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Low-pass rugate spatial filters for beam smoothing

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ABSTRACT

A new application of rugate structures is proposed as low-pass spatial filters for beam smoothing. By using the transfer matrix method to analyze the spatial properties of the bandgap of rugate structures, the low-pass rugate spatial filters with both an almost ideal flat bandpass and a rather steep switching between pass- and stop-bands are designed. The angle-domain bandwidth of the spatial filters can be adjusted by changing the parameters of rugate structures for a given light frequency. The near-field simulations carried out by using the finite-difference time-domain technique confirm the possibility of an efficient light smoothing.

1. Introduction

Many applications in optics require the use of beams of a good spatial quality characterized by a smooth envelope and, respectively, a narrow spatial spectrum. The "clean" beams diverge less in propagation, and they can be focused more tightly and robust against nonlinear filamentation than the "dirty" ones. In laser science, the beam smoothing is usually achieved by using low-pass spatial filters. A simple and conventional low-pass spatial filter is implemented by the use of a telescope consisting of two focusing lenses in a confocal arrangement and an appropriate pinhole in the focus plane [1–3]. The pinhole lets the passing of the low angle-domain components and the blocking of the undesired high ones (related to the "noisy" part of the beam); therefore the beam after passing through the low-pass spatial filter is smoothed. The system, although widely used, has several deficiencies as a relatively large size (at least four focal lengths long), high sensitivity to alignment (since the focused beam must past exactly through the middle of the pinhole) or the absence of efficient focusing lenses in infrared and in ultraviolet frequencies [3,4]. The spatial filters may also be applied to image enhancement and information processing in several regions of the electromagnetic spectrum, such as spatial spectrum analysis, matched filtering, radar data processing, aerial imaging industrial quality control, and biomedical applications.

Currently, some slab spatial filters are performed for the purpose of overcoming the disadvantages of conventional spatial filters [3–12]. The possibilities for the realization of the low-pass, high-pass, and bandpass spatial filters have been demonstrated, whereas the slab filters based on the resonant grating systems [5,6], multilayer stacks combined with a prism [7] and two-dimensional photonic crystals [4,8–10] are only used as one-dimensional spatial filters. However, beam smoothing in fact demands two-dimensional spatial filtering. The spatial filters including metamaterials [3,11,12] can realize two-dimensional spatial filtering, but the fabrication of metamaterials is more difficult than that of multilayer stacks or photonic crystals since the structure unit of metamaterials is much less than the wavelength of light transmitting inside them. As a result, the way to realize two-dimensional spatial filtering for beam smoothing by using metamaterials is limited in practice. Thus it is necessary to do further work on the easily realizable spatial filters for beam smoothing.

Rugate structures are optical thin film with graded refractive-index profiles. Compared with conventional multilayer stacks, they have some advantages including low internal stress, suppression of sidelobes, and continuous index matching for broadband antireflection coatings [13–19]. Hence the performance of some devices such as frequency filters can be greatly improved, and spatial and spatial–frequency filtering using one-dimensional graded-index lattices with defects is proposed [20]. In this paper, we utilize the the spatial properties of the bandgap of rugate structures to design the low-pass spatial filters with both an almost ideal flat bandpass and a rather steep switching between pass- and stop-bands. The effects caused by the spatial filters on two-dimensional beam smoothing are demonstrated by using the finite-difference time-domain simulations.

2. Structure model and numerical simulation

In order to obtain a strongly pronounced frequency property of very smooth high transmittance regions on both sides of the stop-band, we consider the 51-layer Gaussian half-apodized rugate

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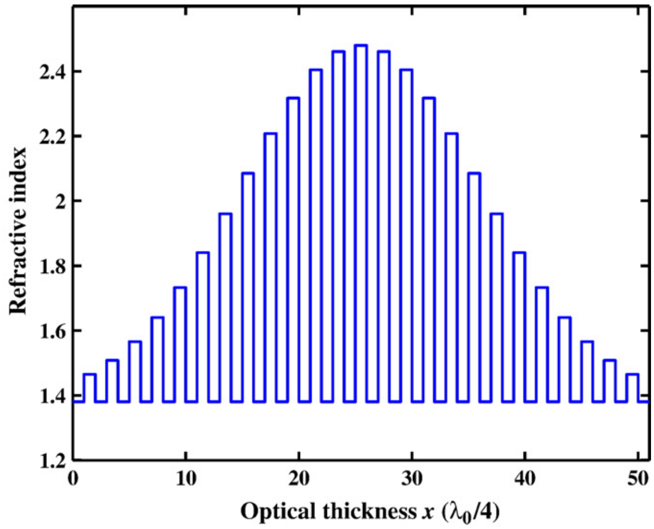

Fig. 1. Refractive-index profile of the Gaussian half-apodized rugate structure. Structure parameters: the substrate index $n_L = 1.38$, the peak-to-peak refractive-index variation $n_p = 1.2$, optical thickness of each layer $d_{opt} = \lambda_0/4$, and $\sigma = 6 \times 10^{-3}$.

structure on a LiF substrate. Its refractive-index profile is shown in Fig. 1, and can be written as [16]

$$n(x) = n_L + \frac{1}{2} n_p [1 + (-1)^m] e^{-\sigma m^2}, \tag{1}$$

where $n_L = 1.38$ (LiF) is the lowest index, $n_p = 1.2$ is the peak-to-peak refractive-index variation, $\sigma = 6 \times 10^{-3}$ is a constant which is chosen so that the refractive index reaches n_L at both ends of the profile; m is the corresponding layer order for optical thickness x, and optical thickness of each layer d_{opt} is one fourth the wavelength at the bandgap center, i.e., $d_{opt} = \lambda_0/4$. For this structure, we only consider the TE polarization when the electric field is parallel to the slab layers.

By using the transfer matrix method [11,12,21], we first calculate the transmittance spectra of the Gaussian half-apodized rugate structure with the different incident angles $\theta = 0°, 20°, 40°$, and $60°$ [Fig. 2(a)–(d)]. The corresponding transmittance spectra of the conventional multilayers with the same index contrast are shown in Fig. 2(a′)–(d′). The frequencies are normalized as f/f_0 ($f_0 = c/\lambda_0$), where c is the speed of light in a vacuum. It is clearly shown from Fig. 2 (a), (a′) that the normalized center frequency of the bandgap at normal incidence is 1, owing that the rugate structure and conventional multilayer are both quarter-wavelength stacks. Besides that, compared with the conventional multilayers, the rugate structures improve the spectral response (i.e., maintain high bandgap reflectance and sharp bandgap) and appreciably suppress the side-lobes. However, this good performance is weakened with the increase of incident angle, and even rather strong oscillations occur at the upper edge of the lowest band at $\theta = 60°$. Fig. 2(a)–(d) also shows that, with the increase of the incident angle, the bandgap will shift to high frequency, and the upper frequency shifts larger than the bottom frequency of the bandgap, which are a prerequisite for the realization of the rugate spatial filters.

Other rugate structures could have similar bandgap properties as the Gaussian half-apodized rugate structures. For comparison we investigate the Gaussian apodized index profile shown in Fig. 3(a), which can be expressed as [15,16]

$$n(x) = n_L + \frac{1}{2} n_p (-1)^m e^{-\sigma m^2}. \tag{2}$$

Here the structure parameters are the following: the substrate index $n_L = 1.8$, the peak-to-peak refractive-index variation $n_p = 1.0$, optical thickness of each layer $d_{opt} = \lambda_0/4$, and $\sigma = 6 \times 10^{-3}$. Fig. 3(b)–(e) shows the transmittance spectra at the different incidence angles. It is seen in Figs. 2(a), 3(b) that the Gaussian apodized rugate structure can also be used to realize the same good frequency property of very smooth high transmittance regions on both sides of the stop-band. Therefore, we can conclude that other rugate profiles with a suitable choice of structure parameters can also be used for achieving the desired bandgap properties [14–17].

Based on the spatial properties of the bandgap, we next design a new low-pass spatial filter made from rugate structures. Keeping in mind the reasons of easy control and fabrication of the optical structures [16], we choose the Gaussian half-apodized rugate structure (Fig. 1) in the following discussion. Usually, spatial filters have a very narrow frequency bandwidth or even the monofrequency. In our work, the normalized center frequency of the low-pass rugate spatial filter is higher than the upper frequency of the bandgap at normal incidence in Fig. 2(a). The blue solid curve in Fig. 4 shows the

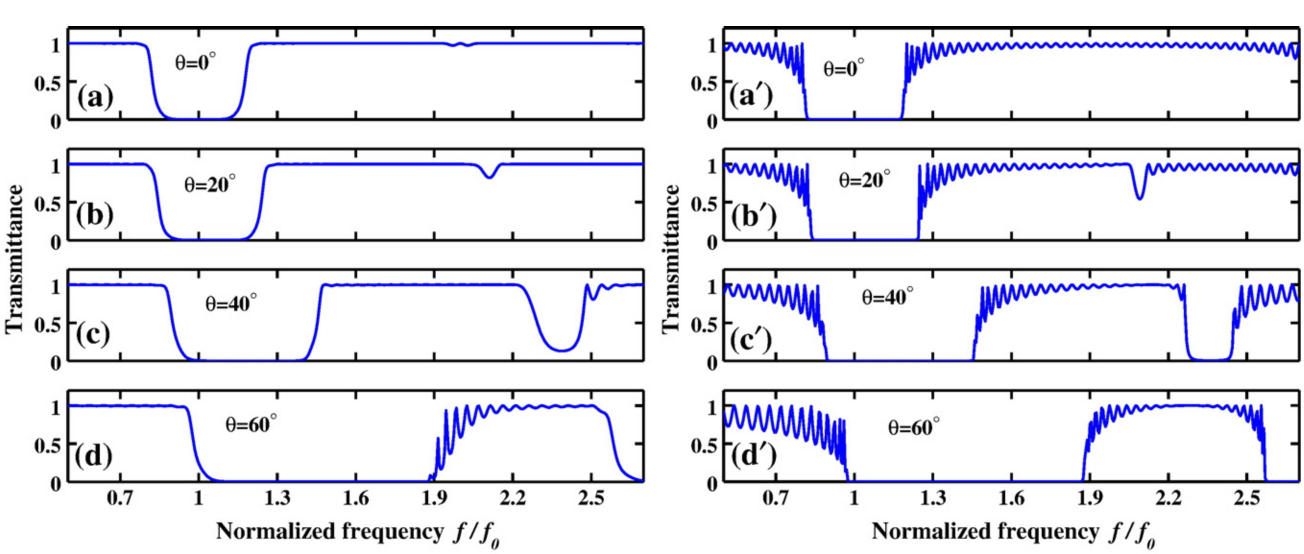

Fig. 2. Transmittance spectra of the Gaussian half-apodized rugate structure in Fig. 1 at the different incidence angles: (a) $\theta = 0°$, (b) $\theta = 20°$, (c) $\theta = 40°$, (d) $\theta = 60°$; (a′)–(d′) the corresponding transmittance spectra of the conventional multilayers with the same index contrast.