Continuous-wave parametric conversion in hydrogenated amorphous photonic wire

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We exploit the high $\chi^{(3)}$ nonlinearity present in hydrogenated amorphous silicon nanophotonic waveguides to demonstrate frequency conversion at telecommunication wavelengths using pump and signal that are both continuous-wave. We reach a frequency conversion efficiency close to -34dB having a on-chip 13mW pump power in a low-loss 1cm long silicon photonic wire. Thanks to the ultra-low pump power and optimised hydrogen concentration during fabrication, optical degradation during illumination was reduced. The nonlinear refractive index is estimated for a set of hydrogenated amorphous silicon waveguides with different hydrogen concentrations by the four-wave mixing process, yielding a maximum value of $n_2=5.76\times10^{-17}$ *m²/W.*

Introduction

Unlike crystalline silicon (c-Si), pure amorphous silicon (a-Si) contains a large density of point defects and dangling bonds due to the absence of long-range order in its atomic structure. These impurities increase optical loss [1] severely and make optical applications at telecommunication wavelengths impossible. Incorporation of hydrogen (H) atoms allows passivation of these defects and reduces the optical absorption substantially at near-infrared wavelengths [2]. In fact, addition of hydrogen during the growth process removes weak Si-Si bonds, saturates the dangling bonds and gives a more ordered Si network [2].

The improvement of both the optical losses down to 3.5dB/cm [3] and 1dB/cm [4] and the high nonlinear figure of merit FOM=2.2 [5] and FOM=5 [6] (where $\mathrm{FOM}=\mathrm{Re}(\gamma)/4\pi\mathrm{Im}(\gamma)$, and γ is the complex nonlinear parameter) of hydrogenated amorphous silicon (a-Si:H) make it a promising materials for nonlinear nanophotonic devices. Recently, availing of this extremely high nonlinearity several nonlinear optical functions were demonstrated such as, parametric amplification [5], wavelength conversion [7] or all-optical signal processing [8]. In this paper, we report frequency conversion using four-wave mixing (FWM) in 1cm long hydrogenated amorphous silicon photonic wires, using continuous wave (CW) telecommunication lasers as pump and signal and we study the effect of the hydrogen concentration on optical degradation.

Experiment

The a-Si:H waveguides are fabricated in 220-nm-thick hydrogenated amorphous silicon deposited on top of silicon dioxide layer using a low temperature Plasma Enhanced Chemical Vapor Deposition (PECVD) process. The a-Si:H film was formed by plasma decomposition of silane (SiH_4) gas and combined with Helium (He) for dilution. In order to study the effect of hydrogen density in a-Si:H on optical losses and degradation, the power was tuned from 180 to 300 W and the He-to-SiH$_4$ ratio (r) from 0 to 9. Waveguides of varying lengths L (1 to 7 cm) were fabricated using 193 nm optical lithography and dry etching. The cross-section of these waveguides is 500×220 nm^2. To allow an effective injection and extraction of the light from the photonic nanowires, grating couplers are added at the input and the output. Thanks to a cutback measurement with very low power and as shown in the table 1, we estimated the propagation losses for TE polarization for different values of r.

He-to-SiH$_4$ ratio r	0	1	6	9
Linear losses α (dB/cm)	-3.4	-3.6	-2.8	-4.3

Table 1: The Propagation loss as a function of H concentration in a-Si-H waveguides, quantified by the He to SiH$_4$ concentration during fabrication.

We found that the loss differed by less than 2dB/cm for different samples. This value can be improved during fabrication process. We note that H concentration in a-Si-H increases by decreasing r. When the H content is increased strongly in the amorphous film, clusters and voids appear which increase the linear loss [3].

At high power, optical degradation appears in the a-Si-H photonic wires [8]. This degradation is probably due to a process in which electron-hole pairs created by energetic photons recombine in the material (Staeber Wronski effect). To investigate the influence of the concentration of H on both the nonlinear properties and the degradation, we performed a FWM experiment. FWM is a parametric third-order nonlinear process that occurs when photons from one or more waves (pump + signal) are annihilated to create news photons (idler) at different frequency namely, $1/\lambda_{idler}=2//\lambda_{pump}-1/\lambda_{signal}$.

To demonstrate this frequency conversion process, we use two CW tunable lasers to generate pump and signal. The pump wave is amplified using an erbium doped fiber amplifier to a maximum output power of 200mW. The maximum signal power is 100mW.

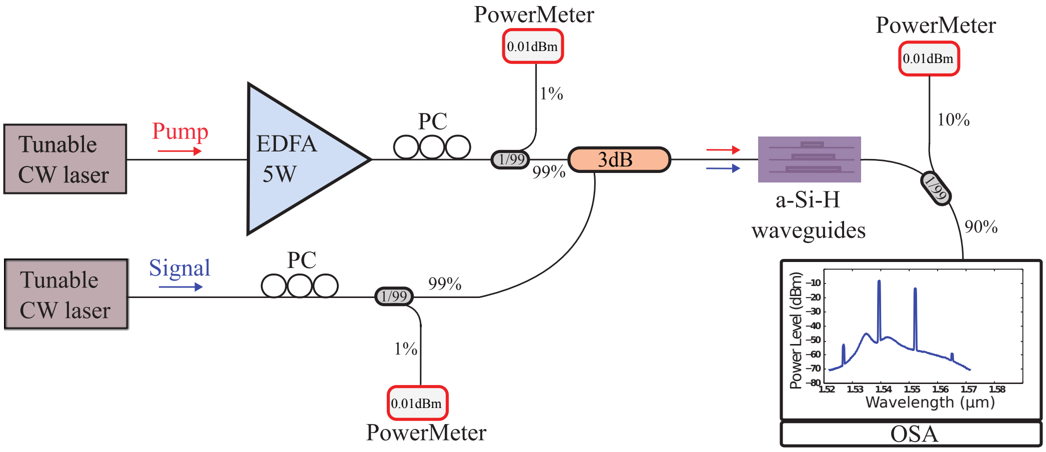

Fig. 1. Four-wave mixing experimental setup using continuous wave pump and signal. EDFA: erbium doped fiber amplifier, PC: polarisation controllers, 3dB: 50/50 coupler and OSA: optical spectrum analyser.

Thanks to a 50/50 coupler both lasers are combined into a single mode fibre. The coupling loss between the cleaved fiber and the waveguides through the input grating coupler is estimated to be 6-7dB. The output beam is coupled to an optical fibre by way of the output grating and sent into an optical spectrum analyser (OSA). The polarization is aligned with the TE mode of the waveguide with the help of polarisation controllers. The schematic description of the experimental setup is shown in figure 1.

The output spectra for 1cm-long a-Si-H (r=0) photonic wire waveguide using P_{pump}= 12.9mW and P_{signal}= 0.632mW are depicted on figure 2a. We observe that in addition to the pump (λ_{pump}=1547.7nm) and signal (λ_{signal}=1550nm) two other peaks appear at λ_{idler1}=1545.4nm and λ_{idler2}=1552.3nm. The both wavelengths satisfy the predicted FWM process $1/\lambda_{idler1}=2/\lambda_{pump}-1/\lambda_{signal}$ and $1/\lambda_{idler2}=2/\lambda_{signal}-1/\lambda_{pump}$. Comparing signal and idler1 amplitudes, we obtain a conversion efficiency (CE) close to -34dB. CE evolution as a function of pump power is represented on figure 2b. Minimum power required to observe FWM is only 400µW pump power and 110µW signal power.

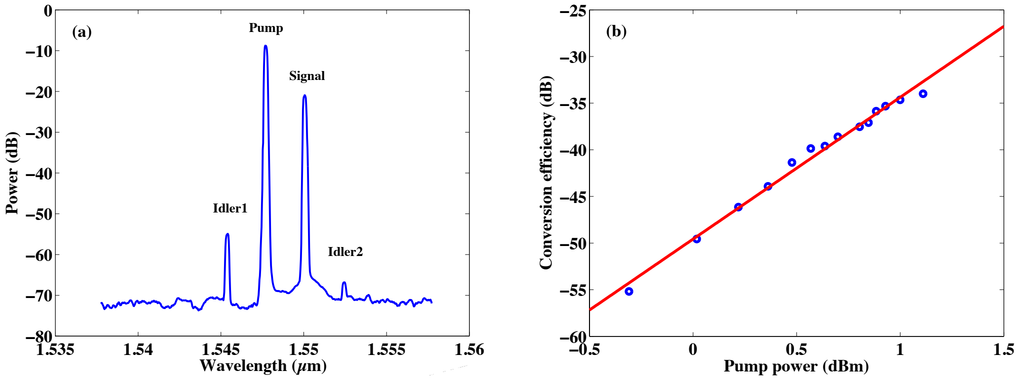

Fig. 2. (a) Output FWM spectra for 1cm long a-Si-H (r=0) waveguide. (b) Conversion efficiency as a function of estimated on-chip pump power, blue circles are the measured data and the red line is the linear fit.

In continuous wave regime, FWM process can be also used to calculate the nonlinear refractive index n_2. Thanks to the ratio of the pump and the idler1 powers (see figure 2) we can calculate the nonlinear phase shift φ using the following equation [9]:

$$\frac{P_{pump}}{P_{idler1}} = \frac{J_0^2(\varphi/2)+J_1^2(\varphi/2)}{J_1^2(\varphi/2)+J_2^2(\varphi/2)} \qquad (1)$$

where J_n is the Bessel function of the nth order. Once the value of the average nonlinear phase shift obtained by changing pump power is determined, the nonlinear refractive index n_2 is readily calculated according the equation (n°2).

$$n_2 = \frac{A_{eff}\lambda_{idler}}{4\pi L_{eff} P_{signal}}\varphi \qquad (2)$$

yielding a value of $n_2=5.4\times10^{-17}$ m²/W. $A_{eff}=0.05\mu m^2$ is the effective nonlinear modal area, $L_{eff}=(1-e^{-\alpha L})/\alpha$ is the effective length of the waveguide and P_{signal} is the average power of the signal. We repeated this procedure for waveguides of r=1 and r=6; the values are depicted on table 2. These n_2 values are close to values reported in the literature [4,7].

He-to-SiH$_4$ ratio r	0	1	6	9
Nonlinear index n_2 (m^2/W)	5.4×10^{-17}	5.76×10^{-17}	1.23×10^{-17}	1.3×10^{-17}[5]

Table 2: Nonlinear refractive index as a function of H concentration in a-Si-H waveguides. The value of n_2 for r=9 was calculated in our previous work [5].

In our previous works we are reported an observation of optical degradation during illumination [8]. In order to investigate the effect of H concentration on this degradation, we recorded the evolution of the idler power as a function of time (figure 3). Average pump plus signal power on-chip is estimated to be around 15mW. High amount of H in amorphous waveguide (r=0) seems to increase resistivity to optical degradation as shown in figure 3 probably due to the large availability of H to link with Si bonds. While in samples with lower

H concentration degradation seems to be more pronounced (r=1 and r=6).

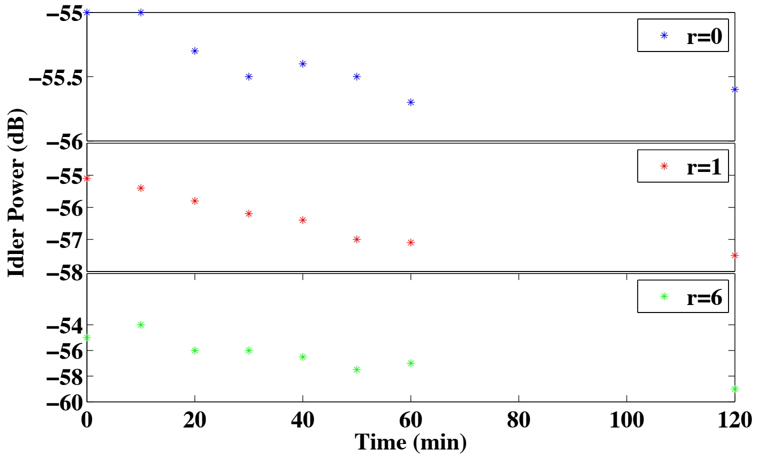

Fig. 3. Idler intensity evolution as a function of time for different H concentrations (r). Pump power is 13mW and signal power is 2mW.

We note that at very high power (e.g. using a pulsed pump with peak power of several watts) degradation persists in all our amorphous waveguides. This degradation can be reversed by annealing the sample at 200°C during only 1min.

Conclusion

In this paper we have calculated using continuous wave four-wave mixing the nonlinear refractive index n_2 of the amorphous silicon waveguides with different H concentrations. The highest nonlinear index $n_2=5.76\times10^{-17}$ m^2/W is obtained in the sample for which r=1. We also found that operating in CW regime decreased the degradation of the sample, and that higher concentration of H in the sample provides a higher resistance to optical degradation.

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