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Polarization-independent asymmetric light transmission in all-dielectric photonic structures

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ABSTRACT

We design, optimize and fabricate an all-dielectric photonic structure, having a significant, polarization-independent asymmetry in light transmission for opposite incident wave directions. The device, consisting of a dielectric Bragg mirror topped with a regular grid of micrometer-sized pillars, acting as a diffraction grating, is potentially scalable into industrial production. The light propagation simulation results are confirmed by direct measurement of the difference in light transmission, reaching 0.55 near 780 nm, and exceeding 0.2 over a spectral range spanning from 750 to 820 nm.

1. Introduction

One of the holy grails of experimental photonics is to create a unidirectional light transmission structure which exhibits a significant difference in transmission for light propagating with opposite wave vectors. While the only practical realization of this concept, commonly used in laboratories, is a device based on Faraday effect in rare earth metal doped crystals, many other ideas have been tested too. These can be categorized into structures containing sub-wavelength metal components in the form of non-symmetric features [1–5], metallic diffraction gratings [6–10] or holes [11–14]. Additionally, a class of devices based on symmetry breaking photonics crystals has been presented [12,15–18]. These includes fibers [19] and state of the art devices containing silicon on-chip optical diode [20,21], as well as a complex structure, combining layers of different indices of refraction with a series of diffraction gratings with varying filling fractions, where a narrow region of asymmetric transmission was predicted in the UV region [22].

The common drawback of most unidirectional transmission devices is their polarization-dependent performance usually a significant asymmetry in transmission is achieved for one linear (or circular) polarization only. In our approach described herewith we overcome this disadvantage in a few micron thick, all-dielectric structure that exhibits polarization-independent asymmetry in transmission of near-infrared light (peaked at 780 nm).

2. The structure design

Working principle of our structure is based on the concept presented in Ref. [23], but with higher symmetry guaranteeing polarization-independent transmission, unlike in the previous demonstrations that had different transmission asymmetry for different input polarizations. The device consists of a dielectric stack (S) with wavelength and angle of incidence dependent reflectance, topped with a rectangular grid of uniformly and equally spaced pillars (P), acting as a diffraction element (see Fig. 1).

The dielectric stack is a Bragg mirror, designed to have high transmittance at 780 nm and high reflectance for longer wavelengths (850–1050 nm) (see Fig. 2 (a)). This choice of transmission characteristics was associated with the operating wavelength of our 3D photolithography setup, used in the next step of the device fabrication process - the dielectric stack has to be transparent at 780 nm, to avoid unwanted reflections of the lithographic laser beam. Additionally, the resolution limitations of the technology (features down to 400 nm in lateral size can be fabricated) restricted the asymmetric transmission wavelength range to the near infrared band of the spectrum.

Materials used in the fabrication process were SiO_2 and Nb_2O_5 for the dielectric stack low and high refractive index layers

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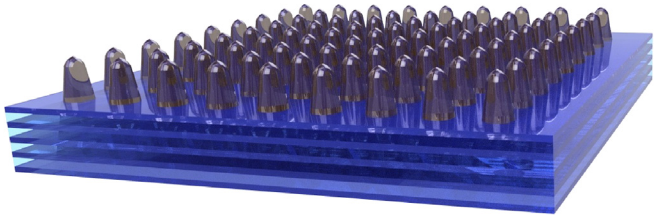

Fig. 1. Schematic model of the all-dielectric structure (drawn to scale), consisting of a Bragg mirror topped with a square grid of the 3D-printed pillars. The glass substrate is not shown and the rendered colors were chosen for clarity: light blue - silica (SiO_2), dark blue - niobia (Nb_2O_5), purple - acrylic resin (IP-L). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

respectively, and a commercial polymer UV curable resin (IP-L) for the pillars. Their optical properties and the structure dimensions are described in detail in section 3.

When light at 780 nm is incident on the structure at zero angle of incidence from the stack side ($S \Rightarrow P$), a high fraction is transmitted through the Bragg mirror and even though it is diffracted afterwards by the pillar grating, the total (angle integrated) transmission is high. On the other hand, light incident from the pillars side ($P \Rightarrow S$) is first diffracted and then its substantial part propagates through the stack at an angle for which the transmission drops significantly this results in low transmittance. To reach the highest asymmetry possible, the structure parameters need to be adjusted to diffract a large fraction of light. At the same time a high absolute transmission and broadband asymmetry region is needed and optimizing these two simultaneously poses a significant challenge.

FDTD simulations of electromagnetic field propagation in our structure were performed, using an open access MEEP environment, ver. 1.2.1 [24]. A 3D simulation box with the resolution of 50 px/micron was used, which corresponds to approximately 16 pixels per the shortest wavelength in the highest refractive index material ($n = 2.176$). We have checked that increasing the resolution by up to a factor of 2 did not considerably change our simulation results. We have also verified that the simulation time was long enough for the results to converge. Periodic boundary conditions were used in the directions perpendicular to the incident beam and PML absorbing layers at the top and bottom. The structure was illuminated with short plane wave pulses, corresponding to vacuum wavelengths between 0.67 μm and 1.43 μm. The pillar geometry was adjusted to follow the ellipsoidal shape of the photolithographic voxel, as measured for our fabrication setup. Specifically, an ellipsoid of revolution can be inscribed in the curvature of the pillar edge, as seen in the cross-section through the center of the pillar in Fig. 3 (a), with the axes $r_x = 200\ nm$ and $r_y = 500\ nm$, corresponding to the size of the lithographic voxel. The refractive index of the pillar dielectric material was set to $n = 1.48$. In separate simulations we have verified that the glass substrate did not considerably alter the simulation results other than adding Fabry-Perot fringes (which would not be measurable in the experiment due to relatively broad spectrum of our laser), so it can be neglected in simulations.

For the initial grating parameters: height $h = 960$ nm, diameter $D = 571$ nm and the spacing between consecutive pillars $x = 951$ nm, Fig. 3 (b) shows calculated, angle-integrated light transmission in two opposite directions: from the pillars side ($P \Rightarrow S$) and from the stack side ($S \Rightarrow P$), as well as their difference - the asymmetry in transmission - peaked at 786 nm and exceeding 0.6. To maximize the result, we have explored the pillar geometry parameter space (height and diameter), looking for the maximum values of the asymmetry at 780 nm - see Fig. 3 (c). This map also gives an estimate of the structure high tolerance to fabrication errors - an important parameter for potential applications, e.g. the deviation in the pillar height of up to 20% ($1.0 \pm 0.2\ \ \mu m$) does not decrease the transmission difference significantly. Further, we varied the distance between pillars, creating similar maps and plotting the maximum asymmetry value for each pillar spacing (Fig. 3 (d)). An optimum value of the grating pitch (x) of $1.07 \pm 0.05\ \ \mu m$ was thus found.

3. Fabrication and characterization

The dielectric Bragg mirror had nine quarter wave layers, alternating Nb_2O_5 (5 layers, n(840 nm) = 2.176, thickness = 109.3 nm) and SiO_2 (4 layers, n(840 nm) = 1.438, thickness = 165.3 nm) (Laseroptik GmbH), manufactured with the electron beam evaporation (Balzers BAK box coater). Niobia

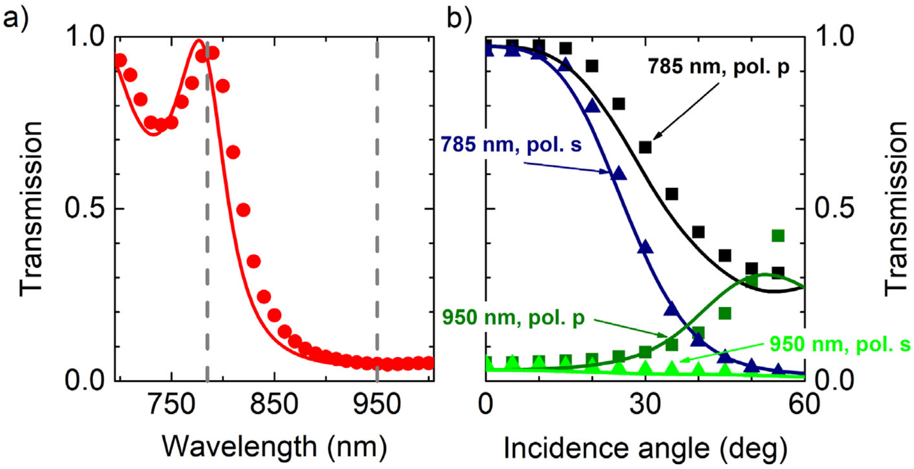

Fig. 2. Measured (points) and calculated (lines) transmission profiles of the dielectric stack. (a) High transmission of the Bragg mirror was designed and measured at around 785 nm, while the photonic bandgap spans the range between 850 and 1000 nm, both for normal light incidence. High and low transmittance wavelengths of 785 and 950 nm respectively (dashed vertical lines) were chosen to demonstrate angle-dependent characteristics of the mirror, which are the key to the structure working principle (see details in text). (b) Measured (symbols) and calculated (lines) mirror angle-dependent transmission proles show decreasing transmittance at 785 nm for two polarizations: p (black) and s (blue) with increasing angle of incidence. On the contrary, transmittance rises (or remains nearly constant) at 950 nm, again for both polarizations (p - olive, s - green). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)