Design of polarization insensitive filters with micro- and nano-grating structures

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For isotropic dielectric thin films, polarization effect is an inherent characteristic. As it will make the performance of optical-electric system go to bad, such polarization-dependent properties are often intolerable and should be eliminated in many applications. In this paper, based on a micro- and nano-optical structure whose period consists of four parts, a polarization insensitive filter is obtained by combining rigorous wave theory and multi-objective immune optimization algorithm. Its working wavelength is 1315 nm which is often used in laser systems. The results of our design show that TE and TM polarized waves have reflectivities of 0.482 and 0.485, respectively at designed wavelength of 1315 nm. And it denotes that two values are both close to the design values, their difference is only 0.003, and polarization deviation is also very little. Therefore, the designed filter can eliminate the effect of polarization deviation very well at 1315 nm wavelength.
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When used at oblique angles of incidence, the reflectances and transmittances about S and P light are different. This strong polarization is inevitable, and it is a desirable property to design polarizers. However, it is undesirable and should be reduced in more applications. Many methods have been used to solve this difficult problem. Most theoretical design procedures are valid for a limited wavelength and/or angular range. And their structures are usually very complicated for too many layers and kinds of coating materials[1,2]. The design and fabrication of non-polarizing beam splitters is still a challenging topic.

Moreover, periodic layers and lattices exhibit many particular characteristics with the development of micro- and nano-technology. Essentially, the sub-wavelength grating can be regarded as an equivalent thin film as its period is much smaller than the incident wavelength. Based on this, sub-wavelength gratings have been expected to realize special functions by combining the actual structure with the theory of optical thin film. In this case, the design work based on sub-wavelength grating structure has been greatly simplified. For example, the design process about shallow grating filter[3], resonance Brewster filter[4], transmission or reflection guided-mode resonance filter[5], broadband high reflection mirror[6], and anti-reflection mirror[7,8]. These research works are usually operating under normal incidence, and their filtering properties should depend on the polarization of the incident beam.

Many papers reported the design of polarization beam splitter by using different kinds of sub-wavelength gratings[9,10] to control polarization state based on micro- and nano-grating structure, but for non-polarization filter design in which polarization effect is insensitive, the relevant reports are very few. Only several design results based on guide-mode resonance effect are reported, which are valid under normal incidence[11,12]. In this paper, based on guide-mode resonance effect, combined with rigorous coupled-wave analysis and multi-objective optimization algorithm, a polarization insensitive filter at 1315 nm and 45° oblique incidence is realized.

Usually, a rectangular groove grating structure is composed of two materials with refractive indices of $n_{\rm H}$ and $n_{\rm L}$ with duty cycle of F. Other parameters of this kind of two-part grating are groove depth d and period Λ. A plane wave is normally or obliquely incident at an angle of θ upon the binary dialectic grating. Then the grating is bound by incident medium with refractive index of n_0 and substrate material with refractive index of $n_{\rm S}$.

In this paper, we resort to a different guide-mode resonance configuration, in which each period is composed of two grating ridges with identical width, as shown in Fig.1(b). In essence, this four-part period grating enables a rich set of Fourier harmonics with concomitant emergence of additional spectral features not available for the classic two-part period grating.

For the proposed structure in Fig.1(b), the spatially modulated permittivity in the grating region can be ex-

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panded into Fourier series as

$$\varepsilon(x)=\sum_n \varepsilon_n \exp\left(\mathrm{i}\frac{2n\pi x}{\Lambda}\right), \quad (1)$$

where the grating Fourier harmonics ε_n are given by

$$\varepsilon_0=(1-F_2-F_4)n_{\mathrm{H}}^2+(F_2+F_4)n_{\mathrm{L}}^2, \quad (2)$$

$$\varepsilon_n=(n_{\mathrm{H}}^2-n_{\mathrm{L}}^2)\frac{\sin[n\pi(1-F_4)]-\sin(n\pi F_2)}{n\pi},$$

$$(n=\pm1,\pm2,\cdots,\pm N). \quad (3)$$

According to the rigorous coupled-wave theory, the coupled wave equation can be deduced from Maxwell equations by Fourier expansion of the relative dielectric constant and electromagnetic field in the grating region. Combining it with boundary condition on both sides of the grating, we can calculate the eigenvalue and eigenfunction. Then diffraction efficiencies and amplitudes of different diffraction levels in transmission or reflection region can be gained.

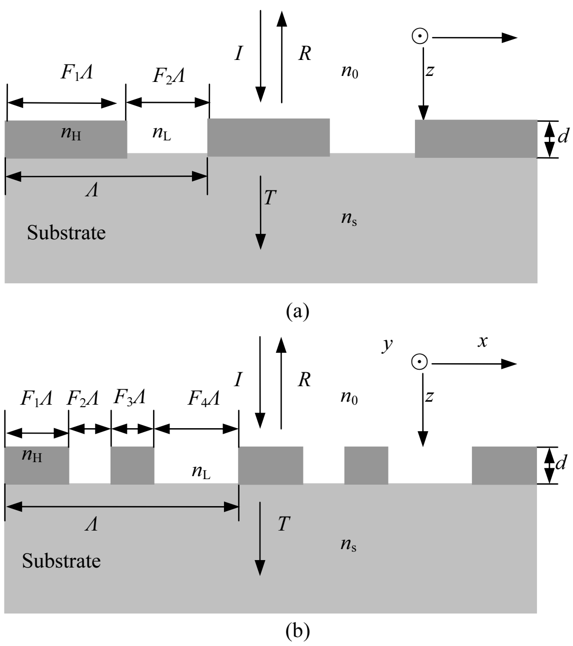

Fig.1 Schemes of the two types of waveguide grating structures: (a) Two-part period; (b) Four-part period

If we resort to a polarization insensitive filter based on this four-part period grating, we could make its spectral response meet the requirement of design objective by adjusting its structural parameters (F_1, F_2, F_3, F_4; Λ, d). To find optimal filter parameters, we adopt analysis/simulation and design/optimization methods. Thus, we numerically solve fundamental electromagnetic equations with pertinent boundary conditions using the rigorous coupled-wave analysis method firstly. This method provides the computational kernels in the design process that is rooted in optimization algorithm. In this paper, we adopt a nonlinear multi-objective immune optimization algorithm in the design process. That is proposed based on humoral immune response principle and ideas of T cell regulation[13]. It includes several vital schemes: constrain handling scheme associated with uniform design reported, specialized antibody affinity design, adaptive antibody evolution mechanism, immune selection, memory pool, antigen pool, and dynamically variable sizes of evolving populations as well. High degree of distribution and parallel processing are the features of this type of optimization algorithm, which make it particularly be applied to the design problem where the function formula between parameters and objective response is not obvious[14].

We want to design a polarization insensitive filter using multi-objective immune optimization algorithm for 50/50 beam division at the 1315 nm wavelength. Considering that some factors in actual application will lead to wavelength drift, we expand the work wavelength region from single wavelength 1315 nm to waveband 1315±20 nm. The filter will be used under 45° oblique incidence, and the incident medium is air (n_0=1.0). In our design, we firstly choose fused-silica as the substrate material (n_s=1.48), silicon as the grating ridges material (n_{H}=3.48), and air as the grating groove material (n_{L}=1.0). Then, other adjustable structure parameters are filling factor F_i(i=1,2,3,4), grating period Λ and groove depth d.

After the design process of analysis, simulation and optimization, we gain a micro- and nano-scale four-part optical grating. Its actual structural parameters are as follows: Λ=523 nm, F_1=0.0825, F_2=0.2717, F_3=0.3685, F_4=0.2777, and d=807 nm. Fig.2 shows computed reflectance (R_0) and transmittance (T_0) of the TE and TM polarization components under oblique (θ=45°) incidence. As can be seen, at design objective wavelength of 1315 nm, the reflectivities of the zero-order reflected wave about TE and TM polarized parts are 0.482 and 0.485, respectively, and the polarization deviation at this wavelength is only 0.003. So we can say that the spectral response of this element matches the target very well. But we should also find from Fig.2 that the polarization deviation will increase obviously when working wavelength drifts from 1315 nm to long-wave or short-wave

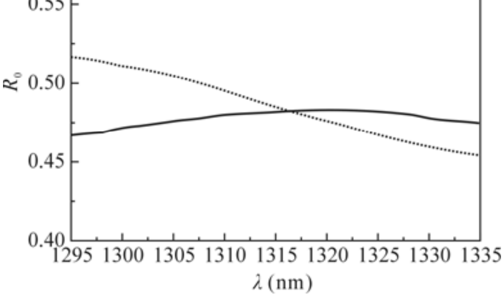

Fig.2 Reflectance curves in the spectral range of our design

direction. However, it can be controlled below 0.5 in wavelength region of 1315±10 nm. This indicates that our design can ensure polarization insensitive at working wavelength of 1315 nm except that the wavelength drift is very serious. A broader spectral view of the reflectance is shown in Fig.3. As can be seen, our design can utilize the spectral response of grating in the wavelength range away from the guide-mode resonance wavelength region.

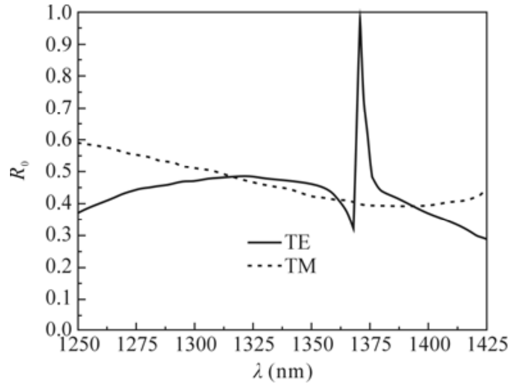

Fig.3 Broad spectral view of reflectance curves

In conclusion, we have introduced a novel polarization insensitive filter with four-part guide-mode resonance grating structure. The proposed structure, in which each period is composed of two grating ridges with identical width, can increase the number of adjustable parameters. In design process, the rigorous wave theory is used to compute spectral response of this device, and the multi-objective immune optimization algorithm is used to establish the structural parameters. The results of our design show that it can eliminate the effect of polarization deviation very well at 1315 nm wavelength. Moreover, it has a compact size. These features make this device suitable for application in optical systems.

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