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Antireflection subwavelength structures analyzed by using the finite difference time domain method

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Abstract

Antireflection subwavelength structures (ASSs) are analyzed by using the finite difference time domain (FDTD) method in the visible light spectrum. Low reflectance can be obtained by both the conical and pyramidal shapes over a broadband range. Comparing the reflectance of different structure shapes and aspect ratios by the FDTD method, it shows that the antireflection efficiencies of the pyramidal structures are better than that of the conical structures when the aspect ratio is up to 0.8. It is found that, for the conical structure surface, the average transmittance increases gradually with the aspect ratio and the average transmittance is about 99.6% with the aspect ratio of 2.0. However, for the pyramidal structure with the aspect ratio ranging from 1.0 to 2.0, the average transmittance is up to 99.7%.

Keywords: Subwavelength structure; Nanostructure; Antireflection; Fresnel reflection finite difference time domain

1. Introduction

The Fresnel reflection describes that a portion of the incident light reflects at a discrete interface between two media having different refractive indices in nature. The Fresnel reflection leads to some disadvantages in imaging systems such as reducing the share of transmitted light, deteriorating the contrast of displays, and generating the formation of ghost images. In outdoor or high brightness circumstances, the portable electronics such as laptop computer, digital camera, camcorder, mobile phone, and PDA face more rigorous condition to solve the problem of Fresnel reflection.

In general, methods of lowering the reflection can be divided into two solutions [1]. One is a multilayered alternation of high- and low-refractive index layers, which is realized by the antireflection coating technology [2,3]. The antireflection coating technology to eliminate unwanted reflection off a diversity of surfaces is widely applied in a variety of products. But it still has the problems associated with limitations in the coating materials and various physical and chemical properties that will affect adhesion, thermal mismatch, and the stability of the layer stack [4,5]. The other solution is an inhomogeneous surface with a gradual change of index, which is realized by the antireflection structure technology [5–11]. Those well-known antireflection structures in nature, which are called moth eye structures, belong to the 2-D subwavelength structures and first discovered

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on the cornea of night-flying moths [6]. Recently, due to the fast development in computer-aided design and micro/nano-fabrication technologies, the antireflection structure technology has been investigated [5,7–12]. An antireflection subwavelength structure (ASS) surface upon a crystal silicon substrate is fabricated by electron beam lithography and etched by an SF_6 fast atom beam [5]. The 2-D conical profile structures are shown with the period of 150 nm and the groove depth of 350 nm. ASSs on crystalline Si are designed by using a rigorous coupled-wave analysis (RCWA) and fabricated using directly formed anodic porous alumina masks. The surface with a periodicity of 100 nm and a height of 300–400 nm is presented. The RCWA method has been often used to investigate theoretically reflection characteristics of ASSs [7,8]. It is sometimes oversimplified in calculation for complex structures. The finite difference time domain (FDTD) method is a powerful numerical calculation. The effect of a nano-porous film on a glass is numerically studied by using the FDTD method [11]. They simulate the nano-porous film with different porous ratios and relatively obtain different effective indices. It is also shown that the average transmission ratio of an antireflection coating composed of the nano-porous film is about 99.5% in the spectrum ranges of 400–800 nm.

In this study, we numerically analyze the optical character of ASS surfaces in the visible light spectrum by using the FDTD method. The conical and pyramidal shapes with different aspect ratios will be chosen to be simulated.

2. Simulation method

The FDTD method is an accurate and available technique to study the antireflection effect of the surface with ASS. In this study, the FDTD method is used to analyze the optical character of ASS surfaces in the visible light spectrum. The sketch the of simulation model is shown in Fig. 1, where n_0 and n_s are the

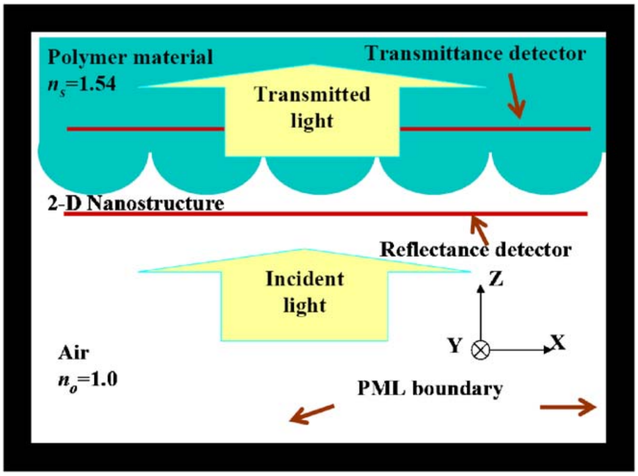

Fig. 1. Sketch of a light-wave propagation through an ASS surface simulated by the FDTD method.

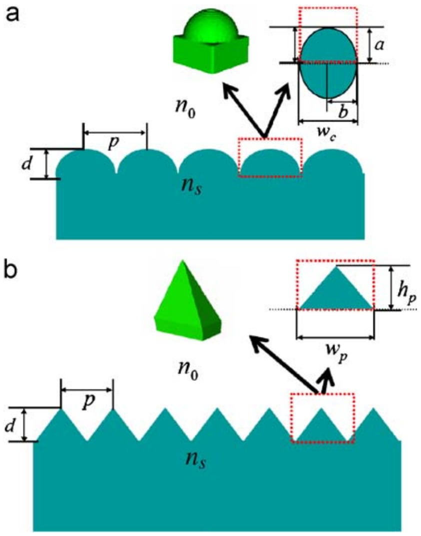

Fig. 2. Schematic diagrams of ASS surfaces with (a) conical and (b) pyramidal shapes.

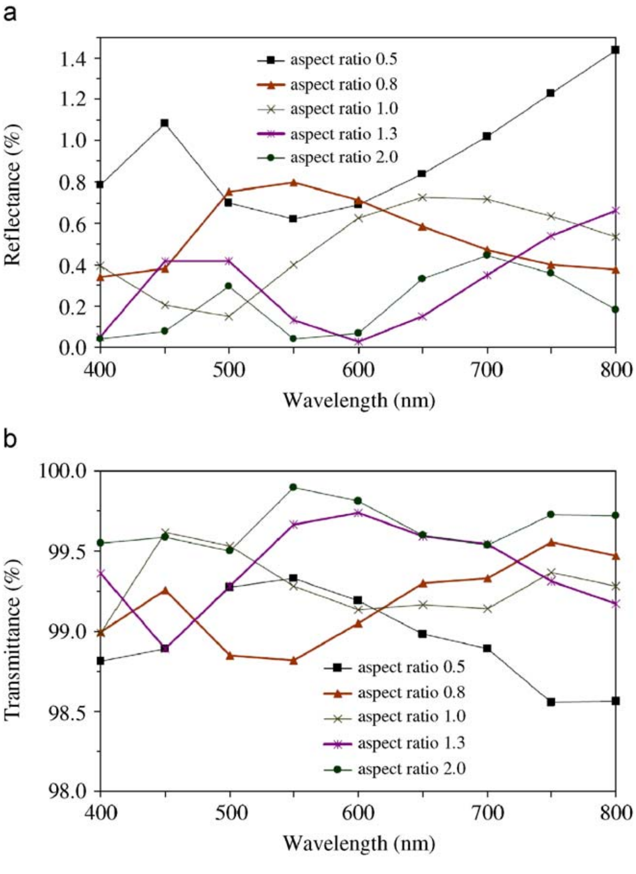

Fig. 3. Variances of the (a) reflectance and (b) transmittance of the conical type with different aspect ratios as a function of wavelength.

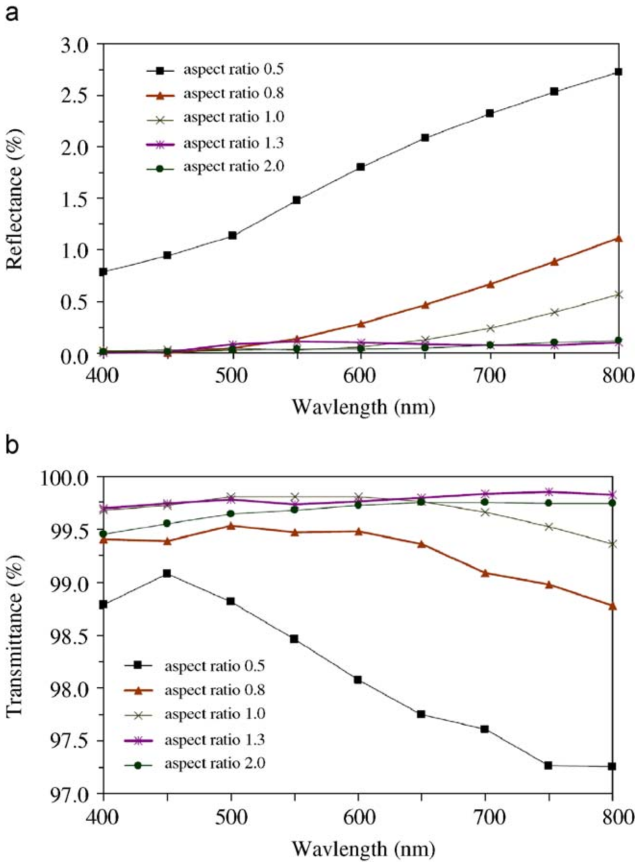

Fig. 4. Variances of the (a) reflectance and (b) transmittance of the pyramidal type with different aspect ratios as a function of wavelength.

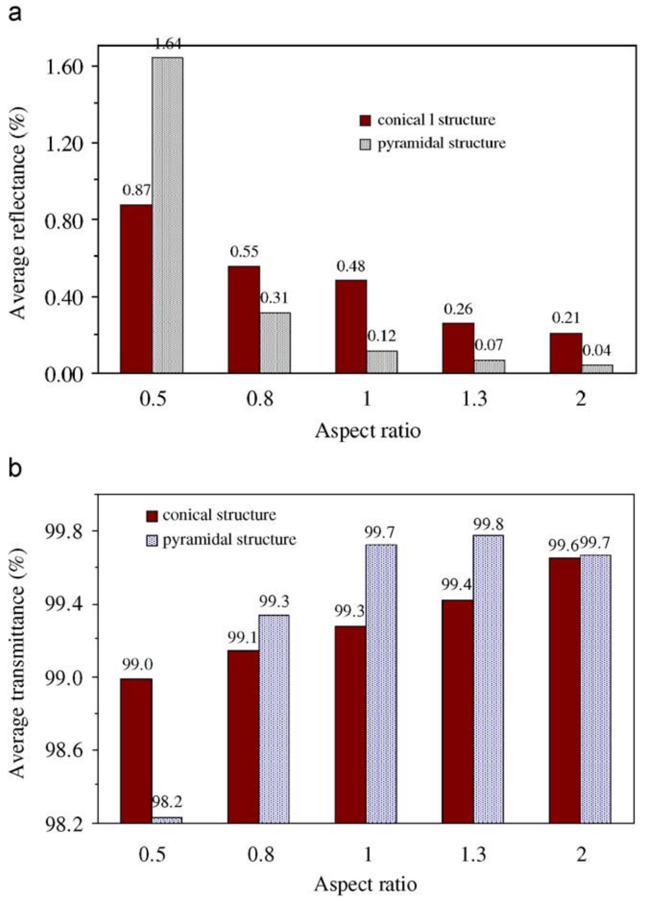

Fig. 5. Averages of the (a) reflectance and (b) transmittance of the two types for different aspect ratios.

refractive indices of the incident medium and polymer material, respectively. Here, we choose $n_0 \approx 1.00$ and $n_s = 1.54$. A light wave propagates from the air through ASS surface into the polymer material and the absorption loss of the medium can be ignored. On the other hand, since the FDTD has finite analysis windows, an artificial boundary condition to suppress reflections at the analysis windows is required. In the FDTD simulation, absorbing boundary conditions are required to truncate the computational domain without reflection. A perfect matched layer is applied to decrease the error induced by the boundary of the simulated area [13]. The dispersion effect, which describes the dependence of refractive index of the medium on frequency, is ignored in this material. Figs. 2(a) and (b) show the schematic profiles of the 2-D periodic conical and pyramidal shapes of ASSs on the polymer material surface, respectively. In Fig. 2, the symbols p, d, w_c, w_p, h_c, and h_p denote spatial period, structure depth of the surface, conical width, pyramidal width, conical height, and pyramidal height respectively. Here we use a half ellipsoid to realize a conical structure, that is, the equatorial radius b of ellipsoid in the X direction is close to a half of the conical width and the equatorial radius a of ellipsoid in the Z direction is equal to the conical height. One can see that the pyramidal and conical ASSs are consisted of a plurality of pyramids and half ellipsoids which are arranged closely in order, that is, spatial period $p = w_c = w_p$.

3. Results and discussion

To understand the effect of the 2-D periodic subwavelength structures, we consider the spatial period p as a constant and the structure depth d as a variable. Let $p = w_c = w_p = 2b = 300$ nm, we take several aspect ratios, defined as d/p, ranging from 0.5 to 2. Figs. 3(a) and (b) show variances of the reflectance and transmittance of the conical type with different aspect ratios in the spectral ranges of 400–800 nm, respectively. One can see that except for the case with aspect ratio of 0.5, the reflectances and transmittances are selected with a certain value of below 0.73% and above 98.8%, respectively, in the spectrum ranges from 400 to 800 nm. For the case with an aspect ratio of 2.0, the reflectances and transmittances are selected with a certain value of below 0.45% and above 99.5%, respectively, in the spectrum ranges of 400–800 nm. The results of the pyramidal type are shown in Fig. 4, which is similar to the conical type. One can see that for the cases with aspect ratios of 1.3 and 2.0, the reflectance are lower than 0.13% and the transmittances are almost over 99.5%. Figs. 5(a) and (b) show the averages of the reflectance and transmittance of the two types for different aspect ratios in the spectrum ranges from 400 to 800 nm. It is seen that the average transmittances are above 99.0% expect for the aspect ratio of 0.5 of the pyramidal type. According to the simulation results, the pyramidal type has higher antireflection efficiency than the conical type for the aspect ratio up to 0.8. For the conical type, it is found that the average transmittance increases gradually with the aspect ratio. The best case can be obtained for an average transmittance about 99.6% with the aspect ratio of 2.0. For the pyramidal type, the average transmittance is up to 99.7%, with the aspect ratio up to 1.0 and the best case is the average transmittance of 99.8% with the aspect ratio of 1.3.

4. Conclusion

We use the FDTD method to analyze the antireflection effect of subwavelength structures in the visible light spectrum. Low reflectance can be obtained by both the conical and pyramidal types for broad-spectrum ranges of 400–800 nm. When the aspect ratio is up to 0.8, the pyramidal structures show higher antireflection efficiency than the conical structures in our simulation results. For the conical type, it is found that the average transmittance increases gradually with the aspect ratio and the average transmittance is about 99.6% with an aspect ratio of 2.0. For the pyramidal type, the average transmittance is up to 99.7% with the aspect ratio ranging from 1.0 to 2.0.

Reference

[1] U. Schulz, Review of modern techniques to generate antireflective properties on thermoplastic polymers, Appl. Opt. 45 (2006) 1608–1618.

[2] A. Macleod, Thin-Film Optical Filters, third ed, Institute of Physics, 2001.

[3] R. Willey, Practical Design and Production of Thin Films, Marcel Dekker, New York, 2002.

[4] P. Lalanne, G.M. Morris, Design, fabrication and characterization of subwavelength periodic structures for semiconductor anti-reflection coating in the visible domain, Proc. SPIE 2776 (1996) 300–309.

[5] Y. Kanamori, M. Sasaki, K. Hane, Broadband antireflection gratings fabricated upon silicon substrates, Opt. Lett. 24 (1999) 1422–1424.

[6] C.G. Bernhard, Structural and functional adaptation in a visual system, Endeavour 26 (1967) 79–84.

[7] Thomas K. Gaylord, W.E. Baird, M.G. Moharam, Zero-reflectivity high spatial-frequency rectangular-groove dielectric surface-relief gratings, Appl. Opt. 25 (1986) 209–214.

[8] Yuzo Ono, Yasuo Kimura, Yashinori Ohta, Nobuo Nishida, Antireflection effect in ultrahigh spatial-frequency holographic relief gratings, Appl. Opt. 26 (1987) 1142–1146.

[9] M.E. Motamedi, W.H. Southwell, W.J. Gunning, Antireflection surfaces in silicon using binary optics technology, Appl. Opt. 31 (1992) 225–229.

[10] D.H. Raguin, G.M. Morris, Antireflection structured surfaces for the infrared spectral region, Appl. Opt. 32 (1993) 1154–1167.

[11] Z. Yang, D. Zhu, M. Zhao, M. Cao, The study of a nanoporous optical film with the finite difference time domain method, J. Opt. A: Pure Appl. Opt. 6 (2004) 564–568.

[12] Hitoshi Sai, Homare Fujii, Koji Arafune, Yoshio Ohshita, Masafumi Yamaguchi, Yoshiaki. Kanamori, Hiroo Yugami, Antireflective subwavelength structures on crystalline Si fabricated using directly formed anodic porous alumina masks, Appl. Phys. Lett. 88 (2006), 201116-1–201116-3.

[13] J.P. Berenger, Perfectly matched layer for the FDTD solution of wave-structure interaction problems, IEEE Trans. Antennas Propag. 44 (1996) 110–117.