Ultra-low Power Frequency Conversion in Two-photon-absorption Free Micro Ring Resonator

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Abstract— All-optical integrated circuits bring the promise to vastly increase the bandwidth, improve the flexibility as well as reduce the cost of future communication networks. All optical integrated components, like switches and wavelength converters, must meet fundamental requirements such as low optical losses, strong nonlinear response and ease of fabrication. To date, however, research on these devices has been based either on semiconductors, such as silicon and GaAs, or highly nonlinear glasses, such as chalcogenides which, although exhibit a Kerr nonlinearity (n2) of 100x–400x silica glass, also present limitations such as remarkable linear and nonlinear losses and, for certain applications, a not developed fabrication techniques. Specifically, the possibility to rely upon a mature technology recently has proved itself to be a powerful solution to fabricate micrometric resonant structures which are able to locally enhance the desired nonlinearities. In this work we present the first example of nonlinear optics in silica glass waveguides using continuous wave (CW) light. We achieve wavelength conversion via four wave mixing (FWM) at ultra-low ($\approx 5$ mW CW) power levels in C-MOS compatible micro-ring resonator.

1. INTRODUCTION

Traditional material systems for the development of all-optical and optoelectronic devices have primarily been based on semiconductors [1, 2]. Typically these materials exhibit a strong nonlinear response when shaped as waveguides, thanks to their large nonlinear coefficients, high index contrast and small effective area. On the other hand they are often linked with some significant drawbacks such as large linear and nonlinear losses [3] that prevent optimal efficiency for high pump power applications. Contrarily, regarding glass (fused silica) technology, traditional silica waveguides are low index contrast structures and thus results in poor confinement and large bend radii, making all-optical signal processing on a single chip unfeasible, not withstanding their extremely low nonlinear response. Sometimes, when the fabrication process are particularly developed and mature, the strategy is that one of fabricating ultra high Q resonant cavities in order to increase the local intensity and consequently the nonlinearities of the device [4]. However, this solution could avoid the applicability of the phenomenon under investigation in fast communication systems, since a huge value of the Q factor drastically narrows the bandwidth.

As alternative approach, using nonlinear glasses such as chalcogenides and Ta2O5, has been developed to offer a substantial nonlinear response comparable to semiconductors. However, such glasses are also prone to linear and nonlinear losses for small device footprints, and for certain applications, their fabrication technology is still quite immature [5]. Here we present a high-index silica glass material (Hydex®) which offers an excellent compromise between the best properties of semiconductors (high nonlinearities and tight field confinement) together with the low loss values of silica glass. Hydex® glass is a high index material ($n = 1.7$) whose developed fabrication technique admits the possibility to vary the index contrast between the core and the silica cladding from 1 to 25% [6] making possible tight bends on the order of 5 $\mu$m in radius and hence, the fabrication of complex resonant microstructures [7, 8].

Furthermore the deposition process using Chemical Vapor Deposition (CVD) and the waveguide core patterned by reactive ion etching makes the entire fabrication process of Hydex totally compatible with current silicon technology [6]. The versatility of high-index glass waveguides have already been largely proved by numerous accomplishments in many applications including optical
sensing of bio-molecules using ring resonators [7], and high-order filters with an 80 dB rejection ratio [9] but the study of the nonlinear properties of this material has never been addressed.

Since the wavelength conversion is a fundamental nonlinear process for future all optical communication systems we decide to perform the nonlinear investigation of Hydex® starting from the Four Wave Mixing experiment (FWM).

2. EXPERIMENTS

The FWM is a parametric process that is used here to generate a new frequency of light from two existing ones [10, 11]. This kind of wavelength conversion process can be an important tool for wavelength-agile optical networks, where wavelength division multiplexing and demultiplexing, signal regeneration and switching/routing applications are required. Recently, ultra-low power CW FWM wavelength conversion was reported in silicon by using micro-ring resonators [2]. It is of fundamental importance, however, to investigate other material systems since silicon is well known to suffer from two-photon absorption (TPA) and induced free carrier losses that can affect performances at high pump powers [11]. Indeed, the intrinsic nonlinear figure of merit for silicon still remains low even if we eliminate this undesirable effect by means of pin junctions to sweep carriers out [12].

Figure 1 is a scheme of the ring resonator used in our experiment. The ring has a Q-factor of 65000, a free-spectral range of 575 GHz, a radius of 48 µm and a cross-section of 1.5 µm × 1.5 µm. The bus waveguides, which have the same cross section as the ring, are buried underneath a SiO₂ layer and they are used to couple light inside and outside the resonator itself.

Two wavelength-tunable CW lasers were used in this experiment; the pump laser (at the INPUT port) was set in such way to provide a power of 5 mW inside the ring and tuned to a TM ring resonance at 1553.38 nm, whereas the signal laser (at the ADD port) had a power of 550 µW and was tuned to an adjacent resonance at 1558.02 nm. The outputs were analyzed using either a power meter or a spectrum analyzer.

3. RESULTS

By the FWM process two idlers are generated according the following formulas:

\[ \omega_{1\text{st Idler}} = 2\omega_{\text{Pump}} - \omega_{\text{Signal}} \quad \text{and} \quad \omega_{2\text{nd Idler}} = 2\omega_{\text{Signal}} - \omega_{\text{Pump}} \]

The output power spectra, as recorded at the through channel, are reported below (Fig. 2-Left) as well as the 1st-idler power as a function of the square of the pump power (Fig. 2-Right). The latter shows a good linear dependence, as expected from theory, and demonstrates that our device does not exhibit saturation due to nonlinear absorption, for pump power up to 20 mW.

The first idler was determined to be exactly on resonance at 1548.74 nm, as it is also clearly shown by the idler detuning curve (Fig. 3-Left). This condition is the best to take advantage of the FWM resonance enhancement factor [13, 14] and is made possible tanks to the negligible dispersion of the system that is proved by the strictly linear behavior of the plot that represents the resonance frequencies spacing (Fig. 3-Right).

In order to quantitatively estimate our device performances, we used a theoretical model that takes into account the resonant enhancement factor due to the cavity geometry [13]:

\[ \eta \equiv \frac{P_{\text{idler}}}{P_{\text{signal}}} = |2\pi R\gamma|^2 P_{\text{pump}}^2 \cdot (FE_p)^4 \cdot (FE_s)^2 \cdot (FE_i)^2 \]

(1)
Figure 2: (Left): Output power spectra at the through port. (Right): 1st Idler power as a function of the Pump power squared.

Figure 3: (Left): Power of the 1st idler as a function of the signal detuning from its corresponding resonance. (Right): Resonance frequencies Vs resonance positions (arbitrary frequency location number).

\[ FE = \frac{\sqrt{2(1 - \sigma)}}{2(1 - \sigma) + \alpha \pi R} \]
\[ \sigma = \left(1 - \frac{\pi}{2F_{\text{inesse}}}\right) \exp \left(\frac{\alpha \pi R}{2}\right) \]

where \( R \) is the ring radius, \( \alpha \) is the linear loss coefficient and \( \gamma \) is the nonlinear parameter. From the measured input and output powers, and by using Equation (1), the nonlinear parameter can be deduced to be \( \sim 233 \text{ W}^{-1}\text{Km}^{-1} \). Our results are comparable to the best results recently reported in silicon structures [2], moreover our glass-based platform offer other advantages such as the ability to produce very good quality high order filters [7, 9], ultra-low losses, as well as the absence of two-photon absorption near \( \lambda = 1.5 \mu\text{m} \), a property which is highly desirable for nonlinear optical applications. Furthermore, the total insertion loss (from laser input to device output) is approximately 3dB, due to the very good coupling efficiencies between the bus waveguides and the ring resonator (\( \sim 100\% \) in resonance). Such coupling efficiencies and throughput are not readily seen for integrated semiconductor waveguides and devices, where coupling efficiencies can be extremely poor [2, 15].

Finally by means of transmission measurements in different length waveguides, we also determined the linear propagation losses to be as little as 0.06dB/cm. This extremely low loss value is orders of magnitude better than in similar semiconductor waveguides, where values greater than 1dB/cm are typically seen in AlGaAs and SOI monomode waveguides [3, 15].

4. CONCLUSIONS
In conclusion, the strong non linearity together with the absence of nonlinear losses and the large reduction in linear losses, reveal some great advantages of our material over the silicon counterpart, especially when re-amplification processes have to be avoided. The estimated \( \gamma \) value together with the intrinsic benefits related with the micro ring resonator technology bring us a step forward toward the realization of integrated multifunctional nonlinear all-optical devices. This kind of
micro-metric optical package could perform fundamental communication system operations like optical amplification and regeneration, wavelength filtering, conversion and switching. We strongly believe that our waveguides can open new frontiers in ultra-fast all-optical signal processing as well as in total secure transmission networks based on entangled photons with the promise of reducing development timescale.

REFERENCES