Si and Si-rich silicon-nitride waveguides for optical transmissions and wavelength conversion around 2 µm

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ABSTRACT

We show that cm-long silicon or silicon-rich nitride waveguides with subwavelength transverse dimensions can efficiently sustain high-speed transmissions at 2 µm. We report the transmission of a 10 Gbit/s signal with negligible power penalty. Parametric conversion in both continuous and pulsed pump regimes is also demonstrated.

Keywords: Silicon waveguide, si-rich silicon-nitride waveguides ; 2 µm optical communications ; wavelength conversion

1. INTRODUCTION

In recent years a number of experiments have explored the potential of various materials in the 2-µm spectral region, with an emphasis on components having subwavelength transverse dimensions to ensure a high density of the photonic circuitry. For instance, efficient data transmission at 10-Gbit/s has been reported using different material platforms such as silicon germanium [1] and titanium dioxide [2]. However, no high bit-rate transmission has ever been reported at wavelengths around 2 µm in either silicon on insulator or any other CMOS-compatible platform. Here, we demonstrate for the first time, penalty-free transmission of a 10-Gbit/s on-off keying signal at 1.98 µm in cm-long Si and SRN waveguides.

In order to fulfil the need of transparent optical networks required for wavelength division multiplexing around 2 µm, frequency conversion is a critical operation that should ideally be realized all-optically. Experimental demonstrations around 2 µm have already been reported in silicon devices that exhibit a large third-order nonlinear coefficient with either picosecond pulses [3, 4] or continuous wave pumping [5, 6]. Stoichiometric Si_3N_4 is another candidate material for applications at 2 µm. However, while it benefits from the absence of two-photon absorption at these wavelengths, its nonlinearity is much lower than silicon. To overcome this limitation, SRN has been explored, since it offers the possibility to precisely engineer both the linear and nonlinear properties of waveguides at the required wavelengths and provides enhanced flexibility in designing low dispersion and highly nonlinear optical structures, operating at high optical powers [7-9]. Here, we show that the same Si or SRN waveguide structure as the one involved for transmission is also suitable for parametric wavelength conversion in the 2-µm range.

2. WAVEGUIDES UNDER STUDY AND EXPERIMENTAL SETUP

A schematic of the waveguide cross section of the Si and SRN waveguides we tested is shown in Fig. 1. Details of the fabrication can be found in [5] and [10] for the Si and SRN components respectively. The Si waveguides are 900 nm wide and 220 µm thick and samples of 7 and 2 cm length have been investigated. They are single-mode around 2 µm with an effective area as small as 0.18 µm^2 leading to a nonlinear parameter of 136 W^{-1}m^{-1}. An important design parameter has been the width of the waveguides, which is crucial in determining the dispersion profile of the Si waveguide. A width of 900 nm ensures that the waveguide operates in the slightly anomalous regime of dispersion at 2 µm.

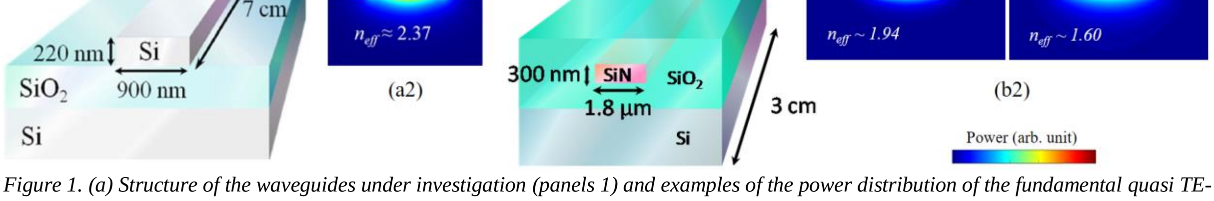

Figure 1. (a) Structure of the waveguides under investigation (panels 1) and examples of the power distribution of the fundamental quasi TE-mode and quasi-TM mode (panels 2, results from a finite difference eigenmode solver) of the Si and SRN waveguides (panels a and b, respectively).

The SRN waveguide is 3 -cm long and can sustain at least the propagation of the fundamental quasi-TE and quasi-TM modes. Its dimensions are much larger in this case (1800 nm × 300 nm), leading to a significantly lower nonlinear coefficient relative to the Si waveguides of our experiments. Owing to the rectangular shape of the waveguide, the properties of the two propagation modes differ significantly. Whereas the quasi-TE mode is highly confined within the SRN core, the quasi-TM mode is much more delocalized and a non-negligible part of the field propagates within the SiO_2 cladding. This difference in the field confinement is also reflected in the effective area that is estimated to be 0.86 μm^2 and 4.75 μm^2 for the quasi-TE and quasi-TM modes respectively. The design of this component has not been optimized for efficient dispersion management, therefore its dispersion is mainly imposed by the strong normal dispersion of the material.

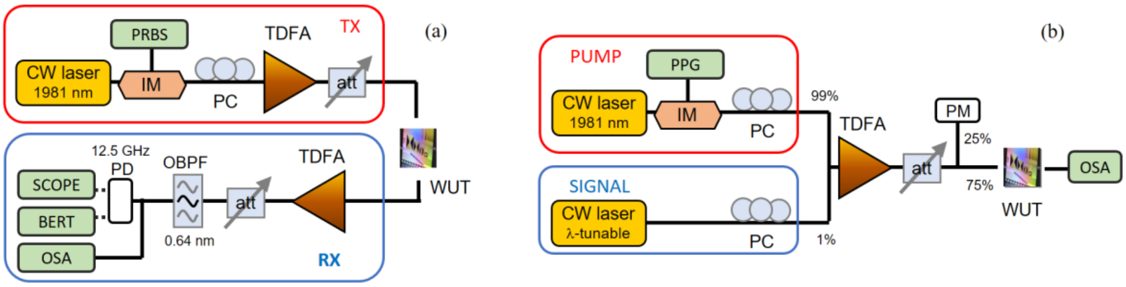

Figure 2. Experimental setups used for (a) 10-Gbit/s transmissions, (b) wavelength conversion.

In order to demonstrate the suitability of the devices for 2-µm optical communications, we have implemented the experimental setup depicted in Fig. 2(a) (more details available in [11]) and based on 2-µm commercially available devices. The transmitter (TX) was based on an intensity modulated laser diode centered at 1981 nm by means of a Niobate-Lithium modulator (IM). Then a first thulium doped fiber amplifier (TDFA) was used to boost the signal before injection into the waveguide. Light coupling in the components was achieved through butt-coupling assisted with lensed fibers. For the SRN case, due to the two-moded nature of the waveguide, the input polarization highly impacts the coupling efficiency. The receiver (RX) used a second TDFA. An optical bandpass filter (OBPF) was also inserted at the output of the system in order to limit the accumulation of amplified spontaneous emission from the TDFAs. An optical spectrum analyzer (OSA) was used to evaluate the optical signal to noise ratio (OSNR).

A second aspect of our work is to evaluate the potential of our waveguides for wavelength conversion applications (Fig. 2(b)). A CW laser tunable between 1965 and 1985 nm was used to generate a signal wave, while the pump beam was kept constant. By means of an intensity modulator driven by an electrical pulse pattern generator (PPG), we were able to study the wavelength conversion process in continuous or pulsed regimes with a typical pump duration of 100 ps. The delay between two consecutive pulses can be adjusted from 200 ps to 1.6 ns. The pump and signal waves were combined using a coupler before being simultaneously amplified by a TDFA. At the output of the system, an OSA was used to evaluate the conversion efficiency (CE) defined here as the ratio between the output powers of the signal and idler waves.

3. EXPERIMENTAL RESULTS

We have summarized the results we obtained for the 10-Gbit/s transmission at 2 µm in Fig. 3 for a 7-cm long Si waveguide and the SRN waveguide operating in the quasi-TM mode of propagation. The typical average power launched to the two waveguides was at the order of mW. Eye-diagrams are provided in panels 1 and 2 and stress that widely open eyes were obtained. The quality of the 10-Gbit/s transmitted signal was quantitatively assessed through systematic measurements of the bit-error-rate as a function of the OSNR on the receiver (panels 3). In all cases, BERs well below 10^{-9} were measured. No significant penalty was observed after transmission through the SRN waveguide whereas a 1 dB penalty, attributed to a residual Fabry-Perot effect has been recorded for the Si waveguide.

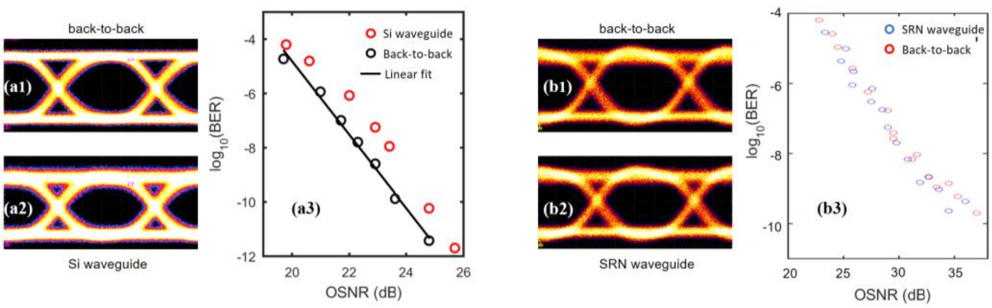

Figure 3. 10-Gbit/s eye diagram recorded in the back-to-back configuration compared to eye diagrams recorded after propagation in the WUT (panels 1 and 2 respectively). Bit-error-rate measurements (BER) as a function of OSNR (panels 3). Results for a 7-cm long Si waveguide and a 3-cm long SRN waveguide are plotted on panel (a) and (b) respectively.

Figure 4 shows the conversion efficiency as a function of the signal wavelength for the two waveguide structures with an estimated input average pump power of 12 dBm. Conversion efficiency as high as -25 dB is demonstrated with continuous pumping in the 2-cm long Si waveguide. A conversion window over 70 nm is demonstrated for the dispersion engineered Si component with an efficiency up to close -10 dB recorded with a pulsed pump. Despite the relatively large effective mode area, conversion efficiencies of ~-24 dB are measured when using a pulsed pump. The moderate bandwidth achieved for the SRN waveguide denotes that, as expected, the pump lies in the strongly normal regime of dispersion.

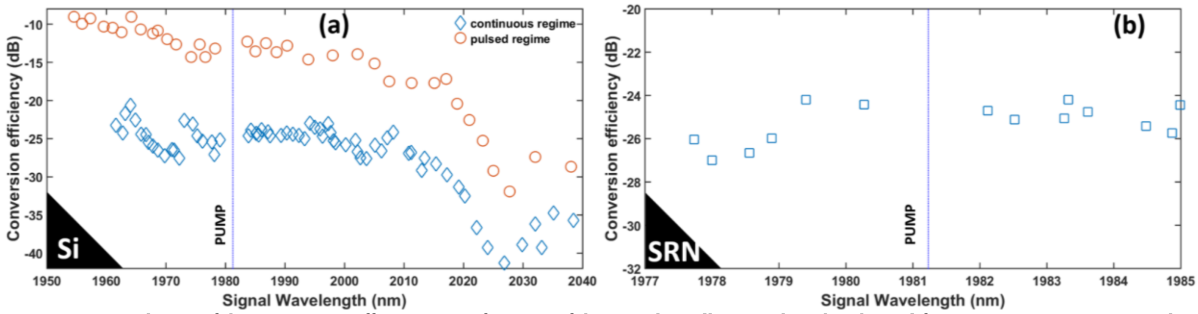

Figure 4. Evolution of the conversion efficiency as a function of the signal or idler wavelength achieved for a pump at 1981 nm. Results have been recorded (a) for the 2-cm long Si waveguide (for continuous operation and for the pulsed regime for a peak power increased by a factor 16) and (b) for the SRN waveguide (in the pulsed regime).

4. CONCLUSION

We have demonstrated that both silicon and silicon-rich silicon nitride waveguides can sustain error-free transmission of high-speed telecom signals around 2 µm in cm-long devices without any significant penalty. We have also shown that such nonlinear photonic chips are suitable for frequency conversion process. Regarding the SRN technology, this first demonstration of wavelength conversion at 2 µm is promising and significant improvement is expected with a design aiming at tailoring the waveguide dispersion. Using a thicker waveguide and taking advantage of the higher confinement of the TE-mode will be explored.

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