Tunable spiral Bragg gratings in 60-nm-thick silicon-on-insulator strip waveguides

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Abstract: We demonstrate spiral integrated Bragg gratings (IBGs) in 60-nm-thick strip waveguides on the silicon-on-insulator (SOI) platform. The length of the spiral IBG is 2 mm, occupying an area of 147 × 141 μm² with a minimum bending radius of 20 μm. Experiments show that the spiral IBGs exhibit a single narrow transparent peak with a Q-factor of 1 × 10⁵ in a broad stopband, induced by the phase shift of the S-junction at the spiral center. This phenomenon is analogous to the electromagnetically induced transparency (EIT) effect. The transparent peak can periodically shift in the stopband upon heating of the S-junction using a TiN-based heater on top. The peak transmittance and Q-factor are dependent on the reflectivity of the spiral IBG. The transparent peak can be completely eliminated under a certain tuning power, and the spiral IBG hence behaves as a bandstop optical filter. The bandwidth is 0.94 nm and the extinction ratio is as high as 43 dB. The stopband can also be shifted by heating the Bragg gratings using a separate TiN heater. The experimental results agree well with the modeling results based on the transfer matrix method.

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1. Introduction

Bragg gratings have been widely used as key functional components in optical communications, sensing and microwave photonic signal processing. Many researchers have been exploring the integrated Bragg gratings (IBGs) on the silicon-on-insulator (SOI) platform for its small footprint and low-cost fabrication. Uniform [1–3], phase-shifted [4–6],
superimposed [7], sampled [3] and phase-engineered [8,9] IBGs have already been demonstrated. Most of them are short Bragg gratings (a few hundreds of microns in length) with large coupling coefficients. For applications that need narrow bandwidths (<1nm) or well-controlled spectral profiles, it is required to fabricate longer IBGs with weaker coupling coefficients. However, implementation of these kinds of IBGs are quite challenging for two main reasons. Firstly, the sidewall corrugations on the strip waveguide are limited to a few nanometers due to the strong overlap of the optical mode with the sidewall [3]. Such small corrugations are very difficult to fabricate, given the limited resolution in photolithography. Several approaches have been demonstrated to solve this issue. One is to use rib waveguides with larger corrugations on the rib or the slab sidewalls, but it requires two etching steps [1, 10–12]. Another one is to use weakly coupled pillars outside the core waveguide [13]. The pillars are of small size, still difficult to fabricate using photolithography. Secondly, long IBGs are quite sensitive to the accumulated phase noise caused by the variation in waveguide width and height [14–16]. The uniformity of waveguide width cannot be guaranteed after photolithography and dry etch; the waveguide height also changes due to the variation of silicon layer thickness in SOI wafers. The width-induced phase noise can be reduced by using wider waveguides [17,18]. However, a wide waveguide may support high-order modes, and the cross coupling among multiple modes could degrade the device performances significantly, especially in grating-assisted couplers and FSR-free Bragg grating filters [19–21]. The spiral configuration has been shown to be an effective way to reduce the phase noise caused by the variation in waveguide dimensions [22–25].

In our previous work, we have demonstrated Bragg gratings based on the 60-nm-thick silicon strip waveguides [26]. Compared to the typical 500 nm × 220 nm strip waveguide, the ultra-thin waveguide processes a fundamental mode with much lower optical confinement in the waveguide core. A small coupling coefficient thus can be achieved using relatively large corrugations on the strip waveguide sidewalls. Meanwhile, as the mode of the ultra-thin waveguide interacts weakly with the sidewalls, the waveguide is less sensitive to the sidewall roughness, resulting in low phase noise. As the ultra-thin waveguides are still sensitive to the waveguide height, we design spiral-shape IBGs to reduce the height variation. The main challenges in making spiral IBGs lie in the effective index variation when the bending radius changes. The bending radius becomes smaller in the center and the bending curvature discontinues at the S-junction. Recently, spiral IBGs based on wide strip waveguides have been theoretically analyzed and experimental demonstrated [24]. It reveals that the spiral IBGs without phase correction show a strong Bragg wavelength perturbation at the center of the stopband. Correction of grating period was proposed to compensate for the bending-induced phase noise. However, the grating period should be well controlled within the range of a few nanometers, imposing a great challenge in device fabrication. Though one can increase the bending radius to reduce the waveguide effective index variation [27], this however inevitably increases the device size.

In this paper, we report spiral IBGs based on the 60-nm-thick strip waveguides on the SOI platform. The typical transmission spectrum of the spiral IBG exhibits a single narrow transparent peak in the stopband of the Bragg grating. Similar characteristic has been observed in a 220-nm-thick passive spiral IBG [24]. Here, our experiment reveals that the transparency peak can periodically shift in the stopband upon heating of the center S-junction. In particular, the transparent peak is absent under a certain tuning power. We also demonstrate that the transmittance and Q-factor of the transparent peak in the stopband are dependent on the reflectivity of the spiral IBG. The paper is organized as follows. Firstly, we present the design and fabrication of spiral IBGs. Then we show the measured transmission spectra of three spiral IBGs with different bending radii. A distributed feedback (DFB) grating model based on the transfer matrix method is used to fit the experimental results. Lastly, we present the experimental results to show the effect of grating coupling efficiency on the device performance.
2. Device design and fabrication

Figure 1(a) shows the schematic structure of the spiral IBG. The bending radius in each half circle remains constant. This structure is similar to that reported in [25]. In the center of the spiral, the two semi-circular waveguides form an S-shaped waveguide with sharp discontinuity in the bending curvature. The discontinuity results in a certain phase shift when light propagates through the center S-junction. The grating corrugation is located at the sidewalls of the spiral waveguide as shown in Fig. 1(b). Two TiN-based heaters are positioned on top of the spiral waveguide and the center S-bend to separately tune the Bragg reflection (tuning power $P_2$) and the phase shift (tuning power $P_1$), respectively. The response time of these heaters is in the order of $\mu$s [28]. Figure 1(c) shows the 3D structure of the active device. The critical dimensions of the device are labeled in the cross-sectional waveguide structure shown in Fig. 1(d). The gap size between the TiN strips is 2 $\mu$m. The resistivity of TiN is around 25 $\mu\Omega$·cm. In order to reduce thermal crosstalk between the two heaters and increase the thermal tuning efficiency, trenches are etched down into the silicon substrate to isolate the heaters. The transverse magnetic (TM) mode has a large modal profile and interacts severely with the TiN heater and the silicon substrate, leading to a much higher propagation loss than the transverse electric (TE) mode. Therefore, we designed the spiral grating based on the TE mode. Figure 1(e) shows the microscopic image of a fabricated active spiral IBG.

![Fig. 1](image)

The key design parameters of the spiral waveguides include the waveguide spacing ($g$), the minimum bending radius ($R_0$), and the number of half circles ($N_B$). The spacing $g$ is chosen to be 5.5 $\mu$m to ensure low crosstalk. Note that this value is quite conservative and could be reduced to make the spiral more compact. The variation of waveguide bending radius results in the change of waveguide effective index and the mode mismatch between two consecutive half circles of waveguides. Using the Lumerical MODE Solutions, we
calculate the effective index variation $\delta n_{\text{eff}}$ relative to a straight waveguide as a function of bending radius as shown in Fig. 2(a). As expected, $\delta n_{\text{eff}}$ decreases as the radius increases. The variation in waveguide effective refractive index generates unwarranted chirp in the spiral grating, making the stopband become broader. For $R_0 = 20\, \mu m$, $\delta n_{\text{eff}}$ is relatively small ($\sim 6 \times 10^{-4}$). According to our calculation based on the transfer matrix method (TMM) [29], such a small value of $\delta n_{\text{eff}}$ causes slight stopband broadening of 0.08 nm, approximately 6% of the original bandwidth. Hence, in our design, we choose $R_0 \geq 20\, \mu m$. The mode mismatch between two sections of curved waveguides with different bending radii will cause junction loss. As the bending curvature changes its sign at the S-junction, the induced loss is the dominate junction loss. The black line in Fig. 2(b) shows the simulated S-junction loss as a function of $R_0$. It can be seen that the S-junction loss decreases as the bending radius increases. Note that the mode mismatch also results in certain phase shift for light propagating through it. Thereby, the spiral grating works like a phase-shifted Bragg grating where a resonance is generated inside the stopband. A high intrinsic resonance quality-factor (Q-factor) can be obtained with a small S-junction loss. The packing efficiency of the spiral, $\alpha$, is defined as $L/A$, where $L$ is the grating length and $A$ is the area of the entire spiral [23].

The packing efficiency is an important parameter to measure the device compactness. The height variation and thus the induced phase noise are small for a spiral with a high packing efficiency. The calculated $\alpha$ as a function of $R_0$ is shown by the blue line in Fig. 2(b). It can be seen that a high packing efficiency can be obtained at the expense of an increased loss. The $R_0$ is chosen to be between 20 $\mu m$ to 35 $\mu m$ in our design, which brings a good compromise between device compactness and loss.

The spiral IBGs are realized by introducing periodic corrugations on both sidewalls of the spiral waveguide in our design. The grating coupling coefficient is determined by the corrugation width $W_{\text{corr}}$ and the minimum waveguide width $W_{\text{min}}$. It should be noted that the difference in coupling coefficient for curved and straight waveguides is negligibly small when $R_0 \geq 20\, \mu m$, and hence we used the straight grating waveguide to calculate the coupling efficiency in our design. The grating period is chosen to set the Bragg wavelength close to 1550 nm.

The device fabrication was started using an SOI wafer with a top layer thickness of 220 nm and a buried oxide (BOX) layer thickness of 3 $\mu m$. Firstly, the SOI wafer was thinned down to 60 nm using thermal oxidation. Compared to plasma dry etch, oxidation can result in smoother surface and more precisely controlled silicon layer thickness. The device patterns were defined by 248-nm deep ultra-violet (DUV) photolithography, followed by anisotropic dry etch of silicon. Then, a 2-$\mu m$-thick silicon dioxide layer was deposited using plasma-
enhanced chemical vapor deposition (PECVD). After that, heaters were made by deposition and dry etching of a 120-nm-thickness TiN layer. Another oxide layer of 0.42 μm in thickness was deposited above the TiN layer by PECVD. Subsequently, contact holes were etched and aluminum was deposited to form metal connection. Finally, trenches were etched deep down into the silicon substrate (100-μm deep) using inductively coupled plasma (ICP) etch to isolate the micro-heaters. The fabrication was done using the IME 180-nm fabrication process.

3. Experimental characterization

We used Yenista Optics’s tunable laser (Tunics-T100S-HP) and component tester (CT400) to characterize the device transmission performance. A polarization controller was placed in front of the device to set the TE polarization. On-chip grating couplers were used for input and output coupling with optical fibers. The coupling loss per facet is about 6.5 dB. We implemented four spiral IBGs with the design parameters listed in Table 1. The grating length of all four devices is around 2 mm. The devices I, II, and III have different \( R_0 \) in order to explore the effect of bending radius on the device performance. Device IV uses the same set of design parameters as device III except the minimum waveguide width \( W_{\text{min}} \). The device I has the most compact size, occupying an area of 147 × 141 μm² with a packing efficiency of 14.1.

### Table 1. Design Parameters for Four Spiral IBGs

| Device | \( R_0 \) (μm) | \( N_R \) | \( \xi \) (μm) | \( W_{\text{min}} \) (nm) | \( \Lambda \) (nm) | \( L \) (mm) |
|--------|----------------|---------|----------------|-----------------|-------------|-------------|
| I      | 20             | 14      | 5.5            | 960             | 100         | 448         | 2.035      |
| II     | 25             | 12      | 5.5            | 960             | 100         | 448         | 1.935      |
| III    | 35             | 10      | 5.5            | 960             | 100         | 448         | 1.975      |
| IV     | 35             | 10      | 5.5            | 1100            | 100         | 448         | 1.975      |

3.1 Optical spectrum measurement

Figure 3 shows the measured transmission spectra for devices I to III. It can be seen that all these spectra exhibit a narrow transparent peak in the grating stopband. It is analogous to the electromagnetically-induced transparency (EIT) effect in the atomic systems due to the coherent interference [30]. This unique feature of the EIT-effect has many applications in narrow-band filtering [31], optical sensing [32], optical modulation [4–6], and optical signal processing [33, 34]. A DFB grating model based on the transfer matrix method is used to fit the experimental results. The phase shift \( \Delta \phi \) and loss at the S-junction are taken into account in our model. The grating coupling coefficient \( \kappa \) is extracted from the measured spectra using \( \frac{2}{\pi n_g \Delta \lambda / \lambda_0} = \kappa \), where \( n_g \) is the group index of the waveguide, \( \Delta \lambda \) is the measured stopband width, and \( \lambda_0 \) is the Bragg wavelength [35]. The effective index difference (\( \Delta n_{\text{eff}} \)) between the two sections in one grating period used in the transfer matrix is obtained by \( \Delta n_{\text{eff}} = \kappa \Delta \lambda / 2 \) [36]. Upon fitting, the phase shift induced by the S-junction is extracted to be \( \Delta \phi = 1.18\pi, 1.16\pi, 1.15\pi \) for the three devices shown in Figs. 3(a)-3(c), respectively. The theoretical model has good agreement with the experimental results. The measurement indicates that the phase shift induced by the S-junction is difficult to eliminate even when the bending radius increases to 35 μm. The insets in Fig. 3 show the magnified resonance peaks. The losses (excluding the coupling loss) of the resonance peaks are 6.7 dB, 6.9 dB, and 7.0 dB for the three devices and the Q-factors are \( 1.7 \times 10^5, 1.25 \times 10^5, \) and \( 1.7 \times 10^5 \), respectively. As the spiral grating works like a phase-shifted Bragg grating, the overall Q-factor \( (\overline{Q}) \) is expressed as:

\[
\frac{1}{\overline{Q}} = \frac{1}{Q_c} + \frac{1}{Q_f} \tag{1}
\]
where $Q_C$ represents the external Q-factor given by the transmittance of the half gratings on both sides of the S-junction, and $Q_I$ represents the intrinsic Q-factor given by the cavity loss including the spiral waveguide loss and the S-junction loss. If there were no intrinsic cavity loss, $Q$ would be equal to $Q_C$. Hence, we can obtain $Q_C$ by measuring the Q-factor of the resonance peak from the spectrum given by the theoretical model by assuming no intrinsic loss. The derived $Q_C$ values are $2.88 \times 10^5$, $3.0 \times 10^5$, $3.25 \times 10^5$ for the three devices, respectively. $Q_I$ is thus calculated to be $2.0 \times 10^5$, $2.1 \times 10^5$, $3.6 \times 10^5$ using Eq. (1). Then the cavity loss per half round-trip is deduced to be 0.07 dB, 0.06 dB and 0.04 dB [36], respectively. It indicates that the cavity loss decreases with an increased bending radius, thus leading to a higher $Q_I$. Note that $Q_C$ is determined by the reflectivity of the Bragg grating. One can increase $Q_C$ by using a high reflectivity Bragg grating.

![Fig. 3. Transmission spectra of three devices with (a) $R_0 = 20 \mu m$, (b) $R_0 = 25 \mu m$, and (c) $R_0 = 35 \mu m$. The solid black lines represent the experimental spectra and the dashed red lines represent the modeled spectra. The insets show the magnified transparent peaks in the stopbands. The 3-dB bandwidths are labeled.](image)

### 3.2 Thermal active tuning

When the S-shaped waveguide is heated locally, the effective refractive index of the grating in this region increases due to the thermo-optic effect, resulting in an increased phase shift. Thereby, the original transparency peak caused by the S-junction will be gradually redshifted. Figure 4(a) shows the evolution of the transparent peak with tuning power $P_1$ for device I. Simulation results with $\Delta \phi$ as the fitting parameter are shown in Fig. 4(b). Similar phenomena were observed for devices II and III. It can be seen that the transparent peak periodically shifts in the stopband. The transparent peak is completely absent when $P_1$ is around 173 mW. In this case, the spiral IBG behaves as a bandstop filter. The full width at half maximum (FWHM) of the stopband is 0.94 nm and the extinction ratio is as high as 43 dB. The single-notch stopband can also be shifted by tuning two heaters simultaneously as shown in Fig. 4(c). Figure 4(d) depicts the extracted peak wavelength shift in one period as a function of tuning power $P_1$. The thermal tuning efficiency is around 4.3 pm/mW. The single-notch stopband shift as a function of total power consumption is shown in Fig. 4(e).
The thermal tuning efficiency is around 1 pm/mW. The tuning efficiency of the two heaters can be improved by reducing the waveguide separation to make the device more compact or by removing the silicon substrate which is the main source for heat leakage.

Fig. 4. (a) Evolution of the transparent peak upon thermal tuning of the S-junction. The spectra are shifted vertically in purpose for better clarity. (b) Simulation results showing the similar evolution trend. (c) Shift of the stopband upon tuning of both the spiral waveguide and the center S-junction. (d) Extracted transparency peak wavelength as a function of the tuning power $P_1$. (e) Extracted central wavelength of the stopband as a function of the total tuning power $P_1 + P_2$.

3.3 Effect of the grating coupling efficiency

In most applications, a high transmittance of the resonance peak is needed. One can increase the transmittance of the resonance peak by reducing the reflectivity of the spiral IBG [37]. Figure 5(a) shows the evolution of the transmission spectrum in response to the tuning power on the S-junction for device IV. Compared to device III, $W_{\text{min}}$ of this device is increased while $W_{\text{corr}}$ is unchanged and thereby the grating coupling coefficient decreases, leading to reduced reflectivity of the Bragg grating. It can be seen that the extinction ratio of the stopband is reduced, while the peak transmittance in the stopband always approaches unit. Figure 5(b) shows the resonance Q-factor as a function of peak wavelength offset with respect to the stopband center wavelength. It can be seen that the Q-factor reduces when the peak moves away from the center of the stopband, due to the reduced reflectivity close to the edges of the stopband. The maximum Q-factor, as shown in the inset of Fig. 5(b), is $7.8 \times 10^4$ obtained at the center of the stopband. However, this maximum Q-factor of device IV is still lower than that of device III. It implies that a higher transmittance of the resonance peak is obtained at the expense of a reduced Q-factor.
Fig. 5. (a) Transmission spectra of device IV in response to the tuning power $P_t$. (b) Q-factor as a function of the resonance offset from the stopband center wavelength. The inset shows magnified resonance peak when Q reaches the maximum.

4. Conclusions

We have demonstrated spiral IBGs in 60-nm-thick strip waveguides on the SOI platform. Our experimental results show that the spiral IBGs exhibit a single transparent peak in a narrow stopband, analogous to the EIT effect. The transparent peak with a Q-factor up to $\sim 10^5$ can periodically shift in the stopband upon heating using a TiN-based heater on top of the S-junction. The sharp peak can be exploited for narrow-band filtering, optical sensing, and optical signal processing. Under a certain tuning power, the transparent peak is completely eliminated, which makes the spiral IBG behave as a band-stop filter. The stopband is 0.94 nm wide and the extinction ratio is 43 dB. The stopband can be shifted by using another separate TiN heater. We experimentally explored the effect of bending radius on the device performances, especially on the Q-factor of the transparency peak. The phase shift induced by the S-junction is inevitable due to the asymmetric mode distribution in the S-junction. However, the loss induced by this asymmetric mode distribution can be reduced by increasing the bending radius and as a result the Q-factor of the transmission peak can be improved. We also investigated the dependence of the peak transmittance and Q-factor on the reflectivity of the spiral IBG. The peak transmittance increases and the Q-factor decreases as the reflectivity decreases. A theoretical model has been used to fit the experimental results with good agreement.

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