Silicon Rich Nitride Micro-resonators

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Abstract: We report optical resonance in planar waveguide silicon rich nitride (SRN) ring resonators with radii down to 29 μm. Due to their high finesse and large free spectral range, these resonators are shown to be well suited as building blocks for highly integrated optical components.

Keywords: Ring resonator, integrated optics, high index contrast materials

Introduction

Digital optical filters are a major field of interest, because of the fact that nearly arbitrary filter functions can be built out of a few rather simple building blocks using digital signal processing theory [1]. One of the main disadvantages in realizing these filters has been the limitation in bending radii, leading to large and thereby expensive components and at the same time limiting the free spectral range of the resonators. Using silicon rich nitrite (SRN) as waveguide material, we have demonstrated resonators having a factor of hundred smaller bend radii than normally used in silica based components. This means that the required area for one resonator loop is nearly four orders of magnitude smaller allowing in principle a 10000 times higher integration density of integrated optical components.

In this article we will discuss the material properties of SRN with a step index of $\Delta n = 0.615$, with respect to properties of microring resonators and coupling to straight SRN waveguides. We show examples of measured resonances, which are in very good agreement with the theoretical predictions.

Silicon rich nitride (SRN)

Thermal oxide (~10 μm) serving as buffer layer was grown on a 4” silicon wafer, upon which the SRN core layer was deposited by low-pressure chemical vapor deposition (LPCVD). Standard photolithography and subsequent reactive ion etching was used to make the structures. The cladding consists of~12 μm boron phosphorous-doped glass (BPSG) deposited by plasma enhanced chemical vapor deposition (PECVD) [2]. The propagation loss of straight SRN waveguides situated on the same wafer as the ring resonators, was measured by the cut back method to be 3.2± 0.4 dB/cm. Polarization dependent loss was measured to around 3 dB. The elevated propagation loss compared to earlier reported values (as low as 0.73 dB/cm [2]) is attributed to particle contamination due to a minor leakage in the deposition equipment.

Ring resonators

In order to couple light in and out of the straight SRN waveguide, a high NA fiber with a mode field diameter of around 4 μm was spliced to a standard fiber. To obtain the required spectral resolution of 1 pm a tuneable laser in connection with an optical spectrum analyser was used to record the narrow transmission resonance. The polarization was adjusted using a polarization controller.

A structure consisting of one or three SRN rings adjacent to a straight SRN waveguide has been studied. All the resonators are in a racetrack configuration as shown in fig. 1.

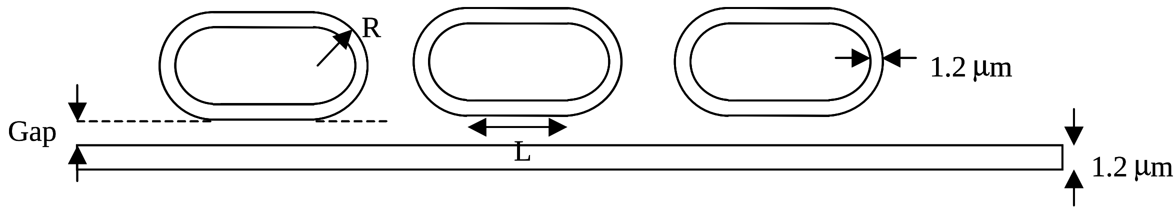

Figure 1. Ring resonator. R is the radius of curvature, and L is the coupling length.

The waveguide width in the resonators as well as the straight waveguide is 1.2 μm and the height is 0.61 μm. The dimension for single mode square waveguides in SRN with a refractive index of 2.06 at 1550 nm is approximately 0.6 μm x 0.6 μm. Although the measured waveguides are able to support higher order modes we do not observe any resonance that can be attributed to other than the fundamental mode. This is due to the elevated bend loss in the resonator loop for higher order modes.

A transmission spectrum of a ring resonator is show in fig. 2. It can be seen that the coupling intensity increases with wavelength. The inserted graph in fig. 2 is a transmission spectrum two single peaks. Different racetrack-structured resonators, with varying radius, ring and coupling length have been analysed.

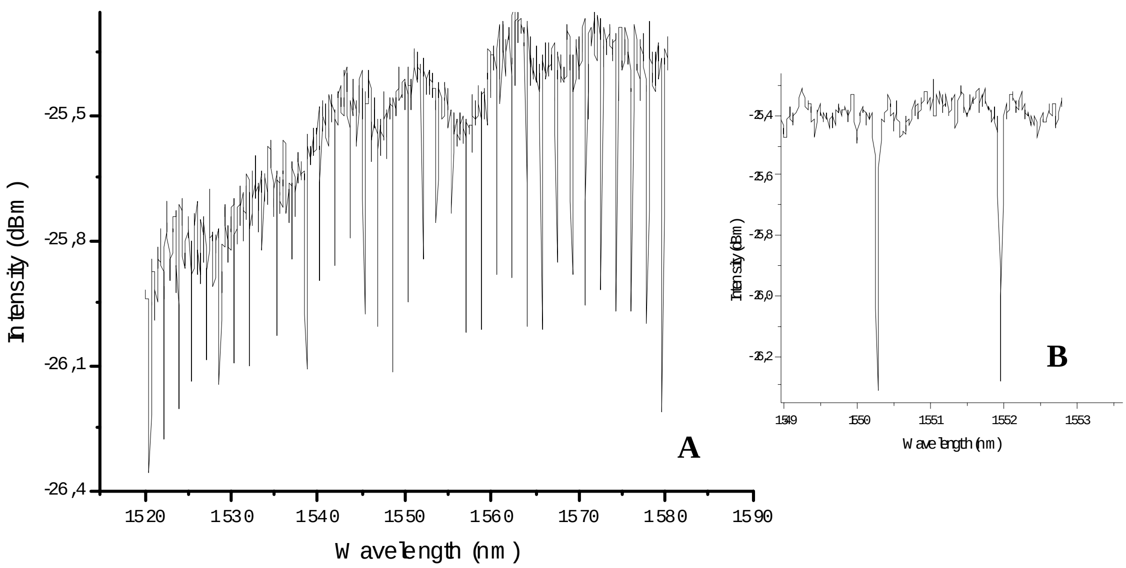

Figure 2. A) Transmission spectrum of a resonator with a radius of 100 μm, separation between resonator and waveguide is 1.0 μm. B) A close up of two peaks, FSR = 1.7 nm at 1550 nm.

When measuring on structures with three resonators, three different resonances are observed for each resonator as illustrated in fig. 3. The spectrum is shown for a resonator with a radius of 31 µm. The free spectral range (FSR) is 2.14 nm.

Racetrack-shaped resonators with radii varying from 29 to 100 µm were investigated. The transmission spectra were analysed using a Lorentzian fit to each absorption peak, determining the free spectral range (FSR) and the full width half maximum (FWHM). In fig. 4 the measured free spectral range (FSR) of the resonators is compared to the theoretical values, showing good agreement. The finesse of these resonators is around 65.

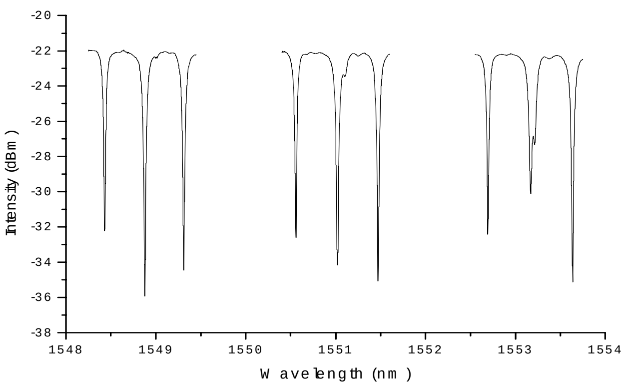

Figure 3. Transmission spectra of resonators with radii of 31 µm, separation between resonator and waveguide is 1.0 µm.

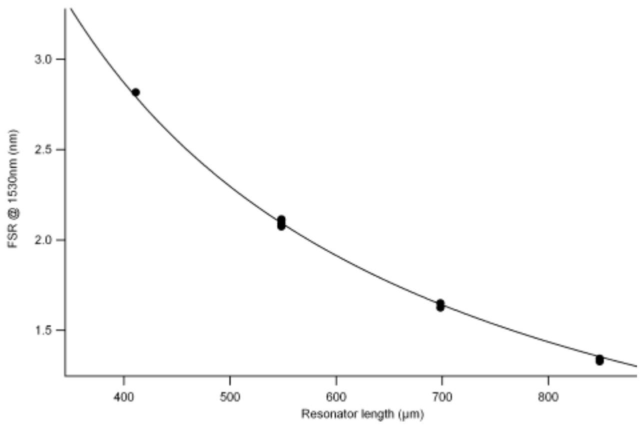

Fig 4. Free spectral range (FSR) as a function of ring resonator length. The round symbols are the measured values; the curve is a theoretical fit.

The curvature loss of the ring resonators is critical. In order to determine the curvature loss, several waveguides with different radius of curvature, and with a varying number of bends from two to ten were measured. We could not measure a difference in insertion loss as a function of the number of bends in a waveguide even for the smallest radius of 20 µm. From these measurements we conclude that the bend loss for one 90-degree bend with 20 µm is below 0.1 dB. This means that in these particular samples the propagation loss in the waveguide is the dominating loss mechanism within the resonator.

To investigate the coupling we use a schematic as illustrated in fig. 5. A fraction (κ) of the intensity of the propagating field in the straight waveguide mode (E_{11}) is coupled evanescently with the resonator mode yielding a field (E_{22}) propagating in the resonator. While this field propagates in the resonator the modal amplitude decreases due to the propagation and bend loss of one round trip in the resonator (γ) yielding a field (E_{12}) coupling out of the resonator with a coupling coefficient (κ). This field interferes with the field in the straight waveguide yielding a field (E_{21}) now propagating in the straight waveguide.

Writing the electric field equations for this scenario:

$$E_{21} = E_{11}\sqrt{1-\kappa} - jE_{12}\sqrt{\kappa}$$
$$E_{22} = E_{12}\sqrt{1-\kappa} - jE_{11}\sqrt{\kappa}$$
$$E_{12} = E_{22}\sqrt{1-\gamma}\cdot\exp(j\cdot 2\pi\,\tfrac{L_{ring}\cdot n_{eff}}{\lambda})$$

where L_{ring} is the physical length of the resonator and n_{eff} is the effective group index. Solving we get the output intensity of the resonance spectra.

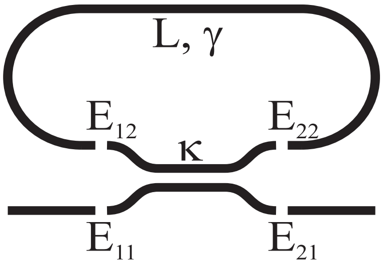

Figure 5. Coupling scheme used for the resonators

$$I_{out} = E_{21}\cdot E^{*}_{21} = \left|E_{11}\right| = \frac{2-\kappa-\gamma-2\sqrt{1-\kappa}\sqrt{1-\gamma}\cos(j\cdot 2\pi\,\frac{L_{ring}\cdot n_{eff}}{\lambda})}{2-\kappa-\gamma+\kappa\gamma-2\sqrt{1-\kappa}\sqrt{1-\gamma}\cos(j\cdot 2\pi\,\frac{L_{ring}\cdot n_{eff}}{\lambda})}$$

Using this expression and inserting the values of the FSR and the total loss in ring, the coupling coefficient for each resonator configuration can be found. The fractional coupling (κ) was calculated for two resonators with different round trip and coupling lengths. The measured and calculated data is displayed in table 1. The loss has been estimated as a propagation loss corresponding to the resonator length and the resulting fractional coupling (κ) is in good agreement with the theory of directional couplers, from which we have $\kappa = \mathrm{Sin}^2(C{*}L_{Coup})$. Taking the coupling coefficient C to be $1.77\cdot10^{-3}$ yields an almost perfect fit with the experimental values of κ.

Resonator length(µm)	548.38	548.38	698.26	698.26
FSR @1530nm (nm)	2.079	2.093	1.628	1.640
Round trip loss in dB	0.1863	0.1863	0.2374	0.2374
Fractional loss, γ	0.0420	0.0420	0.0532	0.0532
Coupling length (µm)	175.9	175.9	34.97	34.97
Fractional coupling, κ	0.0984	0.0896	0.00347	0.00422

Table 1. Measured and calculated data for two resonators.

Conclusion

We have demonstrated microresonators consisting of a waveguide loop made of silicon rich nitrite coupling to a straight waveguide of the same material. Strong resonance with suitable high finesse was observed with a free spectral range of several nanometers. Bend loss is smaller than 0.1 dB per 90 degree bend, down to a radius of 20 um. These resonator loops are an important building block for add-drop multiplexers and digital optical filters, which proves that silicon rich nitrite is a suitable platform for optical large scale integration.

References

[1] Christi K. Madsen, Jian H. Zhao, Optical Filter Design and Analysis: A Signal Processing Approach, 1999, Wiley.

[2] K. N. Andersen, P.C. Nielsen and W. Svendsen. Proceedings of Integrated Photonics Research conferences (IPR) 2002.