Optically Tunable Photonic Bandgap Fiber

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A new type of tunable optical fiber is based on photonic crystal fibers (PCFs), which have a cross-section that usually consists of an air/silica microstructure that is invariant along the fiber axis. Light can be guided either by modified total internal reflection (mTIR) or by the photonic band gap (PBG) effect. In both cases, the guided light is surrounded by a number of capillaries ranging from a few to several hundred; they have unique advantages compared to standard fiber technology with respect to tunability.

For example, the capillaries allow for a high interaction between guided light and an infused liquid material. Tunable PCFs based on mTIR have been demonstrated by pumping a liquid plug across a tapered region of a PCF.[1] Tunability has been explored using the PBG effect by thermally tuning the refractive index of a high-index liquid[2] or a liquid crystal[3] (LC) or by reorienting LCs by external electrical fields.[4] These devices exhibit response time in the range of 10 ms to 1 s.

Here, we describe an optically tunable photonic bandgap fiber that has a faster response time and requires no electrical wiring, because the controlling signal (the pump) is guided in the fiber together with the signal (the probe) allowing for remote tuning.[5] The PCF consists of a 10 μm silica core surrounded by 7 periods of 3 μm air holes [figure, part (a), inset], which are infiltrated for 10 mm with an LC. The presence of an LC in the air holes transforms the PCF from an mTIR type into a PBG guiding type waveguide exhibiting a series of transmission bands (PBGs) within the wavelength span of 400 to 1700 nm [part (a)].

The fiber acts as a spectral filter that screens out wavelengths that are not supported as guided modes by the cladding structure. These modes couple to the cladding and propagate in the LC (b), while the transmitted modes propagate in the core (c). Doping the LC with an absorbing dye increases the optical absorption of the modes propagating in the LC cladding. Using a λ=532 nm pump laser and an azobenzene dye-doped nematic LC absorbing at this wavelength, we demonstrated that varying the power of the pump laser could optically control the spectral position of the PBGs so that all-optical modulation is feasible.

The absorption locally raises the temperature of the LC and the PBGs shift accordingly. The tuning dynamics of the PBGs are in this case limited by the thermal diffusion time of the individual LC capillaries, which is the time for the thermal energy to diffuse from the LC to the surrounding silica. In this design, it is around 100-200 μs (d) for a low pump power of 2-3 mW. The pump tunes the fiber properties within the entire 400 to 1700 nm wavelength span, whereby the pump signal can modulate the power and the effective mode index of a guided mode with a wavelength lying within one of the PBGs, as shown in (d).

In conclusion, we have demonstrated an all-optical tunable photonic bandgap fiber that requires a very low pump power to be tuned.

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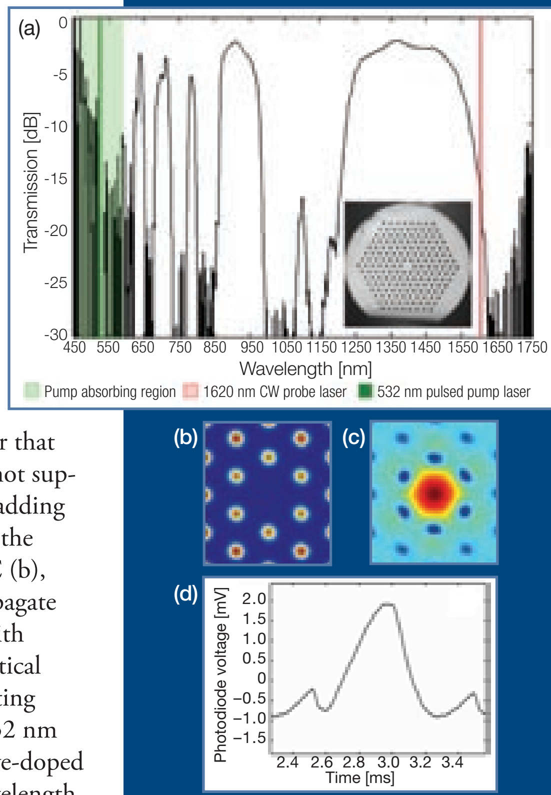

Transmission spectrum of the dye-doped nematic liquid crystal photonic bandgap fiber, which absorbs light with wavelengths between 450 nm and 600 nm. (a) Inset shows an optical micrograph of the PCF end facet. Simulated mode profile of a short-wavelength cladding mode propagating in the LC (b) and guided mode in the core (c). The dynamic response is measured by placing a continuous-wave probe laser on a PBG edge and pumping the LC with a square-wave modulated 532 nm pump laser with a power of 2-3 mW. The probe rise and decay time was 250 μs and 120 μs, respectively, in response to a 500 μs pump pulse (d).

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Brillouin-Zone Spectroscopy of Photonic Lattices

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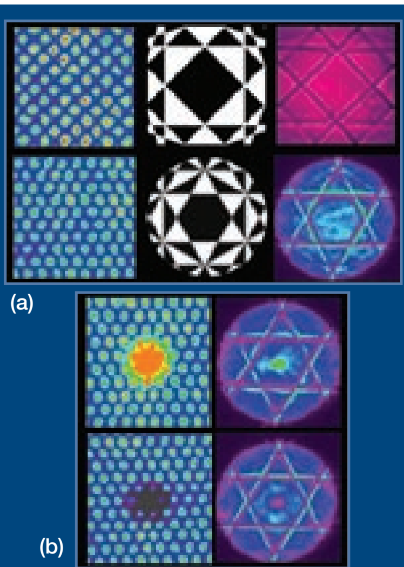
Optics provides much insight into wave dynamics in periodic systems, including the technologically important examples of photonic crystals,[1] photonic crystal fibers[2] (PCFs) and waveguide arrays. The lattice geometries and the wave dynamics supported in them are best presented in momentum space through the extended Brillouin-zone (BZ) map,[3] whose boundaries are defined by the Bragg-reflection planes. The extended BZ map of a lattice can be readily calculated from the lattice structure, or measured point-by-point through Bragg reflections. However, until now, no direct measurement of the BZ structure of such lattices has been demonstrated.



(a) The interference patterns inducing the lattices, the calculated Brillouin zone structures, and the experimentally observed BZ maps of the lattices. Upper row-square lattice, lower row-hexagonal (trigonal) lattice. (b) Input faces of hexagonal lattice with a positive (upper) and a negative (lower) defect, and the experimentally observed Fourier spectrum highlighting the guided defect modes.

In a recent experimental paper, we have presented a novel experimental technique for Brillouin zone spectroscopy of photonic lattices.[4] Our technique facilitates a direct mapping of the borders of the extended BZs, and marking the areas of normal and anomalous dispersion within them. The method relies on exciting the lattice (Bloch) modes with partially incoherent waves, performing an optical Fourier transform and measuring the power spectrum. The method provides a powerful diagnostic tool for photonic lattices and can be extended to other periodic systems beyond optics—for example, cold atoms, sound waves, microwaves, plasmas, etc.

We conducted our experiments in optically induced photonic lattices[5] formed in a highly anisotropic photosensitive nonlinear crystal, using the methods that have recently proven very successful for generating lattice solitons. Experimentally, we pass a laser beam through a rotating diffuser, and launch it through the photonic lattice such that it illuminates approximately 30 sites. The momentum space of the underlying lattice is monitored by placing a camera in the focal plane of the lattice output.

Experimental results of square and trigonal lattices are shown in part (a) of the figure. The upper (lower) row depicts the interference pattern inducing a square (trigonal) lattice, together with its experimentally observed extended Brillouin-zone map. The edges of each BZ are marked by dark stripes, exhibiting a remarkable similarity to the calculated (textbook) edges.

Part (b) presents experiments on photonic lattices with embedded defects. Such geometries correspond to solid and hollow-core photonic crystal fibers. For the positive defect, the guided modes arise from total-internal-reflection (TIR, i.e., states centered around k=0). On the other hand, for a negative defect (for which the average refractive index is lower in the guiding region), waveguiding arises solely from Bragg reflections, with no contribution from TIR. Consequently, there is a central “hole” around k=0, with modes appearing near the BZ edge (bright concentric ring).

Finally, we demonstrated that when the photonic lattice is nonlinear (not shown here), it is possible to mark the areas of normal and anomalous dispersion (diffraction, effective mass, etc.) within every Brillouin zone. When the nonlinearity is self-focusing, Bloch waves from anomalous diffraction regions transfer power to Bloch waves arising from normal diffraction regions, and vice versa for the self-defocusing case. This energy exchange depends on the underlying band curvature.

To summarize, we have demonstrated a single-shot technique for Brillouin zone spectroscopy of photonic lattices, relying on partially incoherent input and Fourier imaging of the output. The technique directly maps the boundaries of the Brillouin zones, the regions of normal and anomalous diffraction within them, and the power spectra of modes guided by embedded defects. ◭

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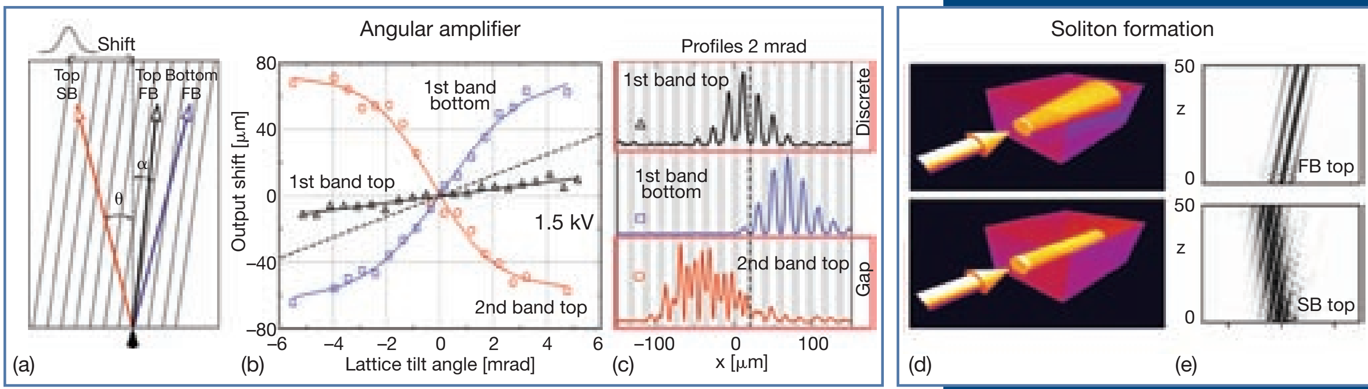

(a) Schematic of Bloch wave refraction in a tilted lattice. (b) Measured output beam displacement corresponding to three types of Bloch waves for different lattice tilts. (c) Output beam profiles. (d) Beam localization in the form of solitons can provide fine resolution for steering applications. (e) Numerically simulated refraction of discrete (top) and gap soliton (bottom) in a tilted lattice.

Tunable Negative Refraction of Light in Photonic Lattices

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Negative refraction attracted a lot of attention during the past few years in connection with experimental demonstrations of the so-called left-handed composite metamaterials. However, negative refraction is a fundamental physical phenomenon that may occur in different systems as a result of anisotropy or periodicity. Periodic structures such as photonic crystals provide an invaluable opportunity to engineer the dispersion and diffraction properties of light, therefore controlling light refraction inside the material. Such control will possibly lead to novel types of optical switching and steering applications.

Researchers have known for more than two decades that negative refraction in periodic structures is possible due to the specific properties of the extended periodic eigenmodes or Bloch waves, and it may occur even in weakly modulated one-dimensional periodic structures.[1] Indeed, when light bends at the interface between homogeneous and periodic media, the refraction angle depends on the effective diffraction coefficients of the Bloch waves propagating inside the periodic structure.

Since diffraction of the Bloch waves depends strongly on the refractive index contrast, the refraction angle can be controlled by dynamically varying the lattice depth. Such tunability of the lattice depth and manipulation of the refraction can be achieved in different physical systems based on electro-optic materials[2] or liquid crystals.[3]

We have demonstrated experimentally control over light refraction in photonic lattices induced optically in a photorefractive crystal with strong electro-optic properties.[4] We realize dynamic tunability of the beam refraction by using a tilted lattice of an electro-optically tunable depth and by selectively exciting different propagating Bloch waves.

We demonstrate that beams associated with different Bloch waves of the lattice bandgap spectrum are refracted differently in relation to the lattice tilt, as shown in part (a) of the figure. The measured output shifts vs. the lattice tilt are pictured in (b) for beams associated with three different types of the Bloch waves.

We observe that the beam refraction associated with the top of the first band is smaller than the lattice tilt (b, dashed line), while for the beams associated with the edges of the Bragg-reflection gap, refraction is strongly increased. In our experiments, we measured a six-fold amplification of the steering angle for beams associated with the bottom of the first and the top of the second band, with positive and negative refraction, respectively. The corresponding beam profiles at lattice tilt of 2 mrad are shown in (c), and they match the corresponding Bloch waves.

Furthermore, we have combined the steering tunability with beam self-trapping through nonlinear self-focusing in the normal diffraction regime (d), and have studied refractive properties of discrete (e, top) and gap solitons (e, bottom). We anticipate that our findings will bring novel ideas for photonic devices with engineered tunable properties for active control of light propagation. ◭

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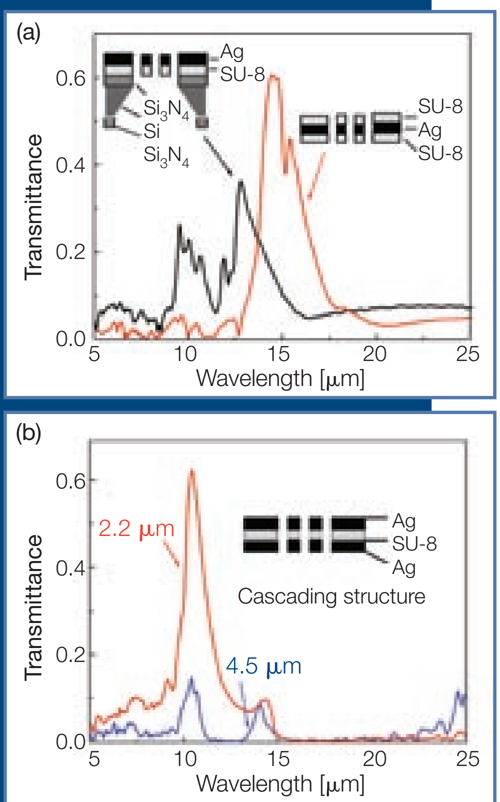
Cascaded Metal Films Perforated with Periodical Hole Arrays

Yong-Hong Ye

A metal film perforated with periodic subwavelength holes can exhibit extraordinary optical transmission.[1-5] In some cases, its transmission can be several percent, which is three orders of magnitude greater than what is predicted by the standard aperture theory. The detailed picture of the transmission enhancement is still under investigation.



(a) The transmission spectra of the single metallic structure (black) and the symmetrical metallic structures (red), and the left inset is the schematic view of the stencil mask; (b) The transmission spectra of the cascaded metallic structure with the SU-8 thickness of 2.2 μm (red) and 4.5 μm (blue).

However, researchers have proposed that excitation of surface plasmon polaritons (SPPs) on the two surfaces of the metal film is involved in the process.

There has been renewed interest in such perforated metal film due to its potential applications in photolithography, near field microscopy and photonic devices. In most of the experiments reported to date, the perforated metal films were fabricated by the focused-ion-beam method, and their transmission enhancement was in the visible and near-infrared regions.

Recently, we introduced a stencil mask method to fabricate such perforated metal films.[2] Large-scale perforated films can be obtained by our method, and our experiment demonstrated that SPPs could also induce transmission enhancement in the middle-infrared region.[3] Moreover, the cascaded structure (two such perforated metal films spaced by a dielectric layer) could be easily obtained by our method. The transmission was further boosted due to SPP coupling interaction between the two metal films.[5]

The maximal transmission of our samples was roughly 60 percent, with the background transmission of approximately 0.5 percent. These large-scale perforated metal films have potential applications in optical filters, optical modulators, etc. In addition, the stencil mask method can be used to fabricate frequency-selective surfaces.[2]

The structure of the stencil mask is shown in the inset of the figure, part (a). We fabricated the suspended SU-8 membrane by the standard silicon process technology.[2] The perforated silver film exhibited two transmission pass bands in the middle-infrared regions, as shown in (a). The longer wavelength (LW) band corresponds to the SPP (±1,0) modes at the SU-8/metal interface, while the shorter wavelength (SW) band corresponds to the SPP (±1,0) modes at the air/metal interface.[3,4]

The structure became symmetrical after another SU-8 film was coated onto the perforated metal surface, and the transmission of the LW band could be boosted by about a factor of two. In the case of the symmetrical structure, because the SPP modes on the two interfaces are the same, resonant tunneling between the interfaces could take place, and thus the transmission was further boosted.[3] As shown in (b), if both surfaces of the SU-8 membrane are deposited with metal layers, the cascaded metallic structure will be formed.

Our results indicate that the intensities and positions of the two pass bands strongly depend on the distance between the two metal layers.[5] Due to the coupling of SPP modes between the layers, the intensity of the SW band can be boosted by a factor of four if the distance is less than 3 μm. The figure indicates that the transmission enhancement can be improved by forming the symmetrical structure and the cascaded structure. ◭

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