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Polarization-independent filters for luminescent solar concentrators

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The efficiency of luminescent solar concentrators could be enhanced by use of wavelength-selective filters, reducing the amount of luminescent light lost. To accomplish this, polarization-independent filters with reflectivity >97% were made by combining layers of cholesteric liquid crystals, either a right- with a left-handed layer, or two right-handed layers with a half-lambda waveplate. Normal cholesteric filters have a reflection bandwidth which is narrower than the spectral and angular range of the luminescent emission. The reflection band is broadened from 80 to 200 nm by employing a pitch gradient in the cholesteric layer. The measured transmission bands compare well with calculations. © *2011 American Institute of Physics*. [doi:10.1063/1.3541543]

Luminescent solar concentrators[1,2] are interesting devices for use in combination with photovoltaic (PV) cells. A luminescent solar concentrator (LSC) is a glass or plastic plate containing or coated with luminescent materials (phosphors or dyes) that absorb sunlight and emit light at longer wavelengths. A large part of the emitted light is trapped by total internal reflection and guided to the LSC edges where it is coupled into small-area, efficient PV cells. Compared to a geometric concentrator, sunlight can be collected over a broader angular range by the LSC. In theory,[3] optical concentration can be a factor of 1000 or higher, but in practice the best LSC-based PV devices to date[4] have an optical concentration of only about 1. The reason for the low efficiency is that there are additional loss processes. One important loss mechanism is the escape of luminescent light with smaller angles than the critical angle for total internal reflection. A second is absorption by the luminescent material without subsequent emission of light due to limited quantum efficiency. A third is reabsorption of the emitted light by the luminescent material: this can be prevented by large shifts between absorption and emission spectra, especially if line emitters are used.[5] The total amount of light escaping the top and bottom surfaces can be very large for an extended lightguide[6] since, after reabsorption, significant fractions of reemitted light will be lost.

An effective way to prevent escape of luminescent light is by applying a wavelength-selective filter on top of the lightguide;[7,8] see Fig. 1. Due to its angular dependence, the wavelength region in which the filter reflects should be relatively broad.[2] There exist several materials that may serve as filters. Two such classes[9] are dielectric stacks and three-dimensional photonic crystals, which, however, behave differently toward the two types of polarized light and reflect in a narrow wavelength range.[10]

In this paper, we use cholesteric liquid crystals (CLCs), which act as Bragg reflectors for circularly polarized light and have the attractive features of self-alignment and that they can be produced over large areas.[7,11] We show that polarization-independent filters can be made either by combining two filters of opposite chirality, or two filters of the same chirality with a half-lambda waveplate. It is possible to make broad-band filters by applying a pitch gradient in the cholesteric stack, exploiting the driving forces of an uv-intensity gradient across the film thickness during fabrication and the different reactivity of a photoreactive (right- or left-handed) chiral monomer and a nematic monomer.[12] We also are able to accurately simulate the reflection spectra of these filters.

We made samples by filling 20 μm cells with mixtures of chiral and nematic monomers, photoinitiator, and uv-absorbing dye, followed by crosslinking with uv light.[8] Our goal was a filter reflecting an emission wavelength around 720 nm wavelength for angles inside the lightguide up to the critical angle of 42° (corresponding to a reflection band between approximately 700 and 900 nm at 0°). To achieve this, the amount of chiral monomer, uv dose, and exposure time were determined such as to fit these requirements.[8] After crosslinking, the solid CLC films were removed from the cells and combined in the manner described below. Angle-dependent transmission measurements were performed in a standard spectrophotometer with glass as incident medium.[8] The spectra were simulated as previously described[8,12] by

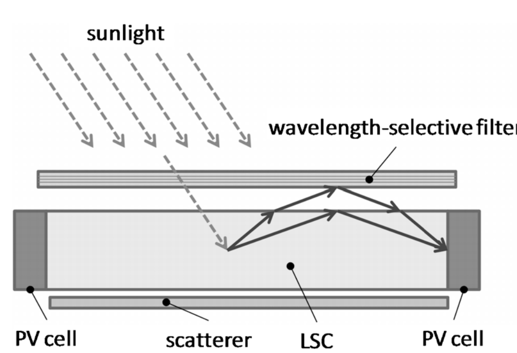

FIG. 1. (Color online) LSC lightguide with wavelength-selective filter (which may be attached to the LSC) and scatterer. PV cells are attached to one or more of the lightguide edges. Sunlight passes through the filter, but the luminescent light is reflected.

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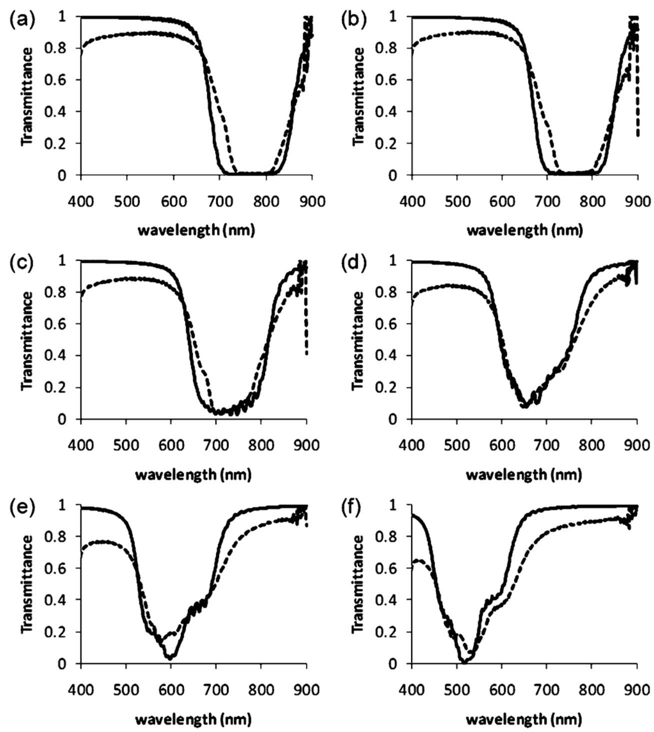

FIG. 2. Transmission spectra for unpolarized light of a right-handed CLC stacked on top of a left-handed CLC. The pitch varies linearly from 437 to 520 nm in the right-handed material and from 429 to 521 nm in the left-handed material. The refractive indices, n_e=1.68 and n_o=1.54, are the same for both materials. Dashed lines indicate the experimental measurements, solid lines indicate calculations. Figures (a) to (f) are for incident angles in glass of 0°, 10°, 20°, 30°, 40°, and 50°, respectively.

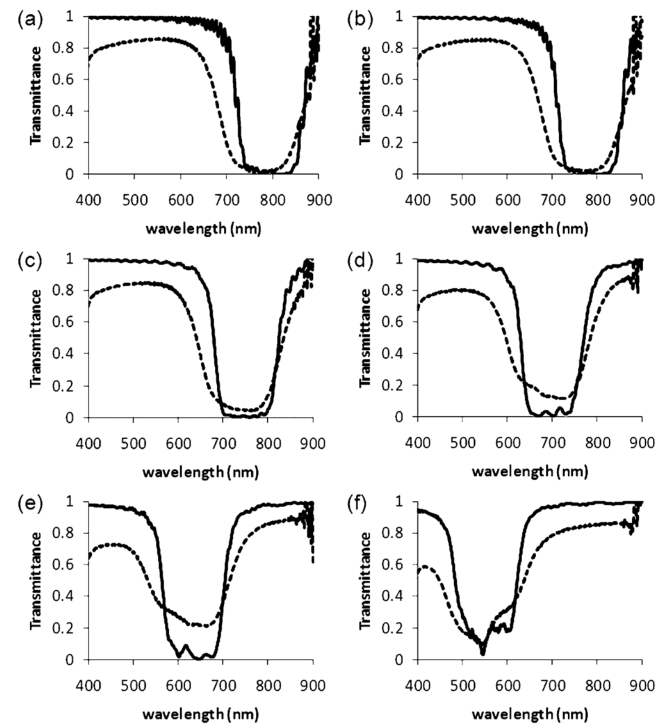

FIG. 3. Transmission spectra for unpolarized light of a configuration with a half-lambda plate sandwiched between two right-handed CLC layers. The pitch varies linearly from 464 to 523 nm in the layers. The refractive indices are n_e=1.68 and n_o=1.54. The half-waveplate has a center wavelength of 825 nm. Dashed lines indicate the experimental measurements, solid lines indicate calculations. Figures (a) to (f) are for incident angles in glass of 0°, 10°, 20°, 30°, 40°, and 50°, respectively.

calculating the propagation of electromagnetic waves in a stack of waveplates.

Figure 2 shows results for a right-handed CLC stacked on top of a left-handed CLC. First, transmission measurements of the individual samples at 0° incidence were made.[8] To fit the calculations to the measurements, the pitches of the materials are chosen such that the left and the right sides of the individual reflection bands superimpose. From this, the spectra for the stack are calculated for all angles, using the known refraction indices n_o and n_e and assuming a linear pitch gradient within each CLC. The transmission for unpolarized light through the double cholesteric stack goes to zero in the region of the reflection band, since the second filter reflects the light that is transmitted by the first. There is a good agreement between experiments and calculations. Outside the reflection band, the measured transmission is lower than calculated, due to scattering at inhomogeneities (not included in the simulations). Furthermore, the reflection band is slightly narrower in the experiment than in the calculation, probably because the transmission measurements are not in the same location as those of the two individual layers.

Another method of obtaining complete reflection of unpolarized light is the usage of a half-lambda waveplate placed between two CLC layers of the same handedness. The half-lambda plate reverses the polarization of light passing through it; left-handed circularly polarized light is turned into right-handed circularly polarized light and vice versa. The configuration used in this experiment is a half-lambda plate sandwiched between two right-handed CLC layers. The results are shown in Fig. 3. Again, the experimental results agree well with those calculated, if the pitches for the calculations are chosen such that the left and the right sides of the reflection band of the individual layers match. The slight mismatch between calculation and experiment can be explained by a small shift between the reflection bands of the two layers.

Both CLC configurations reflect luminescent light of 720 nm for all angles between 0° and 40° and transmit incident light for wavelengths up to 550 nm. A difference between the two configurations is that the right- and left-handed layer stack has a "weak spot" in the 680–780 nm region for incident angles above 30° (visible in Fig. 2), which is not desirable as it would allow the leakage of some luminescent light.

For the final design of a LSC, a challenge for the right- and left-handed configuration is that photoreactive left-handed chiral material is not readily available. The half-wave configuration is also complex, since it consists of three layers and may be more difficult to avoid scattering. However, photoreactive right-handed materials are readily available and the half-lambda plate may be made using the same class of reactive liquid-crystalline materials.[13]

In conclusion, CLCs allow production of polarization-independent filters with characteristics required for use with a LSC. The CLCs demonstrate high reflectivity (>97% at 0°) and close-to-rectangular reflection bands in an optimized range of wavelengths and angles that permit reflection of the luminescent light while transmitting as much as possible of the incident solar spectrum. We demonstrate that we are able to accurately model these systems and can thus predict the reflective nature of complex multilayer CLC systems. In combination with a suitable luminescent material (line emitter with large spectral shift), this provides a route to making an efficient LSC.

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[1]A. Goetzberger and W. Greubel, Appl. Phys. **14**, 123 (1977); W. G. Van Sark, K. W. J. Barnham, L. H. Slooff, A. J. Chatten, A. Büchtemann, A. Meyer, S. J. McCormack, R. Koole, D. J. Farrell, R. Bose, E. E. Bende, A. R. Burgers, T. Budel, J. Quilitz, M. Kennedy, T. Meyer, C. De Mello Donegá, A. Meijerink, and D. Vanmaekelbergh, Opt. Express **16**, 21773 (2008).
[2]D. K. G. de Boer, Proc. SPIE **7725**, 77250Q (2010).
[3]E. Yablonovitch, J. Opt. Soc. Am. **70**, 1362 (1980); U. Rau, F. Einsele, and G. C. C. Glaeser, Appl. Phys. Lett. **87**, 171101 (2005).
[4]L. H. Slooff, E. E. Bende, A. R. Burgers, T. Budel, M. Pravettoni, R. P. Kenny, E. D. Dunlop, and A. Büchtemann, Phys. Status Solidi (RRL) **2**, 257 (2008).
[5]L. R. Wilson, B. C. Rowan, N. Robertson, O. Moudam, A. C. Jones, and B. S. Richards, Appl. Opt. **49**, 1651 (2010); K. Barnham, J. L. Marques, J. Hassard, and P. O'Brien, Appl. Phys. Lett. **76**, 1197 (2000); G. V. Shcherbatyuk, R. H. Inman, C. Wang, R. Winston, and S. Ghosh, *ibid.* **96**, 191901 (2010).
[6]M. G. Debije, P. P. C. Verbunt, B. C. Rowan, B. S. Richards, and T. L. Hoeks, Appl. Opt. **47**, 6763 (2008).
[7]M. G. Debije, M.-P. Van, P. P. C. Verbunt, M. J. Kastelijn, R. H. L. van der Blom, D. J. Broer, and C. W. M. Bastiaansen, Appl. Opt. **49**, 745 (2010).
[8]See supplementary material at http://dx.doi.org/10.1063/1.3541543 for details on experiments and calculations.
[9]M. Peters, J. C. Goldschmidt, P. Löper, B. Bläsi, and A. Gombert, J. Appl. Phys. **105**, 014909 (2009).
[10]H. A. Macleod, *Thin-Film Optical Filters*, 3rd ed. (Institute of Physics, Bristol, 2001).
[11]N. P. M. Huck, I. Staupe, A. Thirouard, and D. K. G. de Boer, Jpn. J. Appl. Phys., Part 1 **42**, 5189 (2003).
[12]D. J. Broer, G. N. Mol, J. A. M. M. van Haaren, and J. Lub, Adv. Mater. **11**, 573 (1999).
[13]J. Lub, D. J. Broer, R. T. Wegh, E. Peeters, and B. M. I. van der Zande, Mol. Cryst. Liq. Cryst. **429**, 77 (2005).