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Research Article

Improved Antireflection Properties of an Optical Film Surface with Mixing Conical Subwavelength Structures

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Based on finite difference time domain method, an optical film surface with mixing conical subwavelength structures is numerically investigated to improve antireflection property. The mixing conical subwavelength structure is combined with the pure periodic conical subwavelength structures and the added small conical structures in the gap between the pure periodic conical subwavelength structures. The antireflection properties of two types of subwavelength structures with different aspect ratios in spectral range of 400–800 nm are analyzed and compared. It is shown that, for the mixing type, the average reflectance is decreased and the variances of the reflectance are evidently smaller. When the added structure with a better aspect ratio exists, the average reflectance of the surface can be below 0.30%. Obviously, the antireflection properties of the optical film surface with mixing conical subwavelength structures can be improved.

1. Introduction

Antireflection coatings have been widely used to realize high efficiency in optical components and optoelectronics devices by eliminating unwanted surface reflections. We expect that the reflectional light is omitted or suppressed in many optical systems. The subwavelength structure (SWS) technology, which is inspired by the moth-eye effect, is a powerful method to realize the broadband antireflective effect. The specific subwavelength structure pattern, called antireflective subwavelength structure, on optical element surface produced by the nanostructure fabrication technology has been widely researched [1–4].

For the theoretical consideration, there are kinds of methods that can simulate electromagnetic wave transmission like rigorous coupled-wave analysis (RCWA), finite difference time domain (FDTD), or plane wave expansion method (PWE), and in the same research it is showed that the FDTD method is the effectual simulation tool used in 3D periodic SWS [5, 6]. It is directly calculated by the full-vector Maxwell's equations [6, 7]. Since it is a time-domain method, FDTD solutions can cover a wide frequency range with a single simulation run and treat nonlinear material properties in a natural way. FDTD method is a systematic approach, with FDTD specifying a new structure to be modeled being reduced to a problem of mesh generation rather than the potentially complex reformulation of an integral equation [8]. In past studies, the antireflection coating has been fabricated in subwavelength structure technology and simulated in FDTD method at the same time. The average reflectances of the simulation and replicated polymer prototype are about 0.50% and 0.54% within the spectral ranges of 400–650 nm, respectively. The results showed that the FDTD method is an effective way to simulate electromagnetic wave propagation [9, 10].

In past works, antireflective characteristics of the SWS depend strongly on its dimensions and geometric shape, and there are some specific shapes can be fabricated like conical, cylinder, that pyramidal shapes. Subwavelength structure in low reflectance can also be obtained by both conical and pyramidal shapes over a broadband range. Comparing the reflectance of different structure shapes and aspect ratios

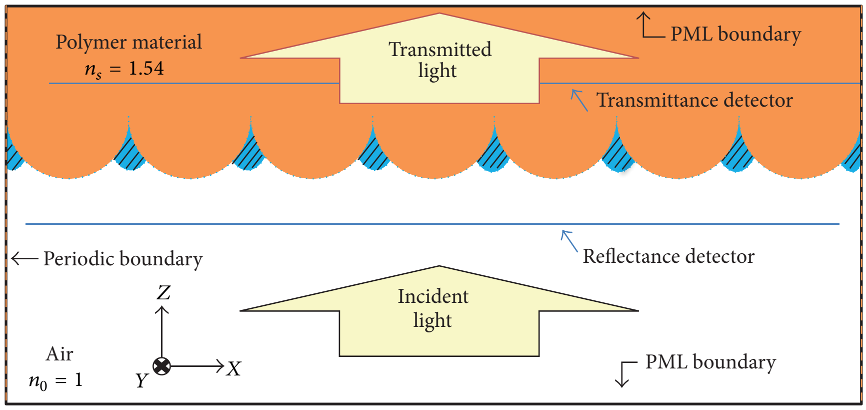

Figure 1: Sketch of the light-wave propagation through an optical film with SWS system simulated by the FDTD method.

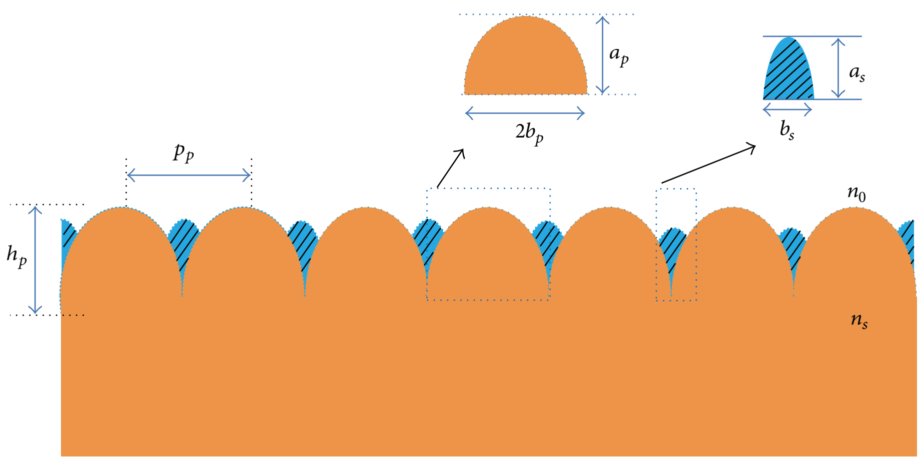

Figure 2: Schematic profiles of SWS surfaces with the composite structure surfaces.

by the FDTD method, it is shown that the antireflection efficiencies of the pyramidal structures are better than the conical structures in some particular ratios. It is also found that, for the conical structure surface, the average transmittance increases gradually with the aspect ratio and the average transmittance is about 99.6% [11].

In this study, we consider a new composite subwavelength structures based on pure periodic conical SWS [11] and adding a small conical structure in the gap between the pure periodic conical subwavelength structures and numerically analyze the optical characters of SWS of surfaces by using FDTD method to directly solve the full-vector Maxwell's equations. For the profile parameter of the conical SWS structures, the antireflection property is analyzed in a spectral range from 400 nm to 800 nm.

2. Structure and Method

We use FDTD method to design the parameters which are based on periodic conical subwavelength structures in different spectral range. We consider that the light wave propagates from the air through the antireflective subwavelength structures surfaces into the polymer material in plane wave, and the absorption loss of the medium can be ignored. The design structured can be fabricated by microreplication process combined with the originated structure fabrication realized by interference lithography, Ni mold electroplating, and replication by the use of UV imprinting onto plactics.

The sketch of simulation model is shown in Figure 1, where n_0 and n_s are the refractive indices of the incident medium and polymer materials, respectively. Here, we choose $n_0 = 1$ for air and $n_s = 1.54$ for polymer material. In FDTD simulation, absorbing boundary conditions are required to truncate the computational domain without reflection. A perfect matched layer (PML) is a useful method to decrease the error induced form the boundary situation [12] in z-direction, and according to the Floquet theory [13] in periodic boundary condition in x-direction, we use the PML and periodic boundary to be the simulate area, and energy of transmittance light wave is measured by detector 1,

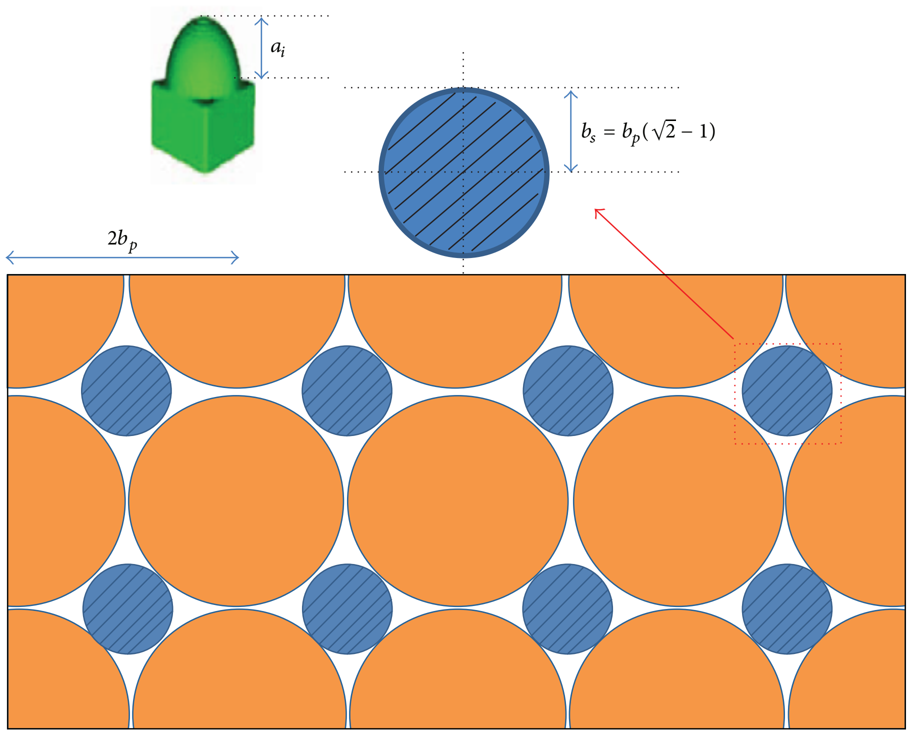

FIGURE 3: Schematic profiles of the SWS surfaces between the pure structures and the small structures.

and energy of reflectance light wave is measured by detector 2, respectively.

Figure 2 shows the schematic diagram of the SWS surfaces with the composite structures, and we can see these structures composed by the pure periodic conical subwavelength structures and extra small structures in the gap between the pure periodic conical subwavelength structures. The parameters of SWS surfaces with the composite structure surfaces in Figure 2, where the symbols p_p and h_p denote pure periodic structure's spatial period and spatial height, and the symbols a_s and b_s denote small structure's height and width. The height of ellipsoid a_p is equal to the spatial height h_p, and the radius of ellipsoid b_p is close to the spatial period p_p.

In this study, we add these small subwavelength structures and discuss their ratios influences to the whole SWS about reflection and transmittance. We can see the connected relation in Figure 3 between b_p and b_s: $b_s = b_p(\sqrt{2} - 1)$.

3. Results and Discussion

First, we describe the effect of the original SWSs which are pure periodic conical structures without small SWSs, and we can see the phenomenon in Figures 4(a)–4(d) in black line with circle pattern. And then, we consider holding the height and width of each pure periodic structure unit, where $p_p = h_p = a_p = 2b_p = 300$ nm, which we defined as the pure structure ratios (PSR), and adopting the small SWS height from ratios 0.00 to 1.00, where we defined the small structure ratios (SSR) as a_s/b_s. The variances of the reflectance for the small structures in spectral ranges of 400–800 nm are shown in Figure 4. One can see that the reflectance has obviously decreased when we add the small SWS, and we show the best ratios which have the lowest reflectance and the same height with the small SWSs and pure periodic SWSs. We can also find that it has a stable reflectance after we use the nanostructure material for the coating surfaces.

We can analyze the data of reflectance; it is shown the average reflectance of pure periodic SWSs that below 0.48%, and the average reflectance of the improved SWS is below 0.29%. In the meantime, we can see that the different ratios of small SWSs have different effects in Figure 4. The reflectance and ratios of small structures have some relations. And in this way, we select three conditions, which are the pure SWSs, the same high small SWSs to the pure periodic SWSs, and the lowest aspect ratios of the small SWSs, in Figure 4. We can see that the reflectance of the pure periodic SWS has a ranges 0.14%~0.72%, 0.03%~0.47%, 0.01%~0.47%, and 0.05%~0.45%, and the new SWSs improved the effect from 0.22%~0.37%, 0.05%~0.27%, 0.02%~0.23%, 0.04%~0.2 2% in Figures 4(a)–4(d). We can also see the variances of the standard deviation for different small structures ratios of each pure periodic structure in Figure 5; it is shown that the small SWSs also have a property to keep the reflectance in a stable state. This antireflection property can be improved about 40–60% from the original structure.

4. Summary

We use the FDTD method to analyze the antireflection effect of SWS in a spectral range from 400 nm to 800 nm.

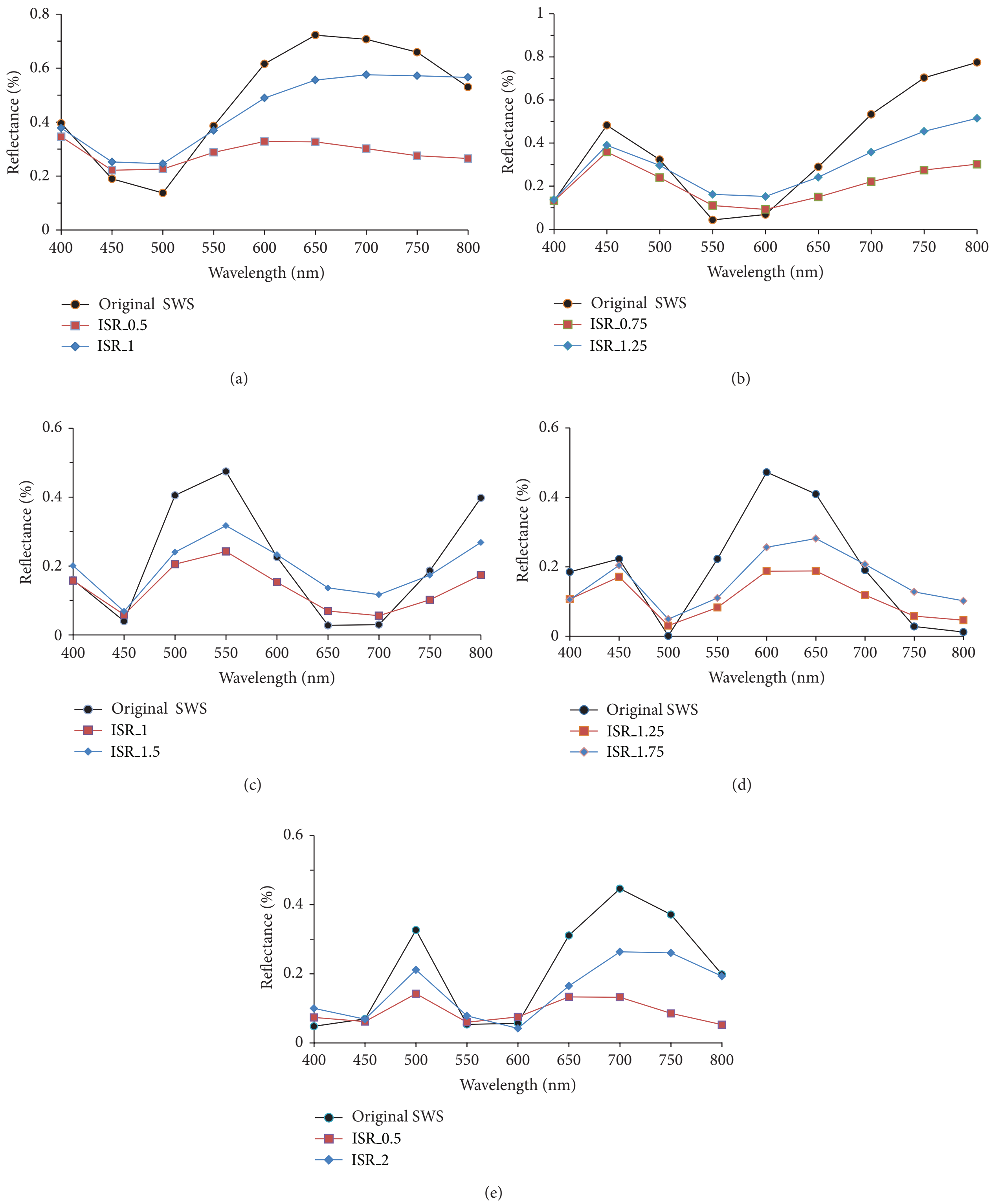

Figure 4: Variances of the reflectances for the pure periodic structures and different small structures ratios.

Such antireflection pattern is useful for solar cells, photodetectors, LEDs, and high-end imaging lens. We consider the pure periodic conical subwavelength structure and adding a small structure in the gap between the structures. It is found that the antireflection function has obviously decreases in different ratios of the added small structures. A better ratio of the small structure is obtained, and the average reflectance can be below 0.30%. The optimal design of

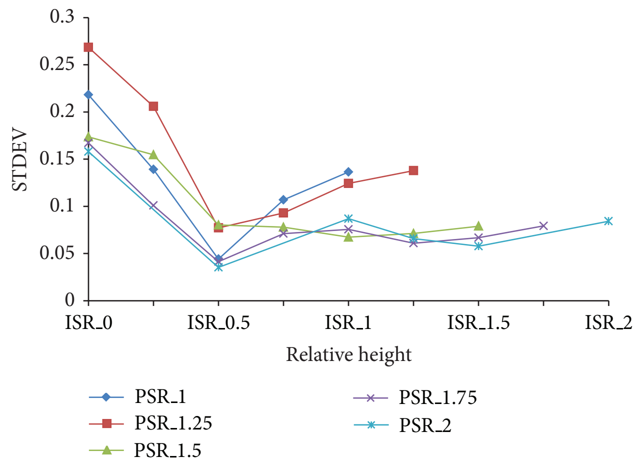

Figure 5: Variances of the standard deviation for different small structure ratios of each pure structure ratio.

the new SWS in conical shape can also steady the entire reflectance.

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