Transmission through chiral twist defects in anisotropic periodic structures

Victor I. Kopp

Chiral Photonics, Inc., Clifton, New Jersey 07012

Ranojoy Bose

Queens College of the City University of New York, Flushing, New York 11367

Azriel Z. Genack

Queens College of the City University of New York, Flushing, New York 11367, and Chiral Photonics, Inc., Clifton, New Jersey 07012

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A long-lived photonic state is observed in measurements of microwave transmission through a helical stack of anisotropic overhead transparencies with various twist defects in the center of the structure. Once account is taken of absorption and of the angular spread of the source, computer simulations of transmission through a polarized localized state are in agreement with measurements. Unlike for isotropic one-dimensional bandgaps, the intensity of the localized mode is not modulated in space on a wavelength scale.

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The understanding and application of localized states created by defects in one-, two-, and three-dimensional photonic structures have advanced rapidly in recent years.[1] Defects have been created in isotropic periodic media by removal or addition of material or by alteration of the refractive index of one or a number of elements of photonic crystals. One-dimensional periodic structures have found particularly wide application as filters and lasers. They are the basis of distributed Bragg reflection lasers. Introducing a quarter-wavelength defect in the middle of a periodic one-dimensional sample produces a photonic mode in the center of the reflection band. Such a defect is used to produce high-Q laser cavities in vertical cavity surface-emitting lasers[2] and may be the basis of large-area coherent laser emission in thin films.[3] There has also been growing interest in the photonic properties of one-dimensional chiral periodic structures. These structures display selective reflection bands for circularly polarized light with the same handedness as the structure.[4] They can be self-organized cholesteric liquid crystals (CLCs) or they can be fabricated in a continuous process. For example, an array of helical dielectric columns produced by glancing-angle deposition upon a rotating substrate[5] exhibits selective reflection.[6]

The selective reflection band of a CLC[4] attests to the presence of a true photonic stop band in which the density of states vanishes for circularly polarized light with the same handedness as the periodic anisotropic structure.[7] Spontaneous emission, which is proportional to the density of states, is suppressed inside the stop band and enhanced at the band edges. At the band edges, long-lived photonic modes lead to low-threshold lasing.[7]

In analogy with isotropic periodic structures, a defect can be produced in a helical structure by addition of an isotropic layer in the middle of a CLC.[8] In addition, a chiral twist defect, created by rotation of one part of the sample about its helical axis without separating the two parts was proposed.[9] Modifying the chiral twist angle from 0 to 180° tunes the defect frequency from the low to the high-frequency band edge. Recently such a spacerless defect was created in sculptured thin films by rotation of the substrate by an additional 90° in the middle of the film fabrication process.[10] A peak in transmission was observed in the middle of the bandgap.

In this letter we report measurements of transmission through a helical stack of rotated anisotropic overhead transparencies that possess various chiral defects. Once absorption and the angular distribution of the wave are taken into account, good agreement is obtained between computer simulations and microwave transmission measurements. Simulations of the intensity distribution inside the sample at the frequency of peak transmission show that the localized intensity varies smoothly without wavelength-scale modulation. We constructed the sample by stacking Highland 701 transparency films with a fixed rotation angle between successive sheets to produce a right-handed structure. The thickness of each transparency was 0.11 mm, and the pitch was equal to the thickness of 88 transparencies, or 9.6 mm. We guided the rotation of transparencies by placing the corner of each transparency between two nylon fishing lines, which were threaded between the two plastic plates of a cylindrical retainer as illustrated in the inset of Fig. 1. The entire structure that supported the rotated transparencies was placed within a cardboard box that was lined with microwave absorber except for 10-cm-diameter holes on the top and the bottom.

A Hewlett-Packard 8722 vector network analyzer was used to measure the spectrum of the transmitted field. The microwave source was a horn that was readily adjusted to emit either right circularly polarized (RCP) or left circularly polarized (LCP) radiation. The horn was placed with its opening in the center of the bottom of the box. The receiving horn was hung 1.3 m from the top of the hole in the box.

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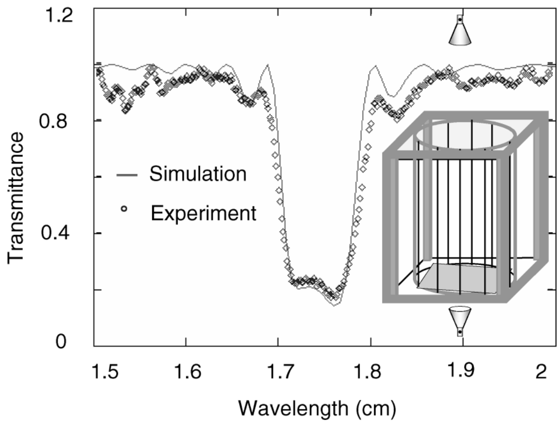

Fig. 1. Transmittance through a stack of 1500 transparencies.

The indices of refraction for radiation propagating perpendicular to the plane of the transparencies and polarized along and perpendicular to the length of the transparencies are $n_{\parallel} = 1.838$ and $n_{\perp} = 1.782$, respectively. We obtained these results by measuring the microwave phase accumulated in propagation through a stack of ten aligned transparencies. From measurements of transmission of LCP radiation, which does not interact resonantly with the sample because $L < L_{\mathrm{co}}$, the absorption coefficient of the transparencies was found to be $0.017\ \mathrm{cm}^{-1}$.

The first sample studied consisted of 1500 transparencies with CLC symmetry as described above. The intensity spectrum of transmitted RCP radiation was normalized to that for transmitted LCP radiation obtained with use of LCP source and receiver horns. The results of simulations for infinite sheets and the actual indices, thicknesses, and pitches are shown in Fig. 1 to be in good agreement with these measurements.

Next, a 90° chiral twist defect was created by addition of a similar stack of 1500 rotated sheets but with the first transparency of the second stack rotated by an additional 90° relative to the sheet on the top of the first stack. The total thickness of 3000 transparencies corresponded to a length of $0.34L_{\mathrm{co}}$. The transmission spectrum for the RCP wave normalized to that for the LCP wave is shown in Fig. 2. A simulation of transmission for normally incident radiation through infinite sheets is also shown in the figure. Including absorption in the simulations suppressed and broadened the line, as shown in Fig. 2. Absorption strongly suppressed transmission through the defect mode because of the long photon dwell time. These results stand in contrast to the weak influence of absorption inside the reflection gap of the periodic structure shown in Fig. 1, for which good agreement was obtained with simulations that did not include absorption because in this case the transit time was considerably shorter than the absorption time. At the relatively long-lived modes at the band edge, seen as oscillations in transmission, absorption suppressed transmission even in this relatively thin sample. The rapid increase with sample thickness of the photon dwell time at resonance for $L < L_{\mathrm{co}}$ limited the sample lengths for which reliable measurements could be made. Simulations showed that at twice the thickness of the present sample, which is still below L_{co}, transmission at resonance would fall below 2×10^{-3} and this would be difficult to observe.

We obtained improved correspondence between the simulations and measurements by including the angular spread of the radiation (Fig. 3). The horns used had an effective aperture of ~4 cm, which gave a 30° acceptance angle for microwave radiation at the frequency of the defect mode. The transmission spectrum for an absorbing sample with a 90° chiral twist was calculated for a Gaussian angular distribution with a standard deviation of 15°. The transmission peak was asymmetrically broadened as a result of the blueshift of the stop band with angle.

A simulation of the intensity distribution inside the sample at the resonant frequency without including absorption is shown as a semilogarithmic plot in Fig. 4. The intensity decays exponentially from the site of the chiral twist defect in the center of the sample, demonstrating that the resonance is a result of coupling to a localized state. In contrast, the energy distribution inside a binary layered structure in a binary sample with the two indices equal to n_e and n_o of the chiral

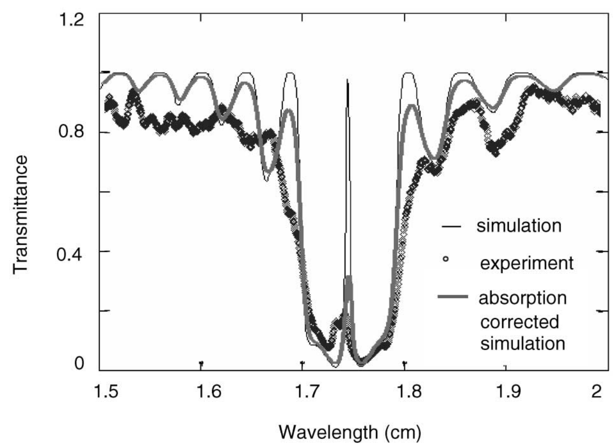

Fig. 2. Transmittance through a stack of 3000 transparencies with a 90° chiral twist in the center.

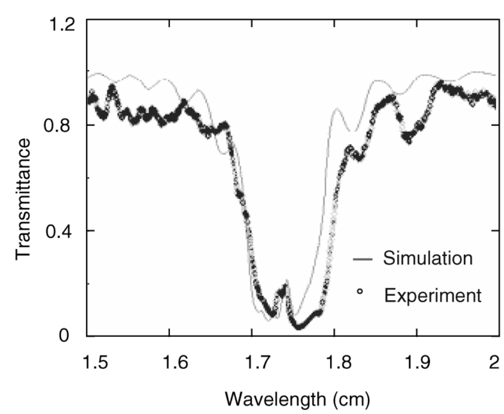

Fig. 3. Transmittance through a stack of 3000 transparencies with a 90° chiral twist in the center. Both angular spread and absorption are taken into account in the simulation.

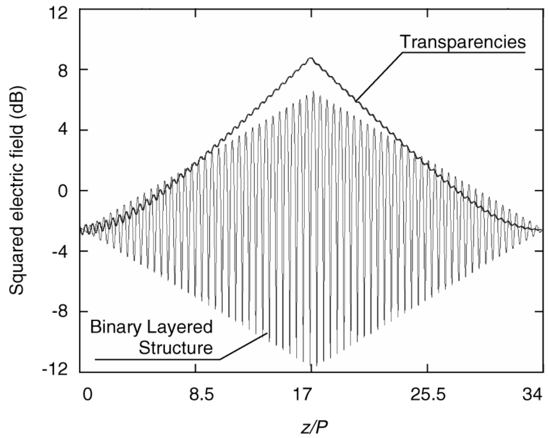

Fig. 4. Comparison of the energy density inside chiral and binary layered structures with the same index contrast and thickness versus coordinate z/P. Pitch P of the chiral structure is twice the period of the binary-layered structure.

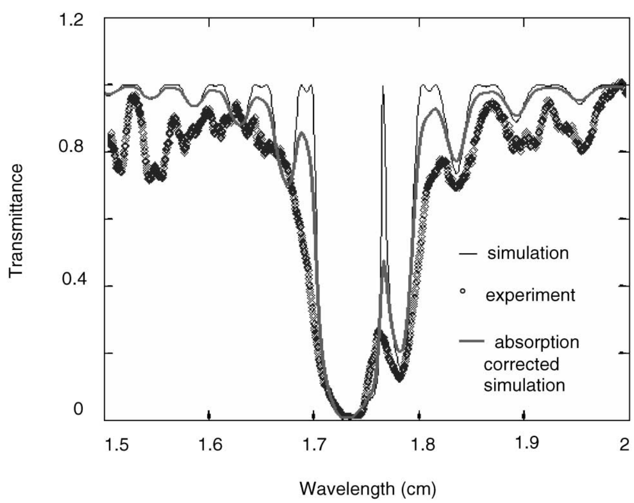

Fig. 5. Transmittance through a stack of 3000 transparencies with a 45° chiral twist in the center.

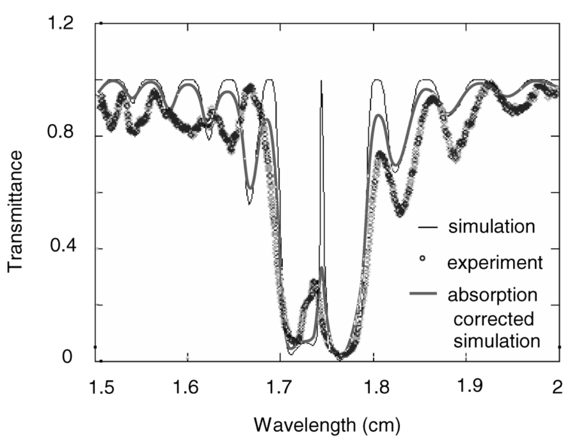

Fig. 6. Transmittance through a stack of 3000 transparencies, with a combination of a 45° chiral twist and a quarter-wavelength separation in the center.

sample is seen to be highly modulated on the scale of the structure period, with an exponentially decaying envelope of peak values and an exponentially increasing envelope of minimum values.

Measurements of transmission through a 45° chiral twist defect in the middle of two stacks of 1500 transparencies as well as a simulation for normally incident radiation with and without absorption are shown in Fig. 5. Measurements and simulations of transmission that were carried out in a defect that was a combination of a chiral twist and a spacer are presented in Fig. 6. The defect in the middle of two stacks of 1500 transparencies consisted of a $\lambda/8$ spacer composed of 11 transparencies stacked without rotation followed by a $-45°$ chiral twist. This combination introduced a 90° net phase shift, producing a mode in the middle of the stop band. Reasonable agreement was obtained once absorption and the angular spread of radiation were taken into account.

In conclusion, our measurements of microwave transmission have demonstrated the existence of localized photonic modes in anisotropic samples with a variety of defects based on a chiral twist. Good agreement was obtained between measurement and one-dimensional simulations. When a defect was incorporated into the structure, transmission was strongly affected by absorption and by the angular spread of radiation at the frequency of the long-lived defect mode.

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References

1. A. Adibi, A. Scherer, and S.-Y. Lin, eds., *Photonic Bandgap Materials and Devices*, Proc. SPIE **4655** (2002).
2. H. Yokoyama and K. Ujihara, *Spontaneous Emission and Laser Oscillation in Microcavities* (CRC, Boca Raton, Fla., 1995).
3. V. I. Kopp, Z.-Q. Zhang, and A. Z. Genack, Phys. Rev. Lett. **86,** 1753 (2001).
4. S. Chandrasekhar, *Liquid Crystals* (Cambridge U. Press, Cambridge, 1977).
5. K. Robbie, D. J. Broer, and M. J. Brett, Nature **399,** 764 (1999).
6. A. Lakhtakia and R. Messier, Opt. Photon. News **12**(9), 27 (2001).
7. V. I. Kopp, B. Fan, H. K. M. Vithana, and A. Z. Genack, Opt. Lett. **23,** 1707 (1998).
8. Y.-C. Yang, C.-S. Kee, J.-E. Kim, H. Y. Park, J.-C. Lee, and Y.-J. Jeon, Phys. Rev. E **60,** 6852 (1999).
9. V. I. Kopp and A. Z. Genack, "Chiral twist laser and filter apparatus and method," U.S. patent 6,396,859 (May 28, 2002).
10. I. J. Hodgkinson, Q. H. Wu, K. E. Thorn, A. Lakhtakia, and M. W. McCall, Opt. Commun. **184,** 57 (2000).