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Abstract

We have experimentally observed superluminal and infinite group velocities in bulk hexagonal twodimensional photonic bandgap crystals with bandgaps in the microwave region. The group velocities depend on the polarization of the incident radiation and the air-filling fraction of the crystal.

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I. INTRODUCTION

The superluminal propagation of wave packets with faster-than- c , infinite and negative group velocities has been observed in a wide range of physical systems, including both passive and active optical media [\[1](#page-6-0), [2,](#page-6-1) [3](#page-6-2), [4,](#page-7-0) [5](#page-7-1)]. Garrett and McCumber [\[6](#page-7-2)] first predicted that a Gaussian wave packet can propagate with negligible distortion through a linear optical medium with a superluminal group velocity, if its bandwidth is restricted to a narrow spectral region of anomalous dispersion within an absorption or gain line. This prediction was later experimentally verified for the propagation of picosecond laser pulses through a GaP:N sample [\[7\]](#page-7-3). Such superluminal behavior does not violate relativistic causality. Any analytic function, such as a Gaussian wave packet, contains sufficient information in its early tail to reconstruct the entire wave packet with a superluminal pulse advancement, but little distortion. Relativistic causality forbids only the *front* velocity, i.e., the velocity of any *discontinuity*, from exceeding the vacuum speed of light, c. It does not forbid the *group* velocity of a wavepacket from being superluminal.

The superluminal behavior of electromagnetic pulses can occur not only in passive, *absorptive* optical media, but also in passive, *dissipationless* optical media, such as periodic dielectric photonic bandgap (PBG) structures [\[8\]](#page-7-4). Optical pulses whose bandwidths are restricted to the PBG are exponentially damped not due to absorption, but interference between multiple Bragg reflections from planes within the transparent periodic dielectric structure. The superluminal propagation of wavepackets through 1D periodic dieletric structures has been observed in the optical spectral region [\[9\]](#page-7-5). Similarly, superluminal propagation has been observed for classical microwave pulses in a 1D periodic dielectric stack placed inside a microwave waveguide [\[10](#page-7-6)]. Other work has demonstrated superluminal behavior in the frequency range of tens of MHz in a 1D photonic structure made of a sequence of coaxial cables with alternating impedance values [\[11\]](#page-7-7). No reported experiment has yet demonstrated superluminal propagation of electromagnetic wavepackets in 2D periodic structures, although we have recently demonstrated for the first time clear experimental evidence for the existence of exponential wave decay in such structures at microwave frequencies [\[12\]](#page-7-8). Here we report on experimental results which imply that superluminal group velocities do occur in such structures.

Microwave measurements have certain advantages which we exploit here. First, one can perform direct, precise phase measurements using a microwave vector network analyzer (VNA). Second, the wavelength is sufficiently large so that high-precision, well-fabricated 2D photonic crys-

FIG. 1: Experimental setup for microwave transmission and phase measurements.

tals can be relatively easily constructed. Third, one can more easily tailor the dispersive properties of the PBG by changing structural parameters, such as the structure air-filling fraction (AFF).

II. EXPERIMENT

The fabrication of our photonic crystals has been described in detail elsewhere [\[12](#page-7-8)]. In summary, we stack acrylic rods in a hexagonal lattice and glue them in place with an acrylic solvent cement. We constructed and tested crystals with as many as eighteen layers of rods, and AFFs of 0.60, using rods with a 1/2-inch outer diameter. The crystals are "bulk" samples rather than "slabs" in the sense that their extruded (non-periodic) dimension is many times the lattice spacing in length.

In Fig. [1](#page-2-0) we show a schematic of the experimental apparatus used for the microwave transmission measurements. We used an HP 8720A VNA, which is capable of measuring both the transmission and phase delay of microwaves detected by a polarization-sensitive receiver antenna (horn). The VNA was swept from 8 to 14 GHz in 15 MHz increments and was connected to identical transmitter and receiver horns. The crystal 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 crystal. With the crystal removed and the rectangular aperture closed, the microwave signal at the receiver was suppressed by more than 45 dB, indicating good shielding by the box. As previously reported, our bulk crystal with AFF equal to 0.60 displays a strong bandgap at \approx 11 GHz [\[12](#page-7-8)].

FIG. 2: Transmission through an AFF equal to 0.60 crystal with 18 layers. (a) TM polarization; (b) TE polarization.

To establish the reliability of the phase delay measurements, we placed sheets of ordinary acrylic of varying widths in front of the receiver horn. The phase delay relative to that of free space propagation was linear in the transmitted microwave frequency, with a slope that depended on the thickness of the acrylic. Using a simple model of phase delay given by

$$
\Delta\phi(\omega) = \frac{\omega}{c}d(n(\omega) - 1),\tag{1}
$$

where d is the sheet thickness, we were able to extract a value of $n = 1.58$ for the index of refraction of acrylic, in good agreement with the accepted value of 1.61 for this frequency range [\[13\]](#page-7-9).

The group velocity measurements were carried out by measuring, for both polarizations, the spectral dependence of the phase delay for crystals with different numbers of layers. The group index was calculated according to the relation [\[6\]](#page-7-2)

$$
n_g(\omega_0) = n(\omega_0) + \omega_0 \frac{\partial n}{\partial \omega} \Big|_{\omega_0},\tag{2}
$$

where $n(\omega)$ is the normal (phase) index of refraction and the group index n_q is defined as the ratio

FIG. 3: Phase index of refraction $n(\omega)$ for an AFF equal to 0.60 crystal with various layer numbers. (a) TM polarization; (b) TE polarization.

of the speed of light to the group velocity. Thus, superluminal group velocities exist in any spectral region where the group index is less than unity.

In order to calculate the group index, it was necessary to unwrap the phase data obtained from the VNA, since it is sensitive to phase modulo 2π . We were able to determine when such phase slips occurred by observing that the unwrapped phase delay at fixed frequencies was a monotonic function of the number of layers except for sharp changes (phase slips) at certain numbers. We adjusted the data by adding $2\pi \times m$ to each phase delay spectrum, where m is the cumulative number of sharp drops observed over smaller layer numbers. We also confirmed the validity of this phase adjustment by considering $\partial n/\partial \omega$, which should go to zero far from the bandgap. We found that it did so if and only if we applied this phase delay adjustment as described.

FIG. 4: Group index of refraction $n_g(\omega)$ for an AFF equal to 0.60 crystal with various layer numbers. (a) TM polarization; (b) TE polarization.

III. RESULTS AND DISCUSSION

In Fig. [2,](#page-3-0) we show the measured transmission bandgap of a crystal with eighteen layers and AFF equal to 0.60, for both incident microwave polarizations. We consider the plane of incidence to be the plane of periodicity (perpendicular to the rods) and define the TE (TM) polarization to have its electric field perpendicular (parallel) to this plane. We normalized transmission measurements by removing the crystal and measuring the total microwave signal at the receiving horn. We find that this crystal exhibits anomalous dispersion within the bandgap, passing briefly through zero dispersion at the bandgap edges, for both TE and TM polarizations (see Fig. [3\)](#page-4-0). We note that the region of anomalous dispersion becomes increasingly well-defined as the number of layers is increased.

From the phase delay data in Fig. [3](#page-4-0) we calculate the group index using Eq. [2.](#page-3-1) The results are displayed in Fig. [4.](#page-5-0) The region of superluminal n_q extends over a wider spectral band for the TM polarization than the TE polarization, and deepens more rapidly as the number of layers is increased. This result is not surprising given that the TM gap is known to form more rapidly than the TE gap as the number of crystal layers is increased [\[12\]](#page-7-8).

We did similar measurements (not shown here) using other crystals with AFF equal to 0.32 and obtained qualitatively similar bandgaps, although they are narrower and shallower for both polarizations, as expected [\[14](#page-7-10)], and have slightly different center frequencies. Both crystal sets display similar superluminal spectral regions, although we found that those with higher AFF typically have greater bandwidth and yield superluminal group velocities which are more superluminal.

IV. CONCLUSION

We have experimentally demonstrated that superluminal including infinite group velocities can exist for analytic signals whose spectral bandwidth lies within the bandgap of a two-dimensional hexagonal photonic crystal. Superluminal phenomena are exhibited by these crystals for both tested AFFs, although the effects are more significant (i.e., group velocities become more superluminal and exist over a wider spectral range) for structures of higher AFF.

This work was supported by ARO grant number DAAD19-02-1-0276. We thank the UC Berkeley Astronomy Department, in particular Dr. R. Plambeck, for lending us the VNA. JMH thanks the support from Instituto do Milênio de Informação Quântica, CAPES, CNPq, FAPEAL, PRONEX-NEON, ANP-CTPETRO.

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