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Multilayer Wavelength-Selective Reflector Films for LCD Applications

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SUMMARY We designed multilayer wavelength-selective reflector films by stacking thin-films of transparent polymer. The optimum structure of the multilayer is determined using a combination of characteristic matrix method and a version of genetic algorithm. Such multilayer films can be used in LCD devices to enhance the color saturation of the display.
key words: *optical design, multilayer, color enhancement film, LCD, genetic algorithm*

1. Introduction

Multilayer plastic films capable of showing iridescent colors were developed for display purposes [1]. Recently, multilayered reflector films are designed and developed for broad wavelength band, broad angular range applications [2]–[4]. Such films are commonly used in liquid crystal displays (LCDs) to increase the overall brightness without affecting the color saturation of the LCD devices.

Typically, such multilayer films are composed of hundreds of coextruded thin layers of polymer. Thickness of any individual layer is less than the wavelength (λ) of visible light, typically less than 200 nm. The multilayer is a periodic or quasi-periodic structure that is formed by repeating one basic unit containing two layers of two different materials (say, A and B). Layers A and B are chosen from transparent, non-absorbing polymers. In case of polarizing reflectors, one of the layers (say, A) is optically isotropic while the other layer is uniaxially birefringent. Such films are highly reflective in one polarization mode and are highly transmissive in the orthogonal polarization mode.

Many methods are available for the design of thin film multilayers [5]. In recent times, the automatic design methods based on local and global optimization techniques attracted much attention. Various authors have used genetic algorithm (GA), a global optimization technique, to design multilayers possessing uniformly high reflectivity over a broad range of angles [4], antireflection properties for infrared wavelengths [6], high reflectivity over a narrow band of wavelengths [6], [7], and high reflectivity in extreme ultraviolet light [8].

In this paper we discuss the design process of a wavelength-selective multilayer film. The film can also function as a polarizing reflector. Such films might be used in LCDs to enhance the color saturation of the device. Our computations reveal that the structure of wavelength-selective (WS) reflector film can be simpler than the conventional broadband multilayer film. This fact also makes the fabrication of our structures significantly easier and cheaper compared to the existing broadband multilayer films.

A computer program is developed. The program implements a combination of a characteristic matrix method and a version of GA and is used to design the wavelength-selective (ws) multilayer film mentioned above. The refractive indices and thicknesses of layers A and B are determined so that the reflectivity spectrum in one polarization mode matches a prespecified target spectrum.

The design method is described in Sect. 2. The reflectivity spectra of the optimum multilayer structure as obtained from the program and the proposed application of the same in LCD devices are described in Sect. 3. A discussion of the design process and the optimum solutions are presented in Sect. 4.

2. Design Method

Figure 1 shows the basic unit of the multilayer consisting of two layers A and B. The principal refractive indices of layers A and B are nA_x, nA_y, nA_z and nB_x, nB_y, nB_z respectively. tA and tB are the thicknesses of the layers A and

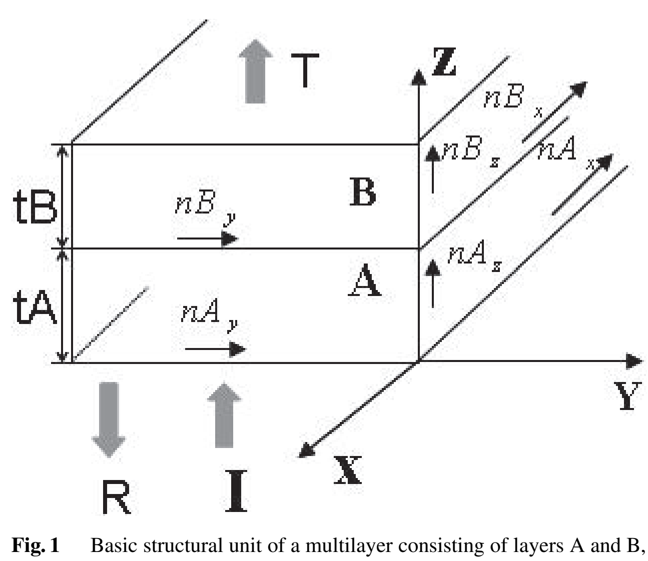

Fig. 1 Basic structural unit of a multilayer consisting of layers A and B, the directions of incident, reflected and transmitted light are indicated with the letters I, R and T respectively.

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B respectively. We consider the case of normal incidence where the incident and transmitted light propagate along the z-axis while reflected light propagates along $-z$-axis.

2.1 Characteristic Matrix

The reflection and transmission properties of a thin-film layer can be computed from a 2×2 matrix known as characteristic matrix [9]. The elements of this matrix are obtained by solving the Maxwell's equations analytically and implementing the boundary conditions on the electric and magnetic fields at any interface between two consecutive layers. The boundary conditions require that the tangential components of the electric and magnetic vectors are continuous across the interface. This solution is appropriate when the lengths of the films in directions normal to the plane of incidence can be assumed to be infinite.

The characteristic matrix, M_{AB} for the basic unit shown in Fig. 1 is given by [9]

$$M_{AB} = M_A M_B \tag{1}$$

where M_A and M_B are the characteristic matrices for layers A and B respectively. M_A and M_B are determined by the admittances αA, αB of layers A and B respectively. In transverse electric or TE (electric field is normal to the incidence plane, yz) and transverse magnetic or TM (electric field is in the incidence plane, yz) modes, for normal incidence, αA and αB are given by [2]

$$\alpha A_{TE} = nA_x \tag{2}$$
$$\alpha B_{TE} = nB_x \tag{3}$$
$$\alpha A_{TM} = nA_y \tag{4}$$
$$\alpha B_{TM} = nB_y \tag{5}$$

In Eqs. (2) and (5), the subscripts TE and TM stand for the TE and TM modes respectively. The optical thicknesses ηA and ηB of layers A and B are given by

$$\eta A_{TE} = \alpha A_{TE} \cdot tA \tag{6}$$
$$\eta B_{TE} = \alpha B_{TE} \cdot tB \tag{7}$$
$$\eta A_{TM} = \alpha A_{TM} \cdot tA \tag{8}$$
$$\eta B_{TM} = \alpha B_{TM} \cdot tB \tag{9}$$

The condition for constructive interference for the pair of layers shown in Fig. 1 is given by

$$\eta A + \eta B = q\frac{\lambda}{2} \tag{10}$$

where q is an odd number. If Eq. (10) is satisfied at a wavelength λ, corresponding reflectivity reaches a maximum.

For a stack consisting of N basic units, the characteristic matrix M is given by [9]

$$M = (M_{AB})^N \tag{11}$$

Reflectivity of the stack can be computed using the elements of M. If the elements of M are $m_{1,1}$, $m_{1,2}$, $m_{2,1}$ and $m_{2,2}$, the reflectivity of the stack is given by

$$R = \left(\frac{(m_{1,1} + m_{1,2}n_L)n_F - (m_{2,1} + m_{2,2}n_L)}{(m_{1,1} + m_{1,2}n_L)n_F + (m_{2,1} + m_{2,2}n_L)}\right)^2 \tag{12}$$

In the above n_F and n_L are the refractive indices for the incident and the emergent media respectively.

2.2 Optimization

The problem of design of the multilayer film is formulated as a constrained optimization problem. The performance of a multilayer is estimated in terms of the difference between the reflectivity spectrum of the multilayer and a prespecified target spectrum. A merit function ϕ is defined to measure this difference. ϕ is given by

$$\phi = \frac{1}{N_\lambda}\sum_{j=1}^{N_\lambda}(R_j - \rho_j)^2 \tag{13}$$

where N_λ is the total number of wavelength sampling points. R_j is the reflectivity of the multilayer at the wavelength sampling point λ_j. ρ_j is the target reflectivity at λ_j. Here, N_λ is 60 (interval = 5 nm), in the wavelength range [400 nm, 700 nm].

ϕ is minimized using a GA method. GA is a stochastic intelligent search method. The algorithm starts with a population of randomly generated solutions. Each solution represents a multilayer structure. The solutions are updated through a given number of generations by applying various operators that roughly mimic the natural evolution process. The evolution process is implemented with the help of operators, such as, tournament selection, uniform crossover and bit mutation [10]. Apart from the three major operators mentioned above, a measure of genetic diversity is introduced to ensure sufficient diversity in the population as it progresses through newer generations. This avoids stagnation around a local optimum.

A speciation scheme is incorporated in order to be able to identify a number of local minima as well as the global minimum.

A brief description of the major operators is provided below.

2.2.1 Design Variables

The design variables are: nA_x, Δn (= nB_y- nA_x) and the six layer thicknesses for the three basic units corresponding to three stacks, e.g., tA_1, tB_1, tA_2, tB_2, tA_3, tB_3. The search for suitable solutions are conducted within a design space defined by following ranges for the eight design variables: [1.45, 2], [0.0, 0.15], [5, 205] [5, 205], [5, 205], and [5, 205]. Thicknesses are specified in nanometer scale.

2.2.2 Binary Coding of Variables

Each design variable is represented as a fixed-length binary substring of 0's and 1's. When decoded, any binary substring s of length l converts to a specific value of the design variable x. This value of x is given by

$$x = x_{min} + \frac{x_{max} - x_{min}}{(2^l - 1)} DV(s) \tag{14}$$

where x_{max} and x_{min} are the maximum and minimum allowed values of x, $DV(s)$ represents the decoded decimal equivalent of s and l is decided by the minimum step allowed in the respective variable.

The structure of any particular multilayer is specified by a binary string S, generated by combining the substrings representing all the design variables. S is given by

$$S = s_v s_{v-1} s_0 \tag{15}$$

where v is the number of variables and $v = 8$.

2.2.3 Tournament Selection

This operator mimics the process of mate selection observed in nature. The fittest among a set of randomly chosen solutions get selected to a mating pool with a preassigned probability p_t.

2.2.4 Uniform Crossover

This operator effectively explores the design space. A pair of bit strings are selected from the mating pool with a probability p_c. A next generation bit string is created from the two parent bit strings by combining bits from each of them according to a randomly generated crossover mask.

2.2.5 Bit Mutation

This operator facilitates local search. It randomly alters each bit of the bit string with a small probability p_m.

3. Multilayer Film: Structure and Optical Properties

The target spectrum is constructed by adding the emission spectra of the red, green and blue LEDs from Philips Lumileds Lighting Company and shows three peaks approximately at $\lambda_B = 462.5$ nm, $\lambda_G = 532.5$ nm, and $\lambda_R = 632.5$ nm. In keeping with the three peaks of the target spectrum the solution is sought among populations of three stack multilayers. We set A as an isotropic layer and B as a uniaxially birefringent layer. A and B are chosen in a way to ensure following relationship among the refractive indices:

$$nA_x = nA_y = nA_z = nB_x = nB_z \neq nB_y \tag{16}$$

All the three basic units of the three stacks use layers A and B, albeit, with differing thicknesses. Figure 2 shows the target spectrum and the reflectivity spectra of an optimized multilayer in TE and TM modes. The optimum solution is: $nA_x = 1.6097$, $\Delta n = 0.1$, $tA_1 = 117.07$ nm, $tB_1 = 74.17$ nm, $tA_2 = 49.48$ nm, $tB_2 = 89.36$ nm, $tA_3 = 79.66$ nm, $tB_3 =$ 81.31 nm. Number of layers in each stack is chosen to be 80 to ensure that peak reflectivity of each stack is above 90%. Corresponding value of ϕ is 1.639. The GA parameters are as follows: population size of solutions = 500, number of generations = 100, tournament size = 5, $p_t = 0.8$, $p_c = 0.8$, $p_m = 0.01$.

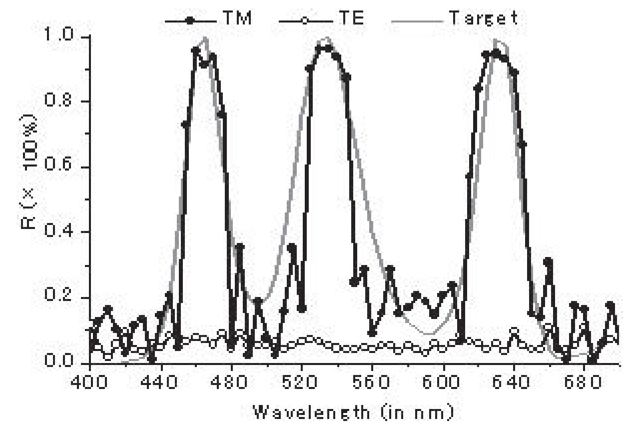

Fig. 2 Reflectivity (R) spectra of the WS multilayer film.

3.1 Application in LCD Devices

Figure 3 illustrates how the WS multilayer film can enhance color saturation of the LCD device.

Figure 3a shows a proposed configuration of the LCD employing the WS multilayer film. This figure only shows the optical components most relevant to the workings of the WS multilayer film. An edge-lit type display is shown. A light guide plate (LGP) is illuminated with the help of a light source placed to the side of the LGP.

In Fig. 3b, the wavelength spectrum of light transmitted from the WS multilayer film is shown. Light transmitted from the multilayer film is mostly polarized in TE mode and is composed of the light that comes out of the light source and gets transmitted directly through the multilayer film and the recycled light that comes back after reflection. The light reflected from the multilayer film is polarized mostly in TM mode and shows three peaks in the red, green and blue region of the visible spectrum. The amount and polarization state of the recycled light depends on the reflection spectrum of the reflector film at the back of the LGP and any diffuser plates or polarization converters that might be used in the path of light. The transmission spectrum in Fig. 3b is computed as the sum of directly transmitted light and the recycled light. We assume that 25% of the output is due to recycling. In comparison with Fig. 3b, the transmission spectrum of a conventional broadband multilayer film is flat. Clearly, the use of the WS multilayer film leads to an output spectrum that depends strongly on the color of light.

The output from the multilayer film passes through the liquid crystal (LC) panel before it finally leaves the LCD device and reaches the observer. The LC panel consists of at least a conventional color filter and liquid crystal cells. The

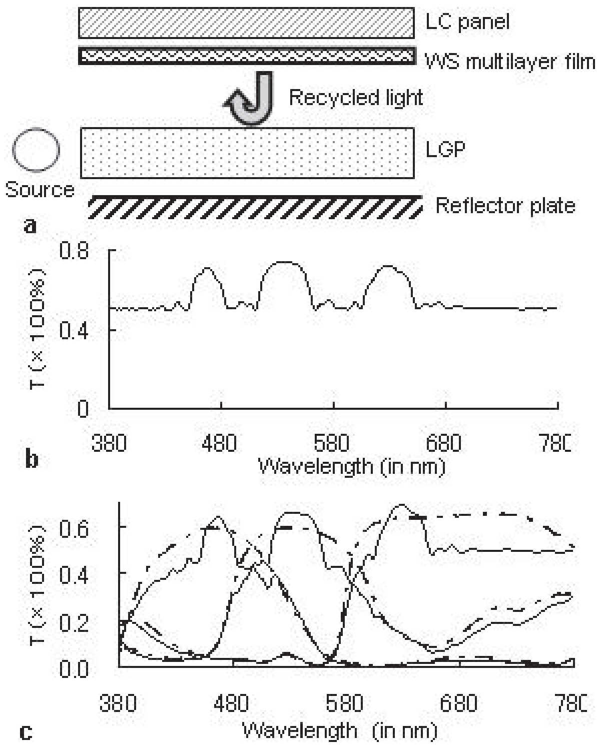

Fig. 3 Color enhancing effect of the WS multilayer film; (a) schematic diagram of the proposed LCD configuration, (b) TE mode transmission (T) spectra of the WS broadband multilayer films; (c) transmission (T) spectra of the LC panel using WS (solid) and conventional broadband (dashed) multilayer films.

color filter is composed of at least three filters; red, green and blue capable of transmitting the red, blue and green portions of the visible light respectively. Hence, the wavelength spectrum of the light emerging from the LC panel is determined by the transmission properties of the color filter.

In Fig. 3c, the wavelength spectrum of the light coming out of the LC panel is shown. The solid line curve shows the output spectrum obtained with the WS, multilayer film. The dashed line curve is obtained with a conventional, broadband multilayer film. A comparison between the two spectra shows that the WS multilayer film is more effective at cutting the light of unwanted wavelengths, and improving the color saturation of the overall display device. Thus, from the point of view of improving the color saturation, the WS multilayer film is clearly more desirable compared to the conventional, broadband multilayer film. The improvement in color saturation depends on the volume of the recycled light. The color saturation of the display device increases as the proportion of recycled light increases.

The color enhancing properties of the WS multilayer film are not limited to the LCD device model shown in Fig. 3a. A real-life LCD device includes additional components, such as, diffuser plates, $\lambda/4$ plates etc. Similarly, an actual LC panel incorporates many other components like, polarizers, compensators etc. Even with the addition of these extra components, the WS multilayer film would still remain useful in enhancing color saturation.

4. Conclusion

We presented a general design method for multilayers. A multilayer is accepted as a solution if it's reflection properties match a given target spectrum closely. The solutions are not limited to layers of optical thickness equal to $\lambda/4$. Also, solutions can be obtained for many different shapes (different bandwidths corresponding to three peaks) of the target spectrum. In the design example provided here, Δn, the difference between refractive indices of the two layers of the basic unit along y-axis and N, the total number of layers comprising the multilayer is much smaller than those used in conventional, broadband multilayer films (typically, $N \geq 800$, $\Delta n \geq 0.24$ and layer thicknesses are less than 200 nm). The relatively smaller values for both Δn and N make such films easier and cheaper to fabricate. The wavelength spectrum of the reflectivity of the multilayer depends strongly on the value of Δn. A desirable range for Δn is $0.02 < \Delta n < 0.25$. If Δn is greater than 0.25, reflectivity becomes high and uniform for relatively broader band of wavelengths around the chosen peaks in red, green and blue region of the visible spectrum. If Δn is lesser than 0.02, reflectivity peaks are unacceptably low.

The WS multilayer film designed here is suitable for use with red, green and blue LED light sources.

If the materials of the layers of the basic units of the multilayer are optically isotropic, same wavelength-selective reflectivity is obtained in both polarization modes.

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