Silica Microdisk Coupled Resonator Optical Waveguide

Sacha Bergeron, Francis Vanier, Yves-Alain Peter
Ecole Polytechnique de Montreal, Engineering Physics Department
P.O. Box 6079, Station Centre-Ville, Montreal (QC), H3C 3A7, CANADA.
Tel: + 1 514 340 4711, Fax: + 1 514 340 3218, Email: {sacha.bergeron, yves-alain.peter}@polymtl.ca.

***Abstract*—This paper presents the first reported experimental results of optical transmission through microdisk Coupled Resonator Optical Waveguide structures made of silica. Transmission through a seven cavity waveguide is presented for an optical delay of 109ps.**

I. INTRODUCTION

Coupled resonator optical waveguides (CROWs) have been proposed as a new type of optical waveguide based on the energy transfer between a series of weakly coupled high-Q microcavities [1]. These structures have shown great potential in many applications such as compact optical delay devices due to their ability to strongly reduce the group velocity of an optical signal [2]. These delay devices are extremely important for the next generation telecommunication all-optical routers, to fulfill the need for optical buffers. Other avenues have been explored to slow light down, such as the use of Bose-Einstein condensate where the speed of light can be exceptionally low (17m/s) but cryogenic temperatures are needed to reach the effect [3]. Coupled resonator optical waveguide structures have been discussed and in some cases demonstrated using different types of cavities: 2D photonic crystals [4], microrings [2], microdisks [5] and microspheres [6]. Conceptual analysis of different technologies by Poon et al. [7] showed great interest in the use of silica whispering gallery mode resonators due to their extremely high quality factors (up to 10^8) and their low optical loss [8]. Microdisks are a type of silica microresonator that can easily be fabricated, using conventional microfabrication processes, into patterns that allow optical coupling between cavities.

This paper demonstrates the first results of optical transmission through a microdisk CROW using silica as guiding medium. We will discuss how these structures are fabricated and results showing optical transmission through a near 500μm waveguide.

II. SILICA MICRODISK CROWS

Slow light propagation in a CROW structure is obtained by trapping light into a series of optical microcavities, each cavity delaying the signal by a few tens of picoseconds before sending it to the next cavity. To fabricate such a structure, we use a conventional fabrication technique presented earlier [9]. An oxydized silicon wafer is used Fig. 1a); the microcavity pattern is defined using photolithography Fig. 1b); microdisks are then transfered into SiO_2 by vertical reactive ion etching Fig. 1c); an isotropic etch is used to shape the silicon support pillar Fig. 1d). Figure 1e) shows a fabricated CROW structure made of eight 35μm radius microdisks with 1.1μm gap between cavities.

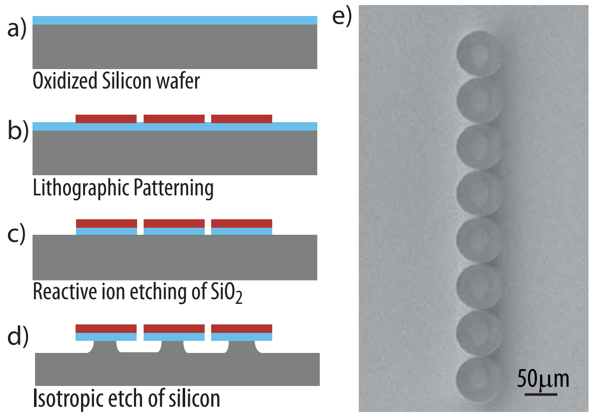

Fig. 1. a-d) Microfabrication process for the silica microdisk CROW structures. a) Initial oxydized silicon wafer, b) Lithographic patterning of the optical cavities, c) Reactive ion etching to transfer microdisks into SiO_2, d) isotropic etch of the support pillar. e) SEM photograph of CROW structure featuring eight 35μm radius coupled microdisks

Light is injected into the CROW by evanescent coupling into one of the end cavity with a tapered optical fiber. Once inserted into the first cavity, the optical signal is trapped in the form of a whispering gallery mode until it can evanescently couple into the next cavity. The gap between two adjacent cavities controls the coupling ($|\kappa|$) and thus the rate with which energy transfers from one cavity to the next. This determines the amount of time (τ_c) the optical signal will remain in each cavity. It is possible to define the group velocity of light inside the waveguide as $\nu_g = \Lambda/\tau_c$ [7]. Λ is the waveguide pitch (distance between two adjacent cavity midpoints). At the other end of the waveguide, the optical signal is extracted by evanescent coupling into a second tapered fiber.

III. RESULTS OF SILICA CROW TRANSMISSION

Figure 2 presents transmission measurements for CROW devices of three (212μm), five (354μm) and seven (496μm) cavities. These measurements were obtained using a tunable laser source and detector setup with a spectral resolution of 25pm and a dynamic range as low as -80dBm.

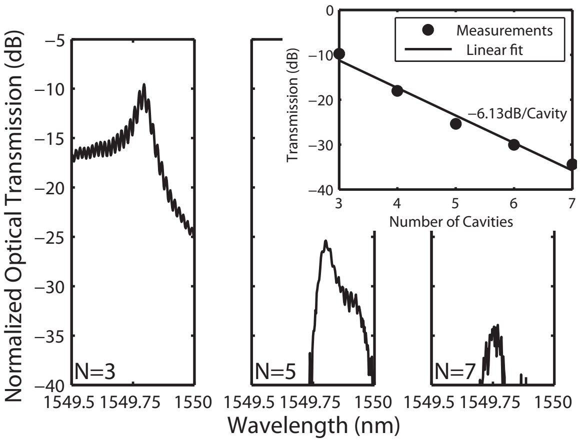

Fig. 2. Transmission spectra of CROW devices using 3, 5 and 7 cavity lengths. Inset presents the attenuation slope of this waveguide.

These results demonstrate transmission through a seven cavity microdisk CROW. The inset of Fig. 2 describes the attenuation of the optical signal along the length of the waveguide. We note a Slope of -6.13dB/cavity.

IV. Discussion

The maximum delay in a CROW device is function of the intrinsic quality factor of an individual cavity (Q_{int}) as $\tau_{max} = Q_{int}/\omega$, were ω is the cavity's resonant frequency [7]. This maximum delay time is defined as the time for $1/e$ of the input power to be lost. Furthermore, it is possible to determine the delay caused by a specific configuration of CROW using

$$\tau = \frac{\pi n_{eff} R N}{|\kappa|\, c}, \tag{1}$$

where n_{eff} is the cavity's effective index of refraction, R is the individual cavity's radius, N is the number of optical microcavities in the waveguide, and c the speed of light.

The coupling coefficient $|\kappa|$ was calculated versus gap by integrating the modal overlap of two whispering gallery modes (see Fig. 3). For a gap of 1.1μm we have $|\kappa| = 0.031$. Using Eq. 1) we obtain a delay of 109ps after seven cavities. Equation 2) describes the relation between the optical loss per cavity α_c (measured experimentaly at $\alpha_c = -6.13$dB/cavity, ses inset of Fig. 2) and the CROW properties [7]:

$$\alpha_c = \frac{m\pi}{|\kappa|\, Q_{int}}, \tag{2}$$

where m is the azimuthal number of the cavity's whispering gallery mode. It is then possible to find a numerical value for the intrinsic quality factor of our individual microcavities, $Q_{int} = 1.3 \times 10^4$. This result is consistent with separately characterized microdisks (upper right inset of Fig. 3) fabricated on the same batch.

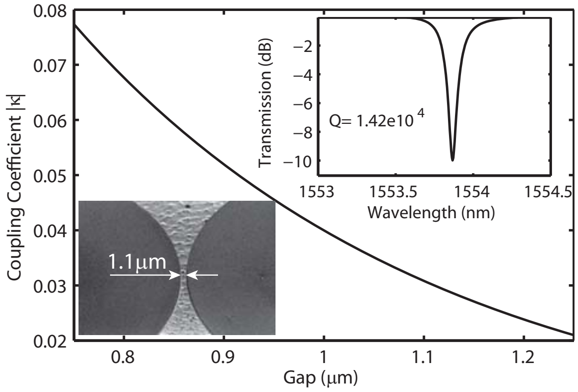

Fig. 3. Main chart shows the calculated value of ($|\kappa|$) in function of the gap between two adjacent microdisks. Lower left inset presents SEM image of the gap between cavities. Upper right inset gives quality factor measurements of an isolated microcavity.

Using this quality factor we find a τ_{max} of 10ps. It is thus extremely important to optimize the fabrication process to minimize geometric defects and surface roughness in order to achieve quality factors several orders of magnitude higher. The range of quality factors needed for long delay CROW structures ($> 10^6$) has previously been demonstrated using silica circular microresonators [8]. We have shown here the feasibility of creating CROW structures with silica microdisks, which will likely lead to the development of all-optical buffers.

V. Conclusion

This paper demonstrated the possibility of creating optical buffers using silica microdisks. When a series of microdisks are coupled together into a CROW structure, it is possible to slow the group velocity of light and thus temporarily store an optical signal. We presented results of transmission through a seven cavity waveguide producing a delay of 109ps. Previous demonstrations of much higher Q silica resonators [8] show the very high potential of using silica microdisk resonators to generate slow light in CROW structures.

References

[1] Yariv et al., "Coupled-resonator optical waveguide: a proposal and analysis." *Opt. Lett.*, **24**(11), 711-713., (1999).

[2] Xia et al., "Coupled resonator optical waveguides based on silicon-on-insulator photonic wires." *Applied Physics Letters*, **89**(4), 041122., (2006).

[3] Hau et al., "Light speed reduction to 17 metres per second in an ultracold atomic gas." *Nature*, **397**, 594-598., (1999).

[4] Olivier et al., "Miniband transmission in a photonic crystal coupled-resonator optical waveguide." *Opt. Lett.*, **26**(13), 1019-1021., (2001).

[5] Nakagawa et al., "Photonic molecule laser composed of GaInAsP microdisks." *Applied Physics Letters*, **89**(4), 041112, (2005).

[6] Astratov et al., "Optical coupling and transport phenomena in chains of spherical dielectric microresonators with size disorder." *Applied Physics Letters*, **85**(23), 5508-5510, (2004).

[7] Poon et al., "Designing coupled-resonator optical waveguide delay lines." *J. Opt. Soc. Am. B*, , **21**(9), 1665-1673, (2004).

[8] Armani et al., "Ultra-high-Q toroid microcavity on a chip." *Nature*, **421**, 925-928, (2003).

[9] Bergeron et al., "Optical wavelength selection and amplification by silica microcavities and erbium doped fiber." *2008 IEEE/LEOS Internationall Conference on Optical MEMs and Nanophotonics,*, 35-36,(2008).