First published in: APPLIED PHYSICS LETTERS **91**, 123515 (2007)

Thin-film polarizer based on a one-dimensional–three-dimensional–one-dimensional photonic crystal heterostructure

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(Received 15 June 2007; accepted 31 August 2007; published online 20 September 2007)

The recent experimental demonstration of polarization stop bands in three-dimensional dielectric circular-spiral photonic crystals is extended in two ways. First, the combination with a one-dimensional set of lamellae on one side allows for "poor-man's optical isolators" or for thin-film polarizers—depending on from which side light impinges onto the device. Second, a chiral three-dimensional photonic crystal sandwiched between two one-dimensional sets of lamellae acts as a thin-film polarizer from both sides. Corresponding polymeric heterostructures are fabricated by means of direct laser writing. Their performance is compared with theory. © *2007 American Institute of Physics*. [DOI: 10.1063/1.2789662]

Chiral molecules can exhibit circular dichroism and/or optical activity—despite the fact that the molecular dimensions are typically several orders of magnitude smaller than the pitch of the spiral described by the tip of the field vector of circularly polarized light (i.e., the wavelength of light). In chiral photonic crystals, e.g., in circular-spiral structures, the two spiral pitches can be brought into resonance and polarization stop bands emerge.[1,2] In a polarization stop band, one incident circular polarization of light is transmitted (with negligible polarization conversion) whereas the other circular polarization is Bragg reflected.[1,2] Clearly, the suppression can be adjusted by the number of lattice constants along the propagation direction, but even less than ten lattice constants and low index contrast can lead to very large effects for appropriate design. Our recent corresponding experimental demonstration based on polymeric three-dimensional circular-spiral photonic crystals allows for normal incidence onto "thin-film" structures located on a substrate.[2] Related chiral structures have, however, also been discussed for waveguide geometries,[3] for optical fibers,[4] for photonic band gap materials,[5–7] for chiral sculptured thin films,[8,9] for layer-by-layer chiral photonic crystals,[10,11] as well as in the context of cholesteric liquid crystals.[12]

Polarization stop bands can be used as "poor-man's optical isolators" for circularly polarized incident light: If, for example, right-handed polarized light from a laser impinges onto the structure, it is transmitted for a spiral photonic crystal composed of left-handed dielectric spirals. Upon back reflection from a mirror behind the spiral photonic crystal, the backward propagating light has left-handed circular polarization. As the spirals keep their handedness when looked at from the other side, the light is not transmitted, hence, blocked from propagating back into the laser source. This device is only a "poor-man's" isolator because it will fail to isolate if the polarization state of light is messed up behind the device, which is in sharp contrast to true optical isolators based on the Faraday effect.

Furthermore, a polarization stop band obviously converts unpolarized incident light into circularly polarized transmitted light, which in itself might be of interest for certain applications. Moreover, the combination of a chiral photonic crystal and a quarter-wave plate clearly acts as a polarizer. In contrast with commercially available thin-film polarizers based on one-dimensional dielectric stacks and Brewster's angle,[13] such heterostructure can work for normal incidence of light. If the device is used in the opposite direction, i.e., if linearly polarized incident light (oriented 45° with respect to the principal axes of the quarter-wave plate) first hits the quarter-wave plate and then the chiral photonic crystal, the overall structure acts as a poor-man's optical isolator for linear incident polarization of light. A chiral photonic crystal sandwiched between two crossed quarter-wave plates can act as a polarizer from both sides.

To obtain compact and monolithic devices, it is desirable to integrate the chiral photonic crystal and one (or two) quarter-wave plate(s). It is the aim of the present paper to demonstrate such heterostructures.

The physics as well as the fabrication of the three-dimensional (3D) circular-spiral photonic crystals have been described previously.[1,2] The quarter-wave plates are simply one-dimensional (1D) periodic sets of lamellae, leading to form birefringence in the long-wavelength limit. The lattice constants of the 3D and the 1D structures, respectively, do not need to be identical but choosing the same lattice constant is possible and eases the theoretical calculations, hence the detailed design. Figure 1 shows the two types of heterostructures discussed above. In what follows, we emphasize the 1D-3D-1D heterostructure, the 1D-3D heterostructure yields very similar spectra. Parameters are $a=1.3$ μm, $c=1.3$ μm, $d=0.78$ μm, $h=3.7$ μm, $2r_x=0.44$ μm, and $N=6$. The volume filling fraction of the spirals in the cubic unit cell is 32.1%. These parameters result from an optimization acknowledging the fabrication restrictions of direct

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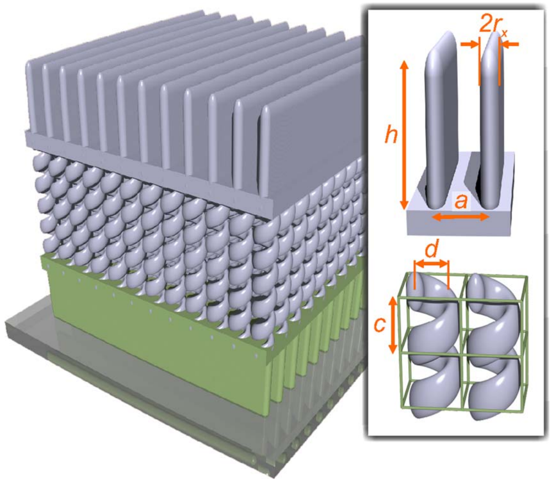

FIG. 1. (Color online) Proposed 1D-3D (blue) and 1D-3D-1D (blue and green) photonic crystal heterostructure composed of a three-dimensional right-handed (RH) spiral photonic crystal with $N=6$ pitches and one or two one-dimensional sets of lamellae, respectively. Parameters are defined on the right-hand side.

laser writing (see below). The thickness of each of the two plates (introduced for mechanical stability) between the spiral crystal and the sets of lamellae is 0.93 μm. The complete 1D-3D-1D heterostructure has a height of only 17 μm.

The calculated optical response (obtained from a scattering-matrix approach[14,15]) of a 1D-3D-1D heterostructure is shown in Fig. 2. This calculation refers to normal incidence onto the structure depicted in Fig. 1 and assumes a refractive index $n=1.57$ for the polymer. The structure is located on a glass substrate with refractive index $n=1.518$. Linear optical (intensity) transmittance spectra are shown for the two incident linear polarizations including +45° and −45° with respect to the lamellae, respectively. Here, +45° leads to left-handed circular polarization, while −45° to right-handed circular polarization. Obviously, the transmittances are different by about a factor of 50. The polarization state emerging from the device is very close to linear and parallel to the incident linear polarization. This becomes evident from the top part of Fig. 2 where we analyze the emerging polarization state at the operation wavelength (see dot). The performance of the 1D-3D heterostructure is quite similar, except that circular polarization is emerging from the device (not shown).

As pointed out above, the 1D-3D-1D heterostructure acts as a polarizer. Furthermore, it also acts as an optical diode in the following sense: Light impinging with a linear polarization oriented at −45° with respect to the lamellae is transmitted for the geometry discussed above. If we now turn around the device by 180° such that the new incident linear polarization corresponds to +45° with respect to the lamellae on the new front side, the light is not transmitted. Unfortunately, this behavior is *not* equivalent to that of an optical isolator. This would require that light transmitted by the device and back reflected from a mirror behind the device would not propagate back into the laser source.

To validate our discussion, we have fabricated the 1D-3D as well as the 1D-3D-1D structure shown in Fig. 1 by standard two-photon direct-laser-writing into the commercially available thick-film photoresist SU-8.[16–19] The following discussion again focuses on the more complex 1D-3D-1D case, electron micrographs of which are shown in

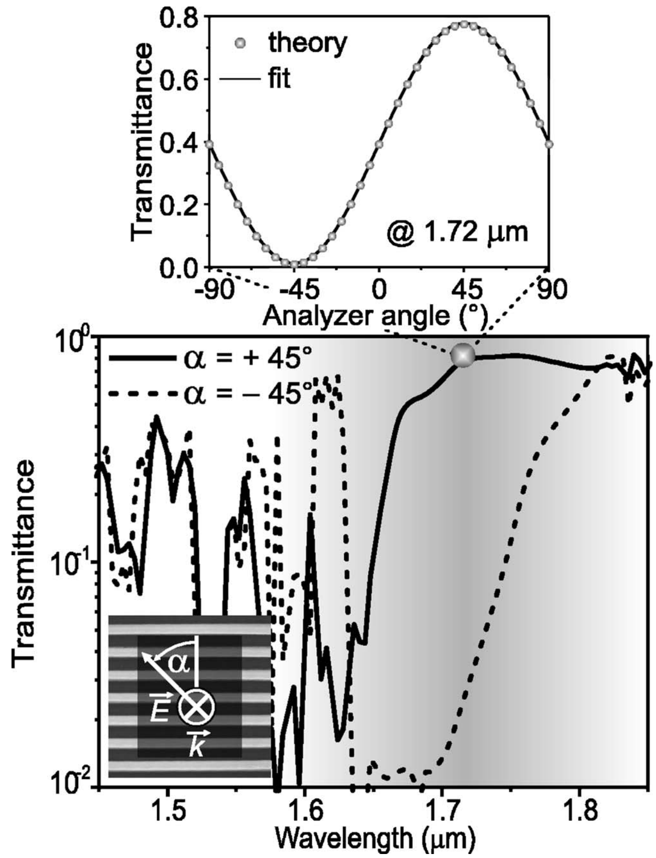

FIG. 2. Calculated normal-incidence transmittance spectra (logarithmic scale) of the 1D-3D-1D heterostructure (Fig. 1). The linear incident polarization is oriented $\alpha=+45°$ (solid) and $\alpha=-45°$ (dashed) with respect to the lamellae, respectively (see inset). Pronounced differences occur in the region of the polarization stop band (gray area). The corresponding transmittance ratio at 1.72 μm wavelength is about 50. The emerging polarization of light at this wavelength is analyzed in the upper part.

Fig. 3. Optical characterization for incident linearly polarized light is shown in Fig. 4. For linear incident polarization oriented at +45° with respect to the lamellae, a transmittance close to 78% is observed at 1.72 μm wavelength, whereas the transmittance is around 1.5% for −45° polarization. Thus,

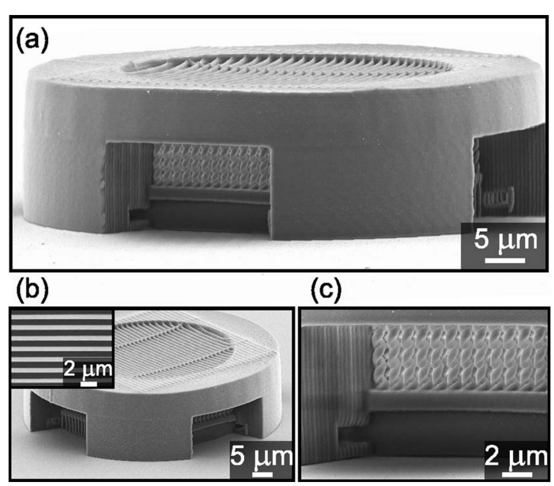

FIG. 3. Electron micrographs of the fabricated heterostructure: (a) glancing-angle incidence view and (b) oblique-view image. The inset shows a normal-incidence close-up view onto the top set of lamellae. (c) close up of (a) revealing parts of the 3D spiral crystal (RH), one of the stabilizing plates, the bottom lamellae, and the surrounding wall with one of the drains (left bottom) allowing for developer circulation.

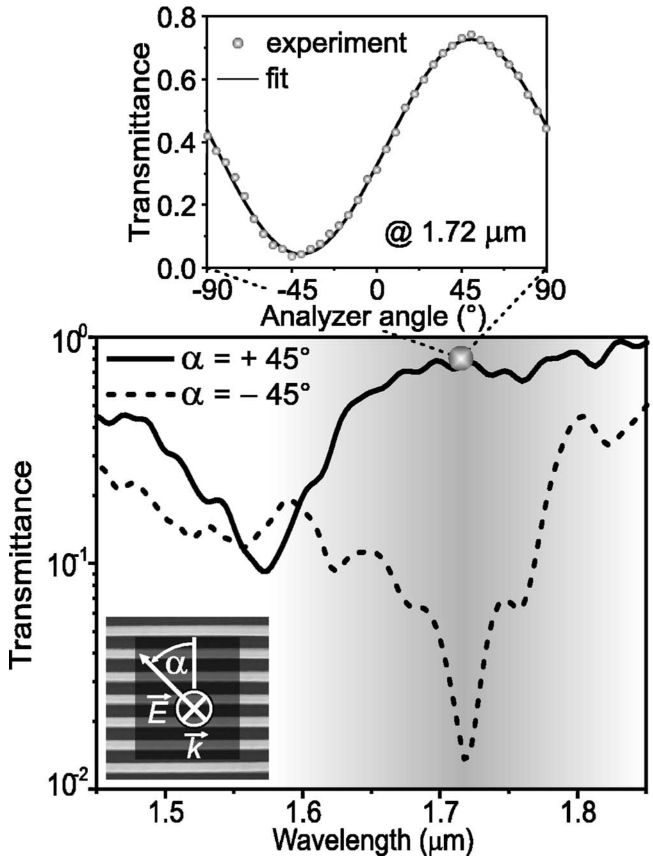

FIG. 4. Measured transmittance spectra. Experimental data obtained from the structure shown in Fig. 3, represented in the same format as in Fig. 2 (theory).

the suppression factor is 52 (17.2 dB). Furthermore, the polarization state of the light emerging from our thin-film optical isolator is very close to linear as determined by rotating a Glan-Thomson polarizer behind the sample (see inset of Fig. 4). The fit (solid) to the data reveals a dependence of the transmittance T according to $T=0.044+0.683\cos^2(\varphi)$, where φ is the analyzer angle. The overall measured behavior (Fig. 4) is in very good agreement with the numerically calculated response (Fig. 2). In particular, the spectral position as well as the depth of the polarization stop bands (gray area in Figs. 2 and 4) agree well. Regarding the deviations with respect to the spectral shape, one should be aware that the experiment introduces a certain angle averaging via the finite opening angle of the incident light (5°). In contrast, the theory refers to strictly normal incidence. We have previously shown that this effect slightly reshapes the spectra.[2] Deviations from perfect linear polarization of the emerging light are likely due to sample imperfections. Nevertheless, we can conclude that the quality of the fabricated structure is very high and that the concept is valid.

In conclusion, we have proposed, fabricated, and characterized photonic heterostructures composed of chiral three-dimensional spiral photonic crystals and one-dimensional sets of lamellae acting as quarter-wave plates. These heterostructures can serve as thin-film polarizers, poor-man's optical isolators, and as optical diodes in the sense defined above.

We thank R. Baets for clarifying discussions regarding optical isolators. We acknowledge support by the Deutsche Forschungsgemeinschaft (DFG) and the State of Baden-Württemberg through the DFG-Center for Functional Nanostructures (CFN) within subproject A1.4. The research of G.v.F. is further supported through a DFG Emmy Noether fellowship (DFG-Fr 1671/4-3). The PhD education of M.T. and M.H. is further supported by the Karlsruhe School of Optics and Photonics (KSOP).

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