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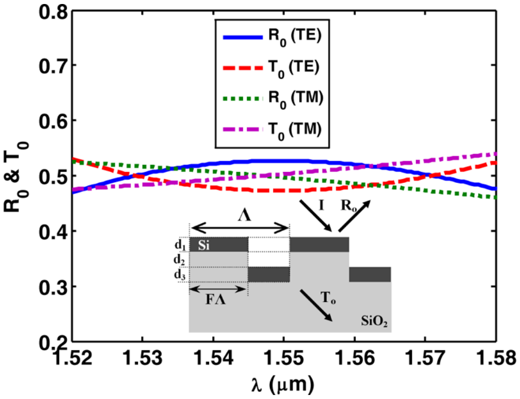

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Abstract: We present wideband nonpolarizing beam splitters (NPBSs) for the telecommunication C-band. We show that silicon-on-insulator subwavelength periodic elements operating near leaky-mode resonance provide useful spectral expressions enabling effective beam division. Particle swarm optimization is the design method of choice. Periodic single-layer and multilevel NPBSs are provided exhibiting ~50/50 beam ratio under oblique and normal incidence. We compare the spectral performance of the beam splitters with that of their thin-film effective-medium counterparts, thereby verifying the resonance-mediated origin of the spectra sought. The beam splitters are found to be reasonably tolerant to deviations in angle of incidence and structural parameters.

Index Terms: Guided-mode resonance, leaky-mode resonance, particle swarm optimization, beam splitters.

1. Introduction

Beam splitters and beam dividers are important elements in optical and photonic systems. There are two main types of beam splitters: a) polarizing beam splitters (PBSs) that separate the polarization components of the input light and b) nonpolarizing beam splitters (NPBSs) that divide the input light beam into two beams traveling in different directions, regardless of their polarization. NPBSs are utilized in many optical systems including interferometers. A common power division fraction is 50/50, but other ratios are also available. Thin-film technology is the dominant means to implement beam splitters, which can be designed for normal and oblique incidence. Traditional NPBSs under oblique illumination are realizable, even though thin film stacks behave differently under transverse electric (TE) and transverse magnetic (TM) polarizations [1]–[4].

Periodic layers and lattices find use in numerous optical systems and devices including communications, medicine, and laser technology. If the lattice is confined to a layer forming a periodic waveguide, an incident optical wave may undergo a guided-mode resonance (GMR), which is also denoted as leaky-mode resonance, on coupling to a leaky eigenmode of the layer system. The external spectral signatures can have complex shapes with high efficiency in both reflection and transmission. The GMR effect in 1-D periodic structures is applied in design and implementation of a variety of optical elements including bandstop/bandpass filters, reflectors, polarizers, and others [5]–[9]. An interesting collection of spectral expressions can be realized even with a single patterned layer [9]. Conjoining resonance photonics and thin-film technology provides enhanced performance and new design aspects. Moreover, applying multilayered interleaved homogeneous and periodic layered structures allows excitation and interaction of multiple leaky modes to further enlarge the variety of spectral expressions that are attainable [10]. In these structures, more than one waveguide and/or coupling grating may be present. Therefore, added flexibility avails in the design stage due to a larger number of available design parameters and degrees of freedom. By judicious device design, adjacent resonances that are supported by the multilevel, layered arrangement enable broadband reflection, polarization, or beam-dividing response.

Nonpolarizing GMR elements have been reported previously in the context of narrowband reflection filters [11]–[15], wideband reflectors [9], and wideband polarizers [16]. Mizutani *et al.* studied and designed a GMR nonpolarizing filter with 2-D rhombic lattice grating structures under 10° (central resonance wavelength $\lambda_R = 688.5$ nm and linewidth $\Delta\lambda_{\mathrm{FWHM}} \sim 0.4$ nm) and 45° ($\lambda_R = 688.5$ nm and $\Delta\lambda_{\mathrm{FWHM}} \sim 0.7$ nm) incidence. They also investigated the effect of fabrication errors on the filter behavior [11]. Lecour *et al.* theoretically demonstrated a narrowband 1-D polarization-independent guided-mode resonant filter for 18° incidence ($\lambda_R \sim 1550$ nm and $\Delta\lambda_{\mathrm{FWHM}} \sim 2.2$ nm) [12]. Fehrembach *et al.* showed that by exciting four eigenmodes at the same time in a multilayer 2-D resonant grating structure, nonpolarizing filters could be realized under nonnormal conical mounting ($\lambda_R \sim 1563.55$ nm and $\Delta\lambda_{\mathrm{FWHM}} \sim 0.2$ nm) [13]. Fu *et al.* designed a multilayer 1-D nonpolarizing GMR narrowband filter operating under normal incidence ($\lambda_R = 500$ nm, $\Delta\lambda_{\mathrm{FWHM,TE}} \sim 2.16$ nm and $\Delta\lambda_{\mathrm{FWHM,TM}} \sim 0.15$ nm) [14]. Grinvald *et al.* theoretically investigated the conditions for achieving polarization independence in 1-D GMR elements. They found that TE-TM modes can be simultaneously and effectively excited under proper conical incidence [15]. Addressing wideband polarization-independent reflectors, Ding *et al.* reported a single-layer silicon-on-insulator (SOI) structure capable of providing ~20 nm flattop bandwidth for both TE and TM polarizations under normal incidence [9]. In case of polarizers, Lee *et al.* designed and fabricated a GMR polarizer with a 40 nm bandwidth centered at 1510 nm with ~97 : 1 extinction ratio operating under normal incidence. Their device transmitted the TE while reflecting the TM polarization [16].

In this paper, we introduce new broadband NPBSs based on leaky-mode resonance effects in layered periodic media. Applying efficient inverse numerical design methods, we show that high-quality beam splitters are achievable using the native resonance response of subwavelength periodic SOI elements. We compare and contrast the device characteristics with those deriving from the effective-medium nature of associated periodic layers.

2. Analysis and Design Methods

To find optimal beam splitter parameters, we engage analysis/simulation and design/optimization methods. Thus, we numerically solve fundamental electromagnetics equations with pertinent boundary conditions using the rigorous coupled-wave analysis method [17]. These numerical results provide the efficiencies of the diffraction orders and associated phases as well as quantitative electromagnetic field distributions. This method provides the computational kernels in the design process that is rooted in particle swarm optimization (PSO). PSO is a robust, stochastic evolutionary strategy useful in electromagnetic design problems [18], [19]. It is inspired by social behavior of animal species like birds, bees, and other “particles” in the search area. The algorithm finds the optimal solution by moving the particles in the search space. PSO lets every individual within the swarm move from a given point to a new point with a velocity based on a weighted combination of the individual’s current velocity, best position found by that individual, and the group’s best position. The standard, real-coded PSO algorithm is used to design the devices of interest; application of PSO to design resonant filters was previously reported [20]. In this paper, the design idea is to utilize spectral regions adjoining a resonance or between resonances that provide proper level of reflectance or transmittance (here 50/50 beam splitting). This is, in general, a challenging problem with no straightforward analytical design procedure. Hence, PSO is employed to design the element and to attain the device parameters that result in the desired spectral response.

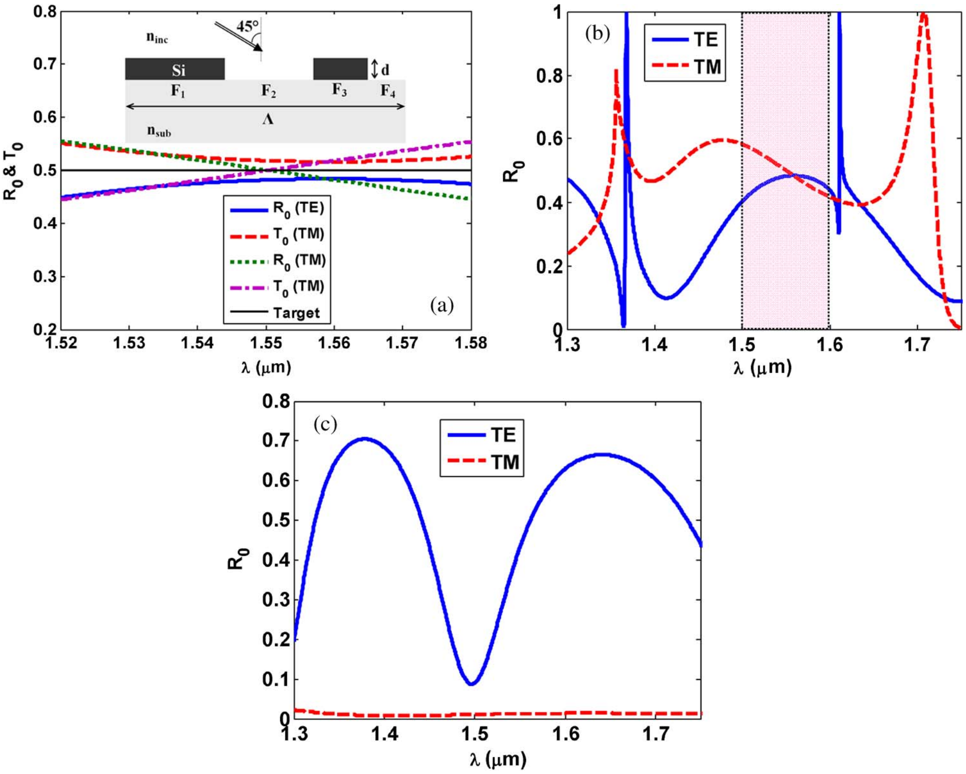

Fig. 1. (a) Reflectance (R_0) and transmittance (T_0) of a single-layer SOI NPBS under $\theta = 45^\circ$ incidence. The structural parameters are period $\Lambda = 620$ nm, thickness $d = 957$ nm, and fill factors $\{F_1, F_2, F_3, F_4\} = \{0.0826, 0.2716, 0.3686, 0.2772\}$. (b) Broader spectral view of the reflectance revealing its resonance character. (c) The reflectance of the second-order EMT thin-film approximation of the periodic element in part (a). Light with TE (TM) polarization has its electric-field (magnetic-field) vector normal to the plane of incidence.

3. Results

We design GMR-NPBSs using PSO aiming for ~50/50 beam division across the 1520–1580 nm optical wavelength band. The first example has a single-layer SOI structure as shown in the inset of Fig. 1(a). The period (Λ) of the grating layer is divided into four parts with filling factors F_1 to F_4 (fractions of each section normalized to the period). The grating thickness is denoted as d. The refractive indices of silicon and fused-silica substrate are 3.48 and 1.48, respectively, and are approximated as constants in this paper. Fig. 1(a) shows computed reflectance (R_0) and transmittance (T_0) of the TE and TM polarization components under oblique $(\theta = 45^\circ)$ illumination. The spectral response of this element matches the target well. The structural parameters of this element delivered by PSO are $\Lambda = 620$ nm, $d = 957$ nm, and $\{F_1, F_2, F_3, F_4\} = \{0.0826, 0.2716, 0.3686, 0.2772\}$. A broader spectral view of the reflectance is shown in Fig. 1(b). As seen, the overlap region in the 1500–1600 nm range falls between two resonances for each polarization state. Thus, we see that this NPBS relies on spectral features associated with leaky-mode resonance.

Although Fig. 1(b) reveals unambiguous spectral expressions associated with leaky-mode resonance, it is of interest to investigate as to what extent the sought polarization properties might be due to effective-medium characteristics of the subwavelength periodic layers, since the structure exhibits the desired performance away from the resonance peaks. Applying effective-medium theory (EMT), we replace the periodic layer by its homogeneous equivalent with second-order EMT index of refraction and compute the response for both polarizations [21], [22]. Second-order EMT refractive index, which is (wavelength/period)-dependent, is an acceptable approximation in high

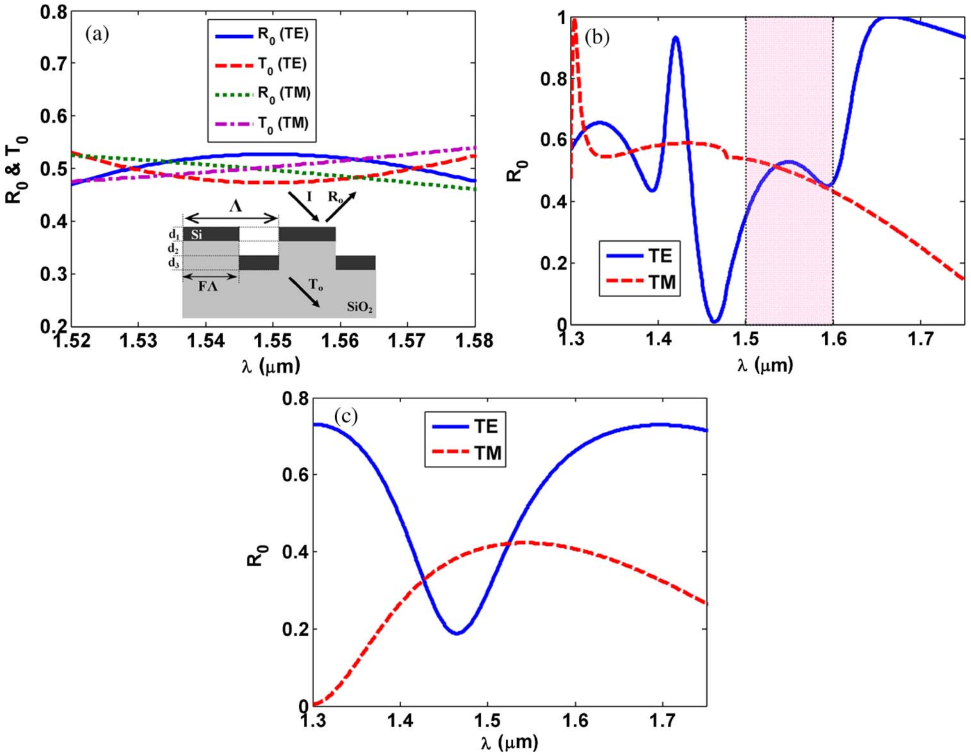

Fig. 2. (a) Reflectance and transmittance of a 50/50 three-level NPBS designed for oblique incidence $(\theta = 45^\circ)$. $\Lambda = 676$ nm, $F = 0.23$, $d_1 = 356$ nm, $d_2 = 117$ nm, and $d_3 = 356$ nm. (b) Broader spectral view of the reflectance response of this element. (c) The reflectance of the three-layer EMT thin-film approximation of the periodic element in part (a). The layers' second-order effective refractive indices are used for TE and TM polarizations.

refractive index contrast grating structures [22]. Fig. 1(c) shows that the resulting element is far from being a 50/50 beam splitter; indeed, the TM response is antireflective.

Referring to Figs. 2 and 3, the application of three-level leaky-mode structures to design optical NPBSs is demonstrated. Fig. 2(a) shows the reflectance and transmittance of a 50/50 NPBS designed for oblique incidence $(\theta = 45^\circ)$.

This Si/SiO$_2$-based beam splitter provides a nearly flat response $(R_0 = T_0 = 0.5)$ over the 1520–1580 nm band for both TE and TM polarizations, thus covering the optical telecommunication C-band (1528–1565 nm). The parameters of this three-level leaky-mode device delivered by the PSO algorithm to meet the target spectral specifications are $\Lambda = 676$ nm, $F = 0.23$, $d_1 = 356$ nm, $d_2 = 117$ nm, and $d_3 = 356$ nm. In addition, Fig. 2(b) shows a broader spectral view of the reflectance indicating the presence of leaky modes. As above, Fig. 2(c) illustrates the response of the three-layer EMT homogeneous thin-film approximation of the periodic element. Clearly, this qualitative thin-film counterpart does not provide the desired spectral features.

Fig. 3(a) shows the reflection and transmission response of a multilevel leaky-mode resonant device designed as a 50/50 NPBS under normal incidence. This element provides good beam-splitting functionality in the 1500–1600 nm band. This PSO-designed three-level element has parameters of $\Lambda = 964$ nm, $F = 0.8869$, $d_1 = 259.2$ nm, $d_2 = 105.7$ nm, and $d_3 = 259.2$ nm. The spectral response of this element across a wide band is displayed in Fig. 3(b). Again, to compare the response of this element with its approximate three-layer homogeneous thin-film counterpart, we compute the second-order EMT refractive indices of the layers. Fig. 3(c) shows the reflectance of the approximate thin-film element where two graphs are drawn for two sets of second-order refractive indices for TE and TM polarization states of incident light. As seen, the approximate thin-film element shows reasonable beam-splitting behavior in the 1500–1600 nm band for the

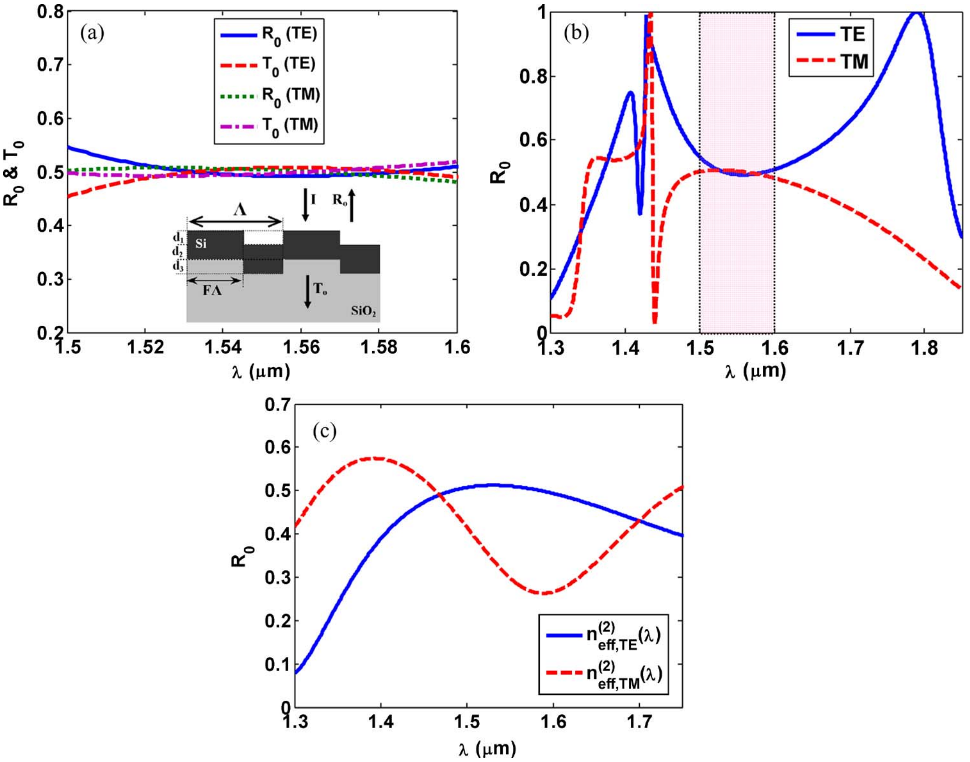

Fig. 3. (a) Reflection and transmission response of a multilevel 50/50 NPBS under normal incidence. The parameters are $\Lambda = 964$ nm, $F = 0.8869$, $d_1 = 259.2$ nm, $d_2 = 105.7$ nm, and $d_3 = 259.2$ nm. (b) Broader spectral response view of this element. (c) The reflectance of the three-layer EMT thin-film approximation of the periodic element in part (a). The layers' second-order effective refractive indices are used for TE and TM polarizations.

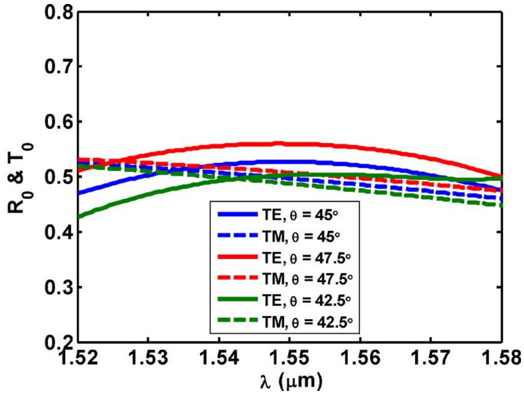

Fig. 4. Reflectance response of the NPBS shown in Fig. 2 versus ±2.5° deviation in angle of incidence (θ).

refractive-index set calculated for TE polarization but worse for TM polarization; both differ appreciably from the spectra in Fig. 3(a).

We now turn our attention to the angular sensitivity of the designed resonant NPBSs to assess their tolerance to deviations in the angle of incidence. To perform this study, we select the multilevel structure shown in Fig. 2. This element is designed to operate under 45° angle of incidence. Fig. 4 illustrates the reflection response of this device with respect to ±2.5° deviation in the angle of

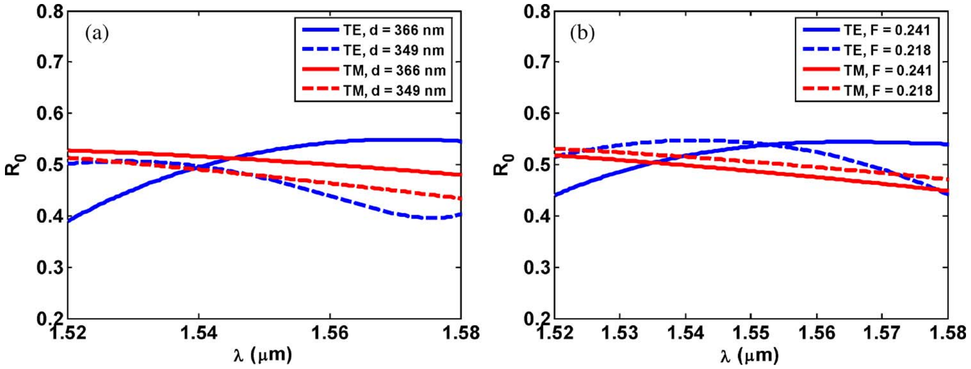

Fig. 5. Reflectance response of the NPBS shown in Fig. 2 versus (a) ±2.5% deviation in d and (b) ±5% in F.

incidence. As seen, the reflectance remains between 0.45 and 0.55 for this angular deviation level. This beam splitter exhibits reasonable angular robustness as necessary for practical applications.

Fabrication of the proposed multilevel elements can be accomplished by deposition of a medium with high refractive index on an appropriate surface-relief pattern etched into a substrate with low refractive index. Prefabrication and manufacturability analysis of the element's performance relative to deviations in the structural parameters is necessary. As an example of such studies, Fig. 5 shows reflectance spectra of the design in Fig. 2 computed for representative deviations in silicon thickness $(d = d_1 = d_3)$ and grating fill factor (F). This particular device is relatively tolerant to deviations in fill factor but less so for layer thickness.

4. Conclusion

In this paper, we present new NPBS operating in the 1520–1580 nm spectral band (telecom C-band). For design convenience and effectiveness, we use a powerful design/optimization method, which is known as PSO [18]–[20]. The spectral response sought is specified *a priori* along with acceptable limits across which the device parameters can range. The PSO algorithm then returns often-complicated structures involving interleaved periodic and homogeneous layers that we sometimes refer to as being "multilevel." These structural profiles connect with parametric spaces that are widely unexplored, thus yielding new potentially useful solutions in functional photonic elements, as recently shown in the case of wideband reflectors [10]. The NPBS shown in this paper represent yet another novel class of photonic devices extracted from this extensive parametric space.

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