Polarization-Independent Optical Broadband Angular Selectivity

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Supporting Information

ABSTRACT: Generalizing broadband angular selectivity to both polarizations has been a scientific challenge for a long time. Previous demonstrations of the broadband angular selectivity work only for one polarization. In this paper, we propose a method that can achieve polarization-independent optical broadband angular selectivity. Our design is based on a material system consisting of alternating one-dimensionally anisotropic photonic crystal (1D PhC) stacks and half-wave plates. 1D PhC stacks have an angular photonic band gap for p-polarized light and half-wave plates can convert s-polarized light to p-polarized light. By introducing alternating 1D PhC stacks and half-wave plates, we predict that one can achieve a central transmission angle at normal incidence and an angularly selective range of less than 30° across the whole visible spectrum.

KEYWORDS: angular selectivity, polarization-independent, photonic crystals, birefringence

The frequency, the polarization, and the propagation direction are three fundamental properties of a monochromatic plane wave (apart from its phase and amplitude). The ability to select light based on these three separate properties is of paramount importance for tailoring the flow of light. Among these three, selecting light according to the propagation direction, which is known as angular selectivity, has long been a scientific challenge and could be a significant benefit for a number of applications, including high-efficiency solar energy conversion,1−3 privacy protection,4,5 and detectors with enhanced signal-to-noise ratios.6 Methods based on metamaterials7,8 and photonic crystals9,10 have been explored for angular selectivity; however, they can only offer narrowband angular selectivity because of the inherent resonant properties. Ideally, an angularly selective system should work over a broadband spectrum.

Several strategies to achieve broadband angular selectivity have also been investigated. (i) For example, the microlouvre approach was proposed by 3M, Inc.,4 while parabolic directors were investigated by Atwater and co-workers.11 The components of the microlouvre or the parabolic directors are much bigger than the wavelength of the visible light, so laws of geometrical optics still hold. Besides, successful experimental demonstrations of the parabolic directors have so far been limited to a small scale due to the difficulties in high-resolution fabrication. (ii) A variety of methods that work for only one of the polarizations have also been investigated. These include methods based on a combination of polarizers and birefringent films,12 anisotropic metamaterials,13 Brewster modes in metamaterials,14 and metallic gratings.15 The fact that these work only for one polarization (Figure 1a,b) greatly limits some of their applications such as high-efficiency solar energy harvesting and car window shields. For solar energy conversion, a recent theoretical work from Atwater’s group has predicted that by limiting the light emission angle, it is possible to significantly increase absolute efficiency for GaAs solar cells with ideal back reflector.7 Compared with the existing angular selectivity technologies working for only one polarization, the polarization-insensitive technology performs better in solar energy conversion because sunlight is randomly polarized. Another promising application is for car window shields; strong direct sunlight can be dangerous for drivers since it can potentially cause traffic accidents. Angular selectivity film on the car window shield can keep drivers’ viewing angle transparent as usual (transparent at viewing angles), but block the direct sunlight (reflective at other angles). In this case, the angular selectivity technology has to be polarization-insensitive because of randomly polarized sunlight.

In 2014, Shen et al. proposed that one can utilize the Brewster angle of two isotropic dielectric media to achieve single-polarization broadband angular selectivity.16 They also proposed that angular selectivity could be achieved for both polarizations using materials with permeability μ ≠ 1. However, it is very difficult to achieve this in the visible

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range because most materials have permeability $\mu \approx 1$. Moreover, even if one cares only about a single polarization, the Brewster angle of two dielectric media is always larger than $45^\circ$ (in the lower index material). In many applications, such as privacy protection screens, having a central transmission angle at normal incidence and a selective angle smaller than $30^\circ$ (viewing angle from $-30^\circ$ to $30^\circ$) are highly desirable. There has yet to emerge a solution to realize a polarization-independent broadband angularly selective system without the limitations of geometrical optics and with a central transmission angle at normal incidence and an angularly selective range of less than $30^\circ$.

In this paper, we introduce a method that in principle achieve polarization-independent optical broadband angular selectivity (Figure 1c,d). Our design rests on (i) the existence of an angular photonic band gap for p-polarized light within 1D PhC stacks consisting of alternating isotropic and anisotropic layers,13 (ii) the fact that a half-wave plate (HWP) can convert s-polarized light to p-polarized light over a limited wavelength range,17,18 and (iii) the fact that alternating 1D PhC stacks and half-wave plates of different thicknesses can be used to broaden the working wavelength range. We predict this angularly selective material system could work over the entire visible spectrum for both polarizations using realistic material parameters; it has a central transmission angle that is normal incidence; it could be transparent for all colors at incident angles less than $30^\circ$ and highly reflecting for larger viewing angles.

**MATERIALS AND METHODS**

We begin with a one-dimensional photonic crystal (1D PhC) consisting of anisotropic layers (A) with permittivity $\varepsilon_A = (\varepsilon_{xx}, \varepsilon_{yy}, \varepsilon_{zz}) = (2.56, 2.56, 2.25)$ and isotropic layers (B) with permittivity $\varepsilon_B = 2.56$. As mentioned above, the selective angle of 1D PhC consisting of only isotropic materials is limited by the Brewster angle and is always larger than $45^\circ$. However, we

![Figure 1](image1)

**Figure 1.** Illustration of angular selectivity on the basis of its polarization. Angular selectivity for single polarization means that (a) p-polarized light is transmitted in one direction and is reflected in all other directions while (b) s-polarized light experiences no angular selectivity. Angular selectivity for both polarizations indicate that both (c) p-polarized and (d) s-polarized light experience angular selectivity over the incident light. So far, achieving angular selectivity for both polarizations has remained elusive.

![Figure 2](image2)

**Figure 2.** (a) Schematic of a one-dimensional photonic crystal (1D PhC) consisting of 80 stacks, each stack consisting of 100 isotropic−anisotropic bilayers. A is an anisotropic material with permittivity $\varepsilon_A = (2.56, 2.56, 2.25)$; B is an isotropic medium with permittivity $\varepsilon_B = 2.56$. (b) p-Polarized and (c) s-polarized transmission spectrum for 1D PhC consisting of 80 stacks, each stack consisting of 100 isotropic−anisotropic bilayers. 1D PhC stacks provide broadband angular selectivity only for p-polarized light, not for s-polarized light. (d) Schematic of our design that can provide polarization-independent broadband angular selectivity. The material system consists of alternating 1D PhC stacks and half-wave plates. The half-wave plate that can convert s-polarized light to p-polarized light is a birefringent film with permittivity $\varepsilon = (2.25, 2.56, 2.25)$. The birefringent axis which is in the direction of $\varepsilon_{xx} = 2.25$ is marked by the purple arrow.
can achieve normal angle transparency using the 1D PhC consisting of anisotropic and isotropic layers. To understand how this material system can achieve normal angle transparency, we look at the analytical expressions for the effective refractive index \( n_A \) of the anisotropic layer (A) for both s-polarized and p-polarized light as follows: \(^{13}\)

\[
n_A^s = \frac{1}{\sqrt{\frac{\cos^2 \theta_s}{\varepsilon_{xx}^A} + \frac{\sin^2 \theta_s}{\varepsilon_{yy}^A}}} \tag{1}
\]

\[
n_A^p = \frac{1}{\sqrt{\frac{\cos^2 \theta_p}{\varepsilon_{xx}^A} + \frac{\sin^2 \theta_p}{\varepsilon_{yy}^A}}} \tag{2}
\]

where \( \theta_s \) and \( \theta_p \) are the refraction angles for s-polarized and p-polarized light in layer A, as described by Snell’s law:

\[
n_A^s \sin \theta_s^A = n_{air} \sin \theta_{inc}
\]

\[
n_A^p \sin \theta_p^A = n_{air} \sin \theta_{inc}
\]

From eqs 1 and 2, considering \( \mu = 1 \) for most real materials, we can see that s-polarized light is only affected by \( \varepsilon_{xx}^A \) while p-polarized light is affected by \( \varepsilon_{xx}^A \) and \( \varepsilon_{yy}^A \). In particular, p-polarized light is affected by \( \varepsilon_{xx}^A \) when incident angle is away from the normal, while s-polarized light is not. At normal incidence, both s-polarized light and p-polarized light are not affected by \( \varepsilon_{xx}^A \) and “sees” the same refractive index of material A and B (\( \varepsilon_{xx}^B = 3.5 \) and \( \varepsilon_{yy}^B = 3.5 \)), so both s-polarized and p-polarized light are transmitted. At nonzero angles, incident s-polarized light still “sees” the same refractive indexes for material A and B because s-polarized light is not affected by \( \varepsilon_{xx}^A \). However, p-polarized light incident at nonzero angle “sees” different refractive indexes for materials A and B because p-polarized light is affected by \( \varepsilon_{xx}^A \), as shown in eq 2. We know that if a 1D photonic crystal has two materials A and B with different refractive indexes, there can be a photonic bandgap.\(^ {19}\)

Therefore, a stack of 1D PhCs opens an angular band gap only for p-polarized light; p-polarized light experiences total transmission at normal incidence while experiencing total reflections at large oblique incident angles. Note the permittivity \( \varepsilon_s = 2.56, 2.56, 2.25 \) is chosen because this material can be easily achieved using widely used polymers\(^ {20,21}\) and mature mechanical methods in industry.\(^ {22-25}\) Higher anisotropy in permittivity \( \varepsilon \) would result in higher index contrast and wider frequency gaps for incidence angles not close to the normal. To cover the entire visible spectrum, 1D PhC layers with various periodicities could be stacked together to enlarge the band gap (see Figure 2a). We consider a multilayer structure consisting of 80 such stacks, each stack consisting of 100 isotropic–anisotropic bilayers. In our material system, 80 stacks is the minimum number of stacks we need to cover the entire visible spectrum. The period of the ith stack (i = 1, 2, ..., 80) should be 1.01(\( i - 1 \))\( \mu m \), where \( a_i \) is the period of the first stack facing the incident light (\( a_1 = 130 \) nm). A total of 100 isotropic–anisotropic bilayers are required for an angularly selective range of less than 30°. A narrower angular range can be achieved by increasing the number of bilayers. The simulation results indicate that such 1D PhC stacks provide angular selectivity for p-polarized light and are nearly transparent for s-polarized light over the entire visible spectrum (Figure 2b,c). The simulation is based on the rigorous coupled wave analysis (RCWA).\(^ {26}\)

Several methods have been studied to achieve polarization-insensitive spatial light modulation, such as half-wave plate,\(^ {27}\) nematic liquid-crystal (LC) combined with mirror,\(^ {28}\) blue-phase liquid crystal over silicon device,\(^ {29}\) and two orthogonal LC layers are separated by two ultrathin anisotropic polymer films.\(^ {30}\) These ideas can be borrowed and help to achieve polarization-insensitive angular selectivity. In this manuscript, we choose half-wave plate because it is easy to integrate into multilayer film system. Based on the discussions above, we propose a material system to achieve polarization-independent angular selectivity (Figure 2d). The material system consists of alternating 1D PhC stacks and half-wave plates. The half-wave plate is a birefringent film with permittivity \( \varepsilon = (2.56, 2.25, 2.56) \). The permittivity is chosen according to the available polymers in industry.\(^ {20,21}\) All 1D PhC stacks in Figure 2d are the same with 80 stacks, each stack consisting of 100 bilayers. p-polarized light is reflected by 1D PhC at large incident angle and is transmitted at small incident angle, and therefore angular selectivity is realized. s-Polarized light is totally transmitted in the 1D PhC and is subsequently transferred into p-polarized light after passing through a half-wave plate. The “new” p-polarized light will then be reflected by the following 1D PhC, so both s-polarized and p-polarized light experience angular selectivity. (Note that, as it travels backward through the half-wave plate, it gets transformed back into s-polarization and can, hence, exit the structure freely.) However, each half-wave plate can work only for a limited wavelength range. By cascading half-wave plates of different thicknesses, broadband angular selectivity can be realized. A large range of polymers can be selected as the materials of 1D PhCs and half-wave plate, such as polyethylene terephthalate (PET), polycarbonate (PC), polystyrene (PS), and polyurethane (PU). All polymers above are optical grade polymers and exhibit glass-like transparency with negligible losses. They have similar refractive indexes to what we use in our simulations. Anisotropic refractive indexes of these polymers can be achieved based on mature mechanical methods such as compression,\(^ {32}\) shear stress,\(^ {33}\) uniaxial/biaxial orientation,\(^ {24}\) and electric field.\(^ {25}\)
the s-polarized light still maintains its polarization after passing through the half-wavelength plate, which decreases the efficiency of the angular selectivity of s-polarized light. To achieve better performance of broadband angular selectivity, we cascade half-wave plates with different thicknesses. The ratio of p-polarized light for half-wave plates with different thicknesses is calculated (Figure 3a). The central wavelength of the half-wave plate increases as the thickness is increased. The central wavelengths of half-wave plates with thicknesses ranging from 1.925 to 3.575 μm cover the entire visible spectrum. In addition, it turns out that the ratio of p-polarized light is not very sensitive to the incident angle (Figure 3b). When the incident angle increases, the central wavelength and the efficiency remain almost constant. The ripples of the ratio of p-polarized light result from the effect of Fabry–Pérot cavity caused by the half-wave plate itself.

To show the performance of angular selectivity in the visible spectrum, we explore three composite structures with different numbers (1, 5, and 13) of half-wave plates. Each of the composite-structures consists of the structures shown in Figure 2d. The incident plane i is at the angle of 45° with respect to the birefringent axis (Figure 4a). All three structures show a good performance of angular selectivity for p-polarized light because 1D PhC stacks themselves provide angular selectivity for only p-polarized light (Figure 4b,d,f). The first structure contains a single half-wave plate whose thickness is 2.75 μm. Such structure shows low transmission at the central wavelength around 550 nm, because s-polarized light transforms into p-polarized light after passing through the half-wave plate and is reflected by the following 1D PhC (Figure 4c). However, when the wavelength is shifted substantially away from the central wavelength, the transmission increases because a part of s-polarized light still maintains its polarization after passing through the half-wave plate and is hence transmitted through the entire structure.

Compared to only a single half-wave plate, the structure with five half-wave plates presents better performance for s-polarized light (Figure 4e). Thicknesses of the five layers are chosen at regular intervals away from \( L = 2.75 \) μm: 2.063 μm (0.75 \( L \)), 2.406 μm (0.875 \( L \)), 2.75 μm (\( L \)), 3.094 μm (1.125 \( L \)), and 3.438 μm (1.25 \( L \)). The central wavelengths of five half-wave plates with thicknesses chosen in such manner are at regular intervals and cover nearly the entire visible spectrum. Thus, s-polarized light can be transformed into p-polarized light in the entire visible spectrum and be reflected by the 1D PhC to remove most of the transmission modes. Even more half-wave plates can be added to get better performance (Figure 4g). Thicknesses of the 13 layers increase from 1.925...

Figure 4. (a) Schematic of our design that can provide polarization-independent broadband angular selectivity. The transmission spectrum is calculated when the incident plane is at the angle of 45° with respect to the birefringent axis. (b) p-Polarized and (c) s-polarized transmission spectrum for a structure containing one-half-wave plate. (d) p-Polarized and (e) s-polarized transmission spectrum for a structure containing five layers of half-wave plates. (f) p-Polarized and (g) s-polarized transmission spectrum for a structure containing 13 layers of half-wave plates.
to 3.575 μm with a 137.5 nm step, so the thicknesses equal 0.7L, 0.875L, 2.75L, 1.125L, and 1.25L (L = 2.75 μm). (b) In each group, the birefringent axis of the half-wave plate with the same thickness rotates at regular intervals: 0°, 22.5°, 45°, and 67.5°. (c) s-Polarized transmission spectrum for a structure containing 20 layers of half-wave plates at different incident planes.

Figure 5. (a) Schematic of our design that can provide polarization-independent broadband angular selectivity for all incident planes. The material system consists of alternating 1D PhC stacks and half-wave plates. The total 20 layers of the half-wave plates are divided into five groups whose thicknesses are chosen as 0.75L, 0.875L, 2.75L, 1.125L, and 1.25L (L = 2.75 μm). (b) In each group, the birefringent axis of the half-wave plate with the same thickness rotates at regular intervals: 0°, 22.5°, 45°, and 67.5°. (c) s-Polarized transmission spectrum for a structure containing 20 layers of half-wave plates at different incident planes.
layers of the half-wave plates that are divided to five groups. The thicknesses of five groups are chosen as 2.063 μm (0.75L), 2.406 μm (0.875L), 2.75 μm (L), 3.094 μm (1.125L), and 3.438 μm (1.25L), respectively. Each group consists of four layers of half-wave plates with the same thickness. The birefringent axis of each half-wave plate rotates 22.5° with respect to the top one, as shown in Figure 5b. The rotating half-wave plates enlarge the angular range of incident planes at which s-polarized light can be converted to p-polarized light. After we test different layers of rotating half-wave plates, four layers is the least number of half-wave plates that can achieve for incident planes ranging from 0° to 80° with the step of 10°.

In conclusion, we present a method that can achieve polarization-independent optical broadband angular selectivity. The key idea in our design is to use a material system consisting of alternating 1D anisotropic PhC stacks and half-wave plates. We achieve an angularly selective range of less than 30° for both polarizations over the entire visible spectrum. All the materials in our simulation are selected according to the typically used polymers and mature mechanical manufacturing methods in the industry. The material system with loss is also discussed in the Supporting Information. Even assuming a realistic material loss, the transmission can still be higher than 80% by optimizing the number of stacks and the periods of bilayers. Such material systems could be used in many applications such as high-efficiency solar energy conversion, privacy protection, and detectors with enhanced signal-to-noise ratios.

ASSOCIATED CONTENT

Supporting Information
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Additional details and supporting figures (PDF).

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