The Application of the Sawtooth Photonic Crystal on Producing Polarized Light

Ting-Hang Pei, Wei-Chou Chen, and Kei-Hsiung Yang

***Abstract*—We have proposed a sawtooth photonic crystal formed by Si–SiO_2 periodic layers designed on a planar medium as a polarizer. The polarizer can produce H-polarized light very efficiently because the frequency of E-polarized light is chosen at the photonic band gap but that of H-polarized light at the photonic conduction band. The best polarization ratio is as high as $2.56 \times 10^5 : 1$ when the normalized frequency a/λ is 0.24 and the incident angle is about 13°. Highly polarized light can be produced in a normalized frequency range from 0.23 to 0.25, and this can possibly be applied to an LED with a certain bandwidth.**

***Index Terms*—Polarization, sawtooth photonic crystal.**

I. Introduction

LIGHT sources emitting polarized light have many important applications such as daylight lamps and backlights for liquid crystal display (LCD) panels. A simple and traditional method to produce polarized light is by reflecting it from a dielectric medium with an input angle satisfying the condition of Brewster's angle. One example is a Brewster-angle laser oscillator producing a polarized laser beam. It is well known that, in LCD industry, absorption-type polarizers have been heavily used to sandwich a LCD panel to obtain high display qualities.

Recently, it was shown that a polarization-enhancing reflector combined with a GaInN light-emitting diode (LED) can provide a polarization ratio as high as 3.5:1 measured in the far field [1]. Other LEDs producing polarized light have been revealed by some publications [2], [3]. Surface emitted polarized light from GaN blue LEDs with a maximum polarization ratio of 5.5 can be reached by using a specially designed photonic crystal (PhC) structure [3]. However, after packaging LEDs with resins, the polarization characteristics would be decreased because of the refraction between resin and air. The conventional packaged LED without any special structure on its surface or at the active layer cannot emit polarized light if the light source is unpolarized. Besides, the polarization ratio has to be higher than 100:1 in LCD industry applications. In order to save electric energy and reach cost down, highly polarized and efficient light source is needed. Energy saving has become the main trend in LCD industry. A more efficient way to produce highly polarized light is directly adding special structure on the surface of the packaged LED or above it. One possibility is using periodic structures such as PhCs to realize the polarization. A well-designed polarization splitter using PhC slab mirror has been shown by Shanhui Fan *et al.* [4]. Another structure such as the sawtooth was fabricated by autocloning in 1999 [5]. Recently, other successful fabrication technologies have also been reported [6], [7]. After preparing the substrate with specific profile, the sawtooth PhC can be fabricated on the substrate using the chemical vapor deposition method. Fabrication of the sawtooth PhC is a well-developed technique nowadays.

In this letter, we demonstrate a properly designed sawtooth PhC composed of Si/SiO_2 alternative layers designed on a planar medium to generate polarized light with very high polarization ratio. Although Si can absorb light in the visible region, however, our design is thin enough so that the total absorption is not very high. A discussion is given in Section III.

Manuscript received December 09, 2010; revised June 06, 2011; accepted June 24, 2011. Date of publication July 12, 2011; date of current version August 31, 2011.

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Digital Object Identifier 10.1109/LPT.2011.2161461

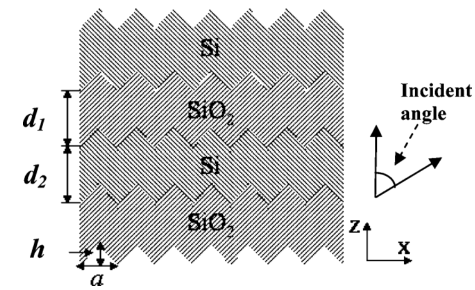

Fig. 1. Cross-sectional view of the sawtooth PhC structure formed by Si–SiO_2 periodic layers.

II. Simulated System

The cross-sectional view of the sawtooth PhC is shown in Fig. 1, where Si and SiO_2 layers are alternatively accumulated along the z-direction. The lattice constant a is the periodic distance along the x-direction. d_1 and d_2 are the thicknesses of the SiO_2 and Si layers, respectively. The height of each sawtooth in the z-direction is h. For convenience, d_1, d_2, and h are shown in terms of a. Each structure with parameters d_1, d_2, and h has a special photonic band structure (PBS). The normalized frequency is expressed as a/λ in the PBS, where λ is the propagating wavelength. Once λ and the normalized frequency are chosen, the corresponding lattice constant a and structural parameters d_1, d_2, and h can be determined simultaneously.

III. Simulation Results

Next, we consider the yellow light with wavelength 589.0 nm, where the refractive indices n_{Si} and n_{SiO2} for Si and SiO_2 are 4.01 [8] and 1.50 [9], respectively. The LED with GaAsP active

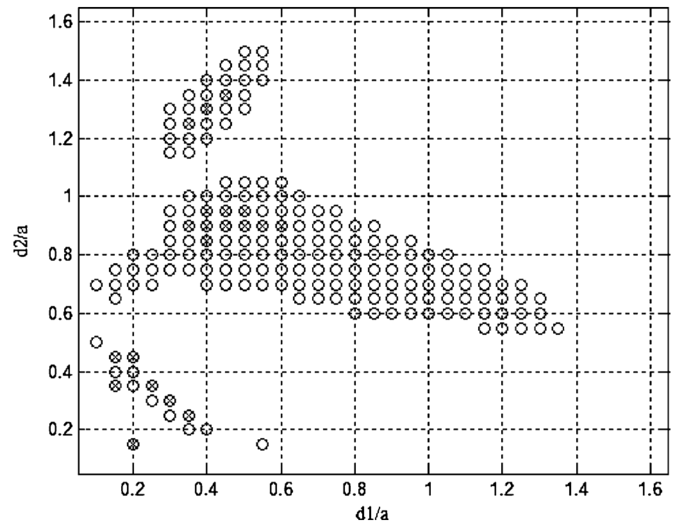

Fig. 2. PBG collection of the E-polarized mode with various d_1 and d_2. The symbol O shows the width of the PBG larger than 0.02 (a/λ) and ❃ larger than 0.045 (a/λ).

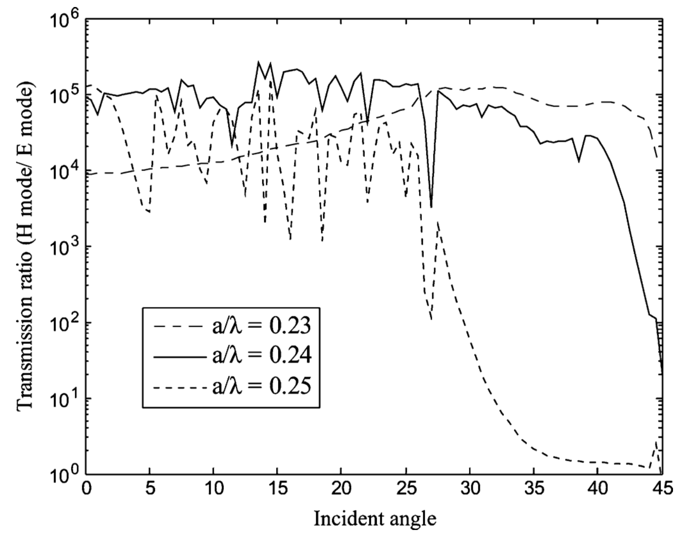

Fig. 4. Transmission ratios of the E-polarized to the H-polarized modes varied with incident angles.

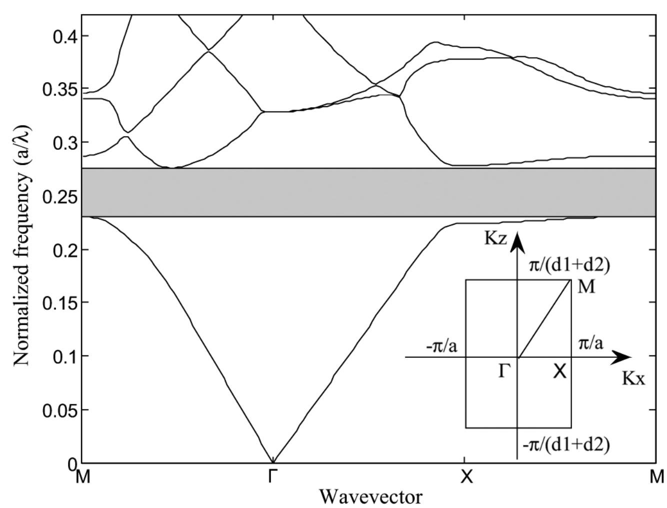

Fig. 3. PBS of the sawtooth PhC for the E-polarized mode when $d_1 = 0.6a$, $d_2 = 0.9a$, and $h = 0.45a$. A PBG (gray region) exists between 0.23 and 0.28. The reduced first Brillouin zone is shown at the bottom-right corner.

layer can emit this wavelength. PBSs of the E-polarized mode (E-field perpendicular to the $x - z$ plane) are calculated for different parameters d_1, d_2, and h by using the plane-wave expansion method. The region of the reduced first Brillouin zone is shown at the bottom-right corner of Fig. 3. A total of 961 plane waves are used to calculate PBSs. The numerical error is less than 1%. The widths of PBGs lager than 0.02 (a/λ) are recorded in Fig. 2 where h is fixed at $0.45a$, and d_1 and d_2 are both between $0.1a$ and $1.6a$ with the interval of $0.05a$. From the calculations, a main distribution exists when d_1 is in between 0.10a and 1.35a and d_2 is in between $0.55a$ and $1.05a$. The other small distributions exist when d_1 is in between 0.10a and 0.40a and d_2 is in between $0.15a$ and $0.50a$, and d_1 is in between 0.30a and 0.55a and d_2 is in between $1.15a$ and $1.50a$, respectively. The symbol ❃ denotes the case when the width of the PBG is larger than 0.045 (a/λ). The larger PBG has an advantage of larger tolerance on the fabrication error. Therefore, a larger PBG is a better choice than a smaller one.

According to the collection of data in Fig. 2, one set of parameters d_1, d_2, and h for demonstrating transmitted polarized light from the sawtooth PhC are $0.6a$, $0.9a$, and $0.45a$, respectively. The corresponding PBS of the E-polarized mode is shown in Fig. 3. A PBG denoted by the gray region exists above the first photonic band within the normalized frequency range from 0.23 to 0.28. The PBS of the H-polarized mode (H-field parallel to the $x - z$ plane) shows no PBG within this frequency region. It means that, if the propagating frequency is chosen within this frequency region, only the H-polarized mode can pass through the sawtooth PhC.

By varying incident angles, transmissions of the E-polarized and H-polarized modes are calculated by using the 2-D finite-difference time-domain (FDTD) method [10], where d_1, d_2, and h are $0.6a$, $0.9a$, and $0.45a$, respectively. The incident angle defined between the transmission and incident directions is shown in Fig. 1. The transmission direction is along the z-axis. A Gaussian wave is excited in the planar medium with a refractive index of 1.5 adjacent to the PhC. Some epoxy resins used in packaging LEDs have a refractive index of 1.5 [11]. If the normalized frequency a/λ is 0.24, the practical values of a, d_1, d_2, and h at $\lambda = 589.0$ nm are 141.4, 84.8, 127.2, and 63.6 nm, respectively. If no sawtooth PhC exists on the planar medium, the critical angle θ_c is 41.81°. After designing the sawtooth PhC with 10 Si–SiO_2 periodic layers on the planar medium, the transmission ratios of the H-polarized to the E-polarized modes varied with incident angles for three cases of normalized frequencies 0.23, 0.24, and 0.25 as shown in Fig. 4. It can be seen that at the normalized frequency 0.23, most parts of ratios are more than 10^4 and the maximum is about 10^5 at around 33°. In the case of the normalized frequency 0.24, a maximum value of 2.56×10^5 is reached at around 13° and the ratio decreases sharply at around 40°. When the incident angle is 45°, a minimum ratio of 25.1 is obtained. In the case of the normalized frequency 0.25, transmission ratios before 27° are

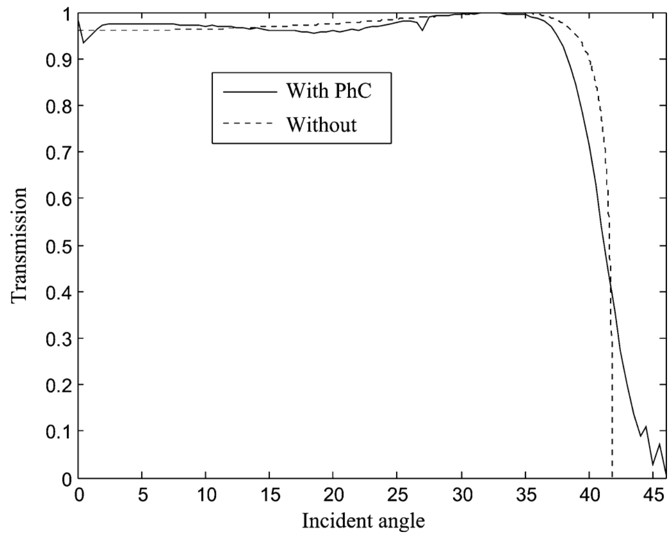

Fig. 5. Transmissions of the H-polarized mode for two cases with the sawtooth PhC on the planar medium (solid line) and without (dashed line) at 0.24 (a/λ).

almost more than 10^3, and large decrease takes place between 27° and 43°. All three cases show that transmissions of the H-polarized mode in the range from 0° to 45° are all larger than those of the E-polarized mode.

Next, the above-demonstrated sawtooth PhC is applied on the LED. Consider a LED emitting light with center wavelength 589.0 nm and bandwidth 48.0 nm. This bandwidth meets most commercial production standards. If the center frequency is chosen at a/λ equal to 0.24, the lattice constant a is 141.4 nm in the sawtooth PhC. Then the normalized frequencies 0.23 and 0.25 correspond to wavelengths 614.6 nm and 565.4 nm, respectively. The difference in wavelength is 49.2 nm which is larger than the bandwidth of the LED. So this sawtooth PhC can be applied on the LED to efficiently produce H-polarized light very well.

Finally, we compare the outputs of H-polarized light between two cases with the sawtooth PhC depositing on the planar medium and without. When the normalized frequency a/λ of light is chosen as 0.24, the transmissions of the H-polarized mode for both cases are shown in Fig. 5. From the calculated results, the transmission of H-polarized light from the planar medium has a maximum of 1.00 at the incident angle 33.7°, which is the Brewster's angle. In the case of the sawtooth PhC depositing on the planar medium, the values of transmission are all more than 0.94 when the incident angles are below 37.0°. There also exists a maximum very close to 1.00 at the incident angle about 33.7°. It is worthy to mention that the role of the sawtooth PhC can enlarge the limitation of the incident angle. Even at an incident angle of θ_c, the transmission is still more than 0.4 and H-polarized light can be observed even at 45°. Integrating the transmitted energy for all incident angles, the total transmitted energy of the H-polarized mode from the sawtooth PhC is a little larger than that from the planar medium. The implementation of the sawtooth PhC on the planar medium not only produces polarized light, but also enhances polarized-light-transmission efficiency from the planar medium without considering absorption. The energy loss can be further discussed here. The field intensity is proportional to $\exp(-\alpha d_2)$ after passing through each Si layer, where α is the attenuation constant [9]. By calculating it at 589 nm, the absorption is about 2.81%. So the total energy loss of 10 Si–SiO_2 periodic layers is about 28.1%. The absorption can be decreased. A possible way is reducing the total periodic layers to 6 so that the transmission ratio is kept as high as 1000:1 in most incident angles.

IV. Conclusion

We have calculated the E-polarized PBSs of sawtooth PhCs with different parameters d_1 and d_2 for the case of Si–SiO_2 periodic layers when h is fixed at $0.45a$, and also have collected the data with the widths of the PBGs larger than 0.02 (a/λ). We have investigated the distributions of the PBGs using different parameters, and efficiently found out the suitable design parameters for the sawtooth PhC. When the sawtooth PhC with 10 Si–SiO_2 periodic layers is designed on the planar medium, the transmission ratios of the H-polarized to the E-polarized modes are more than 10^4 in most incident angles. If the absorption wants to be suppressed, the total periodic layers can be reduced to 6. Such LEDs combining with the designed polarizers are attractive to be used as backlight sources in the LCD industry.

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