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Nonlinear properties of ultra-low losses hydrogen-annealed submicron silicon waveguides

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Abstract
In this communication, we report about fabrication and testing of ultra-low losses silicon-on-insulator (SOI) nonlinear photonic waveguides. In particular, ultra-low losses (<0.5 dB/cm) single-mode strip silicon waveguides can be obtained via a tailored hydrogen-annealing process. Such record-low losses can be leveraged to access nonlinear phenomena with higher efficiency and lower power. As preliminary demonstration of such silicon platform, these waveguides have been used to generate a frequency continuum spanning 1525-1565 nm via self-phase modulation in order to quantify the two-photon absorption (TPA) process. Experimental evidence shows that such low propagation losses can push away the operational limitations of TPA which is still considered as the bottleneck of crystalline silicon (*c*-Si) nonlinear platform. This work paves the way to Kerr-based broadband sources on *c*-Si.

1. Introduction

The compatibility of silicon with microelectronics gives a great potential for optical integration. Active optical devices such as modulators [1], photodiodes [2], and optical switches have been demonstrated in silicon. However, light emission in crystalline silicon (*c*-Si) is difficult to achieve owing to its indirect bandgap. Nonlinear (NL) phenomena such as stimulated Raman scattering [3], self-phase modulation [4] as well as four-wave mixing by Kerr effects could be used to overcome this limitation of *c*-Si. The main drawback sticking with such solutions is coming from the propagation losses and nonlinear losses. At telecom wavelengths, two-photon absorption (TPA) in *c*-Si is an instantaneous nonlinear loss mechanism dominating at high optical intensities which are often required to access X^3 Kerr nonlinearities in silicon nonlinear optical waveguides.

Furthermore, at relatively low optical intensities, before the TPA losses dominate, the linear propagation losses limit the NL broadening via self-phase modulation. In this article we show both the fabrication process of such ultra-low losses waveguides as well as the 1525-1565 nm continuum generation using a 500-nm-wide strip Si waveguide featuring linear losses < 0.5 dB/cm which is the lowest linear losses limit reported so far to our knowledge. The source used in our measurement is an external fiber-based laser with low repetition rate of 20 MHz to avoid TPA-induced free carrier absorption (carriers lifetime is much shorter than the time between two pulses giving the time to the electrons to recombine).

2. Silicon smoothing technology and nonlinear properties

The wafers used are 200-mm diameter SOI wafers with 310-nm-thick crystalline undoped silicon layers on top of 800-nm-thick SiO_2 buried oxides (BOX) [6]. Waveguides are patterned with 193-nm lithography using an $HBr/Cl_2/He\text{-}O_2$ plasma. In order to smoothen the *c*-Si waveguides sidewalls and to get the lowest roughness, an H_2 thermal annealing is applied after photoresist stripping. The best waveguides roughness has been found when the H_2 thermal annealing is applied under 850 °C for 2 minutes and the epitaxy chamber pressure was 20 Torr [6]. After the annealing silicon waveguides were then encapsulated by 1.1-µm-thick SiO_2 layer as a final step. In Fig. 1 inset, we show focused ion beam image of a waveguide fabricated via the aforementioned process.
Linear optical characterization was carried out in order to evaluate the insertion and the linear propagation losses of the waveguides. The linear propagation loss measurements were done via cleaved edge couplers (13 dB/coupler). We derived average propagation losses of ~0.5 dB/cm at 1550 nm for the waveguides with cross-section nominal dimensions ($w \times h$) of <500 nm × 300 nm (Fig. 1). The total insertion loss of several waveguides with different lengths was measured and the propagation losses of the fundamental transverse-electric polarized mode (TE_{00}) was inferred from the slope of the insertion loss as a function of the waveguide length.
The nonlinear index of silicon makes the material intensity-dependent producing blue-shifted spectral components on the trailing edge of a pulse passing through the silicon waveguide and red-shifted spectral components on its leading edge [5]. This process accumulates along the waveguide giving rise to a frequency continuum via self-phase modulation.

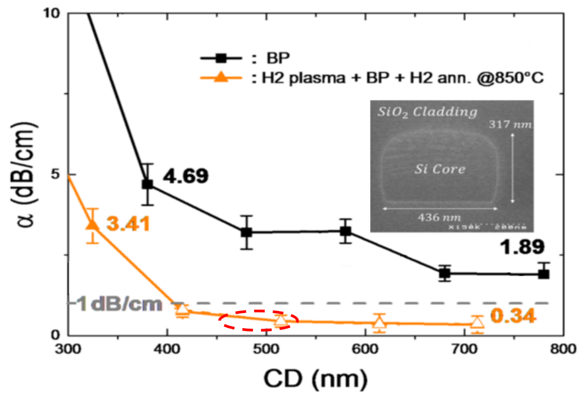

Fig. 1. Experimental optical losses measured at 1550 nm for waveguides patterned with (orange line) and without (black line) smoothening treatments. Cross-sectional SEM image (inset) of a Si waveguide patterned using H_2 resist treatment followed by Si annealing.

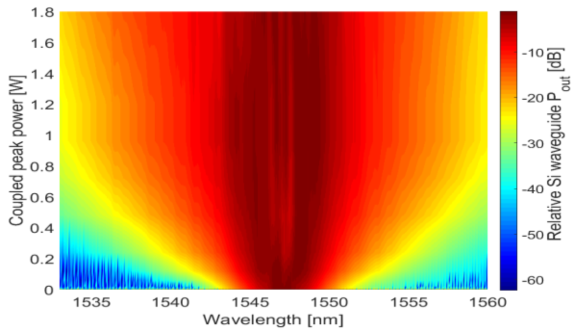

Fig. 2. Spectral broadening via Kerr self-phase modulation (SPM) leading to the generation of a *C*-band frequency continuum in *c*-Si.

Optical pulses of 2-ps duration with peak powers up to 1.8 W at a repetition rate of 20 MHz were injected into the 500-nm-width and 5.2-cm-long silicon waveguides using an external fiber-based laser followed by an erbium doped fiber amplification (EDFA).

Experimental results are illustrated in Fig 2. As shown, by increasing the coupled peak pump power, Kerr nonlinearity can be leveraged into a self-phase modulation (SPM) process capable to generate a 1525-1565 nm-spanning continuum of new optical frequencies around the 1547 nm pump wavelength covering the C-band.

The maximum of the nonlinear phase shift is obtained from the NL spectral broadening using the equation:

$$\frac{\Delta\lambda_{rms}}{\Delta\lambda} = (1 + \frac{4}{3\sqrt{3}}\Delta\varphi_{max}^2)^{\frac{1}{2}} \quad (1).$$

Once the nonlinear phase shift is calculated, the nonlinear parameter γ and the nonlinear index n_2 are deduced from the nonlinear phase shift using the equation $\Delta\varphi_{max}$= Re(γ)PL_{eff}, where P is the coupled peak power, γ is the nonlinear parameter. The latter is related to the nonlinear index n_2 through the expression $\gamma=\frac{\omega n_2}{cA_{eff}}$, where ω is the angular frequency, c is the speed of light and A_{eff} is the effective area. The effective length L_{eff} is given by $L_{eff}=\frac{1-e^{-\alpha.L}}{\alpha}$. The nonlinear parameter and the nonlinear index are respectively $\gamma = 82\ W^{-1}m^{-1}$ and $n_2 = 3.38 \times 10^{-18}\ m^2\ W^{-1}$.

It is now worth to point out that, when propagation losses reach very low values α (dB/cm), L_{eff} converges towards $L_{max} \sim 1/\ \alpha$. This simply means that, as we approach the ideal lossless propagation regime limit, nonlinear phenomena (such SPM or FWM) may accumulate significantly over very long distances, without needing to use optical powers where the TPA-related absorption would start taking over and operating as a dominating loss mechanism over the desired nonlinear processes. Concretely, in our case the maximal length over which the SPM phenomena accumulate using 0.5 dB/cm single-mode strip waveguides is well above 8 cm. Such effective length is the longest according to our knowledge, especially when operating with such small cross-sections (<500 nm x 300 nm) waveguides, presenting anomalous dispersion at telecom wavelengths, which is in turn a condition to get nonlinear phenomena such as spontaneous FWM for quantum telecom applications. In order to determine the factor of merit of our silicon waveguides we need the TPA coefficient. In Fig. 3, we plot the inverse of the waveguide transmission as a function of coupled peak power.

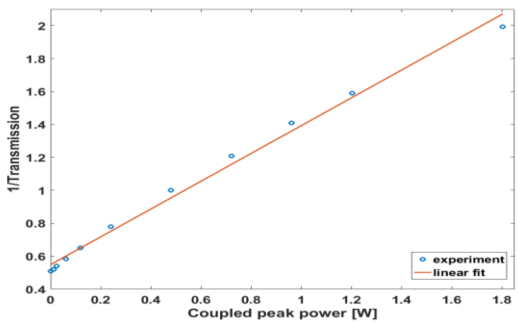

Fig. 3. Inverse of the measured waveguide transmission (at low coupled powers) versus coupled peak power (circles) with its linear fit.

From this curve we can extract the imaginary part of the nonlinear parameter Im(γ) using the following equation [7]:

$$\frac{1}{T} = \frac{P(0)}{P(L)} = 2\mathrm{Im}(\gamma)L_{eff}e^{-\alpha.L}\mathrm{P}(0) + e^{-\alpha.L} \quad (2),$$

which is valid in the presence of both linear propagation loss and TPA. $P(0)$ and $P(L)$ are the optical peak powers at the entrance (coupled peak power) and at the end of the waveguide, respectively, α = 0.11 cm^{-1} is the linear propagation losses, Im(γ) = $\beta_{TPA}/(2A_{eff})$ is the imaginary part of the γ nonlinear coefficient due to TPA. This allows us to extract $Im(\gamma) = 5.9\ W^{-1}m^{-1}$. With $A_{eff} \sim 0.18\ \mu m^2$ we infer a TPA coefficient β_{TPA} equal to $2.12 \times 10^{-12}\ mW^{-1}$. The factor of merit is determined using the relation: FOM = n_2 / $\beta_{TPA}\lambda$. A very good FOM of 1.0 is obtained, which is at least twice higher than *c*-Si FOM previously reported in [8] and [9].

Moreover, we anticipate that the position of the TPA band-edge may be tuned via the material H_2-annealing parameters so to shift the low nonlinear loss spectral region to shorter wavelengths, and this is currently the subject of further investigations.

3. Conclusion

We reported about fabrication and testing of ultra-low losses single-mode strip silicon waveguides nonlinear properties at telecom wavelengths. Propagation losses ≤0.5 dB/cm may be used to access significant nonlinear phenomena by using optical powers well below the TPA threshold onset.

Acknowledgements

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