Ultracompact, bandwidth tunable filter based on subwavelength grating

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Abstract: We demonstrate an ultracompact bandwidth tunable filter based on subwavelength grating (SWG) on silicon-on-insulator (SOI) wafer. A bandwidth tunability of ~6 nm is achieved and the length of coupling region is only 100 μm. © 2019 The Author(s)

OCIS codes: (130.0130) Integrated optics; (130.7408) Wavelength filtering devices

1. Introduction

In optical communication networks, wavelength-division multiplexing (WDM) system is used to increase the capacity of links and initially designed with fixed channel spacing that varied between 20 nm in coarse WDM (CWDM) to 0.8 and 0.4 nm in dense WDM (DWDM) [1]. And now WDM technology is in transition from fixed frequency grids to elastic ones to further improve spectral efficiency [2]. Tunable optical filters, reconfigurable in both bandwidth and central wavelength, become more and more important, and different technologies for tunable filters based on free-space optical technology [3], liquid crystal modulation [4], integrated silicon-on-insulator (SOI) platform have been demonstrated [5,6]. Among these key technologies, tunable filters based on SOI platform attract lots of attention, due to low insertion loss and low cost, improved stability, and high-density chip-scale integration [5].

Existing solutions for tunable filters on SOI include structures based on microring resonators (MRRs) [5], Mach Zehnder interferometers (MZIs) [6] and cascaded grating-assisted contra-directional couplers (GACDCs) [7] and so on. For MRRs and MZIs structures, the devices have limited bandwidth (less than 10 nm) and small free spectral range (FSR), which cannot meet the demands of high-capacity transmission applications [8]. The filters with cascaded GACDCs have impressive tunable bandwidth and no FSR limitation, but sidewall-etched Bragg gratings of cascaded GACDCs have a coupling length of hundreds of microns [7] (usually more than 300 μm), as a result, the whole device takes too much footprint on SOI. Recently, a GACDC using subwavelength grating (SWG) draws our attention since it shows advantages of short coupling length, large bandwidth, and high fabrication tolerance [9]. However, the crux of the GACDC using SWG lies in its strong sidelobes, resulting in high crosstalk, which would affect adjacent channels in WDM system.

In this paper, we propose a compact bandwidth tunable filter with cascaded GACDCs using subwavelength grating (SWG). And apodization is employed to suppress sidelobes and realize a high suppression ratio. Using thermally controlled cascaded GACDCs, a tunable bandwidth of ~6 nm is obtained in experiment with a short coupling length of 100 μm.

2. Device design and simulation

Fig. 1(a) and (b) show the schematic of the proposed device. It consists of a pair of cascaded GACDCs, each GACDC operates as a drop filter, and both GACDCs are identical. Each drop filter is composed of two waveguides, the upper strip waveguide is tapered from two ends to its center, and the bottom waveguide is a curved SWG waveguide. The drop port of GACDC1 is connected to the input port of GACDC2, therefore, the final output of the device is determined by the product of the two GACDCs drop ports.

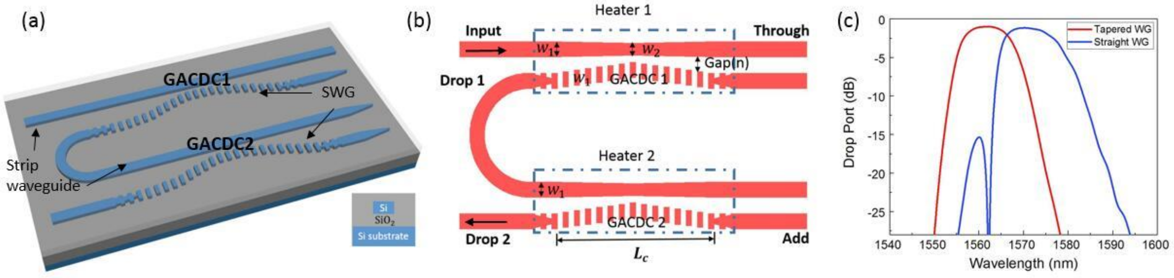

Fig. 1 Schematic configuration of the proposed tunable filter with cascaded GACDCs using SWG; (a) the 3D view, (b) the top view, *Gap(n)*: the coupling gap of the n-th period of the grating; (c) simulated transmission spectra of drop1 port of single GACDC for tapered waveguide (red line) and straight waveguide (blue line).

The working principle of the tunable filter is as follows: For GACDC1, when the light is launched into the input port of the strip waveguide, the co-directional coupling is suppressed by the phase mismatching of the two waveguides, while the contra-directional coupling can be achieved. With the assistance of SWG, light with wavelength $\lambda_D = (N_1 + N_2)\ \Lambda_G$ can be reflected back to the drop port of SWG waveguide, and the transmission spectrum at the drop will present a passband shape, where N_1 and N_2 represent respectively the effective indexes of the TE_0 mode in the strip waveguide and SWG waveguide, λ_D is the central wavelength and Λ_G is the grating period. In the same way, GACDC2 works as a passband filter and is used to drop the light from the drop port of GACDC1. As a result, the final dropped signal is determined by two GACDCs. To realize the wavelength and bandwidth tunable, a metal strip is placed on the top of each GACDC as a micro-heater. By applying independent currents on the micro-heaters, the spectra of the device can shift differentially or simultaneously for bandwidth or wavelength tuning. To suppress sidelobes, apodization of a Gaussian profile $Gap(n) = g_{min} + 1000(1 - exp(-a(n - 0.5N)^2 / N^2))$ is used to taper the gap between strip waveguide and SWG waveguide [10], where N is the period number, a is the apodization index, and g_{min} is the minimum coupling gap. Due to the short wavelengths are contra-coupled more strongly at the two ends compared with the center of the GACDC, the two ends of the apodized GACDC form a Fabry-Pérot cavity at short wavelengths and create strong sidelobes on the left-hand of the spectrum [11]. To solve this problem, a feasible solution is to change the width of the strip waveguide along the length of the coupler letting the wavelength has the same coupling efficiency along the length. The three-dimensional finite-difference time-domain (3D-FDTD) method is applied to simulate this drop filter. After optimization, we set coupling length L_c= 100 μm, Λ_G = 378 nm, η = 50%, N = 300, the apodization index a = 5, waveguide width w_1 = 500 nm, w_2 = 475 nm, minimum gap width g_{min} = 160 nm. Fig. 1(c) shows the simulated transmission spectra of drop1 port of single GACDC for tapered waveguide (red line) and straight waveguide (blue line). It can be seen that the strong sidelobes on the left-hand of the spectrum is effectively suppressed for tapered waveguide compared with the GACDC using straight waveguide, the 3 dB bandwidth is 12 nm, and the side-lobe suppression ratio (SLSR) at the drop port is about 27 dB.

3. Experiments and results

The proposed devices were fabricated using E-beam lithography (EBL) on a SOI wafer with a 3-µm-thick buried oxide layer and a 220-nm-thick top silicon layer. The devices were then etched by an inductively coupled plasma (ICP) etching process. A 2-µm-thick silica layer was deposited on the structure as upper cladding by plasma enhanced chemical vapor deposition (PECVD). Then 100-nm-thick Ti micro-heaters and 1-µm-thick Al pads were deposited through EBL and lift-off processes. The transmission spectra of the fabricated devices were measured using a tunable laser (Keysight 81960A) and a power meter (Keysight N7744A) scanning from 1508 nm to 1610 nm with a step size of 5 pm. The TE grating couplers are employed to couple light into and out of the devices. Fig. 2(a) depicts the micrograph of the device.

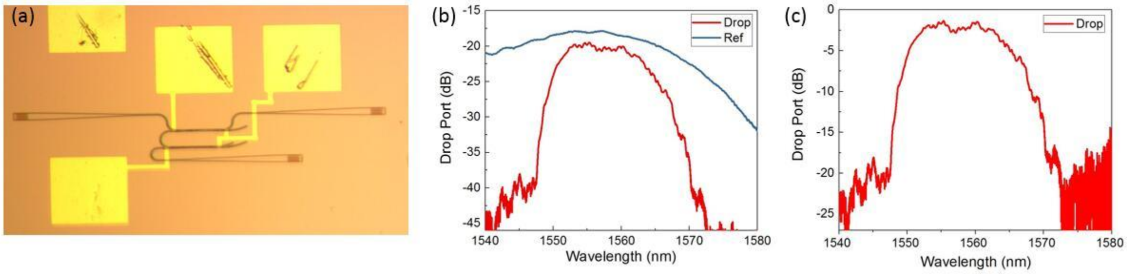

Fig. 2. (a) Micrograph of the device; (b) measured spectra of drop1 port of GACDC1; (c) normalized spectral response of drop1 port of GACDC1.

Fig. 2(b) and 2(c) show the spectrum response of the drop port of GACDC1. The measurements were normalized using the response of a pair of TE grating couplers. The drop exhibits a SLSR of ~18 dB, lower than the simulation results, which is limited to fabrication uncertainties. The insertion loss (IL) is very low, less than 2 dB. Due to the wavelength-dependence of grating coupler, normalization elevates the right-hand noise of response spectrum as shown in Fig. 2(c).

To achieve different bandwidth, the two GACDCs are heated separately. We change the temperature of a single drop filter, and its resonant wavelength shifts, resulting in smaller band overlap between two drop filters, therefore, narrower passband in the final output. As shown in Fig. 3(a) and 3(b), a continuous tuning of the 3 dB bandwidth from 10 nm down to 4 nm with the insertion loss changing from 2 dB to 4 dB is experimentlly observed. During the tuning, the stop-band edges are determined by another drop filter, as a result, the SLSR degrades from 25 dB down to 15 dB.

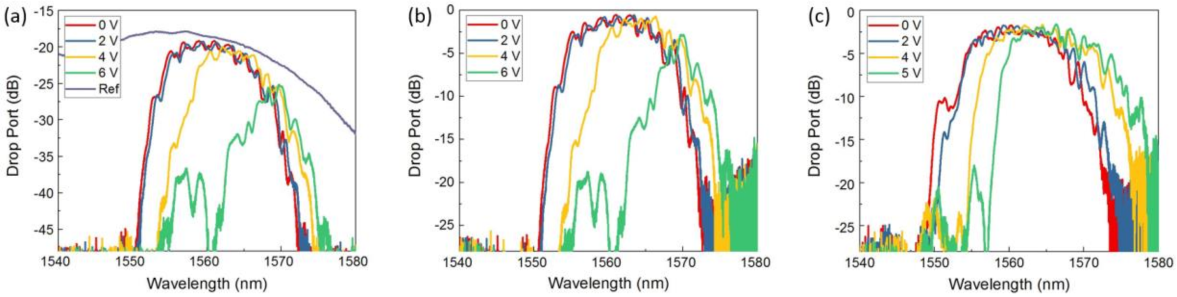

Fig. 3. (a) The drop spectral response of the device for different voltages applied to one drop filter; (b) normalized spectral response of drop port for different voltages applied to one drop filter; (c) normalized spectral response of drop with the voltage applied to both drop filters.

By applying the same temperature to both GACDCs, the center wavelength can be tuned. As shown in Fig. 3(c), the center wavelength is changed continuously over 7 nm with the insertion loss changing within 1 dB, which is limited by the damage of micro-heater when applying voltage above 6 V.

Table 1. Recent results with on-chip tunable filters

Publication	Filter Type	Contra-coupling Length	Tunable BW	IL	Contrast
J. St-Yves *et al*. [7]	Cascaded GACDCs	312 μm	~5.4 nm	< 0.5 dB	15~55 dB
J. Jiang *et al*. [12]	Cascaded Gratings	500 μm	12 nm	< 2 dB	18~30 dB
This Work	Cascaded GACDCs	100 μm	6 nm	~ 2 dB	15~25 dB

Table 1 shows a comparison of up-to-date publications with on-chip tunable filters based on gratings. Our device shows the shortest coupling length, which is very attractive to high-density chip-scale integration. And it is noteworthy that the maximum tunable bandwidth of our device is about 6 nm due to the damage of micro-heater. we also observe a slight redshift of the center wavelength at a higher temperature, indicating thermal crosstalk between the two GACDCs, thus, the heater design can be optimized for higher tuning efficiency. To improve performance further, grating couplers of weak wavelength-dependence is needed for more accurate measurement as well.

4. Conclusion

In summary, we have demonstrated an ultracompact bandwidth tunable filter based on SWG waveguide with a short coupling length of 100 μm. By heating the GACDC separately, the proposed device shows a continuous tuning of the 3 dB bandwidth from 10 nm down to 4 nm. The tunable filter has a maximal bandwidth of 10 nm with a high contrast of 25 dB and a minimum bandwidth of 4 nm with a contrast of 15 dB. Meanwhile, the device exhibits a center wavelength tuning of ~7 nm with the insertion loss changing within 1 dB. This flexible tunability of bandwidth and wavelength makes the device very attractive for next-generation high-capacity optical networks.

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