Unprecedented parametric gain from a CMOS compatible silicon photonic wire

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***Abstract*—Using dispersion engineered hydrogenated amorphous silicon waveguides, an on-chip parametric amplification of 26.5dB at telecommunication wavelengths is demonstrated. This gain is enough to overcome the fiber-chip coupling losses and leads to an off-chip amplification of 6dB. Net on-chip amplification over a 100nm wavelength range is achieved.**

***Index Terms*— amorphous silicon, parametric gain**

I. INTRODUCTION

There is a large interest in the nonlinear response of Silicon-On-Insulator (SOI) waveguides [1]. The high refractive index - and thus high achievable confinement - combined with the high nonlinear index of silicon leads to unprecedented nonlinear parameters, several orders of magnitude larger than the values found in single mode fiber [1,2]. In recent years, a lot of progress has been made in silicon-based nonlinear optics and several nonlinear functions such as wavelength conversion [1,3] and parametric gain [1,3] at telecommunication wavelengths have been demonstrated. However, the high nonlinear absorption in crystalline silicon -the two-photon absorption- [4] has severely limited the efficiency of these devices in this wavelength range.

To overcome this problem, a nonlinear polymer, which does not suffer from two-photon absorption, can be used as a cladding material in a slot-waveguide geometry [5]. Although the figure of merit, defined as

$$FOM = \frac{-Re(\gamma)}{4\pi Im(\gamma)}$$

with γ the nonlinear parameter, is significantly higher in these Silicon Organic Hybrid (SOH) waveguides than in basic crystalline silicon photonic wires, the lack of efficient phase matching deteriorates the nonlinear operation significantly. A different approach to integrated nonlinear optics at telecommunication wavelengths is the use of other materials as a waveguide core material, such as chalcogenide glass, which has intrinsically a high FOM. This is however not a CMOS-compatible solution.

In this paper we demonstrate the use of hydrogenated amorphous silicon (a-Si:H) waveguides as an efficient nonlinear waveguide platform. Results reported so far in literature on a-Si:H waveguides do not show a substantially improved figure of merit compared to crystalline silicon waveguides [6,7]. The a-Si:H film properties (e.g. the bandgap of the material) are however very dependent on the deposition method used. The amorphous silicon waveguides presented in this paper are found to have a similar FOM as state-of-the-art SOH waveguides [8]. Making use of the high FOM together with its high linear refractive index not only leads to record nonlinear parameters [8], but also allows for wide dispersion engineering of the waveguides. In these high index contrast hydrogenated amorphous silicon waveguides, the waveguide dispersion can overcome the normal material dispersion of the a-Si:H. Therefore, efficient phase matching can be achieved, giving rise to exponential parametric gain for waveguides with anomalous dispersion. In this paper, we demonstrate a

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Four Wave Mixing parametric gain of 26.5 dB at telecommunication wavelengths based on these dispersion engineered a-Si:H waveguides. This value should be compared to the state-of-the-art parametric gain reported in crystalline silicon waveguides of 4.2dB [3]. This shows that the use of amorphous silicon waveguides leads to a dramatic increase in achievable parametric gain. It could therefore become a new platform for nonlinear integrated optics.

II. AMORPHOUS SILICON WIRES

The a-Si:H photonic wire waveguides were fabricated on 200 mm silicon wafers in a CMOS pilot line. On top of the 1950 nm of high-density plasma oxide, 220 nm of a-Si:H was deposited using a low-temperature Plasma Enhanced Chemical Vapor Deposition process [9,10]. The 1.1cm long and 500nm wide waveguides were fabricated using 193 nm deep UV stepper lithography and dry etching [9,10]. Diffraction grating couplers were used for fiber-chip coupling. The wavelength dependent fiber-chip coupling loss ranges from 7 to 8dB per grating coupler in the wavelength range of interest.

III. PARAMETRIC GAIN AND DISPERSION

The phase matching condition for the nonlinear process of degenerate four wave mixing is given by [11]

$$\Delta\beta = 2\gamma P + \beta_{sig} + \beta_{idler} - 2\beta_{pump} = 0$$

where γ is the nonlinear parameter of the waveguide, P the peak pump power in the waveguide and β_{sig}, β_{idler} and β_{pump} the propagation constants of the signal, idler and pump respectively. In a first order approximation, when the signal and idler wavelengths are close to the pump wavelength this equation becomes

$$\Delta\beta = 2\gamma P + \beta_2\omega^2 = 0$$

where β_2 is the second order waveguide dispersion coefficient at the pump wavelength. As can be seen from this equation, to achieve phase matching for efficient nonlinear conversion, it is necessary to pump in a nonlinear medium with anomalous dispersion ($\beta_2<0$). By designing the photonic wire waveguide dimensions and choosing the right cladding materials it is possible to overcome the normal a-Si:H material dispersion. The simulated anomalous dispersion of the TE mode of the a-Si:H waveguide used in the experiments, with a waveguide width of 500nm, 220nm thickness and air top cladding, can be seen in Figure 1. The strong anomalous dispersion is a direct result of the high confinement caused by the high index of the a-Si:H and the air cladding used.

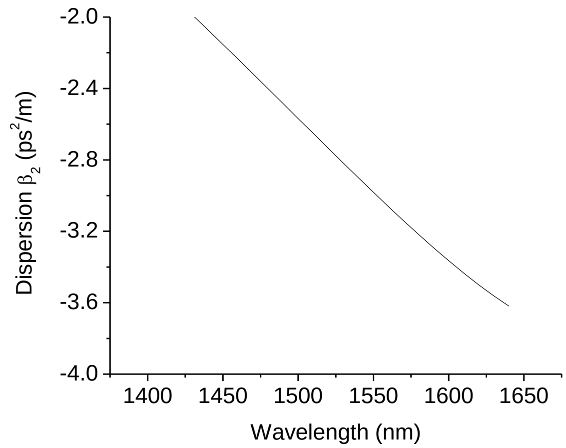

Figure 1: The simulated dispersion of the TE mode of the a-Si:H waveguide used as a function of the wavelength

IV. EXPERIMENTAL RESULTS

The nonlinear parameter of the highly nonlinear a-Si:H waveguides was determined by measuring the power dependent transmission as well as recording the spectrum at the output of the waveguide when picosecond pulses are injected in the a-Si:H waveguides [8]. The real part of the nonlinear parameter was found to be 770/Wm and a figure of merit of 2.1 was obtained. This FOM is comparable to the value found in SOH waveguides, while a much higher nonlinear parameter is achieved.

To study the parametric gain in the a-Si:H waveguides a pump-probe setup is used. Picosecond pulses (3.8ps FWHM, 10MHz repetition rate) around 1535nm are used as pump pulses. Weak probe pulses which need to be synchronized with the pump pulses and which need to be tunable over a large wavelength range to study the wavelength dependence of the parametric gain are generated by the nonlinear process of self phase modulation in fiber. This is done by amplifying the secondary output of the picosecond laser by an EDFA. The resulting spectrally broadened pulses are then attenuated and filtered by a 1.2 nm tunable filter. These weak pulses are tunable over a 40 nm band. The probe pulses are synchronized by a tunable delay line and are then combined with the pump pulses before they are injected into the 1.1cm long a-Si:H waveguides. The output of the waveguide is spectrally analyzed. The gain experienced by the weak probe is determined by comparing the case where the probe and pump pulse are not overlapping in time with the case when they are overlapping and by integrating the power spectral density, similar as in [12]. The output spectra in the synchronized / non-synchronized case can be seen in Figure 2. The (amplified) signal and converted idler can clearly be seen, together with the pump pulse output spectrum affected by self phase modulation. The measured on/off gain and wavelength conversion efficiency can be seen in Figure 3 for an on-chip peak power of 5.3W (average on-chip power 0.23 mW). The probe is tuned from 1550 nm to 1590 nm and converted to a wavelength band ranging from 1480 nm to 1520 nm. A peak on/off gain of 26.5 dB and wavelength conversion efficiency of 27dB is achieved at a signal wavelength of 1562nm. This gain is enough to compensate for the total insertion loss of 20.3 dB and leads to an off-chip amplification of 6.2 dB.

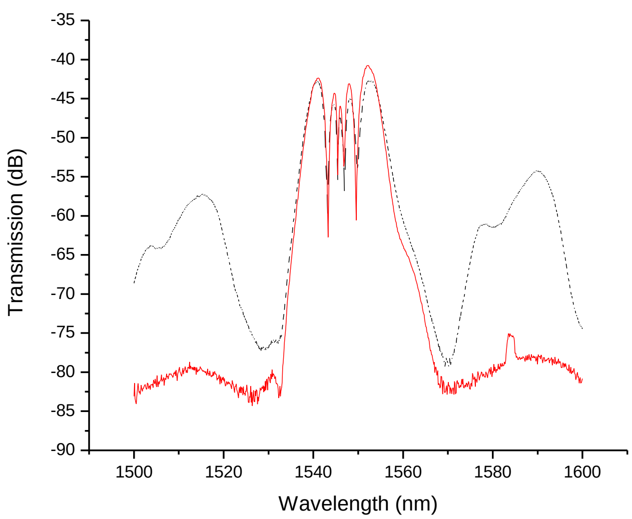

Figure 2: The spectrum at the output of the waveguide when the pulses are not overlapping in time (red, straight) and when they are overlapping in time (black, dotted)

V. CONCLUSION

The parametric gain and wavelength conversion efficiency was studied in hydrogenated amorphous silicon waveguides using a pump-probe setup. A peak on/off gain of 26.5dB was measured. The achieved parametric gain is two orders of magnitudes higher than the result obtained in c-Si. Further enhancement of the gain bandwidth can be expected by using more complex waveguide cross-sections, in which there are more degrees of freedom to engineer the waveguide dispersion. These results show the high potential of hydrogenated amorphous silicon waveguides for integrated nonlinear optical functions at telecommunication wavelengths.

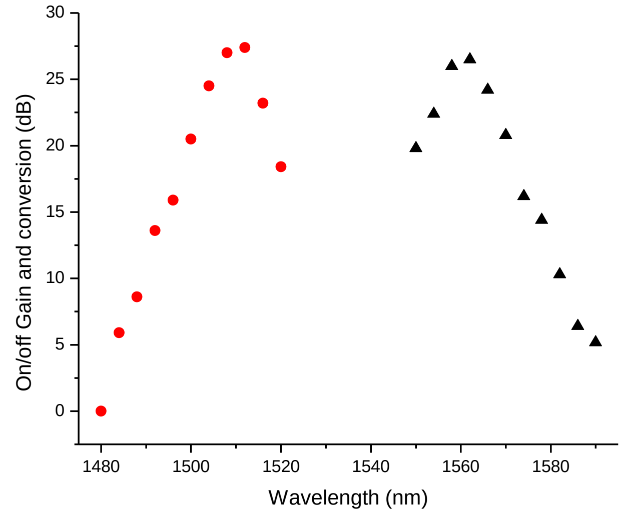

Figure 3: The on/off gain (triangles) and conversion (dots) in function of the probe wavelength.

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