabricated and experimentally characterized [3]. Several authors have performed theoretical calculations of bandgaps in these materials [4, 5], as well as experimental studies of the transmission through a 2D photonic crystal slab at a wavelength of 1.55 nm [7]. In addition, applications of these and other similar kinds of photonic crystals to microwave mirrors, substrates for planar antennas, and photonic crystal heterostructures, have already been proposed and studied [8]. A one-dimensional photonic crystal bandgap has also recently been observed in the radio-frequency region [9].

In the visible and near-infrared part of the spectrum, there has been much recent progress in the fabrication of 2D “photonic crystal fibers” [10]. One type of these optical fibers consists of 2D hexagonal-close-packed glass structures, fabricated by stretching out a macroscopic hexagonal lattice of heated, hollow glass cylinders into a microscopic glass structure of the same geometry. These structures can also be constructed with a central “defect,” such as a hexagonal central hole consisting of seven nearest-neighbor hollow cylinders removed from the center of the structure. The resulting hexagonally shaped central hole can serve as a waveguide for electromagnetic radiation, since the surrounding periodic dielectric structure (cladding) possesses a photonic bandgap. Inside the cladding structure only evanescent wave solutions should be able to propagate transversely to the central axis of the structure.

As a first step towards the study of the properties of these 2D optical waveguide structures, we have performed some measurements of an analogous dielectric structure in the microwave region of the electromagnetic spectrum. Since Maxwell’s equations are scalable, it should be possible to directly apply the results obtained in the microwave region to structures designed for different wavelengths, such as the visible and near infrared. There are at least two significant reasons for conducting these studies with microwave-scale structures. First, their large scale allows relatively easy fabrication and characterization. Second, without any scaling, these low-loss periodic dielectric structures could be relevant for electron beam devices at microwave and millimeter wavelengths (e.g., travelling-wave tubes and
backward-wave oscillators). This is especially significant since electron beams could interact strongly with electromagnetic waves at these wavelengths when they co-propagate either longitudinally down a central hole, or transversely across the top surface of these periodic dielectric structures[11]. One possible future application of hollow-core photonic crystal fibers is the acceleration of relativistic electrons to high energies using short-duration laser pulses co-propagating along with a relativistic electron beam inside the fiber. The results of our measurements should be directly relevant to the design of these kinds of electron beam devices[12].

Theoretical calculations of the bandgap structure of periodic holes in a hexagonal array have been carried out by Johnson et al[5, 6]. The structure used in our experiment is similar to the one considered in these calculations, except for the presence of small, triangular, interstitial holes between each trio of adjacent acrylic rods, which we believe are negligible for the determination of the bandgap. The Johnson calculations show that for a lattice constant $a$, hole diameter $d = 0.9a$, and slab thickness $0.6a$, the bandgap should be located at $\nu_{bg} \approx 0.4c/a$. For our system this implies $\nu_{bg} \approx 10$ GHz. Based on optical fiber experiments [10], we expect that a photonic bandgap should be present in our structure around 12 GHz.

In Fig. 1 we show a schematic of the experimental apparatus used for the microwave transmission measurements. The photonic crystal slab was constructed by stacking together acrylic pipes (23 cm long, 1/2 inch outer diameter, 3/8 inch inner diameter) in a hexagonal lattice, resulting in a structure with an air-filling fraction of approximately 0.60. The pipes were then glued together at their surfaces of contact using a standard acrylic cementing solvent. The dielectric constant of acrylic (polymethyl-methacrylate) at 10 GHz is 2.59[13]. The microwaves were generated by a commercial microwave network analyzer (Agilent 8722ES) connected to a microwave transmitter horn. The analyzer was swept from 8 to 14 GHz in 15 MHz increments. The slab and receiver horn were placed 1.6 m away in a box measuring 60 cm on a side, with microwave-absorbing walls. Microwaves entered the box through a 14 cm $\times$ 17 cm rectangular aperture. These dimensions were chosen to minimize diffraction effects through the aperture without allowing leakage around the slab. We normalized transmission measurements by removing the slab and measuring the total microwave signal at the receiving horn. With the slab removed and the rectangular aperture closed, the microwave signal at the receiver is suppressed by more than 45 dB, indicating good shielding by the box.
In Fig. 2 we show the normalized microwave transmission as a function of frequency for various numbers of photonic crystal slab layers. For the case in which the electric field is perpendicular to the dielectric rods [transverse magnetic or (TM)], there is a clear bandgap centered at 11 GHz whose depth increases with the number of layers. The bandgap is about 1.5 GHz wide and its width and center frequency appears to be independent of layer number. Note that the minimum transmission value is above our background transmission, indicating that these measurements are above the noise. For the case of the electric field parallel to the rods [transverse electric or (TE)], we find a narrower (~ 1 GHz), shallower bandgap centered at 10.5 GHz. To quantify the bandgap depth, we average the transmission value for each slab layer number, in a frequency window from 10.5 GHz to 11.5 GHz in the TM case and 10.25 GHz to 10.75 GHz in the TE case. Fitting the results to an exponential decay, we find a $1/e$ power decay length of 5.2 layers and 8.1 layers, respectively.

We have also taken transmission measurements at various angles of incidence, using a 20-layered slab. The results are shown in Fig. 3 for a plane of incidence perpendicular to the dielectric rods (i.e. no wave-vector component perpendicular to the plane of periodicity). As was previously seen in Fig. 2, the configuration TM bandgap is deeper and wider than the TE bandgap. The angle data show that for both polarizations a larger angle of incidence shifts the bandgap to higher frequencies. Using the -15 dB points as a reference, a higher angle of incidence produces a narrower bandgap in the TE case but not in the TM case.

In conclusion, we have demonstrated the existence of a photonic bandgap in a 2D hexagonal photonic crystal slab. Its depth depends on the number of layers, with an exponential decay of transmission on the order of several layers. We have also measured the dependence of transmission on the angle of incidence and polarization of the incoming radiation, finding that the bandgap persists at high angles but is shifted and in certain cases narrowed.

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FIG. 1: Experimental setup for measuring the photonic bandgap of the photonic crystal slab.
FIG. 2: Microwave transmission versus frequency for electric field (a) perpendicular (TM) and (b) parallel (TE) to the dielectric rods, for various numbers of slab layers. The inset shows the average transmission versus number of slab layers in a frequency window from (a) 10.5 GHz to 11.5 GHz and (b) 10.25 GHz to 10.75 GHz.
FIG. 3: Microwave transmission versus frequency for several angles. (a) Electric field perpendicular to rods (TM). (b) Electric field parallel to rods (TE).