Towards long wavelength sources integrated on a silicon chip

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Abstract: By exploiting the strong optical third order nonlinear response of silicon nanophotonic wire waveguides we demonstrate the integration of complex sources on a silicon chip such as a wavelength translator and a frequency comb.

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1. Introduction

The transparency of the silicon-on-insulator (SOI) wire waveguide platform beyond the telecom window up to ~4 μm [1] has recently been used to introduce a new set of applications on the SOI platform geared towards sensing. Especially the strong and specific absorption lines of many molecules in the mid-infrared wavelength region [2], sometimes referred to as the "molecular fingerprint region", could enable chip-scale optical sensors with a high sensitivity and selectivity.

The integration of a long wavelength narrow line width or broadband source [3,4] in this wavelength range would be a major step towards the integration of sensing devices in the mid-infrared. Through nonlinear optical mixing such sources and devices can be integrated on the SOI platform. The absence of two-photon absorption beyond 2.2 μm - hampering efficient nonlinear interactions at telecom wavelengths - allows for efficient nonlinear interactions in the mid-infrared in silicon waveguides. Furthermore the combination of the high nonlinear index in silicon, 200 times larger than the one of silica, and the high confinement in these waveguides allows for extremely high nonlinear parameters. In addition, the high confinement enables the possibility of judicious dispersion engineering of the silicon waveguides which allows for phase matching of the waves interacting in the nonlinear process over more than an octave. Here we discuss several nonlinear devices realized in the mid-infrared based on nonlinear interactions in silicon waveguides.

2. Silicon based mid-ir devices

The core of the nonlinear silicon devices presented here consists out of 1 cm long, 1600-1650 nm wide waveguides fabricated on a 200 mm silicon on insulator wafer with a 400 nm thick device layer. The nonlinear parameter was found to be ~40 $(Wm)^{-1}$.

As a first demonstration we show the possibility of making a wavelength translator [5,6] linking the telecom band and the mid-infrared wavelength region. Using a Finite element solver the group velocity of a 1650 nm wide waveguide as a function of the wavelength was simulated. As can be seen on Figure 1, the group velocity dispersion is positive at 2190 nm, while the fourth order dispersion of the waveguide is negative. The special dispersion profile of this waveguide can be exploited to phase match the optical waves involved in the nonlinear process over more than an octave. Indeed in the nonlinear process of four-wave mixing the phase matching condition can be approximated as

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

Here, β_2 and β_4 are the second and fourth order dispersion respectively at the pump wavelength, γ the nonlinear parameter of the waveguide, P the pump power and $\Delta\omega$ the signal detuning from the pump. On the condition that the second order dispersion is small and positive, while the fourth order dispersion is negative this equation has a solution for a large signal detuning. This condition is fulfilled in the waveguide (see Figure 1a) when the pump is centered at 2190 nm, therefore it is possible to down convert signals over more than an octave from the telecom band to ~3700 nm. By pumping the waveguide with short (2ps) pulses we show the down conversion of signals to long wavelengths (see Figure 1 b) and also demonstrate the amplification of the telecom signal.

In another experiment, a slightly different waveguide was used to generate an octave spanning frequency comb. In the experiment a 1600 nm wide waveguide was pumped with very short (70 fs) pulses [4] coming from an OPO, centered around 2290 nm. At this wavelength the waveguide dispersion is slightly anomalous. As shown in Figure 2, the pulses are spectrally broadened and an octave spanning supercontinuum is generated at the output of the waveguide. It is known that the supercontinuum can preserve the phase coherence of the pump pulses, when short pulses are used [7]. This property is exploited in this experiment. Here we quantity the phase coherence of the supercontinuum by beating the generated supercontinuum with a narrow band laser at 1586 nm, 2418 nm and 1580 nnm and measuring the beat note with a mid-infrared photodetector. The beat notes obtained have a linewidth in the order of 50 kHz, limited by the instabilities of the pump optical parametric oscillator. The narrow bandwidth beatnotes show that the supercontinuum consists out of a set of narrow bandwidth lines and is as such a frequency comb.

In short, the combination of the high nonlinearity of silicon waveguides with the enormous possibilities in dispersion engineering allow to make complex devices in the mid-infared such as an optical wavelength translator as well as an octave spanning mid-infrared frequency comb.

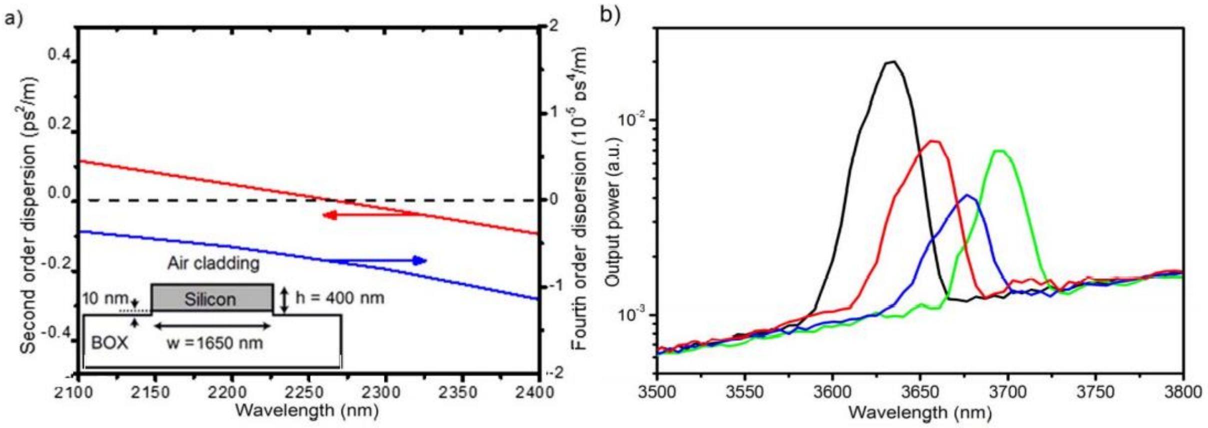

Figure 1: a) The dispersion of the silicon waveguide shown in the inset. B) the downconverted signals of respectively a telecom signal at 1565 nm (black), 1559 nm (red), 1554 nm (blue), and 1550 nm (green).

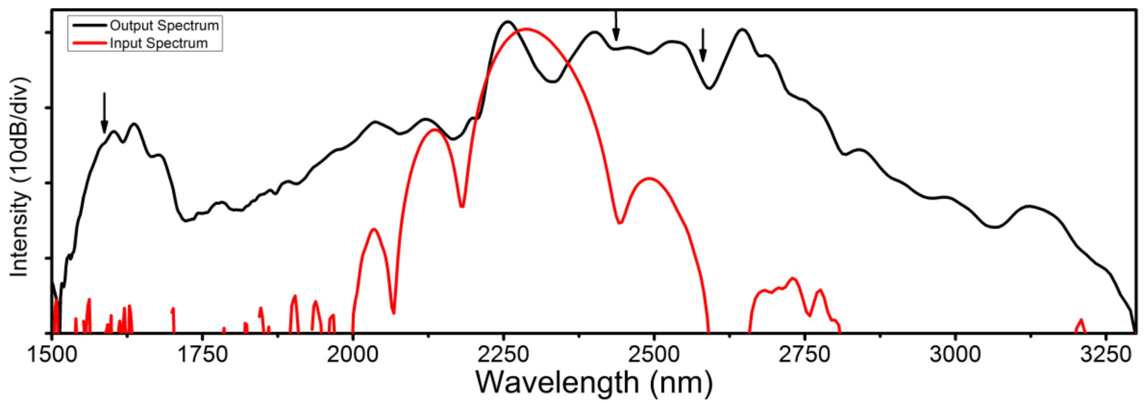

Figure 2: The input and output spectrum of the short pulses travelling through the 1 cm long silicon waveguide. The arrows indicate at which wavelength the coherence is measured.

3. References

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