Integrated Passband Optical Filter with High-Order Phase-Shifted Bragg Grating in Silicon-on-Insulator Technology

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ABSTRACT

An integrated passband optical filter based on a high-order phase-shifted Bragg grating (BG) realized in silicon-on-insulator technology is presented. Five half-wave cavities are placed between six BG mirrors defined by laterally corrugating a strip silicon waveguide through electron-beam lithographic process. The BG mirrors are dimensioned in order to provide the proper reflectivity at Bragg wavelength such to tailor the spectral transmission of the multi-cavity filter. A passband window within a 1 THz stopband region having nearly-Gaussian transfer function with a -3dB bandwidth of ~25 GHz, low insertion loss of less than 1 dB, minimum stopband attenuation of ~35 dB, and a passband-to-stopband transition bandwidth of ~30 GHz is observed. These features, which are unreported for such class of structures, illustrate the potentials of this approach for realizing FSR-free bandpass optical filters with arbitrary bandwidth, strong out-of-band rejection, and fast roll-off. Effects of waveguide corrugation depth on the stopband width has also been investigated.

Keywords: Integrated optical filters, silicon photonics, Bragg gratings, Fabry-Perot filters.

1. INTRODUCTION

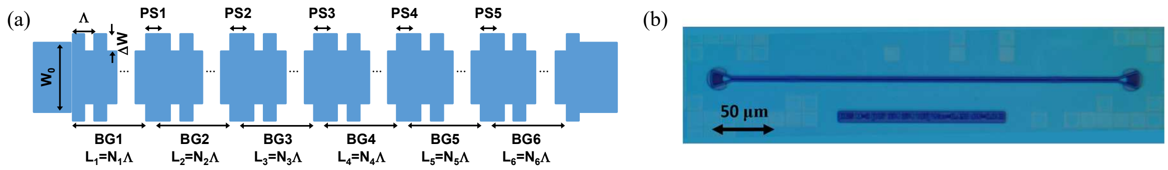
Tunable optical passband filters based on silicon waveguides enhance the flexibility and the operation of photonic integrated circuits (PICs) in a variety of applications for silicon photonics systems. As such, a large amount of research has been spent in the last decade in designing and fabricating optical filters in silicon-on-insulator (SOI) technology realizing advanced passband transfer functions (TFs). For a given filter bandwidth, desirable additional features are: strong stopband rejection (SBR), flat passband and low insertion loss, sharp passband-to-stopband transition, and wide free-spectral-range (FSR). Microring resonators (MRR)-based approaches proofed excellent performances for applications spanning from microwave photonics [1] to optical communications [2] and sensing [3] systems. Yet, it is challenging to achieve high FSR-to-bandwidth ratios (namely, high values of the filter finesse) unless increasing filter complexity, like resorting to Vernier-operation [3], where MRRs with different FSRs are combined to suppress as much as possible resonances but the operating one.

A FSR-free passband TF can be obtained by collecting the light reflected from a Bragg grating (BG), which can be realized in SOI technology by laterally corrugating either strip or rib silicon waveguides. However, minimum achievable reported bandwidths are greater than ~50 GHz [4], [5], and the SBR is typically limited to ~10 dB, if no apodization is employed in the grating design. Alternatively, phase-shifted (PS) BGs exhibit a sharp passband window within the grating stopband [6]-[8] with additional advantages of transmission-mode operation and large SBR with no need of apodization. By using a contra-directional coupler architecture, the device can also operate as a narrow-band add-drop filter [8]. Similarly to serially-coupled MRRs, the spectral transmission of a PSBG passband window can be tailored using a multi-cavity design in which several PS sections are encompassed between different BG mirrors, each with proper reflectivity at the Bragg wavelength. Away from Bragg condition, incident light is strongly attenuated over a stopband region whose extension is determined by the grating coupling coefficient, which is set by the waveguide corrugation depth. This approach thus enables in principle the realization of optical filters with arbitrary bandwidth, large stopband-to-passband ratio, strong SBR, and sharp transition band, and we recently reported a 6-th order SOI PSBG exhibiting a transmission window with a -3dB bandwidth of ~100 GHz, a 40dB attenuation over a 120 THz-wide stopband region, and a ~300 dB/nm roll-off [8].

Here, a 5-th order cavity design producing a 25 GHz passband window within a 1 THz stopband is reported and experimentally characterized. Thermal tunability, as well as the influence of the waveguide corrugation depth on the stopband width for the employed fabrication process are also investigated

2. PSBG FILTER DESIGN, FABRICTION, AND CHARACTERIZATION

The schematic structure of the proposed high-order PSBG is reported in Fig. 1(a). Five quarter-wave phase-shift sections are placed between six BG mirrors defined by producing periodic variations in the width of a silicon strip waveguide through electron-beam lithographic process on a SOI wafer. The average waveguide width is



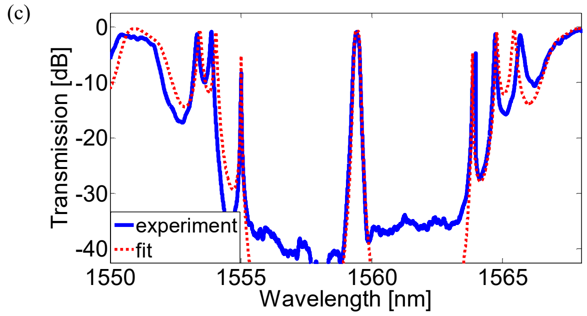


TABLE 1. DESIGN SUMMARY

$N_1=N_6$	135
$N_2=N_5$	270
$N_3=N_4$	33
Λ	320 nm
W_0	500 nm
ΔW	60 nm

Figure 1. (a): High-order phase-shifted Bragg Grating (BG) schematic structure; (b): Picture of the fabricated device; (c): Measured spectral transmission and numerical fit.

W_0=500 nm; the corrugation has a period Λ=320 nm and an ideally rectangular shape, with a depth ΔW=60 nm on each sidewall of the grating. An image of the fabricated device is shown in Fig. 2(b). The summary of the design is also reported in Table I, for a total device length of ~280 μm. Grating couplers (GCs) are used for vertical coupling with input/output optical fibers.

The measured transmission spectrum of the structure, after normalization to the transmission of a reference GC pair, is shown in Fig. 1(c) where a sharp passband window within an 8 nm (1 THz) stopband region is observed. The passband window transmission peak is ~-0.7 dB, whereas the out-of-band rejection is more than ~35 dB over the whole stopband region. The measured spectrum has been fit using a model based on transmission matrix method (TMM). From the fit, also shown in the figure, the effective coupling coefficient of the fabricated grating is extracted. The details of the passband window are illustrated in Fig. 2(a), together with the fitting curve, exhibiting a -3dB bandwidth of 26 GHz, and a -3dB to -30dB transition bandwidth of 27.5 GHz on the steeper edge. The mismatch between the measured transfer function and the simulated response, where the design of Table I for the number of periods in the BGs is used, is ascribed to random oscillations of the BG wavelength along the structure, due to fabrication imperfections. This also produces a slower filter roll-off at the high-frequency detuning. Flatter passband response and steeper roll-off could be in principle achieved by controlling the effective index in the PS sections through local heaters. Thermal tuning of the filter response has been assessed by changing the chip temperature; the results, in Fig. 2(b), indicate a spectral shift of about 0.075 nm/°C.

3. EFFECT OF CORRUGATION DEPTH

A wide stopband region is desirable in several applications, such as OSNR monitoring or single-channel extraction in WDM multichannel system, with the passband width depending on the specific application. As such, the effect of the waveguide corrugation depth ΔW on the stopband width has been investigated by using 1st-order PSBG, where a single half-wave cavity is embedded between two BG mirrors, for three different values of waveguide corrugation depths: 46, 60, and 72 nm. The number of periods in the BGs is 250 for all the considered samples. The measured spectra are shown in Fig. 3(a), along with the corresponding fitting curves, from which an estimate of the grating coupling coefficients for each considered ΔW is retrieved. These values, reported in Fig. 3(b), are compared with those obtained from coupled-mode theory (CMT), in which the results of modal analysis are used for the two waveguide sections in the grating with nominal widths $W_0 \pm \Delta W$, assuming no smoothing effect due to fabrication process. Although the approximated CMT is expected to overestimate the coupling coefficient, the

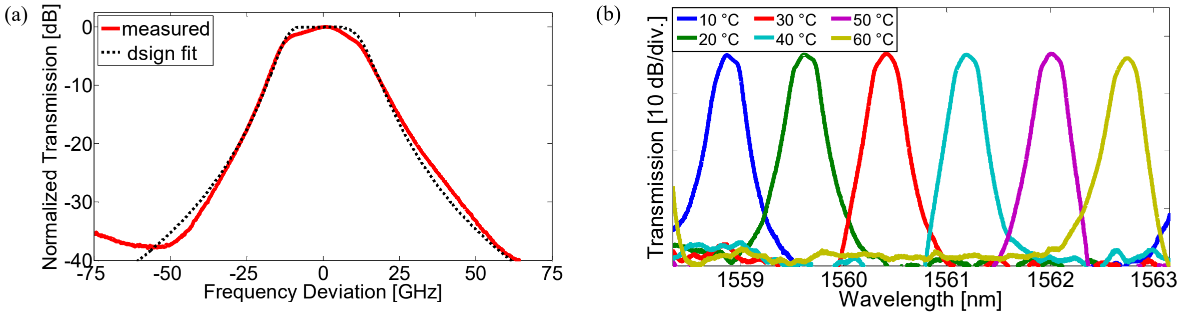


Figure 2. (a): Measured passband transmission window from the high-order PSBG and numerical fit; (b): Thermal dependence of the spectral transmission around the passband window.

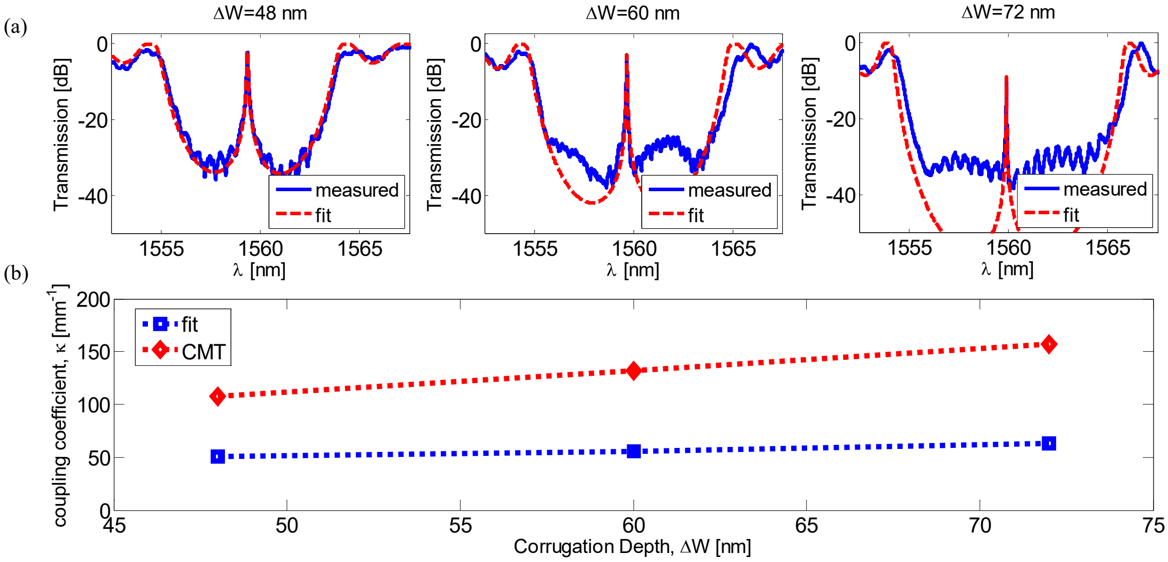


Figure 3. (a): Measured transmission of 1^{st} order PSBGs with different values of corrugation width ΔW. (b): Estimated and calculated grating coupling coefficient versus waveguide corrugation width.

effect of residual lithographic smoothing is evident from Fig. 3(b). Nevertheless, the results from the fitting can be used for design calibration, by acting on the number of periods to compensate the effect on passband window due to reduced coupling coefficient. The estimated propagation loss, obtained by fitting the peak transmission and 3dB bandwidth of the passband windows are comprised between 3 and 4 dB/cm for all the samples. The highest *ΔW* value exhibits a stronger sensitivity to propagation loss due to the corresponding increase of cavity Q-factor.

4. CONCLUSIONS

A thermally-tunable integrated passband optical filter based on a high-order phase-shifted Bragg grating in silicon-on-insulator technology has been designed, fabricated and characterized. A 25 GHz bandwidth passband transfer function with out-of-band rejection exceeding 35 dB over 1 THz stopband and low insertion loss of ~1 dB is reported in an ultra-compact footprint of less than 150 μm^2. Effect of grating corrugation on the stopband width has been investigated, and the coupling strength reduction due to lithographic smoothing has been estimated through a fitting procedure. Integrated high-order phase-shifted Bragg gratings in silicon waveguide may be of practical interest in microwave-photonics applications and optical network technologies for future 5G systems.

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