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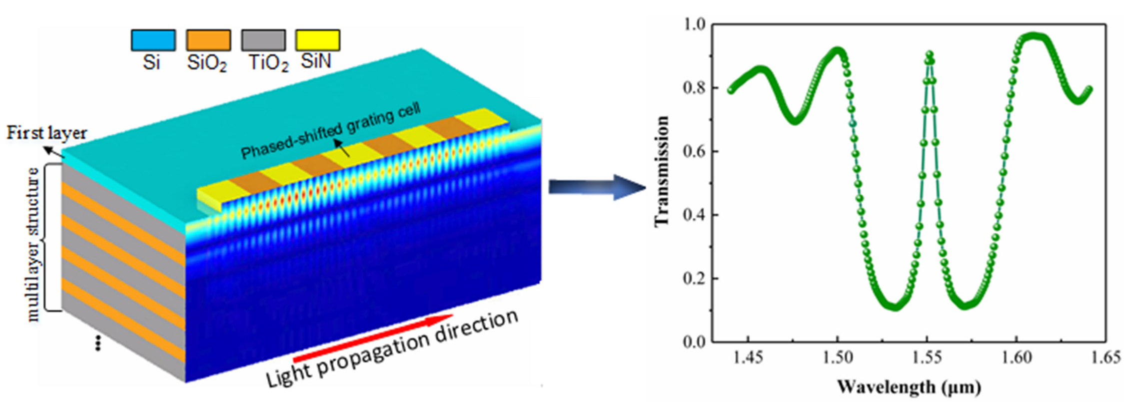

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Design and Analysis of a Novel Phase-Shifted Bragg Grating for Bloch Surface Waves

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Abstract: A novel phase-shifted Bragg grating (PSBG) for Bloch surface waves (BSWs) propagating along the interface between a semiconductor thin layer and a multilayer stack is proposed. This structure is composed of a set of a special ridge fabricated on a multilayer stack supporting a Bloch surface wave. The multilayer stack is periodic, with the unit cell composed of two layers with different materials and thicknesses. The light confinement capability and transmission properties of the proposed structure are investigated in the wavelength range of 1450–1650 nm by using the finite-element method and finite-difference time-domain method. Compared to existing PSBG structures based on surface plasmon polaritons waves, the proposed configuration does not include any metal and the absorption losses upon propagation of the surface wave are negligibly small. Simulation results also indicate that the proposed structure exhibits outstanding transmission properties. The proposed PSBG for BSWs could be applied in narrow bandpass filtering, all optical computing, and enable on-chip integration photonic circuits.

Index Terms: Phase-shifted Bragg grating, Bloch surface waves, guided waves, resonance domain.

1. Introduction

Various optical devices have been proposed and realized [1]–[6]. These devices have been based on different theories as optical interconnection technology has developed. Among the numerous reported schemes, surface plasmon polaritons (SPPs) are one of the most promising candidates and have attracted considerable attention as they can provide truly nanoscale confinement [7]. However, most of these conventional SPP structures have difficulty in integrating mode confinement capability and propagation loss due to the existence of metal materials. Although propagation loss can be reduced by limiting the usage of metals or employing lower loss metals, the loss is still large for subwavelength scale [8]. Bloch surface waves (BSWs) are another type of surface electromagnetic

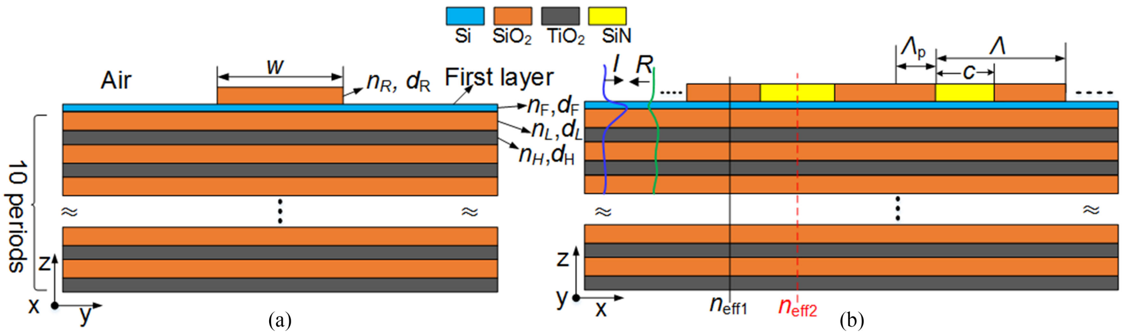

Fig. 1. (a), (b) The SiO_2 YZ cross-section and XZ cross-section of the proposed PSBG structure for Bloch surface waves, respectively.

wave that can be sustained on the surface of periodic layered media [9]. Bloch surface polariton exhibits similar characteristics as surface plasmon polaritons. However, BSWs configurations show lower optical absorption and allow larger spectral tenability [10]. Additionally, BSWs can be excited by transverse electric (TE) and transverse magnetic (TM) polarized inputs under a certain multi-layer structure, but SPPs can only be excited by TM polariton [11]. For all-dielectric configurations, the absorption losses upon the surface wave propagation are negligibly small [12]. Bloch surface waves waveguiding on an ultrathin ridge have been experimentally analyzed [13]. BSWs have great potential applications in sensing [14]–[16] and modulating [17], among other applications and thus BSWs have attracted significant attention and many optical devices for Bloch surface waves have been developed, such as waveguides [11], [18], [19], resonators [20], and phase-shift gratings [21].

In the present work, we propose a novel PSBG configuration for Bloch surface waves consisting of a set of ridge layers with two symmetrical Bragg gratings separated by a "defect" structure. The ridge is fabricated on a multilayer supporting a BSW by using the finite element method (FEM) and finite-different time-domain (FDTD) method, and the field confinement capability and transmission properties of the PSBG for BSWS are researched. Simulation results demonstrate that the proposed PSBG has good transmission properties and the absorption losses of the proposed configuration are negligibly small due to the structure not including any metal. The proposed device can be applied in all optical integrated circuits, analog computing, and temporal differentiation of the envelope of the BSW pulse.

2. Geometries and Theories of Phase Shifted Bragg Grating for Bloch Surface Waves

The geometries and parameters of the proposed phase-shifted Bragg grating structure are shown in Fig. 1. The proposed multilayer includes ten periods and is made of alternating layers of dielectrics with different materials and thicknesses. A thin dielectric ridge with width W is placed on top of the multilayer structure truncated with the first layer. The proposed multilayer structure is periodic, with the unit cell made of two layers with the $d_L = 350$ nm and $d_H = 385$ nm, respectively, and the thicknesses of the first layer and ridge are designed as $d_F = 40$ nm and $d_R = 100$ nm, respectively. As shown in Fig. 1(b), the PSBG for BSWs is composed of two symmetrical Bragg gratings separated by a special layer and the Bragg grating cell is composed of two strips made of different materials. The width of SiN is considered as $c = \Lambda/2$. Furthermore, the Bragg grating period (Λ) can be defined as [22]:

$$\Lambda = \frac{m\lambda_c}{2n_{\text{eff}}} = \frac{m\lambda_c}{n_{\text{eff1}} + n_{\text{eff2}}} \tag{1}$$

where m is an integer which represents the grating order. Choosing $m = 1$, λ_c is the center wavelength of the Bragg grating spectral response, n_{eff} is the average effective index of the PSBG different material cross-section along the light propagation direction. n_{eff1} and n_{eff2} represent

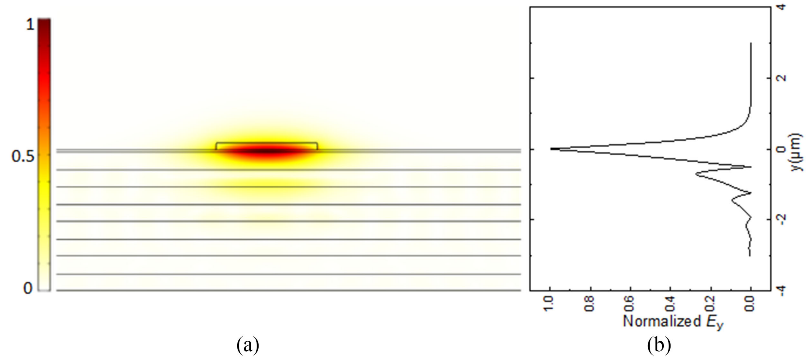

Fig. 2. (a), (b) The 2D and 1D normalized electric field distribution of the SiO_2 cross-section of the proposed PSBG for Bloch surface waves, respectively.

effective indices of the PSBG structure different material cross-sections, respectively. In this work, a quarter phase-shifted length ($\Lambda_p = \lambda_c/(4n_{eff1})$) is introduced for the designed structure. The total number of Bragg gratings is set as $2N$.

3. Transmission Characteristics of the Proposed PSBG for Bloch Surface Waves

For detail parameters of the proposed PSBG structure, d_F, d_R are set as 40 nm, 100 nm, respectively. The Bragg grating spectral response center wavelength (λ_c) is assumed as 1550 nm. Additionally, the calculated Bragg grating period (Λ) and the phase-shifted length are 240 nm, 248 nm, respectively. To achieve a better understanding of the proposed PSBG characteristics, this research studies the electric field distribution of the PSBG configuration cross-section along the direction of light propagation. Firstly, the model properties of the YZ cross-section of the SiO_2 layer are studied by using the finite element method based on COMSOL Multiphysics. To ensure meshing and that boundary conditions and related calculation parameters were sound, a convergence analysis was conducted [23]. According to reference [24], n_L, n_H, n_F and n_r were set at 1.444, 2.48, 3.45 and 1.444, respectively, at the wavelength of 1550 nm. Simultaneously, the refractive index of SiN is 1.76 [25]. The 2D normalized electric field distribution of the cross-section at a wavelength of 1550 nm is plotted in Fig. 2(a). It is clear that the electric field is strongly confined to two sides of the first layer. The light propagates along the two interfaces of the first layer and the Bloch surface waves are excited in the studied configuration. To get a more intuitive understanding of this phenomenon, the 1D normalized electric field distribution of the cross-section center position is illustrated in Fig. 2(b). It can be seen that most of electric field energy is concentrated on the area of the coordinates' origins. The electric field distribution indicates that the proposed PSBG has a strong field confinement capability and the absorption losses are negligibly small. In this case, the effective index of the cross-section is 1.53.

The transmission properties of the proposed PSBG were investigated using the three-domain finite-different time-domain method based on FDTD solutions [26]–[28]. In order to achieve more accurate results, the Berenger's perfectly match layer (PML) boundary condition [29] was applied and the PML number is set as 16. Besides, the simulation time is extended to 1500 fs due to the strong resonance of the system, and the mode optical source is applied to excite the special light propagation mode. The mesh accuracy is set as 6, and grating structure meshes are refined. Finally, other settings are default. The number of grating period cells (N) of PSBG is taken as 20. To highlight the transmission characteristics of the proposed PSBG, a similar 40-cell Bragg grating without phase-shifted structure was also investigated. Transmission spectra of these two schemes are shown in Fig. 3. Compared to the Bragg grating without phase-shift, the transmission spectrum of the proposed PSBG structure exists as a narrow spectrum window with a peak wavelength at 1550 nm which is found within the stop-band of the Bragg grating. Nonetheless, the bandwidth

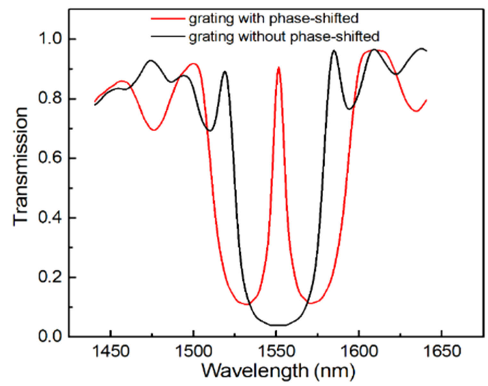

Fig. 3. Transmission spectrums of a PSBG grating with two Bragg grating of 20 periods and a 40 periods grating without phase-shifted structure.

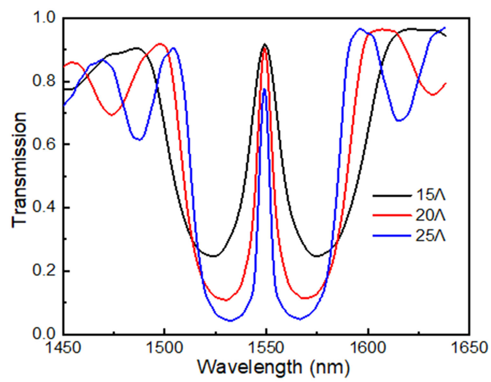

Fig. 4. Transmission spectra of the proposed PSBG for Bloch surface waves with different number grating cell at $n = 15$, 20 and 25, respectively.

of the stop-band of Bragg grating with phase-shifted is widened. The transmission properties of phased-shifted Bragg grating are correlated with the number of Bragg grating cells. Therefore, the transmission spectrums of different number grating cells are studied. As shown in Fig. 4, the stop-band of transmission spectra of PSBG are widened gradually with the decrease of the Bragg grating cell number and the peak of transmission spectra is increased gradually with the decrease of the grating cell number as the reflection power of light is reduced.

To further demonstrate the transmission characteristics of the proposed PSBG for Bloch surface waves, the 2D electric field distributions at different wavelengths along the light propagation direction are presented in Figs. 5(a) and (b). At a wavelength of 1530 nm located at stop-band, little light passes through the proposed PSBG, which implies that the vast majority of light is reflected. However, at a wavelength of 1550 nm, most of the light passes through the structure. The results conform well to the transmission spectrum curve of the Bragg grating with phase-shifted as shown in Fig. 3. It also indicates that the incident light can be propagated with Bloch surface waves. To better evaluate the performances of the proposed PSBG for Bloch surface waves, the quality (Q) factor is introduced. The Q factor is widely used in evaluating the energy storage capacity of the resonant cavity and can be defined as the ratio of the peak center wavelength to its full width half maximum (FWHM) [30]. Namely:

$$Q = \frac{f_R}{\Delta f} \tag{2}$$

where f_R is the resonant frequency and Δf is the full width half maximum. The Q factor of the proposed PSBG with different Bragg grating cell numbers was investigated and is shown in Fig. 6,

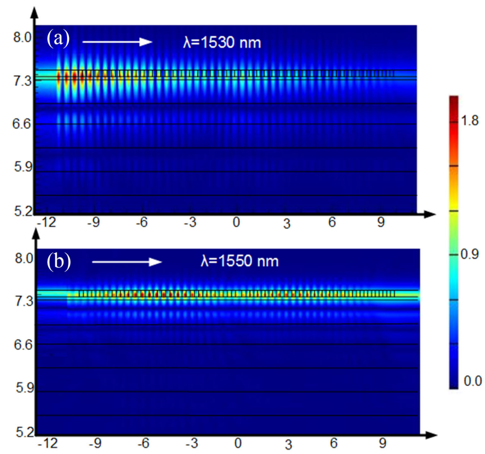

Fig. 5. (a) The electric field distribution of the incident wavelength at 1530 nm in the XZ-plane (inside the stop-bandgap). (b) The electric field distribution of the incident wavelength at 1550 nm in the XZ-plane (outside the stop-bandgap).

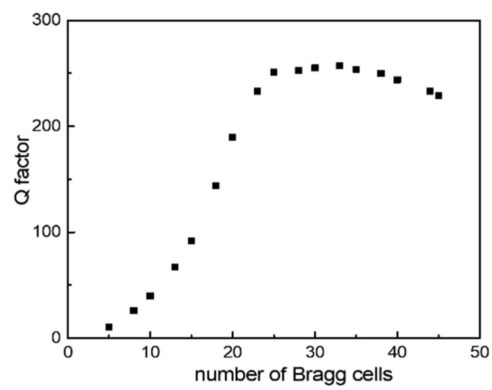

Fig. 6. The dependence of the Q-factor on the number of PSBG grating cell.

when the number of Bragg grating cells is less than 30, and the value of the *Q* factor increases gradually. However, when the number of Bragg grating cells is larger than 30, the *Q* factor value decreases gradually with an increase in the grating cell numbers. This increase in Bragg grating cells is due to an increased reflection coefficient of PSBG. A large reflection coefficient contributes to the increase of the *Q* factor of the cavity by capturing more light into the resonant cavity. Conversely, the propagation and scatting losses of the resonant cavity will reduce the *Q* factor. Therefore, when $N < 30$, the *Q* factor increases due to the increase of the reflective coefficient. On the contrary, when $N > 30$, the *Q* factor decreases due to the increase of propagation and scatting losses. It is therefore important to conduct an optimal design for the proposed PSBG structure. For the proposed configuration and materials used in this work, the number of Bragg grating cells is 30 when the properties of the PSBG is optimal. In this case, the calculated *Q*-factor is 255.

4. Conclusion

In conclusion, a novel phase-shifted Bragg grating for Bloch surface waves has been proposed. The transmission properties of the proposed PSBG configuration have been investigated using the finite element and finite-difference time-domain methods. Compared to a traditional PSBG structure which is based on surface plasmonic polaritons, the proposed PSBG is composed of dielectrics and does not contain any metals, so that the absorption losses are negligibly small. Simulation results show that the proposed PSBG has good filtering properties at the communication wavelength window. Applications of the proposed PSBG are in the fields of narrow bandpass filtering, all optical computing, and could enable on-chip integration photonic circuits.

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