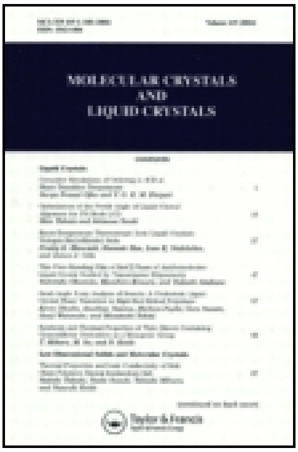

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Analysis of the Reflective Polarizer Based on Dielectric Nanofibers

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Numerical calculations were carried out to find the mechanisms of a nanofiber based reflective polarization sheet (RPS) using the finite-difference time-domain (FDTD) method. The simulation showed that the birefringence of nanofiber layers can make a reflective polarizer with small energy loss. In addition, the simulation demonstrated that the diameter of nanofibers and the spacing between them affected the extinction coefficient of RPS depending on its polarization. According to the calculations with various diameters of the nanofiber, there exists an optimum diameter of the nanofibers for maximum extinction coefficient.

Keywords Backlight; LCD; nanofiber; nanophotonics; polarizer; reflective polarization sheet

Introduction

Currently, a reflective polarization sheet (RPS) is being used in the back-light-units (BLU) of liquid crystal displays (LCD) in order to maximize the amount of transmitted light by placing it between the light source and the panel. The mechanism of RPS is illustrated in Fig. 1. A RPS reflects the opposite polarization, and the scattering reflector at the bottom turns it into a random polarization before it returns to the polarization sheet. In other words, it recycles the opposite polarization and converts it into the main polarization by bouncing the light back and forth repeatedly between the polarizing film and light source. In this way, the use of a RPS can give a much higher brightness level when used in the optical film of the BLU for LCDs [1].

A polarizing sheet is an optical film, which can make the unpolarized light into a polarized light. A polarizing sheet can be largely divided into an absorption type or a reflection type. The absorptive polarizer transmits the light polarized in a particular direction and absorbs the light polarized in the perpendicular direction. The absorptive polarizer is also called a dichroic polarizer because it has a dichroism, which shows different absorption levels depending on the polarization of the incident light as shown in Fig. 1(a). It is made by doping either iodine or dye into the polyvinyl alcohol film with stretching.

On the other hand, a reflective polarizer transmits the polarized components corresponding to the polarizing direction of the film, while it reflects the light orthogonal to

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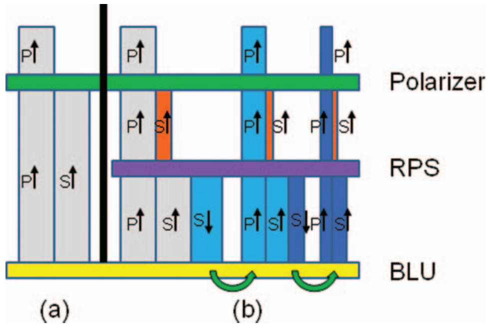

Figure 1. Photon recycling using RPS increases the efficiency of the BLU significantly. (a) an absorption type polarizer and (b) a reflection type polarizer are compared. S and P correspond to the two orthogonal polarizations.

the polarizing direction of the film. For example, the cholesteric liquid crystal (CHLC) can reflect one component of circular polarization, and the multi-layer polymer film with birefringence can reflect the light in different amounts with respect to the two linear polarizations [2,3]. The wire-grid polarizer also belongs to the reflective polarizer and finds its use frequently in micro-wave applications. As nanofabrication technology has advanced, the wire-grid polarizer in optical wavelength was also developed and studied recently [4–6]. Most wire-grid polarizers take advantage of the boundary conditions imposed by metallic nanowire [7]. Although its performance is outstanding in the laboratory, its fabrication demands high resolution lithography and results in a high cost.

In this work, we calculated the polarization characteristics coming from the multiple dielectric nanofiber layers. The dielectric birefringent sheet with nanofibers embedded in a host polymer showed a homogeneous index distribution in the normal direction to the nanofiber. However, it showed an index difference in the parallel direction to the fiber due to the birefringence caused by stretching the nanofiber. The theoretical analysis looked into the mechanisms of this type of polarizer using finite-difference time-domain (FDTD) method. The numerical computation can determine how the parameters of the nano-structures change the performance of the RPS based on the dielectric nanofiber.

Simulations

Prior to the simulation, it was necessary to review the structure of the commercial RPS based on the dielectric nanofibers. The schematic diagram of the structure is shown in Fig. 2. Basically, a mother fiber is few hundred microns in diameter and is comprised of hundreds of nanofibers as shown in Fig. 2. The nanofibers are the sub-fibers contained inside a large mother fiber. If the material of the nanofibers is properly chosen, it has different indices depending on the polarization direction when stretched in a long direction. On the other hand, the material surrounding nanofibers inside a mother fiber does not have birefringence under stretching. If the refractive index of the nanofiber is controlled so it matches that of the neighboring medium for the polarization perpendicular to the fiber. The light will recognize the fiber structure as a uniform medium instead of complicated nano-structure for the perpendicular polarization. As for the light polarized parallel to the fiber, it experiences the index difference at the surface of nanofibers. The index difference induces the reflection,

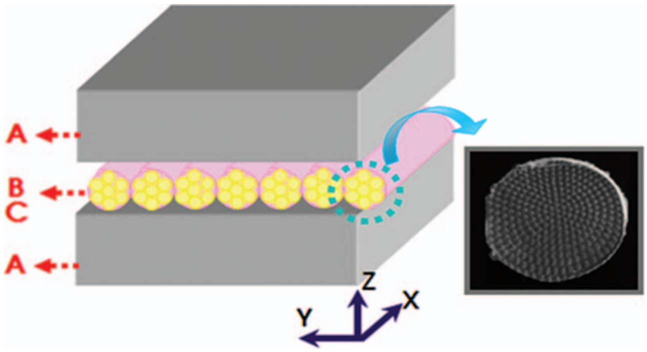

Figure 2. Nanofiber has birefringence, which makes the indices different in x and other directions. A, B and C represent different polymers.

which adds up to a significant level as the light passes the multiple layers of nanofibers. Since the mother fiber contains hundreds of nanofibers, a sheet consisting of a few layers of the mother fibers gives the same effect as tens of stacks of nanofibers. In this manner, the reflection at the surface of nanofibers goes up to a significant level. Since the dielectric material ideally does not absorb the light, the reflection increases monotonically with the increase of layer thickness.

As noted earlier, the author selected the FDTD method in order to calculate the polarization characteristics of dielectric nanofibers. The FDTD method is being widely used nowadays to solve the Maxwell equation in regards to the field of wireless communication and nanophotonics [6,7]. In principle, the FDTD method is precise, even at a scale limit smaller than a wavelength, as far as numerical errors and quantum effects are ignorable. Since the nanofibers treated in this paper are usually larger than a tenth of a wavelength, the FDTD approach is presumed to give good numerical data which cannot be obtained by applying the scalar diffraction theory. In the simulation, we used a three-dimensional (3D) FDTD with periodic boundary conditions in the y direction, which saved a significant amount of computation time and enabled the scanning of a wide parameter range compared to nominal 3D calculations. The periodic 3D FDTD assumes that a physical situation is symmetrical along one axis in terms of optical structure and dipole sources. For instance, if one simulates a circular profile in this quasi-2D model, it corresponds to an infinitely long cylinder in the y direction. Therefore, the periodic FDTD modeling is an efficient tool for analyzing the polarization behavior of nanofibers with accuracy and speed.

Two examples of the permittivity profiles are shown in Fig. 3. The first nanofiber film, as noted in the examples, was composed of 124 layers of dielectric nanofibers, in which the diameter was about 500 nm. The diameter and the number of layers varied, depending on the parameter to scan in each calculation. The period was assumed to be twice the diameter of the nanofiber, and the wavelength used for the simulations was 530 nm. The randomness was assigned to the position and the diameter of nanofibers in order to avoid possible abnormal traits due to the periodic structure because the average coordinates of the nanofibers satisfy a hexagonal lattice. Polarization behavior was basically characterized by the transmission efficiency of a nanofiber film when the plane wave was incident on the layer in a normal direction. The transmission was defined as the ratio of the transmitted energy to the incident energy. The energy of a plane wave was measured by integrating the Poynting vector along the detector line, which was placed parallel to the layer (x direction), before

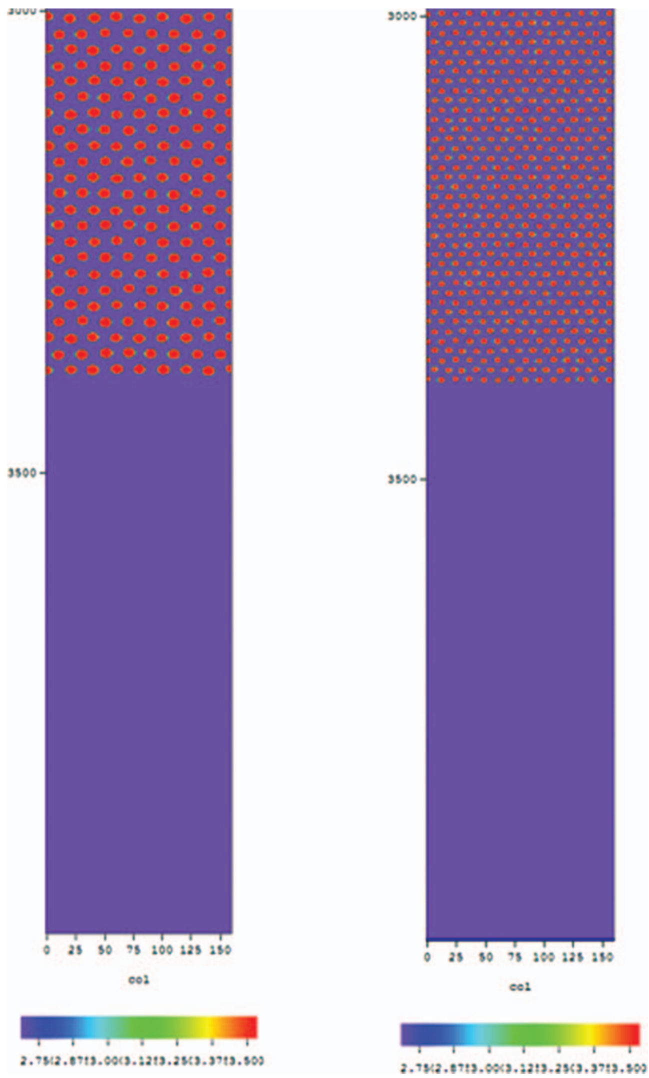

Figure 3. The examples of the permittivity profiles used in FDTD simulation. When t and d represent the thickness of the layer and the diameter of the fiber, respectively, (a) t = 108 μm, d = 0.5 μm and (b) t = 108 μm, d = 0.3 μm.

and after the wave went through the block of layers. In the same manner, the reflection was defined as the ratio of the reflected energy to the incident energy. As for the polarization, E_x and E_y polarization existed since the plane wave propagated in a z-direction. However, the simulation was not performed for E_x polarization since the nanofiber was supposed to have the same refractive index as that of the neighboring medium. Therefore, it did not cause reflection at the interface as mentioned earlier.

Results and Discussion

The transmission of the polarized light through nanofiber layers was calculated with various diameters of nanofiber and thicknesses of nanofiber film. The two instances of the calculated

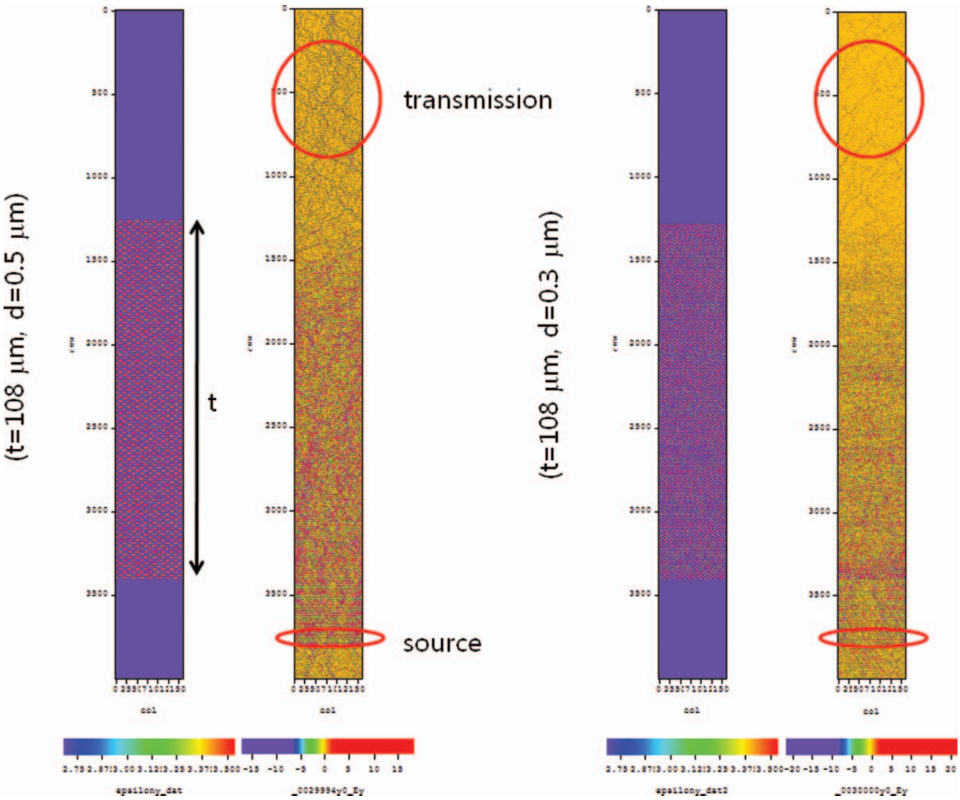

Figure 4. The permittivity profiles(left) and the electric field distributions(right) for the two RPS structures: (a) t = 108 μm, d = 0.5 μm and (b) t = 108 μm, d = 0.3 μm.

electric field profiles are displayed in Fig. 4. Each result showed the permittivity profile on the left and the electric field distribution on the right for comparison purpose. In Fig. 4, the positions of source dipoles and the transmitted wave are designated with circles. Also, the thickness of the nanofiber layer is denoted as **t** in the figure. Fig. 4 indicates that a nanofiber layer with the diameter of 0.3 μm has a lower transmission than that of the one with a diameter of 0.5 μm. The simulation results are summarized in Fig. 5. In essence, the transmission decreased as the layer thickness increased for all diameters of the nanofibers. However, the slope of the curve depended on the diameter of the nanofiber. For a given thickness of the layer, 0.3 μm had the lowest transmission. The transmission of 0.4 μm, 0.5 μm, and 0.2 μm followed in ascending order. The smallest diameter did not guarantee the lowest transmission since 0.2 μm had the highest transmission. This indicated that the transmission can fluctuate as the diameter shrinks. Since the reflection of the film was caused by the reflection of individual nanofibers, the reflected wave can interfere partially in small scale. Therefore, the interference can play a more important role in the nanofiber film of small diameter. Considering that the wavelength was 0.53 μm and the index of nanofiber was 1.88, the diameter of 0.3 μm corresponded to about two wavelengths in terms of the round trip optical path. If the constructive interference occurred at the diameter of 0.3 μm, then the next peak should have appeared at 0.15 μm. Therefore, the 0.2 μm is between

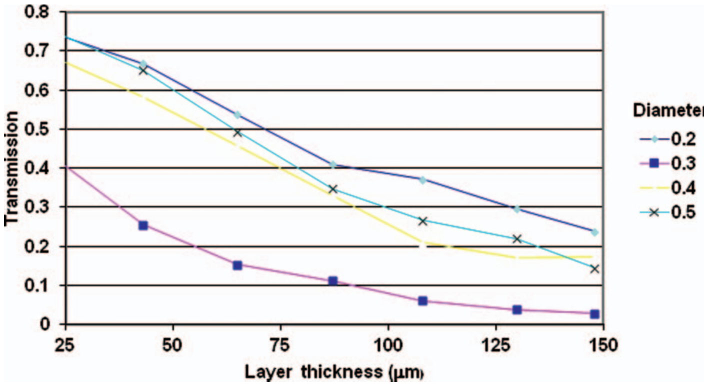

Figure 5. Transmission of RPS based on a nanofiber as a function of layer thickness and the diameter.

those two constructive interference peaks. In other words, it was close to the destructive interference. Therefore, interference may explain the soaring of transmission at 0.2 μm.

In order to confirm the exponential behavior of the transmission curve, it was converted into a logarithmic plot as shown in Fig. 6. The data showed linear decay in the log plot, which meant the data had exponential decay as a function of the layer thickness. From the slope of the curve in the log plot, the attenuation factor was extracted. The attenuation factors were 0.011, 0.0059, 0.0051, and 0.0042 per micron for the diameters of 0.3, 0.4, 0.5, and 0.2 μm, respectively. The highest attenuation factor was four times larger than that of the smallest one. In this way, the polarization characteristics of dielectric nanofiber film were greatly affected by the diameter of the nanofiber. Consequently, the polarization characteristics of the RPS based on dielectric nanofiber can be optimized through the future research on the effect of the smaller diameter and the density of the nanofibers in the film.

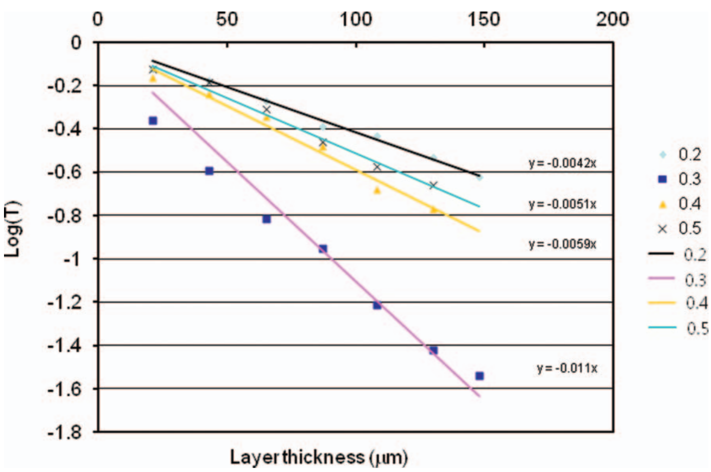

Figure 6. The extinction coefficients for different diameters were calculated from the log plot of transmission curve.

Conclusions

A RPS based on the nanofibers was analyzed using the FDTD method. This type of RPS is basically a polymer sheet containing the birefringent nanofibers with surrounding non-birefringent polymer. The nanofibers has an index matching with the host matrix in a direction perpendicular to the fibers and an index mismatching parallel to the fibers. The nanofiber and non-birefringent polymer is converted into fabric form and laminated into a sheet.

Numerical calculations were carried out to find the mechanisms of nanofiber-based RPS using the FDTD method. The simulations showed that the birefringence of nanofiber layers can make a reflective polarizer with small energy loss. In addition, the simulations demonstrated that the diameter of nanofibers and the spacing between them affect the extinction coefficient of RPS depending on the polarization. The calculated attenuation factors of transmission were 0.011, 0.0059, 0.0051, and 0.0042 per micron for the diameters of 0.3, 0.4, 0.5, and 0.2 μm, respectively. The interference can play a more important role in the nanofiber film of small diameter. Therefore, the polarization characteristics of the RPS based on dielectric nanofiber can be optimized by varying the diameter and the density of the nanofibers in the film.

Acknowledgment

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