Low intensity inelastic photon scattering in silicon wire waveguide below the bandgap

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Abstract: We study the spontaneous photon scattering that arises in silicon waveguides at low power. Power dependence, temperature dependence, spectrum and response time point out its origin as pump scattering on a thermal bath of excitons.

OCIS codes: 290.0290 , 270.0270, 270.2500, 190.4390

Introduction When a pump beam is propagated through a silicon nanophotonic waveguide, a very small fraction of the light is scattered to other frequencies. At very low intensity, the amount of scattered light is proportional to the power of the pump beam. This may impact on the quality of photon pairs generated through the Kerr nonlinearity in silicon [1–3]. This scattering has been observed before [3], but never studied in detail. Here we characterise this scattering and investigate its origin via spectral measurements, time, power and temperature response.

Experiments. Our sample is a 11.3 mm long silicon wire waveguide (SWW) whose section is $500 \times 220\,\mathrm{nm}^2$. This SWW is optically pumped by a monochromatic beam at telecom wavelength. The scattered light is isolated from the pump by appropriate filtering stages and is detected with single photon detectors. The collection bandwidth is $\nu \in [0.4, 2.4]$ THz. A time to digital converter allow for measuring time/frequency correlation and emission response time. The spectral properties are investigated with an additional tunable filter. The silicon chip temperature T is controlled between 300 and 575 K.

Results. As previously reported [3], the photon flux exhibits both a quadratic and a linear contribution (Fig.1a) The quadratic part is attributed to photon pair generated via spontaneous four wave mixing, and is in good agreement with the theoretical expectation. The aim of this work is to study the linear contribution. It could be explained by nonlinear loss on the quadratically generated flux but it is excluded as nonlinear losses are too low (absent within our measurement error of 2.5% and for power less than 3 mW) and not compatible with Fig.1a. A small contribution to the flux comes from imperfect filtering operation. This contribution is measured by replacing the SWW by a fiber-attenuator. It is found to be weak in comparison to the flux generated into the SWW in every experimental condition that we investigated.
The evolution of the flux as a function of the temperature is studied at low power (0.5 mW) such that the dominant contribution is the linear scattering. Fig.1b shows that the flux grows linearly with the absolute temperature in the interval $[300, 575]$ K.
Fig.1c presents our spectral measurements. Again, the pump power was set at low power (250 μW) to minimize the photon pair generation. Both the photon pair generation spectrum and the noise due to imperfect filtering were measured as well. As predicted by theory [3], the photon pair generation spectrum showed a sinc^2 profile. The noise

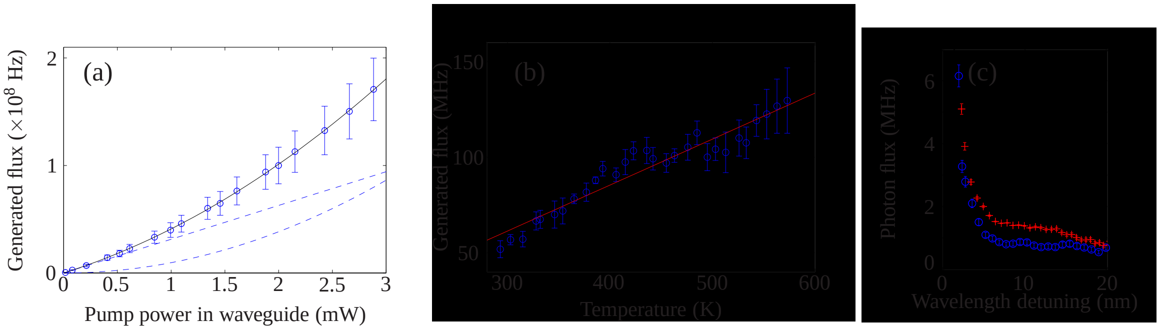

Fig. 1. Investigation of the scattering in the SWW. (a) Power dependence of the flux generation. Data points (circles) are fitted by a second order polynomial law (solid line) whose linear and quadratic contribution are illustrated (dotted lines); (b) Temperature dependence of the generated flux (circles) and linear fit (solid line); (c) scattering spectrum at the Stokes detunings (crosses) and anti-Stokes detunings (circles) and fit proportional to $1/\text{detuning}$ (solid line). Error bars come from statistical error as well as error on out-coupling losses.

from the filtering line was found to be very weak and didn't show any increase at small frequency detuning. The contributions from these two processes represent 5% of the flux presented in Fig.1c. The data points thus represent well the spectrum of the scattered light. Solid curve is a fit assuming the scattered light is proportional to ν^{-1} where ν is the frequency detuning.

Finally, we exclude any relation of the scattering with carriers in the silicon media. For that, we measured the response time of the scattering emission with a pulsed pump. The scattering emission was found to be instantaneous within our time resolution ($\approx$ 100 ps). This is in strong contrast with the lifetime of free carriers that was measured to be 4 ns.

Discussion and conclusion. At very low intensity, a scattering that is proportional to the power of the pump beam was observed. We show qualitatively and quantitatively that the scattering intensity increases linearly with temperature within our experimental condition ($[300, 575]$ K) and decreases as the inverse of the frequency detuning ν over the invetigated bandwidth $0.4\,\text{THz} < |\nu| < 2.4\,\text{THz}$. Both of these observations are consistent with the scattering of the pump on a one dimensional thermal bath of excitons for which the scattered power would be a proportional to a Bose-Einstein distribution [4] : $P^{scat}[\text{W}] = k\left[(\exp(\text{h}|\nu|/\text{k}_\text{b}T)-1)^{-1} + \frac{1}{2}(1-\text{sign}(\nu))\right]\Delta\nu[\text{THz}]\,L[\text{cm}]\,P[\text{W}]$ where L is the SWW length, P is the power inside the SWW, $\Delta\nu$ is the bandwidth over which the flux is integrated, ν is the frequency detuning, and k is a constant. For the parameters (temperature and detunings) we investigated, this law approximates to a Rayleigh-Jeans distribution $\propto \text{k}_\text{b}T/\text{h}|\nu|$. We estimate the constant k to be $3.5\times10^{-10}/\text{Thz}/\text{cm} \pm 30\%$. In our opinion, these excitations are most likely phonons, but not the usual acoustic or optical phonons of bulk crystalline silicon. Rather they probably find their origin either in geometric effects due to the shape of the waveguide, or in defects within the silicon. This result is particularly interresting in the context of photon pair generation. It shows that the noise figure can be significantly reduced removing with a filter the flux generated at small frequency detuning. This constrasts strongly with photon pair generation in silica fiber for which the noise originating from Raman scattering is strong over a broad band from 0 to -20 THz.

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