Bacteriorhodopsin: A Natural (Nonlinear) Photonic Bandgap Material

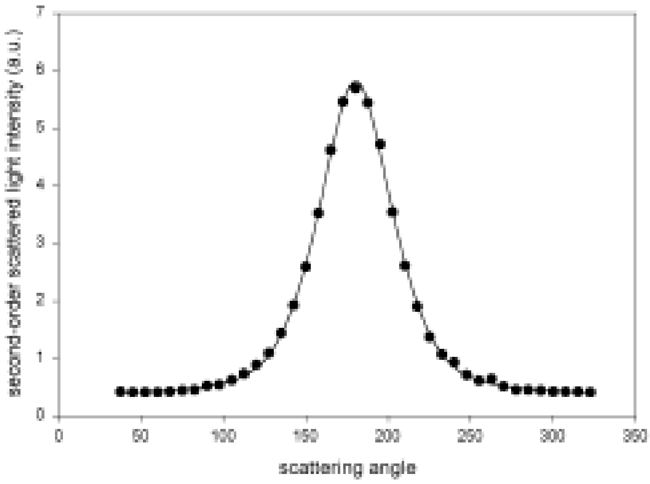
By Koen Clays, Sven Van Elshocht, and André Persoons

Photonic bandgap materials, often also called photonic crystals, are engineered materials with a periodicity in dielectric properties.[1] This periodicity results in a range of forbidden energies for a photon: Photons with a wavelength in the corresponding photonic bandgap cannot propagate through the material. Recently, second-harmonic generation has been realized in a photonic crystal.[2] In a nonlinear photonic crystal, the optical nonlinearity of the harmonic-generating material (the hyperpolarizability) is decoupled from the linear optical properties (the refractive index). This has important consequences on phase-matching schemes for efficient nonlinear conversion in these materials.

The purple membrane of *Halobacterium halobium* has received considerable attention as a candidate material for optical information processing. The two-dimensional purple membrane consists of patches of the protein bacteriorhodopsin. The small optical moiety, the retinal chromophore, is embedded in this large protein matrix. The molecular hyperpolarizability of retinal and derivatives was analyzed previously both theoretically and experimentally.[3] The second-order nonlinear optical properties of the protein could be experimentally determined by means of hyper-Rayleigh scattering.[4]

We have now studied the angular dependence of the hyper-Rayleigh scattering as a function of time during the ongoing process of the solubilization. In Fig. 1 we show the angular dependence that is observed before any solubilization takes place. The solid curve is a fit to a theoretical model that accounts for both coherent and incoherent contributions to the hyper-Rayleigh signal. The coherent contribution can be described by a sinc^2 function [$\mathrm{sinc}(x) = \sin(x)/x$]. The argument x of the function, $(4\pi L_{coh}/\lambda)\sqrt{n_\omega n_{2\omega}}\sin\theta/2$, is determined by the coherence length L_{coh} for coherent second-harmonic generation and by the refractive index n at both fundamental ω and second-harmonic wavelength 2ω. The intensity of the hyper-Rayleigh signal at an angle θ is also determined by the optical nonlinearity at the fundamental wavelength λ of the retinal itself. The best fit to the experimental data (the solid curve in Fig. 1) is found by combination of the nonlinear optical properties (the hyperpolarizability) of only the small retinal moiety with the linear optical properties (the refractive index) of the large protein matrix. Therefore we can, for the first time to our knowledge, attribute nonlinear photonic bandgap properties to this natural material.[5]

This has important consequences, since all photonic bandgap materials reported so far exhibit a high degree of order and are, therefore, artificially engineered structures. Crystals of bacteriorhodopsin are self-assembled nonlinear photonic crystals with a coherence length that is limited only by the physical size of the crystal. Genetic engineering and counter-ion position modulation can fine tune the relevant properties for a specific application.



Bacteriorhodopsin Figure 1. Angular dependence of second-harmonic light intensity scattered by a suspension of purple membrane before any solubilization.

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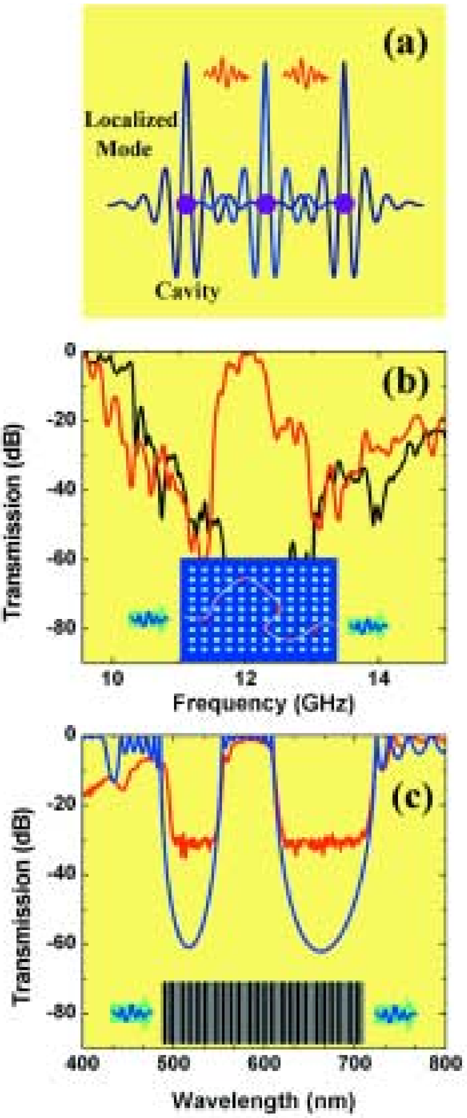
PHOTONIC CRYSTALS

Propagation of Photons by Hopping

By Mehmet Bayindir and Ekmel Özbay

By breaking the periodicity of photonic crystals, it is possible for one to create highly localized defect modes within the stop band.[1] If we provide enough overlap between cavity modes, photons can hop from one cavity to the neighboring cavity, as illustrated in Fig. 1(a), which can be considered as the classical wave analog of the tight-binding (TB) approximation in solid-state physics. This novel waveguiding mechanism, which we call the coupled-cavity waveguide (CCW),[2-5] has a pivotal role in overcoming the problem of guiding light around sharp corners in optoelectronic components and circuits. Conventional metallic or dielectric waveguides undergo significant radiation loss when sharp bends are introduced.

First, we demonstrate CCWs at microwave frequencies by using layer-by-layer dielectric-based three-dimensional photonic crystals.[2-4] We formed the cavities by removing a single rod from each unit cell of the crystal. Fig. 1(b) (red) displays the transmission characteristics of a ten-unit cell zigzag CCW [see Fig. 1(b) inset]. A guiding band or defect band was formed with-



Propagation of Photons Figure 1. (a) Schematic of the propagation of photons through localized coupled-cavity modes within a photonic bandgap structure. (b) Transmission characteristics of a zigzag CCW (red) and a perfect photonic crystal (black). (c) Measured (red) and calculated (blue) transmissions through the silicon-oxide/silicon-nitrite pairs with silicon-oxide cavity layers.

in the photonic bandgap because of the interaction between localized cavity modes. Almost complete transmission of the electromagnetic wave was achieved throughout the waveguiding band regardless of the direction of propagation. The transmission spectrum of the perfect crystal (black) is also plotted for comparison.

Since the Maxwell equations have no fundamental length scale, our microwave and millimeter wave results can be extended to optical frequencies. We observed the guiding of light through localized optical cavity modes in one-dimensional photonic bandgap structures that were fabricated with silicon-oxide/silicon-nitrite pairs with silicon-oxide cavity layers [see Fig. 1(c) inset]. As shown in Fig. 1(c) (red), nearly 100% transmission was measured throughout the cavity band. The theoretical results (blue) obtained from the transfer matrix method simulations are in good agreement with the measurements.

We can also report that the group velocity tends toward zero and the photon lifetime increases drastically at the CCW band edges. This observation has practical importance, inasmuch as the efficiency of nonlinear processes can be increased because of low group velocity and large optical field amplitude. At the CCW band edges, both requirements are satisfied simultaneously. Moreover, the spontaneous emission can be enhanced at the CCW band edges. It is also important to note that all the experimental results, namely, dispersion relation, group velocity, and photon lifetime, agree well with the prediction of the TB photon picture.

Acknowledgments

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Guiding Mechanism in Photonic Crystal Fibers

By Albert Ferrando, Enrique Silvestre, Juan José Miret, Pedro Andrés, and Miguel V. Andrés

Photonic crystal fibers (PCFs) are thin silica glass fibers that possess a regular array of microscopic air holes that extend along the entire fiber length. For certain geometries PCFs present a photonic bandgap structure. Light propagation is forbidden within the bandgaps, whereas conduction bands are constituted by radiative modes.

The most common PCF comprises a triangular two-dimensional air-hole lattice with a missing central hole.[1] In this structure the dispersion relation of guided modes appears in the semiinfinite forbidden band whose lower bound is determined by the lowest-order Bloch mode that can propagate in the periodic structure.[2] Inasmuch as this bound determines the effective cladding index that is lower than that of the core, this nonintraband guidance is considered by some authors as having been produced by total internal reflection (TIR).

Alternatively, guidance is also possible in honeycomb PCF structures in which the defect is generated by an off-lattice air hole. Here the guided modes lie on the forbidden band that exists between the first two conduction bands of the honeycomb photonic-crystal cladding.[3,4] Inasmuch as the average index of the cladding is now higher than the refractive index of the airhole defect core, guidance cannot be interpreted in terms of a TIR mechanism. Instead, the intraband guid-