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# Subwavelength structures for broadband antireflection application

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ABSTRACT

The subwavelength structures are designed and fabricated for broadband antireflection application. Under target of zero reflectivity, the parameters of periodic 2-D continuous conical structures are analyzed by the finite-difference time-domain (FDTD) method. The corresponding conical structures are obtained with spatial period of 350 nm and structure height of 300 nm, respectively. The 2-D continuous conical structured surface is fabricated by micro-replication process combining with the originated structure fabrication realized by interference lithography, Ni mold electroplation and replication by using UV imprinting into plastics. 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. In a word, the subwavelength structured surface with low reflection is developed and proved to be highly consistent with the simulation results.



## 1. Introduction

With the development of portable consumer electronics, the demands for light-weight, thinner thickness of module, large area, cheaper mass production, and friendly working in outdoor circumstances have been become an important focus. To combine the technologies of subwavelength structure with micro-replication is a powerful method to meet the purposes and it is expected to play a major role.

The subwavelength structure technology can be realized as putting a plurality of subwavelength structures onto the element surface. The well-known subwavelength structures being called moth eye structures were first discovered on the cornea of night-flying moths by Bernhard [1]. The moth eyes are prominent due to the antireflective structures in nature. Such antireflective effect realized by using subwavelength structure, called as antireflective subwavelength structure (ASS). Recently, it has been proposed as an applicable alternative based on both the theoretical and experimental studies [2–4]. Under target of zero reflectivity, the functional dependences of the reflectivity on filling factor, groove depth, angle of incidence, and polarization for rectangular groove with high spatial-frequency dielectric gratings are calculated using rigorous coupled-wave analysis [2]. The gratings are shown to be capable of exhibiting zero reflectivity. In long-wavelength of infrared region, the results show the transmittance increases significantly. The fabrications of the two-dimensional (2-D) antireflective subwavelength structures (ASSs) in the visible spectral range have been reported for semiconductor materials [3]. However, the 2-D ASSs for a crystal silicon substrate are fabricated by electron beam lithography and etched by an $SF_6$ fast atom beam [4]. A conical profile structure is shown with the period of 150 nm and the groove depth of about 350 nm. Comparing with coating technology, it has advantages of wide spectral bandwidth and large field of view being expected to be useful for large number of applications [5] such as light emitting diodes, photo detectors, solar systems, displays and glass components.

Micro-replication technology is a cost-effective and efficient fabricating process for the optical element with microstructure or even smaller nanostructure. The process steps of micro-replication technology are originated structure fabrication, metallic mold electroplation, and replication to imprint into plastics. There are several approaches to fabricate the original structure template, such as interference lithography [5,6], gray-scale lithography [7], photolithography [8], and ultra-precision machining [9]. For mass replication, polymers are especially suitable owing to their plasticity at relatively low temperatures. There are essentially two types of materials being used in such replication. One is thermal plastic materials such as polymethyl methacrylate (PMMA), polycarbonate (PC), etc. which is frequently used in injection molding and hot embossing. The other is thermal set materials such as UV curable material which are often used in ultra-violent (UV) imprinting

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processes. For thermal plastic materials, elevated temperature is required to make a viscous state of thermal plastic polymer and to fill cavity under applied pressure. Besides, due to different thermal expansion of template and polymeric microstructure, mechanical locking effect frequently happens after a heat-up and cool-down cycle and damages the microstructure in the demolding process [10]. Comparing to thermal plastic material, liquid type UV curable material has relative good filling property especially in micrometer or less microstructure. With UV irradiation, it also can be cured at room temperature which eliminate microstructure damage problem in demolding step.

In this study, we show the numerical calculation results of the 2-D continuous profile of ASSs using a novel method based on the finite-difference time-domain (FDTD) method [11]. The periodic conical structured surface is fabricated by micro-replication process combining with the originated structure fabrication realized by interference lithography, Ni mold electroplation and replication by using UV imprinting into plastics. The optical property of the fabricated element shows good agreement with the simulation results.

## 2. Simulation method and results

FDTD method is a powerful computational electrodynamics modeling technique. Recently, it is used to precisely study the anti-reflection effect of ASS surface. In this study, the FDTD method is used to design the parameters of the periodic conical shape with antireflection function in the spectral range of 400–700 nm. To meet this requirement, we choose gapless periodic subwavelength ellipsoid array as simulated geometric mold. We consider that the 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 (PML) is applied to decrease the error induced by the boundary of the simulated area [12]. The sketch of simulation model is shown in Fig. 1, where $n_0$ and $n_s$ are the refractive indices of the incident medium and polymer material, respectively. Here, we choose $n_0 = 1.00$ for air and $n_s = 1.54$. The dispersion effect which describes the dependence of refractive index of the medium on frequency is ignored in this material. Fig. 2 shows the schematic diagram of the profile of ASSs on the polymer material surface. One can see that

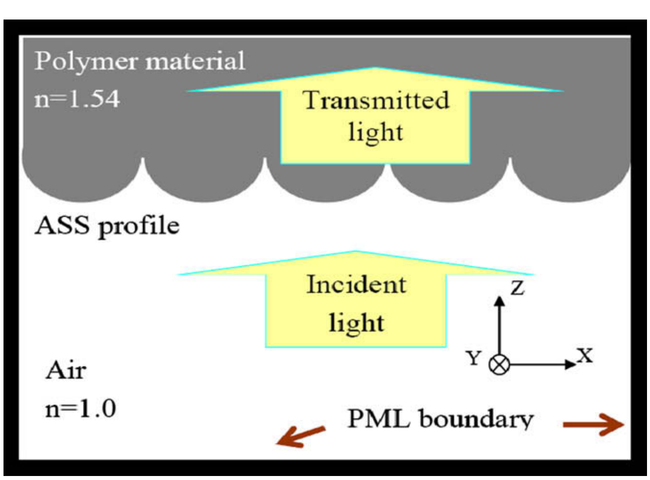


**Fig. 1.** Sketch of the light-wave propagation through an optical film with ASSs simulated by the FDTD method.

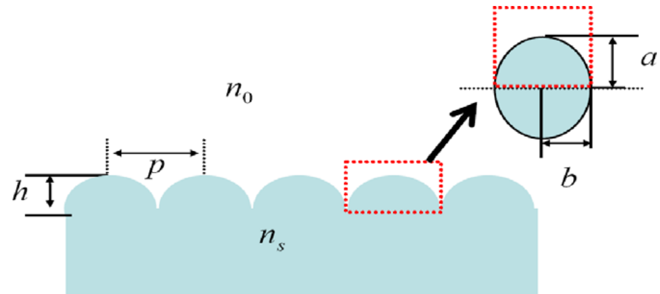


**Fig. 2.** Schematic diagram of the ASS profile on the polymer material surface.

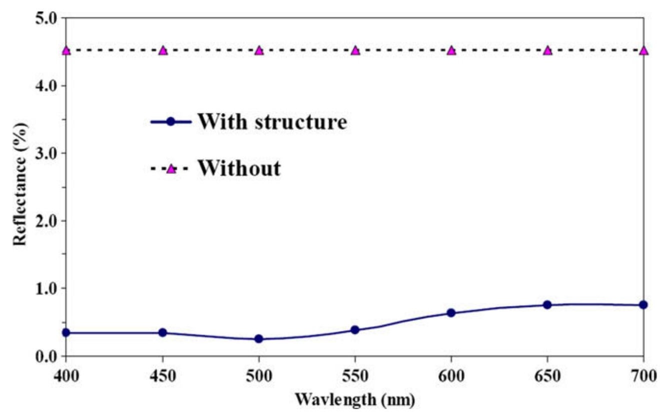


**Fig. 3.** Simulation values of the reflectance of light propagating from the air into the polymer material $n_s = 1.54$ with and without conical subwavelength structured surface.

the ASSs are consisted of a plurality of half subwavelength ellipsoids and arranged closely in order. The radius of ellipsoid $b$ in the $Z$ direction is close to a half of the spatial period $p$. The structure height $h$ is equal to the other radius of ellipsoid $a$.

The parameters of ASS surface being used in the FDTD method are the spatial period $p = 2b = 350$ nm and the structure height $h = a = 300$ nm. The variance of the simulation results of reflectance in spectral range of 400–700 nm are shown with the solid line drawn through the circle in Fig. 3. The average simulated reflectances are about 0.45% and 0.50% in spectral ranges of 400–650 nm and 400–700 nm, respectively. Being ignored with the dispersion effect, when the light propagates from the air $n_0 = 1.00$ into the polymer material $n_s = 1.54$ at the normal incidence, the theoretical reflectance is about 4.52% and shown with the dotted line drawn through the regular triangle in Fig. 3.

## 3. Fabrication process and results

The designed structures are fabricated by micro-replication process combining with the originated structure fabrication realized

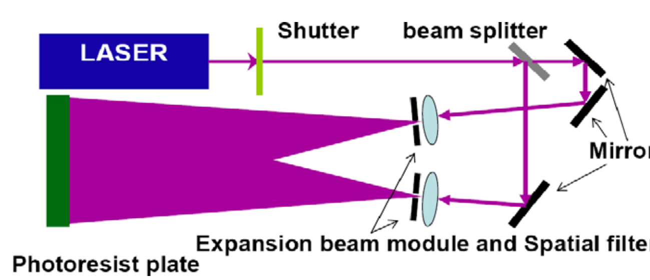


**Fig. 4.** Schematic diagram of the optical setup for interference lithography.