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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 electroplating 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 antireflection 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 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.

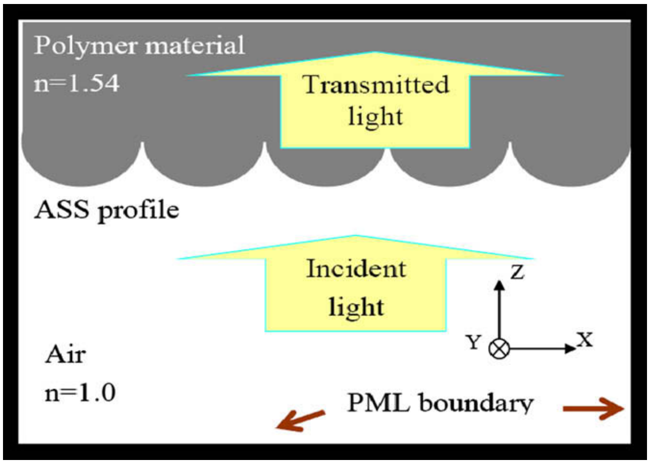

Fig. 1. Sketch of the light-wave propagation through an optical film with ASSs simulated by the FDTD method.

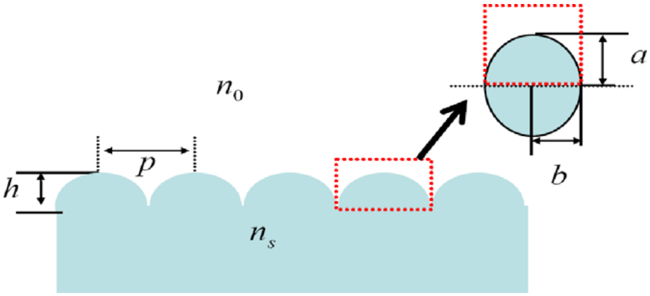

Fig. 2. Schematic diagram of the ASS profile on the polymer material surface.

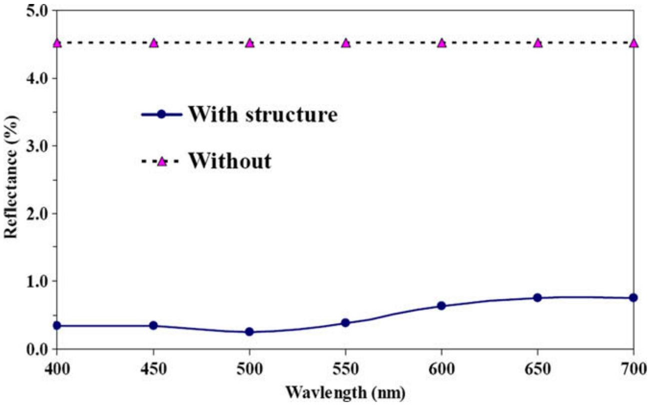

Fig. 3. Simulation values of the reflectance of light propagating from the air into the polymer material $n_s = 1.54$ with and without conical subwavelength structured surface.

The 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

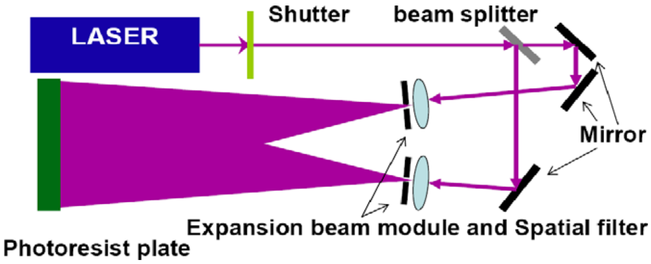

Fig. 4. Schematic diagram of the optical setup for interference lithography.

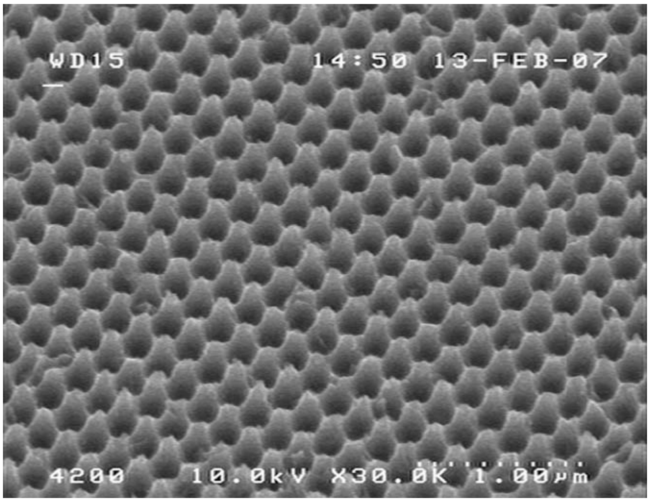

Fig. 5. SEM photo of the conical ASS surface on Nickel mold.

Fig. 6. Picture of the bonded roller mold adhered with ASS Ni mold.

by interference lithography, Ni mold electroplation and replication by using UV imprinting into plastics. Interference lithography is a useful technique to fabricate the periodic structures with sub-micro period realized by the interference pattern which is formed by the superposition of at least two coherent waves [5]. A positive photoresist layer coated on a substrate is exposed to the interference pattern. The photoresist profile which non-linearly depends on the interference pattern is formed after the development process [6,13]. Fig. 4 shows the schematic diagram of the optical setup for interference lithography. A laser beam is split by the beam splitter and directed respectively with the mirrors, then spatially filtered and expanded at the output end. The photoresist plate fixed by a holder is positioned where the expanded beams superpose each other. The exposure time is controlled by a shutter. Because of the currently available photoresists are sensitive in wavelengths of blue or UV region and the smallest fabricated structure period depends on the interference wavelength, an argon ion laser emitting up to 1.3 W is chosen at a single wavelength of 364 nm. And a resist Shipley Microposit S1818 (Shipley Company, Marlborough, MA, USA) is used. Such photoresist has relatively high absorbance and moderate contrast. Under the suitable fabrication conditions, an original structure template is fabricated. A micro-electroplating process is then applied to transfer the photoresist structure template onto the Ni mold. The metallization processes include sputtering of 100 nm Ni layer, electroplating Ni, backside lapping, and mold releasing. The manufactured SEM photo of Ni mold is shown in Fig. 5.

With the Ni mold, the polymer ASSs are duplicated by using UV imprinting process. A modified imprinting process by using roller is proposed in the experiment. The bonded nanostructure roller mold is shown in Fig. 6. The dimensions of the bonded roller mold are 20 cm in diameter. The roller mold is set up in a nanoimprinting equipment produced by ITRI and shown in Fig. 7. The imprinting steps can be summarized as shown in Fig. 8. Firstly, the UV curable material is dispensed in liquid form onto the Ni template to fill concave cavity of ASS. For good demolding property, a flexible polyester (PET) film as ASS substrate is bended and placed over dispensed resin to avoid air bubbles trapped in the resin layer. Here we take Toyobo PET film (thickness 188 μm) supplied by Toyobo Co., Ltd., Osaka, Japan. The PET film is transparent to the UV irradiation. The coated template with PET film is then laminated by height controlled roller and moved from one side to the other to remove redundant resin and control the UV resin layer thickness. A thickness of 200 μm is obtained in the coated resin layer. The general wavelength region 250–420 nm of the UV light is used in the

Fig. 7. Picture of the roller imprinting equipment designed by ITRI for continuous nanostructure duplication.

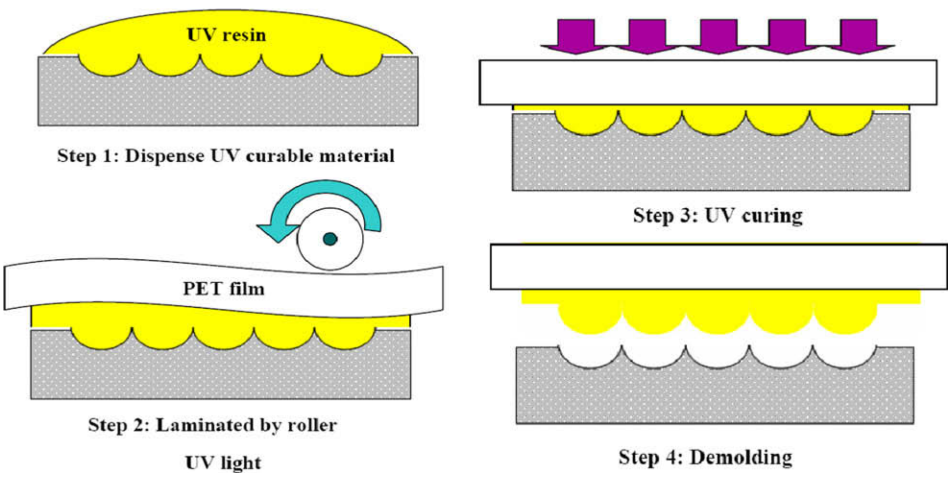

Fig. 8. Schematic illustration of the UV imprinting process.

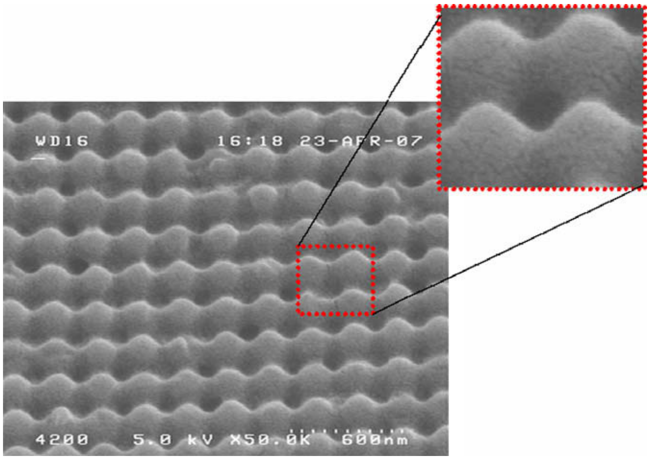

Fig. 9. SEM photo of the conical ASS surface.

experiment and the exposure intensity is 40 mW/cm^2 which is measured by the photometer at wavelength of 365 nm. The sample is then exposed to the curing system for 12 min and the resin is solidified at room temperature. After curing step, the flexible PET film with ASSs can be pealed off from Ni mold. The SEM photo of the prototype is shown in Fig. 9. One can see that the ASSs are duplicated successfully.

4. Measurement results and discussions

The reflectance of the replicated prototype is measured with the MODELV-570 spectrometer supplied by JASCO International Co., Ltd. The measured results of the fabricated prototypes with and without conical subwavelength structured surface and difference between experimental and simulation values as a function of wavelength are shown in Fig. 10. Comparing the results of the surface with and without subwavelength structures, one can see that the reflectances have very obvious reduction when the subwavelength structures exist on the surface. In the spectral ranges of 400–650 and 400–700 nm, the average reflectances of the replicated prototype are about 0.54% and 0.66%, respectively. The different values between experiment and simulation results are shown with the dashed line drawn through the square in Fig. 10. The different values between experiment and simulation results are shown with the dotted line drawn through the regular triangle in Fig. 10.The average difference value is close to 0.16% in 400–700 nm range. It is seen that, in 400–650 nm range, the difference values are very small and the average difference value is only 0.092%. That is, the experimental results are highly consistent with the simulation results in 400–700 nm range, above all, in 400–650 nm range.

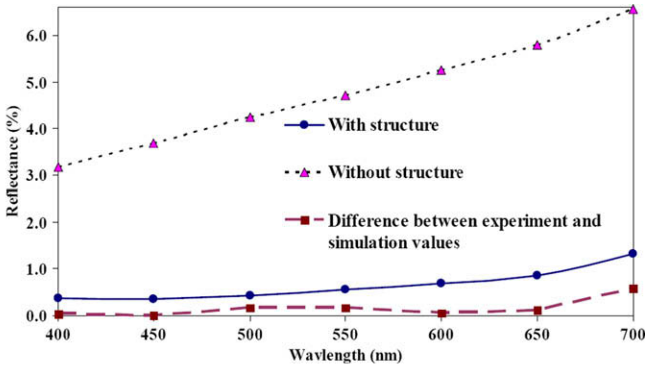

Fig. 10. Measured reflectances of the fabricated prototypes with and without conical subwavelength structured surface and difference between experimental and simulation values as a function of wavelength.

5. Conclusion

A subwavelength structured surface for broadband antireflection application is designed and fabricated. Under target of zero reflectivity, the parameters of 2-D periodic continuous conical structures are analyzed by the FDTD method. A set of structure parameters are obtained with the spatial period $p = 350$ nm and the structure height $h = 300$ nm. Then, such 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% in the spectral range of 400–650 nm, respectively. Consequently, the subwavelength structured surface with low reflection is developed and proved to be highly consistent with the simulation results in 400–700 nm range, above all, in 400–650 nm range.

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