Grating assisted contra-directional filters with high rejection ratio in silicon nitride rib waveguides

(Student Paper)

Xiaomin Nie [1,2], Nina Turk [1,2], Zuyang Liu [1,2], Roel Baets [1,2]
[1] *Ghent University - imec, Photonics Research Group, Technologiepark 126, B-9052 Ghent, Belgium*
[2] *Center for Nano- and Biophotonics, Ghent University, Belgium*
e-mail: Xiaomin.Nie@ugent.be

ABSTRACT

In this work, we report an on-chip filter that has a high rejection ratio and an unlimited free spectral range (FSR) on the red side of the stop/pass band. This filter is based on a grating assisted contra-directional coupler and is fabricated with one step electron-beam lithography on a silicon nitride rib waveguide platform. This type of filter is able to couple the light into a bus waveguide contradirectionally, instead of reflecting the light back to the input as in the case of a Bragg reflector. We experimentally demonstrate a filter with a stop band centered at 789 nm with an average rejection ratio of 43 dB and bandwidth around 1.7 nm.

Keywords: on-chip filter, silicon nitride, grating assisted contra-directional coupler, e-beam lithography.

1 INTRODUCTION

On-chip filters are essential components for a wide range of applications including lasers, optical sensors [1] and wavelength-division multiplexers (WDM) [2]. Various types of filters such as Bragg gratings, Mach-Zehnder cascades [3] and ring resonators [4] have been studied and developed on a diversity of waveguide platforms. As one of the most popular on-chip filters, ring-resonator add-drop filters have received a lot of attention. Nevertheless, they are not suitable for applications that require a very large or unlimited free spectral range (FSR). For example, in an on-chip Raman spectroscopic system [5], one wants to reject the pump light while leaving the wide spectral range where Raman signals are generated unaffected. In such situations, a Bragg reflector provides a suitable solution. However, the fact that the Bragg reflector directly reflects light back to the input could be problematic to the laser source. Usage of Bragg reflectors in such situations would require the integration of an on-chip circulator, which is difficult and might bring extra complexity and cost. Filters based on the grating assisted contra-directional coupler (GACDC) can be a good candidate in such cases. They inherit the merit of large FSR from the Bragg reflectors, while have no, or very weak, reflection at the operating wavelength. As a compact 4-port device, GACDCs are attractive as wavelength-selective add-drop filters and pump rejection filters. GACDCs were first implemented in planar optical waveguides based on silica and III-V materials [6]. After that, researchers have developed GACDCs on silicon-on-insulator (SOI) platform at the telecommunication wavelengths [7]. However, little effort has been spent to implement GACDCs operating at shorter wavelength on the silicon nitride platform where optical bio-sensing applications such as on-chip Raman spectroscopy are growing and developing. In this paper, we demonstrate a GACDC filter implemented for TE-like modes on the silicon nitride rib waveguide platform. To allow device operation in the near infrared region (such as at the often used wavelength of 785 nm), the gratings need to have a period smaller than what can be achieved by conventional deep-UV lithography. Therefore, e-beam lithography is used to realize the current prototype device. In the future however the proposed device can be realized by deep-UV immersion lithography in a CMOS fab.

2 WORKING PRINCIPLE

The proposed GACDC consists of two silicon nitride rib waveguides with different width and a first order grating in between, as shown in Fig. 1(a). When light containing different wavelength components is injected into the waveguide a, different types of coupling can occur when the corresponding phase-matching condition fulfilled. At wavelength λ_D, the forward-propagating mode in waveguide a can be coupled to the backward-propagating mode in waveguide b when the following phase-matching condition is fulfilled with the assistance of the grating.

$$k_a(\lambda_D) - \frac{2\pi}{\Lambda} = -k_b(\lambda_D) \tag{1}$$

where $k_{a,b}(\lambda_D) = 2\pi n_{a,b}/\lambda_D$, with $n_{a,b}$ the effective refractive index of modes in waveguide a and b. This is the inter-waveguide contra-directional coupling. Solving (1), we get the expression $\lambda_D = (n_a + n_b)\Lambda$.

What can also happen is the coupling between the forward and backward mode in waveguide a at wavelength λ_a determined by:

$$k_a(\lambda_a) - \frac{2\pi}{\Lambda} = -k_a(\lambda_a) \tag{2}$$

where $k_a(\lambda_a) = 2\pi n_a/\lambda_a$. This is the intra-waveguide back reflection. Again, we can calculate that $\lambda_a = 2n_a\Lambda$. In some applications, to make sure that the filter has a flat spectral response in the long wavelength region. it is preferable to have $n_a < n_b$, which means the signal should be injected into the narrow waveguide.

The coupling strength can be estimated by calculating the coupling coefficient κ_D and κ_a according to the coupled mode theory [8]:

$$\begin{aligned} \kappa_a &= \frac{\pi}{\lambda n_a} \iint e_a^*(x,y)\Delta\epsilon_1(x,y)e_a(x,y)dxdy \\ \kappa_D &= \frac{\pi}{\lambda n_a} \iint e_a^*(x,y)\Delta\epsilon_1(x,y)e_b(x,y)dxdy \end{aligned} \quad (3)$$

where $\Delta\epsilon_1(x,y)$ stands for the first order Fourier expansion coefficient of the perturbation introduced by the grating and $e_{a,b}(x,y)$ is the normalized electric field distribution of the fundamental TE-like mode in waveguide a or b. With the coupling coefficient, we can calculate the theoretical transmission at the through port when perfect phase matching is fulfilled:

$$T = 1 - \tanh^2\left(|\kappa|^2 L\right) \quad (4)$$

where L is the total length of the grating.

3 SIMULATION AND DESIGN

To design the filter, we use a commercial mode solver FIMMWAVE. The intensity distribution is shown in the cross section in Fig. 1(b). Solving the modes for different wavelengths will generate dispersion curves, which can be used to calculate the phase matching condition and determine the corresponding grating period for a desired filtering wavelength.

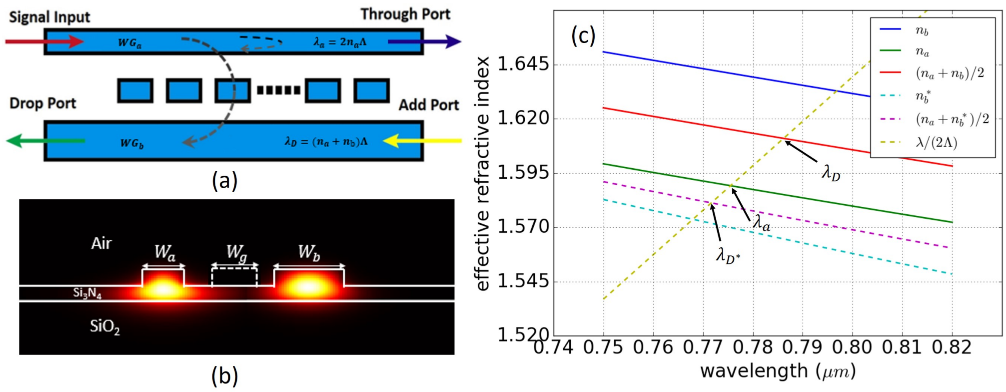

Figure 1. (a) Schematic top view of the proposed GACDC. (b) Cross-sectional with the simulated intensity distribution of the fundamental TE-like modes in the rib waveguides. (c) Dispersion curves of the modes. Phase matching wavelengths are indicated with arrows.

We consider a device that contains two rib waveguides with width W_a=340 nm and W_b=580 nm. The two waveguides are placed 780 nm away from each other with a grating in between with width W_g=320 nm, period Λ=244 nm and grating duty cycle η=0.5.

In Fig. 1(c), we plot the effective refractive index curve for the fundamental TE-like modes in the rib waveguides a and b as well as their average. These dispersion curves intersect with the curve $y = \lambda/(2\Lambda)$ at the wavelength λ_a=776 nm for the intra-waveguide back reflection and λ_D=787 nm for the inter-waveguide contra-directional coupling. The contra-directional coupling coefficient is calculated from the simulated electric field distribution: κ_D=9.06$\times10^{-3}$ μm^{-1}.

According to (4), theoretically, the extinction ratio at the contra-directional coupling wavelength can go infinitely high as one keeps increasing the total length of the grating. Realistically however, there should be a limitation. To explore what extinction ratio we can achieve in practice by increasing the grating length, a variety of lengths up to L=4.9 mm is considered in the design.

The devices were fabricated on a silicon nitride wafer with one step of e-beam lithography and reactive-ion etching (RIE). The full thickness of the silicon nitride layer is 300 nm and the desired etch depth is 150 nm.

4 MEASUREMENT RESULTS AND DISCUSSION

The fabricated devices are measured on a setup which contains two fibers that are positioned near-vertically (10 degree away from normal) to the chip. The light is coupled into and out of the chip through on-chip grating couplers. The devices are first measured with a broadband supercontinuum source to characterize the spectral response in a relatively wide wavelength range. An optical spectrum analyzer (OSA) is used to analyze the spectral response of the GACDC filters. The through-port spectrum of a device with L=4.9 mm is shown in Fig. 2(a) together with a transmission spectrum of a reference waveguide. We can immediately notice three dips in the transmission spectrum. The two dips at 789 and 777 nm are in agreement with the two intersections λ_D and λ_a shown in Fig. 1(c). The small discrepancy could be explained by the fabrication uncertainties. Variations in the waveguide widths, etch depth as well as the wafer thickness can change the effective indices of the waveguide modes and shift the exact wavelengths at which phase matching happens. A third dip at around 775 nm can be explained as the contra-directional coupling between the forward propagating mode in waveguide a and a high order TM-like backward propagating mode in waveguide b. After we add the dispersion curves of this high order mode labeled with n_b^* and the average labeled with $(n_a + n_b^*)/2$ in Fig. 1(c), the third intersection at wavelength λ_D^* emerges, in agreement with the measurement result. In the spectrum, we can also observe the drop of transmission in the wavelength range shorter than 770 nm. This is due to the fact that in this wavelength range, the grating starts to couple light into the radiation modes in the oxide cladding.

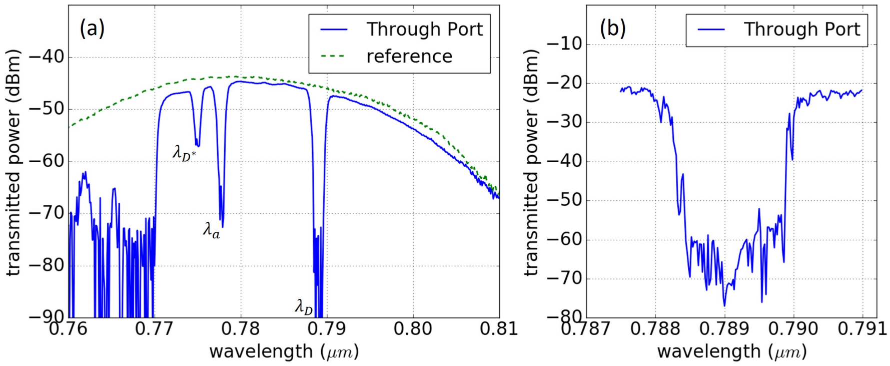

Figure 2. Measured through-port transmission spectra of a fabricated GACDC device: (a) measured with a supercontinuum source in a wide wavelength range, (b) a high resolution zoom-in measurement with a Ti:Sapphire tunable CW laser.

To take a closer look at the contra-directional dip at λ_D, we use a Ti:Sapphire tunable CW laser together with an optical power meter to scan the spectrum in the wavelength region centered around λ_D with a step size of 20 pm. The measured transmission spectrum is shown in Fig. 2(b), where we can see a stop band with bandwidth around 1.7 nm and rejection ratio on average 43 dB.

The reasons why we could not get even higher rejection ratio could be multifold. On the one hand, fabrication uncertainties and non-uniformities introduce stitching errors and geometrical variations that could reduce the extinction ratio and broaden the bandwidth of the stop band. On the other hand, light having leaked into the 150 nm thick Si_3N_4 slab could travel around in the chip and set a lower boundary to the signal strength that one can measure on the chip. Future work will focus on the investigation of these effects.

5 CONCLUSION

We designed and characterized an on-chip GACDC filter that operates in the near infrared range (< 800 nm) on a silicon nitride rib waveguide platform. The working principle was explained, followed by the simulation results that allowed us to design the filter. Experimentally, we demonstrated a device that has a stop band centered at the inter-waveguide contra-directional coupling wavelength λ_D=789 nm. The extinction ratio measures in average 43 dB, while the bandwidth is around 1.7 nm. On the red side of the stop band, the filter offers a flat spectrum response with an unlimited FSR. All these features make it suitable and promising as a pump rejection filter for applications such as on-chip Raman spectroscopy.

REFERENCES

[1] K. De Vos, I. Bartolozzi, E. Schacht, P. Bienstman, and R. Baets,"Silicon-on-insulator microring resonator for sensitive and label-free biosensing," Opt. Exp., vol. 15, no. 12, pp. 7610–7615, 2007.

[2] X. Wang, W. Shi, R. Vafaei, N. A. F. Jaeger, and L. Chrostowski, "Uniform and sampled Bragg gratings in SOI strip waveguides with sidewall corrugations," IEEE Photon. Technol. Lett. 23, 290–292, 2011.

[3] F. Horst, W.M. Green, S. Assefa, S.M. Shank, Y.A. Vlasov and B.J. Offrein, "Cascaded Mach-Zehnder wavelength filters in silicon photonics for low loss and flat pass-band WDM (de-)multiplexing" Optics express, 21(10), pp.11652-11658, 2013.

[4] F. Xia, M. Rooks, L. Sekaric, and Y. Vlasov, "Ultra-compact high order ring resonator filters using submicron silicon photonic wires for on-chip optical interconnects," Optics express, 15(19), pp.11934-11941, 2007.

[5] A. Dhakal, A. Subramanian, P.C. Wuytens, F. Peyskens, N. Le Thomas, R. Baets, "Evanescent excitation and collection of spontaneous Raman spectra using silicon nitride nanophotonic waveguides," Optics Letters, 39(13), p.4025-4028, 2014.

[6] M. Qiu, M. Mulot, M. Swillo, S. Anand, B. Jaskorzynska, A. Karlsson, and A. Forchel, "Photonic crystal optical filter based on contra-directional waveguide coupling," Applied Physics Letters, 83(25), 5121-5123, 2003.

[7] W. Shi, X. Wang, W. Zhang, L. Chrostowski, and N. A. F. Jaeger. "Contradirectional couplers in silicon-on-insulator rib waveguides," Optics letters, 36(20), 3999-4001, 2011.

[8] P. Yeh and H.F. Taylor, "Contradirectional frequency-selective couplers for guided-wave optics," Applied optics, 19(16), pp.2848-2855, 1980.