Nonlinear Optics in Silicon Wire Waveguides: Towards Integrated Long Wavelength Light Sources

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ABSTRACT

Most of the research on silicon-on-insulator integrated circuits so far has been focused on applications for telecommunication. By using the large refractive index of silicon, compact complex photonic functions have been integrated on a silicon chip. However, the transparency of silicon up to 8.5 μm enables the use of the platform for the mid infrared wavelength region, albeit limited by the absorption in silicon oxide from 4 μm on. This could lead to a whole new set of integrated photonics circuits for sensing, given the distinct absorption bands of many molecules in this wavelength region. These long wavelength integrated photonic circuits would preferably need broadband or widely tunable sources to probe these absorption bands.

We propose the use of nonlinear optics in silicon wire waveguides to generate light in this wavelength range. Nonlinear interactions in just a few cm of silicon wire waveguides can be very efficient as a result of both the high nonlinear index of silicon and the high optical confinement obtained in these waveguides. We demonstrate the generation of a supercontinuum spanning from 1.53 μm up to 2.55 μm in a 2 cm dispersion engineered silicon nanowire waveguide by pumping the waveguide with strong picoseconds pulses at 2.12 μm [1]. Furthermore we demonstrate broadband nonlinear optical amplification in the mid infrared up to 50 dB [2] in these silicon waveguides. By using this broadband parametric gain a silicon-based synchronously pumped optical parametric oscillator (OPO) is constructed [3]. This OPO is tunable over 70 nm around a central wavelength of 2080 nm.

Finally, we also demonstrate the use of higher order dispersion terms to get phase matching between optical signals at very different optical frequencies in silicon wire waveguides. In this way we demonstrate conversion of signals at 2.44 μm to the telecommunication band with efficiencies up to +19.5 dB [4]. One particularly attractive application of such wide conversion is the possibility of converting weak signals in the mid-IR to the telecom window after which they can be detected by a high-sensitivity telecom-band optical receiver.

INTRODUCTION

Silicon photonics is considered as one of the most promising platforms for future photonic integrated circuits. The platform can rely on well-established CMOS fabrication technologies enabling high yield and potential co-integration with electronic circuits. So far, most research has focused on the dense integration of optical functions for the telecom wavelength range given the prospect of highly integrated complex circuits for datacom and telecom applications on a silicon chip. More recently, as a result of the broad transmission window of silicon (1100-8500 nm) [5] silicon has been proposed as the waveguide material for long wavelength integrated photonic circuits. Such integrated circuits are especially useful in the field of spectroscopic sensing in the mid-wave infrared (2000-8000 nm). This wavelength region, sometimes denoted as the fingerprint region is of great interest because of the strong specific absorption features due to the absorption through vibrational states of many molecules in this wavelength region.

The traditional silicon-on-insulator platform is limited by the absorption of the buried silicon oxide layer to about 3800 nm [5], and several integration platforms for the longer wavelength range have been proposed and demonstrated such as silicon-on-saphire, germanium on silicon and silicon on porous silicon [5-7]. However, in this paper the traditional silicon-on-insulator platform is used to demonstrate the nonlinear interactions of optical waves in the 2000-2500 nm wavelength region. These interactions can be very efficient in silicon photonic wires as a result of some specific properties of these wires. First, the combination of the high nonlinear index of silicon with the high lateral confinement due to the high index contrast between silicon and silicon oxide enables record nonlinear parameters for these silicon photonic wire waveguides [8]. Secondly, the high optical confinement allows for engineering the dispersion in the photonic wire which enables the phasematching of the optical signals involved in the nonlinear process [9,10]. We demonstrate that by the use of nonlinear optics in silicon waveguides we are able to make tunable coherent sources as well as broad white light sources. We additionally demonstrate the conversion of light from the mid IR to the telecom wavelength range and back.

THEORY

The third order nonlinearity, leading to the optical Kerr effect, in silicon is very strong. The Kerr nonlinearity in silicon demonstrated by its high nonlinear index is more than two orders of magnitude larger than the one in silica . The high confinement in silicon photonic wire waveguides obtained by exploiting silicon's high linear refractive index results in an effective nonlinearity parameter $\boldsymbol{\gamma} = \frac{\boldsymbol{n_2 \omega}}{\boldsymbol{A_{eff} c}}$ which can exceed the one found in single mode fibers by five orders of magnitude [8]. Here n_2 is the nonlinear index of silicon, ω the angular frequency of the light and A_{eff}, is the effective mode area in the waveguide. The high nonlinear parameter of silicon photonic wire waveguides has enabled the integration of low-power optical functions such as wavelength conversion [11], supercontinuum generation [12] and parametric gain [13] in the telecom window. However at telecom wavelengths silicon suffers from nonlinear absorption, the two-photon absorption, limiting the efficiency of the nonlinear processes at these wavelengths [14]. By working at mid-IR wavelengths near $\lambda \approx 2200$ nm, where the photon energies are approximately half the band gap energy of silicon, two-photon absorption can be efficiently suppressed [15]. Furthermore the high confinement in the silicon nanowire waveguides allows for dispersion engineering and thus phasematching in the nonlinear process. Indeed, efficient four-wave mixing (FWM) occurs only when

$$\Delta \boldsymbol{k} = \Delta \boldsymbol{k_{lin}} + \Delta \boldsymbol{k_{nl}} = \boldsymbol{k_s} + \boldsymbol{k_i} - 2\boldsymbol{k_p} + 2\boldsymbol{\gamma P} \quad (1)$$

in which k_p, k_s and k_i are the linear propagation constants of the pump, signal and idler waves, respectively. The term $2\gamma P$, in which γ is the effective nonlinear parameter of the waveguide and P is the peak power of the pump pulse, accounts for nonlinear phase shifts of the pump, probe and idler signals as a result of self-phase and cross-phase modulation [16]. The phasematching condition can be approximated around the pump frequency by a Taylor expansion of the waveguide dispersion relation around ω_{pump}, and taking account the conservation of energy in the FWM process. This produces the phase matching condition

$$\beta_2 \Delta\omega^2 + \frac{1}{12}\beta_4 \Delta\omega^4 + 2\gamma P = 0 \qquad (2)$$

in which $\Delta\omega$ is the frequency detuning between pump and signal (and also between pump and idler) [2]. Indeed, when the detuning of the pump and the signal is small and the fourth order dispersion can be neglected, phasematching is achieved on the condition that the waveguide is pumped at wavelengths where the dispersion is anomalous ($\beta_2<0$). When the fourth order dispersion is not negligible, e.g. when the detuning is large, the sign of the fourth order dispersion has to be opposite to the sign of second order dispersion to achieve phasematching.

EXPERIMENTS

Silicon-on-insulator photonics wire waveguides

The silicon photonic wires used in this paper were all fabricated in a CMOS pilot line, using 200 mm SOI wafers consisting of a 220 nm silicon waveguide layer on a 2 µm buried oxide layer. The wires are 900 nm wide with no top cladding, as shown in the inset of Fig. 1. The geometry of the waveguide is chosen such that the dispersion of the photonic wire waveguide is anomalous in a region around 2200nm. The group velocity dispersion β_2 of the fundamental quasi-TE mode is calculated using a commercial finite element mode solver (RSoft FemSim) and is shown in Fig. 1. The group velocity dispersion of the waveguide is anomalous in between the two zero dispersion wavelengths 1810 nm and 2410 nm. By averaging the nonlinear susceptibility of bulk silicon over the electric field of the fundamental TE polarized waveguide mode, the real part of the nonlinearity parameter is estimated to be $Re(\gamma) = 150$ (W·m)−1 [2] in the wavelength region of interest. Additionally, the high index contrast of silicon enables small footprint for relatively long photonic wire waveguides. In Fig. 2 a two cm long wire wrapped in a spiral structure can be seen.

Recently we have demonstrated waveguide losses as low as 0.6 dB/cm [17] in such waveguides in the 2000-2500 nm wavelength region in a cutback experiment where the insertion losses of 1,2,4 and 7 cm photonic wire waveguides were measured.

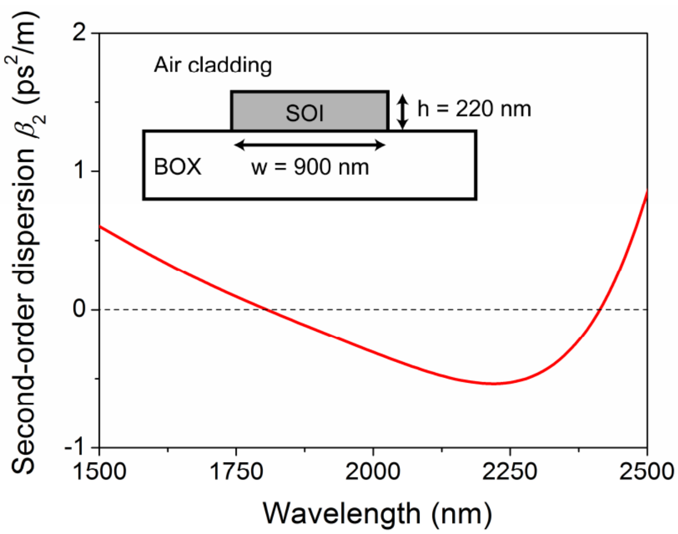

Fig. 1 Group velocity dispersion of the silicon wire waveguide as a function of the wavelength, exhibiting anomalous dispersion ($\beta_2 < 0$) between 1810 nm and 2410 nm. The inset shows the fabricated wire waveguide dimensions.

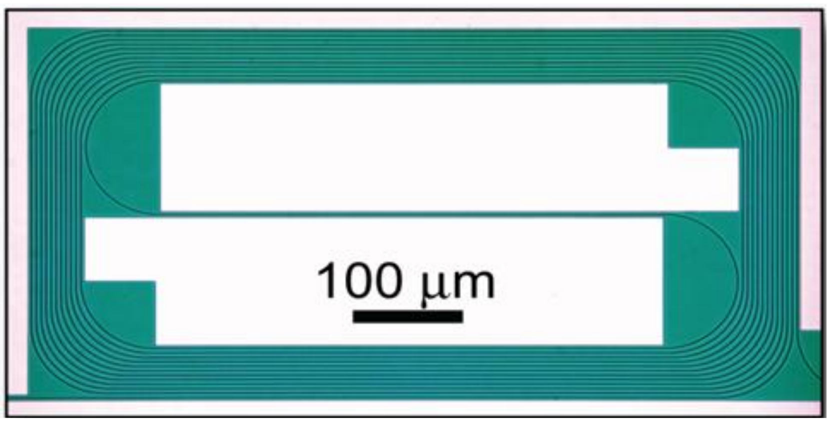

Fig 2. The high index contrast of between silicon and its cladding enables small footprints for the photonic wire waveguides. In the figure a microscopic image of a 2 cm photonic wire closely wrapped in a spiral structure is shown (footprint of 625 µm x 340 µm). The cross-section of the photonic wire is the same as shown in the inset of Fig. 1.

Efficient parametric amplification in silicon photonic wires

The silicon photonic wire shown on Fig. 1 has low anomalous dispersion between 1810 and 2410 nm suggesting that it can be used to achieve broadband phasemathing close to the pump wavelength. Indeed, we demonstrated a mid-IR optical parametric amplifier having a bandwidth broader than 580 nm centered around a pump wavelength of 2173 nm with unprecedented values of on-chip parametric gain. A gain of more than 40 dB in a 2 cm waveguide was achieved [2]. Moreover, we demonstrate that on-chip gain exceeds 50 dB in narrow Raman-scattering-assisted bands. This result is an enormous improvement of previous demonstrations [18]. This was possible by reducing the waveguide loss in a longer waveguide, to have longer interaction lengths. The waveguide loss of the photonic wire was measured in a cutback experiment to be less than 2.8 dB/cm.

In the experiment, the silicon wire is pumped with a picosecond pulse train at λ ~ 2173 nm (FWHM∼2 ps, repetition rate ~76 MHz) from an optical parametric oscillator. A short-wave infrared continuous wave laser was used as a probe signal. The polarization of the pump and probe are controlled to excite the quasi-TE mode in the photonic wire mode with in-line fiber polarization controllers. The pump and probe are multiplexed with a 90/10 fused-fiber coupler and lensed fibers are used to couple in and out the photonic wire. The coupling loss is ∼10 dB/facet. The output is coupled to an optical spectrum analyzer, the spectrum is recorded with a 1 nm spectral resolution. Fig. 3(a) shows the parametric amplification of an overlay of continuous wave signals with wavelengths varying from 2209nm–2498 nm, generating the corresponding idler waves from 2129 nm–1914 nm. Figure 3(b) plots the measured on-chip amplification and conversion gain, defined as the ratio between the peak power of pulsed signal/idler at the end of the waveguide and the coupled input continous wave signal power (see [18] for details). It is also shown that due to the high gain the signal can deplete the pump leading to saturation. For example, for input signals powers of > -19 dBm the output power saturates at ~20 dBm.

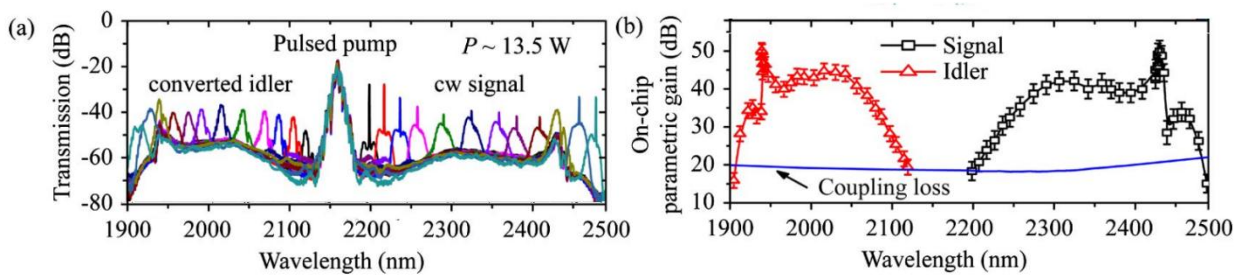

Fig 3: a) Series of four wave mixing spectra with the pulsed pump copropagating with a cw mid-IR signal at various wavelengths. The pulsed pump is centered at λ ~ 2173 nm, and has P ∼ 13.5W. (b) Spectrum of on-chip parametric signal gain (black squares) and idler conversion gain (red triangles). Fiber-waveguide coupling loss measured with the cutback method is shown by the blue trace.

Converting signals from the mid-infrared wavelength window to the telecom window and back.

By exploiting the higher order dispersion coefficients in a silicon photonic wire waveguide phase matching can be achieved for signal and idler waves spaced spectrally far from the pump wavelength. Doing so we can convert signals from the telecom window to the mid-infrared and back. To achieve phase matching for signals spectrally far from the pump, it is necessary to include higher orders of dispersion as in eq. (2). As discussed in the theory section phasematching can be achieved on the condition that the sign of the fourth order dispersion is opposite to the sign of the second order dispersion, which allows for optical gain in a discrete spectral narrow band. By doing this, we are able to amplify telecom signals at 1620 nm by 8.4 dB and convert them to the mid IR. Additionally we are able to amplify mid IR signals at 2440 nm to the telecom wavelength band around 1620 with an efficiency of 18.4 dB. The on chip peak power of the 2 ps pulses used was 37.4W.

Broadband light generation for spectroscopic application through the process of supercontinuum generation in silicon wire waveguides

Broadband supercontinuum generation is of great interest for applications such as spectroscopy and optical coherence tomography, where the ultra-broadband and spatially coherent nature of the source can be used to improve measurement throughput and resolution. The enormous progress made on the development of supercontinuum generation in the last decade based on photonic crystal fibers has lead to the commercialization of these supercontinuum sources in different spectral ranges. The enormous nonlinear parameter in the silicon photonic wires as well as the strong Raman gain in silicon, both ingredients for a supercontinuum light source suggests the possibility of silicon-based supercontinuum light generation.

Indeed when the 900 nm wide and 2 cm long photonic wire is pumped with 2 ps long pulses (78Mhz rep rate) at 2120 nm with a on-chip peak power of 12.7W a broad supercontinuum is generated. The supercontinuum finds it origin in the amplification of background noise [1]. Similar as in the previous sections the bright pump pulses provide gain in a broad band close to the pump as well as in a narrow band far from the pump, the latter through phasematching via higher order dispersion terms. In the absence of signals in these spectral bands background noise gets amplified. This can be seen in Fig. 4: in the vicinity of the pump where there is no signal at the input of the 2 cm waveguide light is generated by amplification of white background noise.

Close to the pump, light is generated near wavelengths of 1990 nm and 2250 nm by phase matching in the vicinity of the pump. Further away from the pump, light is generated at wavelengths of 1870 nm and approximately 2510 nm by higher order phasematching. The light generated in these sidebands is sufficiently bright such that by four wave mixing, light at new wavelengths gets created. Through this process, for example, light at a wavelength around 1700 nm is generated through cascaded mixing, where the peak at 1870 nm serves as the degenerate pump and the input pulse at 2120 nm acts as the signal. Fig 4 shows the result of the nonlinear mixing at a sufficiently high peak power of 12.7 W. The generated supercontinuum spans from 1535 nm all the way to to the mid infrared. The peak around 1600 nm is believed to be the result of Cherenkov radiation referred to as dispersive wave generation [19].Measurements with the help of an FTIR reveal that the supercontinuum extends up to 2550 nm.

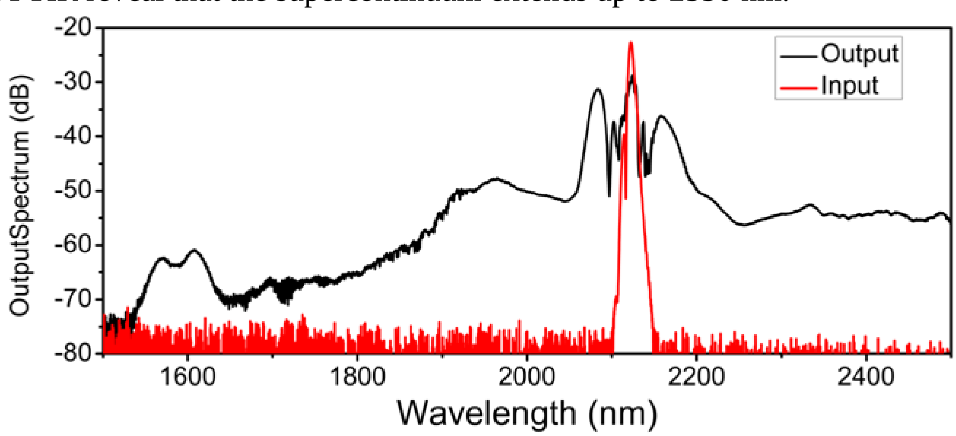

Fig 4: The output spectrum of the supercontinuum generated by optically pumping a 2cm photonic wire waveguide with 2ps pulses at 2120 nm with a peak power of 12.7 W. In red the input spectrum of the pump pulses is shown.

A silicon-based synchronously pumped Optical Parametric Oscillator

The high nonlinear gain obtained in the silicon photonic wire waveguides can be exploited to construct tunable coherent sources by adding feedback to the chip. We construct such an optical parametric oscillator (OPO) by placing the silicon chip inside a single mode fiber loop cavity.

The enormous single pass gain and conversion efficiency, possible by reduced waveguide losses to 1 dB/cm in a new chip, of almost 60 dB, when the peak power of the pump pulses reaches 24W, can compensate the high round trip losses in a band around 2075 nm. When the round trip time of the cavity is synchronized to the repetition rate (78 MHz) of pump pulses oscillation can be achieved. Because of the dispersion in the fiber it is possible to sequentially synchronize pulses having different wavelengths..The maximum on-chip output pulse energies can reach 1.66 pJ at a wavelength of 2087 nm and is tunable in a 70 nm span around 2075 nm.

CONCLUSION

In short, we have demonstrated several nonlinear optical in low loss silicon waveguides for mid infrared spectroscopic applications. We demonstrated a highly efficient mid infrared amplifier with a bandwidth exceeding 580 nm and a peak gain of more than 40 dB. We also demonstrated the amplification of mid infrared signals as well as their conversion to the telecom wavelength range with an efficiency as high as 19.4 dB. The latter could be very useful for the detection of mid-IR signals with telecom detectors after being upconverted in a silicon wire waveguide. Potentially removing the necessity of noisy, cooled mid infrared detectors while leveraging from the well established telecom detectors. Additionally a broadband source was demonstrated in the form of a supercontinuum extending from the telecom wavelength up to the mid infrared as well as a widely tunable coherent silicon based optical parametric oscillator.

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