Ultra-Compact Bandwidth Tunable Filter via Subwavelength Grating-Assisted Contra-Directional Coupler Employing Double Grating Arrays Perturbations

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Abstract: An ultra-compact tunable filter based on subwavelength grating and taper waveguides with double grating arrays perturbations has been proposed. The bandwidth tunability of ~7.6 nm is achieved with a coupling length of only 60 μm.

1. Introduction

Silicon photonics has developed successfully for optical communications in the past decades [1]. Wavelength division multiplexing (WDM) is one of the most practical technologies to further increase communication capacity, in which optical filters are one of the most essential yet basic components for selecting signals [2]. In order to adapt to different communication requirements, various kinds of filters have been demonstrated on a silicon-on-insulator (SOI) platform. Among them, some filters have been reported on the SOI platform with typical structures such as micro-ring resonators, interferometers and AWGs, and they could have compact footprints or good fabrication tolerance [3]. However, their performances are limited by free spectrum range (FSR) or non-flat tops, which may not meet requirements for dynamic, gridless and smart-network scenarios. To solve these problems, recently, grating-assisted contra-directional couplers (GACDCs) have been proposed as an effective method for optical filters without FSR [4,5]. This kind of device also has merits of broad bandwidth, flat-tops, low insertion losses and low crosstalk. Whereas they usually occupy large footprints on an SOI wafer since the coupling length of the Bragg grating-based structure is usually as long as several hundred microns.

Recently, subwavelength grating (SWG) waveguides have been utilized for shorter coupling length compared with traditional waveguides [6–8]. SWG is a discrete structure with a period much smaller than the wavelength of propagation light. The equivalent refractive index of SWG waveguide could be adjusted closer to that of the silica cladding, thereby leading to larger coupling coefficients. Thus, the SWG based waveguides could realize a shorter coupling length, which makes the device more compact. However, these devices employing the principle of contra-directional coupling usually suffer from strong sidelobes, and various kinds of apodization methods are reported to suppress it [2].

In this paper, we propose and demonstrate an ultra-compact bandwidth tunable filter based on cascaded GACDCs, and each GACDC contains an SWG waveguide and a taper waveguide with double perturbation grating arrays. Taking advantage of the high coupling efficiency of SWG waveguides assisted by the separate and flexible perturbation introduced by the grating arrays, the coupling length of the GACDC is reduced to only 60 μm. Moreover, the curved SWG waveguide is used as an effective apodization method to suppress sidelobes [7], and taper waveguide could further enhance the sidelobe suppression ratio (SLSR). In the thermal tuning, a tunable bandwidth of ~7.6 nm and the SLSRs from 23 to 38 dB are observed.

2. Design for a single GACDC

Figure 1(a) shows the schematic of a single GACDC for our proposed device, which could serve as a drop filter consisting of an SWG waveguide, a taper waveguide and double grating arrays. The widths of taper waveguide w_1 and SWG waveguide w_2 are set to be 400 nm and 600 nm respectively to avoid undesired co-directional coupling. The perturbations are separated as two grating arrays to induce suitable coupling perturbations between the fundamental modes in the taper waveguide and the SWG waveguide. To couple light into the SWG waveguide with low loss, SWG-strip tapers are introduced at two ends.

The working principle of the GACDC could be described as follows: When the continuous wave (CW) light is launched into the taper waveguide, the light that satisfies the phase-matching condition $\lambda_D = (n_1 + n_2)\Lambda_G$ could be reversely coupled to the SWG waveguide with the assistance of grating arrays perturbations, where n_1 and n_2 represent the effective index of the fundamental mode of the SWG waveguide and that of the taper waveguide respectively, Λ_G is the grating period and λ_D is the central operation wavelength. The transmission spectrum at the

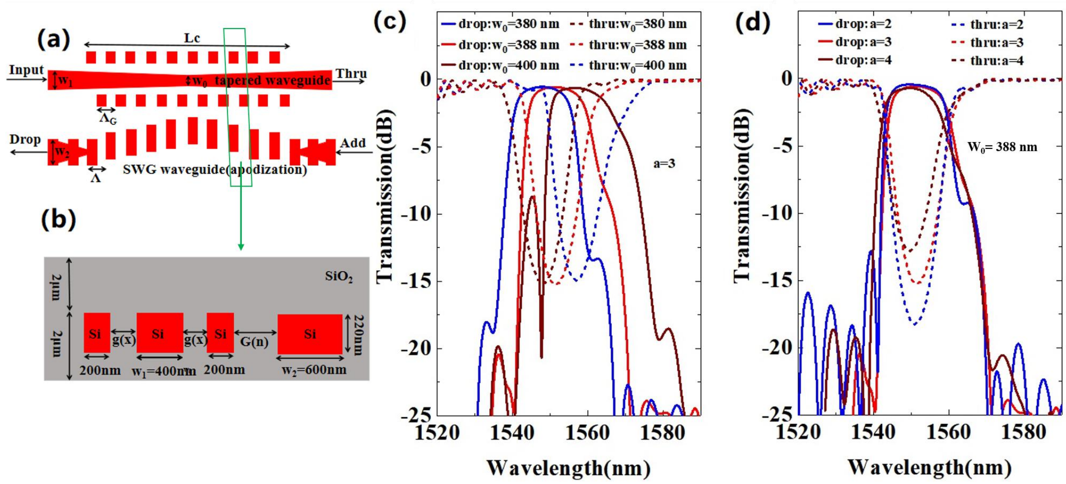

Fig. 1. Schematic configuration of a single GACDC: (a) the top view and (b) the cross-section of the coupling region. Simulated transmission spectra (c) with different w_0 when a=3 and (d) with different apodization index when w_0=388 nm for a single GACDC

drop port of the GACDC presents a passband shape. To suppress sidelobes, the gap between SWG waveguides and grating arrays is apodized as a Gaussian function, which could be expressed as:

$$\mathrm{Gap}(n) = g_{\min} + 1000\left(1 - \exp\left(-\mathrm{a}(n - 0.5N)^2 / N^2\right)\right), \qquad (1)$$

where N is the period number, a is the apodization index, and $g_{\min}$ is set to be 70 nm which is the minimum gap between waveguides and grating arrays. In addition, symmetrical double perturbation grating arrays are introduced to suppress some undesired reversely coupling [9]. The periods of the SWG and the grating arrays are Λ = 250 nm and Λ_G = 386 nm, respectively. The duty cycle of the SWG waveguide and perturbation are both set to be η = 50 %. The coupling region length is set to be 60 μm to have a tradeoff between the coupling length and the insertion loss.

The three-dimensional finite-difference time-domain (3D-FDTD) method is implemented to simulate the performances of the filter. To obtain a better SLSR, we optimize the center width of the taper waveguide w_0 and the apodization index a. Figure 1(c) shows the simulated transmission spectra of the drop and thru port with different w_0. It's shown that the sidelobes on the left-hand of the spectrum are effectively suppressed with a proper w_0, compared with the GACDC using straight waveguide (w_0=400 nm). Figure 1(d) shows the simulated transmission spectra of drop and thru port with different apodization index. Finally, we set the apodization index to be 3 and center width of the tapered waveguide w_0 to be 388 nm, in this optimized case, the insertion loss is about 0.6 dB with the SLSR about 20 dB for a single GACDC.

3. Discussion for the tunability

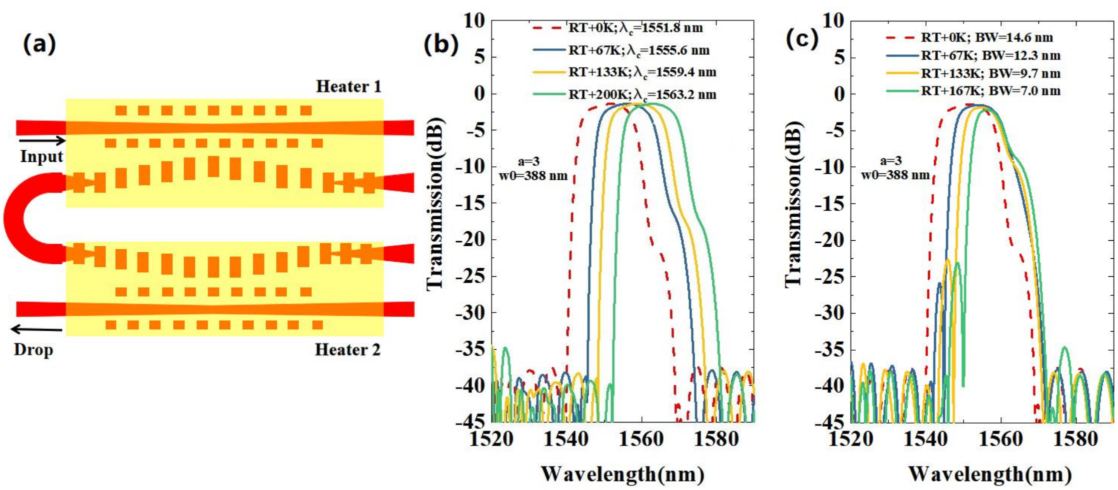

Fig. 2. (a) The top view of the proposed tunable filter based on cascaded GACDCs; (b) Simulation of center wavelength tuning; (c) Simulation of bandwidth tuning.

The schematic of our proposed tunable filter composed of a two-stage cascaded GACDCs is shown in Figure 2 (a). The drop port of one GACDC is connected to the input port of the other identical GACDC. The drop port response at the final drop port could be effectively regarded as the overlap between the two GACDCs. We evaluate the temperature dependence by $d_{neff} = dn_{Si} / dT \times d_{neff} / dn_{Si} \times dT$ [2]. To achieve different center wavelengths of the response at drop port, two GACDCs could be heated simultaneously. By applying the same power on both GACDCs, the center wavelength could be tuned accordingly as shown in Figure 2(b), and the center wavelength is tuned continuously over 12 nm. To achieve tunable bandwidth, one GACDC could be heated separately. When the temperature of one single drop filter is changed, the center wavelength of its drop port spectra would shift, resulting in smaller band overlap between two drop filters, therefore, the narrower passband is achieved at the final output. As shown in Fig. 2(c), continuous tuning of the 3 dB bandwidth from 14.6 nm down to 7 nm with the insertion loss changing from 1.4 dB to 2.1 dB is observed. During the tuning, the stop-band edges are determined by another drop filter, as a result, the SLSR degrades from 38 dB down to 23 dB. It's noted that the response spectra of the drop filter are not the ideal rectangle shape, the insertion loss will increase during thermal tuning.

4. Conclusion

Table 1. Recent results with on-chip tunable filters based on gratings

Publication	Filter Type	Coupling	Tunable BW	Insertion loss	SLSR
J. St-Yves *et al*. [4]	Cascaded GACDCs	312 μm	~5.4 nm	< 0.5 dB	15~55 dB
M.T.Boroojerdi *et al*. [5]	Cascaded GACDCs	312/318 μm	10.6 nm	2.6 dB	31dB
J. Jiang *et al*. [10]	Cascaded Gratings	500 μm	12 nm	< 2 dB	18~30 dB
This Work (Sim.)	**Cascaded GACDCs**	**60 μm**	**7.6 nm**	**1.4 dB**	**23~38 dB**

The comparison of recent publications of tunable filters based on gratings assisted structures is shown in Table 1, which indicates that our proposed cascaded GACDCs tunable filter assisted by the double perturbation grating arrays has effectively reduced the coupling length without performance compromised, and the length of the coupling region of our GACDC is only 60 μm, to the best of our knowledge, this is the shortest contra-coupling length among above tunable filters.

In summary, we have proposed an ultra-compact bandwidth tunable filter based on cascaded GACDCs assisted by double perturbation arrays SWG waveguides. Thanks to the flexibility of perturbation introduced by the double grating arrays, the required power transfer could be realized over short coupling length. Moreover, we apply the apodization method employing taper waveguides with gap variation, the SLSR has been improved. In our simulation, continuous tuning of the 3dB bandwidth is obtained from 14.6 nm down to 7 nm, while the insertion losses change from 1.4 dB to 2.1 dB. The device also exhibits a maximal bandwidth of 14.6 nm with a high out-of-band SLSR of 38 dB and a minimum bandwidth of 7 nm with an out-of-band SLSR of 23 dB. This flexible tunability of bandwidth makes the device a very attractive approach for dynamic WDM systems in the future.

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