Sub-nm resolution cavity enhanced micro-spectrometer

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Abstract: A novel on-chip spectrometer device using combined functionalities of a micro-ring resonator and a planar diffraction grating is proposed. We investigate the performance of this architecture by implementing it in a silicon-on-insulator platform. We experimentally demonstrate such a device with 100 channels, 0.1 nm channel spacing and a channel crosstalk less than -10 dB. The entire device occupies an area of less than 2 mm\textsuperscript{2}. Based on our initial results we envision that this device enables the possibility of the realization of low-cost and high-resolution ultra-compact spectroscopy.

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References and links

1. Introduction

Sub-nanometer resolution, wide spectral range and CMOS compatible spectrometer would enable applications in low cost on-chip chemical and biological analysis [1-4], optical metrology [5,6] and optical coherence tomography [7]. Several difficulties arise in the design of such devices. Architectures like diffraction gratings (DG) [8-10] and arrayed waveguide gratings (AWG) [11-14] have their resolution linked to the number of grooves/waveguides. Since the size of the entire spectrometer needs to increase in order to accommodate more grooves/waveguides, the area of the device increases with the square of the resolution improvement.

![Diagram of spectrometer with ring](image)

Fig. 1. (a). Micrograph of the spectrometer with ring. Note that the ring resonator’s drop port is used as input of the grating spectrometer. (b) Close-up view of ring resonator. c) Zoom in the diffraction grating. The teeth opposite to the grating facets are used to decrease back reflection. d) Close-up view of the spectrometer output waveguides.

High order diffraction is generally employed to improve the resolution of AWG devices, however this comes with a reduction of the free spectral range (FSR) limiting, therefore, the total spectral range of operation. It is also possible to build a spectrometer using an array of ring resonators [15,16]. In this case, high resolution with a small device area could be...
achieved, but due to fabrication limitations each ring resonator is required to be individually tuned, increasing system complexity.

Here we design and fabricate a high resolution, large FSR, small footprint, on-chip spectrometer by combining high quality factor (Q) ring resonators and a DG spectrometer.

2. Device theory

The principle of operation consists of using a ring resonator to pre-filter the light to be analyzed by the DG spectrometer. The cavity (Fig. 1(b)) transmits from the input to the drop port only the resonance wavelengths (as shown in Fig. 2(a) (black line)). This filtered optical signal then propagates from the prop port to the diffraction grating input (Fig. 1(a)). At this point, the light then leaves the waveguide, diffracts out towards the reflective diffraction grating (Fig 1(c)). The diffraction grating then, diffracts light from each resonance into distinct waveguides (or channels, Fig. 1 (d)), where it is collected by these waveguide and guided to the edge of the chip. Figs. 2(a) and 2(b) shows respectively the transmission spectrum for the DG spectrometer alone and the combined ring resonator and DG spectrometer. Notice that the channel transmission bandwidth, which is traditionally defined by the DG spectrometer, is now set by the ring cavity resonance width. One can also notice the need for aligning the resonator FSR with the DG channel spacing.

![Fig. 2](image-url)

**Fig. 2.** (a) Theoretical ring resonator input to drop port transmission spectrum (in black) and transmission spectrum of DG spectrometer for different channels. b) Theoretical transmission spectrum for the combined ring and diffraction grating spectrometer. The small peaks are due to the overlap of the residual transmission from the DG spectrometer with the neighboring resonances.

When designing the ring resonator filter, for a given waveguide intrinsic loss, a compromise needs to be made between the resonance width and the peak efficiency in which the light power is transmitted from the input to the drop port (drop efficiency). The resonance width $\Delta \lambda_{\text{FWHM}}$ dependence on the drop efficiency $\eta$ is given by Eq. 1 [17]:

$$\Delta \lambda_{\text{FWHM}} = \frac{\lambda^2}{\pi n_g L} \left[ \frac{\tau - \sqrt{\eta \tau}}{1 - \sqrt{\eta \tau}} \right]^{1/2} \left( \frac{\tau - \sqrt{\eta \tau}}{1 - \sqrt{\eta \tau}} \right)^{-1/2}$$  \hspace{1cm} (1)

where $\tau = 10^{-\alpha L/20}$ is the resonator round trip amplitude efficiency, $\alpha$, $L$ and $n_g$ are the ring resonator waveguide loss, length and group index respectively, and $\lambda$ is the resonance wavelength. The coupling of the input and drop waveguides to the cavity was assumed to be symmetric. In such a configuration, the input port to drop port loss as well as the resonance width is minimum [18]. Note that the resonance width $\Delta \lambda$ is directly related to the loss. Assuming losses of 1-2 dB/cm routinely achieved in silicon waveguides [19]. The graph on Fig. 3(a) shows how the resonance width changes the drop efficiency for different waveguide losses.
3. Design and fabrication

We design the DG spectrometer using the Rowland arc hitecture. To reduce spherical aberration, a non-uniform groove spacing is employed [20]. Metal heaters are added above the silicon layer [21] to align the resonator and spectrometer transmission combs using the thermo-optic effect in silicon. The diffraction grating spectrometer contains 25 channels with spacing of 1 nm. To match the ring resonator FSR to the DG spectrometer channel spacing we use an 83.5 µm radius ring with waveguide cross-section of 450 x 250 nm. The FSR changes with wavelength according to $\lambda^2/n_g L$, but considering a slight positive group velocity dispersion ($\partial n_g/\partial \lambda \approx 3.6 \times 10^{-3}$ nm$^{-1}$) this change is extremely small: the total change in FSR across the range of operation (25 nm) is approximately 1% for light polarized in the plane of the device (TE polarization).

We fabricate the device using a CMOS compatible process. We start with a silicon-on-insulator (SOI) wafer with a 250 nm top silicon layer and a 3 µm buried oxide layer. A 60 nm layer of SiO$_2$ is deposited using high-temperature low-pressure chemical vapor deposition (HTO) to be used as a hard mask. The grating, ring and waveguides are defined by e-beam lithography on a PMMA resist mask. The pattern is transferred to the oxide layer using a CHF$_3$/O$_2$ reactive ion etch (RIE). The silicon layer is etched using chlorine RIE. A layer of 160 nm of SiO$_2$ is deposited using HTO to conformally fill the 100 nm gaps in the waveguide to ring coupling, then 1 µm of SiO$_2$ is deposited using plasma enhanced chemical vapor deposition to clad the device. We define the heaters using photolithography (using SPR955CM and LOR5A resists) and then deposit a NiCr film. After liftoff, the wafer is diced and polished for optical testing.

4. Testing and results

We measure the device transmission spectrum by coupling laser light from a tunable laser into the input waveguide using a lensed fiber and measuring the transmitted power as a function of wavelength. The input light is TE polarized and the output light is collected using a microscope objective and filtered for the TE polarization before detection.

We achieve a channel FWHM of 0.05 nm across 10 different channels of the composed ring and EDG spectrometer, which represents a decrease in the channel width by 10 times compared with the DG spectrometer alone. This channel width corresponds to a quality factor of $Q = \lambda/\Delta \lambda = 30,000$.

Figure 3(b) shows the device transmission. The transmission is normalized to the ring through port power level to eliminate coupling losses. The device insertion loss varies between -18 and -23 dB, where -10 dB is due to the Fresnel reflection of the diffraction grating and can be eliminated by coating it with a metal or using Bragg reflectors [9]. Other
losses are attributed to stitching in the waveguide definition during e-beam lithography. A small mismatch between the resonator FSR (0.97 nm) and the DG spectrometer channel spacing (1 nm) cause a misalignment between the resonance and the DG spectrometer channel that builds up from one channel to the next in a Vernier effect. The outcome is a misalignment between the 11th spectrometer channel and the 11th ring resonance. Therefore only 10 of the 25 channels on the DG spectrometer are used. This issue can be eliminated by more detailed characterization of fabrication.

5. Increasing channel density

Serializing devices either spatially or in time can increase the spectrometer channel density. The space serialization approach consists of using multiple combined ring-DG spectrometers, so that the input of a spectrometer is connected to the through port of the previous device, as shown in Fig. 4(a). The peak wavelength of each spectrometer is shifted relative to the others. The number of devices needed in order to achieve the a spectral density where the channels are separated by $\Delta\lambda_{\text{FWHM}}$, is equal to the DG spectrometer channel width divided by $\Delta\lambda_{\text{FWHM}}$. In spite of the area increase, this approach is still more compact than using a traditional diffraction grating spectrometer since in this proposed approach the area increases linearly with resolution as opposed to quadratic in traditional DGs.

In time serialization, Fig. 4(b), only a single combined spectrometer is used and the output spectrum is measured several times. In each measurement the device transmission spectrum is shifted. Notice that this approach also requires active tuning of the ring and the EDG spectrometer.

By applying the time serialization technique we were able to reduce the channel spacing from 0.97 nm to 0.097 nm, and were able to measure 100 channels using the device.

Fig. 4. (a). Space serialization schematic. Multiple devices are concatenated, where each device transmission spectrum is spectrally shifted. (b). Time serialization schematic. Same device is used to make the measurements but with shifted spectral transmission at each measurement.

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Fig. 5. Transmission spectrum for a combined ring and diffraction spectrometer using a time serialization technique for reducing channel spacing.
A zoom in on the series of channels is depicted in Fig. 6(a). Figure 6(b) shows a density plot where each horizontal line corresponds to the transmission spectrum of each channel. Notice that the overlap of the residual transmission from the DG spectrometer with the neighboring resonances can be seen in the side diagonal lines, and their transmissions are at least 10 dB lower than the peak (main diagonal line).

Fig. 6. (a). Zoom-in of the transmission spectrum for waveguide 5 in Fig. 5. (b). Density plot of the transmission spectrum for a combined ring and diffraction spectrometer using a time serialization technique, where each horizontal line refers to a channel of the spectrometer.

6. Summary

We showed that by using an optical micro ring cavity combined with a diffraction grating spectrometer it is possible to decrease the final device channel width while preserving small footprint. This is because the channel width of the combined device is decoupled from the number of grooves of the diffraction grating. Using time serialization, a device with channel spacing of 0.1 nm, 100 channels, -10 dB crosstalk was demonstrated in a 2x1 mm$^2$. To the best of our knowledge this is the highest number of channels and smallest channel spacing for a device of the reported size. While the idea was implemented in a silicon based material which is suitable for IR spectroscopy, the concept can be extended to other wavelength regimes such as the visible range by employing other material platform such as SiN for the realization of the resonator and the grating.

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