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Add-drop filter based on TiO$_2$ coated shifted Bragg grating

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Abstract: We present a titanium dioxide coated shifted Bragg grating in a silicon-on-insulator platform enabling optical add-drop functionality. The device works on the basis of mode conversion due to shifted sidewall structure followed by mode splitting based on an asymmetric Y-coupler. We experimentally demonstrate the working principle of the device. A reflection bandwidth of 2.2 nm with 14 dB extinction ratio is obtained with a 300 µm long shifted Bragg grating. The performance of the device is also compared without the titanium dioxide coating. A scope of spectral tunability with titanium dioxide re-coating (0.8 nm per 1 nm re-coating) by atomic layer deposition is experimentally verified.

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References and links
1. Introduction

Optical add-drop filters are a key building block of wavelength division multiplexing (WDM) systems for routing wavelengths in between different transmission lines [1]. In past years, various add-drop filters have been proposed based on micro ring resonators [2, 3], arrayed waveguide grating [4], and grating assisted couplers [5]. To satisfy the constraints of integrated optics devices the individual footprint of the components became lower and lower over the years. The reduction of footprint requires high index contrast guiding platforms such as in silicon-on-insulator (SOI). A micro ring resonator based four port optical add-drop device is the most common in use and usually exhibits reasonably low footprint. High spectral selectivity can be achieved with a silicon micro ring resonator due to large Q-factor. The ring resonators, however, experience significant bus-to-ring coupling losses for perturbation from the optimal geometry during fabrication, yielding an eventual reduction of the overall Q-factor of the device. Another limitation of the ring resonator is the small free spectral range (FSR). A large FSR covering the whole optical C band may require a ring radius less than 10 µm which prohibitively increases the radiation loss. Recently, a silicon ring resonator with 1 µm radius has been reported with a FSR of 80.5 nm [6]. However, the small device radius leads to significant fabrication challenges. Thus, a reflection based four port add-drop device is advantageous in on-chip optical signal processing. Previously, tilted Bragg Grating (TBG) based four port add-drop devices were demonstrated on optical fiber [7] and on ion-exchanged waveguide [8]. TBGs help inter-modal coupling at the resonant wavelength and the cross-coupled wavelength drops with a mode splitting arrangement. But TBGs also produce unwanted reflection at the same mode and cross-talk [9]. In order to overcome this problem, segmented gratings were proposed with the grating being patterned on the top of the waveguide [9–11]. Top etched gratings require additional etching steps and are subject to unintentional mismatch of the etch boundaries of the roof segments [12]. To alleviate the process complexity, it is desirable to have structures that can be realized with single etching step, which save the production time and cost of the device, and increase the repeatability.

In this article, we experimentally demonstrate the functionality of an add-drop device based on a sidewall patterned Shifted Bragg Grating (SBG) and an asymmetric Y-coupler. The geometry is close to the one presented by H. Qiu et al. [13]. This particular waveguide grating is equivalent to two identical gratings written across either sides of the waveguide with a longitudinal offset of half a period. The entire structure is patternable with a single lithographic step compatible with complementary metal oxide semi-conductor (CMOS) process. An additional titanium dioxide (TiO$_2$) coating can be added with atomic layer deposition (ALD) method. Amorphous TiO$_2$ is chosen among other ALD materials because of its refractive index (2.23 at $\lambda = 1550$ nm) is much higher than air’s but lower than silicon’s. Thus, a thin coating of TiO$_2$ over silicon waveguide reduces the index contrast and allows narrower reflection bandwidth with comparatively larger
Fig. 1. (a) 3D schematic of a four port shifted Bragg grating (SBG) with asymmetric Y-branches. (b) Working principle of a four port add-drop device in 2D and zoom in the SBG is given with arrow mark. Waveguide height = h, waveguide width = w, grating amplitude = w, period of the grating = Λ, and the grating fill factor f = d/Λ.

grating features. The acute precision of ALD technique can be used as post-fabrication spectral tuning. As added advantage, the conformal nature of ALD helps to reduce the surface roughness of the waveguide with TiO$_2$ coating [14]. With an optimal thickness the thin TiO$_2$ coating can also work as an antireflection coating and improve the fiber-to-chip coupling efficiency. In section 2 we briefly describe the working principle of the whole device. In Section 3 we discuss about the design and fabrication of the device. We present the measurement results in section 4.

2. Add-drop operation based on mode conversion

An illustration of a four-port add-drop device with two asymmetric Y-junctions on two sides of a SBG is shown in Fig. 1(a). The concept of a four port add-drop operation is explained in Fig. 1(b). All the four ports: IN, DROP, THROUGH, and ADD support only the fundamental propagating mode of the corresponding waveguides. The stem of the Y-junctions can accommodate both the fundamental (TE$_0$) and first-order (TE$_1$) modes. Any signal launched through the wide or narrow port excites TE$_0$ or TE$_1$ mode at the stem of the Y-junction, respectively. This can be justified in terms of close matching of the modal effective indices at the single mode ports and the effective indices of the TE$_0$ and TE$_1$ modes at the Y-junction stem as explicitly described in [15]. Thus the four wavelengths, as an example, launched through the IN port excite the TE$_0$ mode at the stem. The asymmetry of the SBG helps power coupling from the symmetric TE$_0$ mode into the asymmetric TE$_1$ mode at resonance. The coupling condition from a forward propagating TE$_0$ mode to a backward propagating TE$_1$ mode at resonant wavelength $\lambda_c$ can be reached with [9]

$$\Lambda = \frac{\lambda_c}{n_{TE_0} + n_{TE_1}},$$

where $\Lambda$ is the grating period. $n_{TE_0}$ and $n_{TE_1}$ are the effective indices of the TE$_0$ and TE$_1$ modes at $\lambda_c$, respectively. The reflected TE$_1$ mode at $\lambda_c$ couples into the DROP port at the Y-junction with proper limiting condition being fulfilled as described in [16]. The TE$_1$ mode coupled at the
DROP port slowly converts into the TE\(_0\) mode of the same port as it propagates sufficiently far away from the Y-junction. The off-resonant transmitted wavelengths are not influenced by the SBG, and maintain their initial modal nature until the THROUGH port. The dropped wavelength (\(\lambda_c\)) can be launched into the system through the ADD port, exciting the TE\(_1\) mode at the stem. The generated TE\(_1\) mode at the resonant wavelength converts into the TE\(_0\) mode upon reflection from SBG and couples into the THROUGH port.

3. Design and fabrication

The waveguide modes are solved with rigorous Fourier Modal Method (FMM) [17, 18]. In FMM the waveguide modes are solved in terms of grating modes of an artificial infinite cross grating. Each period of the infinite cross grating represents the cross section of the waveguide and its surrounding media [20]. The propagation of the optical field through the waveguide grating region is analyzed with recursive S-matrix algorithm formulated with Redheffer’s star product and binary power algorithm as described in [19]. The reflected and the transmitted power of each propagating modes are calculated from the S-matrix elements and normalized with the input mode power.

We consider quasi-TE polarization, i.e. the electric field is oriented along the lateral direction of the waveguide, for our design. The thickness of the guiding silicon layer is fixed at 220 nm which comes with the commercially available SOI wafers. The width of the buried oxide layer (BOX) is 2 \(\mu\)m. The Bragg wavelength is chosen as \(\lambda_c = 1550\) nm. The material refractive indices at the operating wavelength 1550 nm are: \(n_{Si} = 3.48\), \(n_{TiO_2} = 2.23\), and \(n_{SiO_2} = 1.44\). The waveguide width (\(w_g\)) is optimized to 800 nm in order to ensure that the waveguide accommodate only the fundamental and first-order quasi-TE modes. The thickness of the TiO\(_2\) coating is fixed to 180 nm. We plan to deposit the TiO\(_2\) coating with atomic layer deposition (ALD) technique which allows a precise and conformal coating over the target. The TiO\(_2\) coating reduces the index contrast of the waveguide allowing larger grating amplitude which yields a narrow reflection bandwidth, while relaxing the fabrication process. Moreover, the conformal TiO\(_2\) coating reduces the surface roughness and improves the noise level of the reflected signal [14, 21]. The considered thickness of the TiO\(_2\) ensures a low reflection from the waveguide end facet at 1550 nm wavelength [14, 22].

Figure 2 shows the intensity of the modal field distributions of the TE\(_0\) and TE\(_1\) modes for a 800 nm wide and 220 nm thick silicon waveguide with 180 nm coating of TiO\(_2\). The modal effective indices are \(n_{TE_0} = 2.7744\), for the TE\(_0\) and \(n_{TE_1} = 2.4020\), for the TE\(_1\) modes. A grating period \(\Lambda = 300\) nm is calculated for the Bragg wavelength 1550 nm from Eq. (1). We consider a grating amplitude \(w = 80\) nm with a fill factor \(f = 0.5\) and the shift of the sidewall (longitudinal offset) is

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**Fig. 2.** Intensity of modal field distribution of a silicon waveguide (\(W_g = 800\) nm, \(h = 220\) nm) with 180 nm thick TiO\(_2\) coating and 2 \(\mu\)m BOX layer. (a) Fundamental mode (quasi-TE\(_0\)). (b) First-order mode (quasi-TE\(_1\)).
Fig. 3. Normalized reflectivity of the TE$_1$ mode as a function of the number of grating periods. For each grating length ($\Lambda \times$ number of periods) the reflected power of the TE$_1$ mode is normalized with the power of incident TE$_0$ mode.

half of the period ($\Lambda/2$). The power coupling from the input TE$_0$ mode to the reflected TE$_1$ mode as a function of propagation distance is obtained in terms of reflectivity as shown in Fig. 3. We consider 1000 grating periods for nearly 100% reflection thus the grating length is 300 $\mu$m.

Although we discussed the operating principle of a reflection based four-port add-drop device but considering the identical geometry and operating principle of the Y-junctions on either side of SBG [see Fig. 1(b)] we use a three-port layout for the purpose of demonstration as shown in the Fig. 4(a). The width of the single mode ports forming the Y-junction are 370 nm and 430 nm. The angle at the Y-junction is set to 1° which ensures an adiabatic branching of the field and fulfils the condition of mode splitting set by Eq. (18) in [16].

We fabricated the device on a SOI wafer with 220 nm thick silicon guiding layer and 2 $\mu$m thick BOX. The structure was patterned with electron beam lithography process (Vistec EBPG 5000+ES HR) on spin coated layer of negative tone resist hydrogen silsesquioxane (Fox-16). We used an area dose of 8000 $\mu$C/cm$^2$ with acceleration voltage of 100 kV. The development was done with Microposit 351 developer diluted with water. The developed structure on the resist layer was etched down to BOX layer with inductively coupled plasma etching using hydrogen bromide and oxygen (Oxford Instruments Plasmalab 100). After cleaving the sample with hand, the TiO$_2$ layer was grown with atomic layer deposition technique (Beneq). We used TiCl$_4$ and H$_2$O precursors at 120°C temperature as described in [23].

Scanning electron microscopic (SEM) images of the Y-branch and a section of the SBG are shown in Figs. 4(b) and 4(c), respectively. For an efficient coupling of optical signal between the connecting optical fiber and the waveguide we consider 2 $\mu$m wide waveguide as input and output. These 2 $\mu$m wide waveguides are connected to the single mode ports with adiabatic tapers. The length of the tapers can be as low as 18 $\mu$m [22] although we used 50 $\mu$m long tapers.
4. Experimental results

4.1. Measurement setup

The device is characterized by using a standard end-fire measurement setup. Light from an Amplified Spontaneous Emission source (ASE, Agilent 83438A, 1510 nm < \( \lambda \) < 1580 nm) is boosted with an erbium doped fiber amplifier (EDFA, Keopsys) and injected in the waveguide structure by means of a tapered lens fiber. The output signal, collected in the same way, is sent to an Optical Spectrum Analyzer (OSA, Ando, AQ 6315 A). Both lens fibers and the samples are placed on piezo-actuated stages having a resolution of 30 nm. Note that the output of the device can be either the THROUGH or the DROP port corresponding, respectively, to the transmitted and reflected signal of the shifted Bragg grating. The configuration used for this sample [see Fig. 4(a)] allows us to measure both signals without changing the input coupling, making the comparison more reliable between the two arms of the Y-junction. The OSA has a sensitivity of -90 dBm and, in our case, the resolution is set to 200 pm, which is thus the uncertainty on the measurement. Such a resolution is sufficient to determine accurately the position of the band gap and this sensitivity allows a reduced signal to noise ratio of the measurement. Each spectrum is normalized by the input signal measured directly from the ASE source in order to ease the comparison between the results.

4.2. Mode conversion demonstration

The numerically simulated normalized reflection spectra for an ideal SBG structure is shown in Fig. 5(a). We measured the reflected signal from the SBG at the DROP port [see Fig. 4(a)]. The reflection spectra, which is normalized with the input, is shown in Fig. 5(b). We note that the spectral width of reflection at full width half maxima (~3 dB) is 2.2 nm which matches very well the simulated spectral width of 2 nm. The extinction ratio of the reflected signal is 14 dB which
is significantly high for this kind of complex structure. The spectral width at -10 dB is 5 nm thus the sharpness of the reflection peak is very high. The simulated and measured signal at the THROUGH port are shown in Figs. 5(c) and 5(d), respectively. Nevertheless, the measured peak is red shifted by 3 nm from the designed Bragg wavelength. This small shift arises from slight change of the waveguide and grating parameters from the designed values during fabrication. With our device specification we estimated that a 5 nm change of waveguide width can introduce a 3 nm shift of resonance. The sidewall grating features are not exactly normal to the waveguide which change the effective fill factor. However, the shift of the resonance with the fill factor is not as critical as with the waveguide width. We estimated a fill factor change by 0.1 can introduce a 2.8 nm shift of resonance. Post fabrication tuning of this small resonance shift can easily be tuned by varying precisely the thickness of the TiO₂. This will be discussed in detail in the following.

To confirm the add operation of the device we have interchanged the IN and DROP port. This time the signal is launched through the DROP port (the new IN port) and collected at the IN port (the new DROP port) without changing the fiber to chip coupling of the previous measurement. No change has been observed in the reflection spectra by interchanging the ports. Thus, a signal centered at the resonant wavelength and narrower than the obtained reflection bandwidth can be added into the transmission line.

Fig. 5. (a) Simulated (FMM) spectral response of the SBG at the converted mode TE₀ to TE₁. (b) Measured reflection spectra at the DROP port. (c) Simulated transmission spectra at the THROUGH port at TE₀ mode. (d) Measured transmission spectra at the THROUGH port.
Fig. 6. (a) Filtered transmission spectra at the THROUGH port with (red curve) and without (black curve) SBG. The inset gives the raw data before filtering. (b) SEM image of the cross section of the waveguide with under etching. The waveguide is covered with 35 nm TiO$_2$ coating. (c) Central wavelength (red curve) and the extinction ratio (black curve) of the transmission dip as a function of the TiO$_2$ coating thickness.
4.3. Fine tuning of the Bragg wavelength

We have compared the performance of the TiO\textsubscript{2} coated SBG with a similar SBG with air cladding and observed the spectral response as a function of the TiO\textsubscript{2} coating layer thickness. The period of the air cladded SBG is set to 320 nm to keep the Bragg wavelength at $\lambda = 1550$ nm. The grating amplitude and the fill factor are fixed to 80 nm and 0.5, respectively. The normalized transmission spectrum at the THROUGH port is shown in Fig. 6(a) by the red curve. The transmission spectrum at the THROUGH port of a reference structure with identical Y-junction and tapers, but without the SBG, is shown by the black curve in Fig. 6(a). Both spectra are filtered with Fourier transform to reduce the noise level yet maintaining the spectral nature of the system. For comparison the raw data of both the measurements are shown at the inset. The power level of both the spectra are comparable outside the resonant zone thus the SBG does not contribute significant off-band loss. One can estimate the insertion loss of about 1.6 dB. Figure 6(a) shows that the high index contrast between silicon and air yields to a wide transmission bandwidth (3 dB) of 6 nm. Moreover, the center of the spectral band gap is blue-shifted to 1531 nm. We attribute the reason to be under etching of the silicon waveguide into the BOX layer as shown by the SEM image of waveguide cross section in Fig. 6(b). The under etching further increases the index contrast between the silicon waveguide and its surrounding and the field become more confined within the silicon core hence the resonant condition become different due to variation of effective indices. We can remark the very sharp edges of the photonic band gap and its huge extinction ratio of about 22 dB. By measuring the spectral response response of the device after several consecutive TiO\textsubscript{2} coatings, we observed, in transmission, a shift of the photonic band gap. The position of the central wavelength of the transmission band gap is measured with increasing coating thickness as shown (red curve) in Fig. 6(c). By applying a linear fitting we can easily calibrate the required thickness of the TiO\textsubscript{2} layer to tune the transmission band gap at the desired wavelength. We have measured a shift of the resonant wavelength of 0.8 nm per 1 nm of TiO\textsubscript{2} coating over a broad wavelength range covering the whole optical C-band (1530 nm to 1570 nm). Thus we can consider this re-coating technique as a tool for post fabrication tuning of resonant structures. However, the extinction ratio (in dB scale) of the transmission band gap is reduced linearly with the increasing coating thickness as shown in Fig. 6(b) with a linear data fitting in dotted black line. We measured that the extinction ratio drops from 24 dB to 12 dB, in the extreme case of a 35 nm thick coating. This shift of resonance and reduction of extinction ratio with the increasing thickness of TiO\textsubscript{2} coating can be understood in terms of modal effective index and index contrast, respectively. With every additional coating the modal effective indices increase leading to a shift of resonance towards longer wavelengths. Furthermore, the addition of TiO\textsubscript{2} coating decreases the index contrast which reduces the intermodal coupling coefficient. Thus, for a fixed grating length the extinction ratio reduces with increasing TiO\textsubscript{2} thickness.

5. Conclusion

We have experimentally demonstrated optical add-drop functionality with TiO\textsubscript{2} coated shifted Bragg grating (SBG) and asymmetric Y-coupler in SOI platform. The reflected signal at the DROP port is obtained with 2.2 nm band width and 14 dB extinction ratio for a 80 nm grating amplitude. The high extinction ratio appears due to careful selection of waveguide width (800 nm) that ensures no additional propagating modes apart from the $TE_0$ and $TE_1$ modes. Hence, we avoid any unwanted power distribution in other higher order modes. Moreover, the TiO\textsubscript{2} coating provides low noise level in the reflected signal. The results are compared with another SBG with air cladding material, on which several successive TiO\textsubscript{2} coatings have been deposited. The acute precision of thickness (0.068 nm per cycle for TiO\textsubscript{2}) and conformal nature of atomic layer deposition (ALD) technique is explored to demonstrate post-fabrication spectral tunability of SBG with thin TiO\textsubscript{2} re-coating. The thin coating of TiO\textsubscript{2} plays a significant role on spectral tunability without affecting the bandwidth. Quantitatively, a coating thickness ranging from 0 nm
to 35 nm provides a linear wavelength tuning range of 0 nm to 30 nm within optical C-band.

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