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Mid-infrared to telecom-band stable supercontinuum generation in hydrogenated amorphous silicon waveguides

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***Abstract*—We demonstrate the generation of a stable supercontinuum in a 1-cm-long hydrogenated amorphous silicon waveguide by pumping the wire with 1950 nm picosecond pulses in the anomalous dispersion regime. The supercontinuum extends from 1460 to 2485 nm for a coupled peak power of 28.1 W.**

I. Introduction

Many applications such as optical coherence tomography [1] and vibrational spectroscopy [2] can make use of an ultrabroadband light source. This can be achieved through a process called supercontinuum generation. This process occurs when spectrally narrow-band incident pulses undergo nonlinear spectral broadening to yield a broadband spectrally continuous output. Over the past decade, much research has been done on supercontinuum generation using photonic crystal fibers [3], resulting in the commercialization of broadband supercontinuum sources targeting various spectral ranges.

On-chip integrated supercontinuum sources may aid to reduce the size, power consumption and cost of systems targeting the above applications. For example, telecom-band supercontinua are reported in planar waveguides composed of amorphous chalcogenides [4] or silicon nitride [5]. However, chalcogenide is not CMOS compatible and silicon nitride has only a small effective Kerr nonlinearity parameter γ. Another attractive approach is to use the large nonlinearity available in silicon-on-insulator (SOI) wire waveguides. However, crystalline silicon's large nonlinear two-photon absorption (TPA) has limited the generation efficiency and requires working at mid-IR wavelengths near $\lambda = 2200$ nm to efficiently suppress TPA. Supercontinuum generation in a crystalline silicon wire has been demonstrated using a 2120 nm picosecond pulsed pump source [6]. However, compact laser sources around this wavelength are hardly commercially available.

In this work, we generate a supercontinuum source spanning the wavelength range from 1460 nm to 2485 nm by pumping a 1 cm hydrogenated amorphous silicon wire at a wavelength of 1950 nm, using a commercial Thullium-based fiber laser source. The large linear refractive index (n $\sim$ 3.6) of hydrogenated amorphous silicon allows for a similar confinement as in the c-Si case and the high nonlinear index of the hydrogenated amorphous silicon results in a large effective nonlinearity of these wires. Moreover, a-Si:H has a larger bandgap compared to crystalline silicon, resulting in only modest TPA. Degradation of the a-Si:H was reported when pumping at a wavelength of 1550 nm. This is believed to be caused by the free carriers that are created due to the presence of TPA at these wavelengths [7]. However, when pumping at 1950 nm, the properties of a-Si:H are stable over time. In this paper we show that when pumping at 1950 nm, there are low nonlinear losses up to 13 W coupled peak power. The combination of the relaxed pump pulse requirements in terms of pulse energy and wavelength and the generated supercontinuum spectral range makes the hydrogenated amorphous silicon wire waveguide platform attractive for development of highly integrated wideband infrared optical sources.

II. Experimental setup

The a-Si:H photonic wire waveguides used were fabricated in a 200 mm CMOS pilot line at *imec*. 220 nm a-Si:H was deposited on top of a $2\mu m$ buried oxide layer. The wires are 900 nm wide and have no top cladding, as shown in figure 1. Under these conditions, the wire exhibits anomalous dispersion ($\beta_2 < 0$) at 1950 nm.

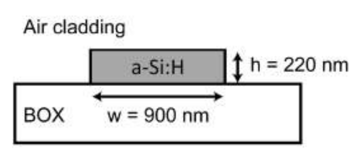

Fig. 1. Cross-section of the hydrogenated amorphous silicon waveguide used in the experiments.

To generate a broadband supercontinuum, the a-Si:H photonic wire waveguides are pumped by a picosecond pulse train at a center wavelength of 1950 nm (2 Micron High Power Mode-Locked Fiber Laser, FWHM = 1.2 ps, repetition rate = 26 MHz). Using a cut back technique the linear loss in the photonic nanowires is found to be approximately 2.2 dB/cm. The waveguide used in the supercontinuum experiments has a length of 1 cm. The incoupling loss at 1950 nm was found to be 14 ± 1 dB. The output spectrum is analyzed with a mid-IR optical spectrum analyzer at a 1 nm resolution.

III. Measurement results

Figure 2 shows the evolution of the supercontinuum spectrum with increasing pump power from 11.2 W coupled peak power (red curve) to 28.1 W coupled peak power (black curve). The supercontinuum generation is largely dominated by the phase-matched process of modulation instability, i.e. the amplification of background noise at wavelengths for which the phase-matching condition in eq. 1 is satisfied.

$$\beta_2 \Delta\omega^2 + \frac{1}{12}\beta_4 \Delta\omega^4 + 2\gamma_{Re} P = \Delta k_{lin} + \Delta k_{nonlin} = 0 \quad (1)$$

Here, β_2 and β_4 are the second- and fourth-order waveguide dispersion, $\Delta\omega$ is the detuning from the pump, γ_{Re} is the real part of the effective nonlinearity parameter and P is the peak pump power. For $\beta_2 < 0$ and $\beta_4 > 0$, this results in 2 modulation sidebands on each side of the pump: a broad one, labeled MI(1) close to the pump and a more narrow one, labeled MI(2) further away as can be seen at an input power of 11.2 W. Even at this low input power, the pump pulse spectrum is broadened by self-phase modulation (SPM), which also results in interference fringes near 1950 nm. In turn, this causes broadening of the sidebands.

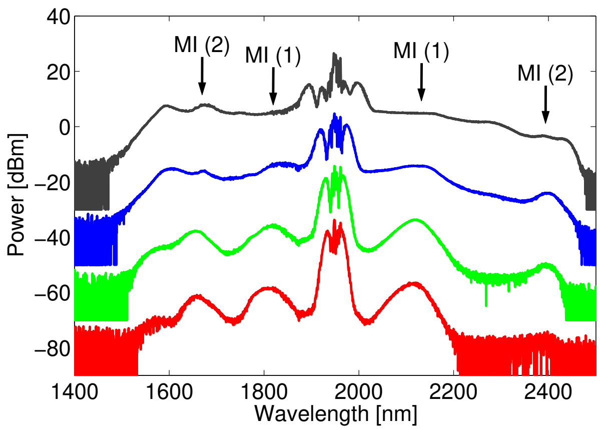

Fig. 2. Measured output spectrum for increasing values of coupled input peak power: 11.2 W (red), 12.7 W (green), 16.6 W (blue) and 28.1 W (black). The spectra are vertically offset by multiples of 20 dB for clarity.

When the coupled peak pump power increases, the spectral intensity of the sidebands increases and both the pump and sidebands become more broad (12.7 W) up to the point where all peaks merge together (16.6 W). Finally, at the highest pump power of 28.1 W, figure 2 shows that the spectral broadening of all generated peaks leads to increased flatness of the output spectrum on both sides of the pump. Under these conditions, the supercontinuum extends from 1460 nm to 2485 nm.

When pumping the a-Si:H wire waveguides at 1550 nm with picosecond pulses with a coupled peak power of 5.2 W, degradation of the material is reported already after 5 minutes. The degradation is believed to be the result of the free carriers created due to the presence of TPA. The material can be restored to its original state by thermally annealing the sample [7]. However, when pumping the a-Si:H waveguides at 1950 nm the output spectrum is found to be stable. The sample was exposed to 72 W coupled peak power at 1950 nm. After three and a half hours, the output spectrum had not changed. Also an 11 hours measurement with 72 W coupled peak power was performed which showed no degradation.

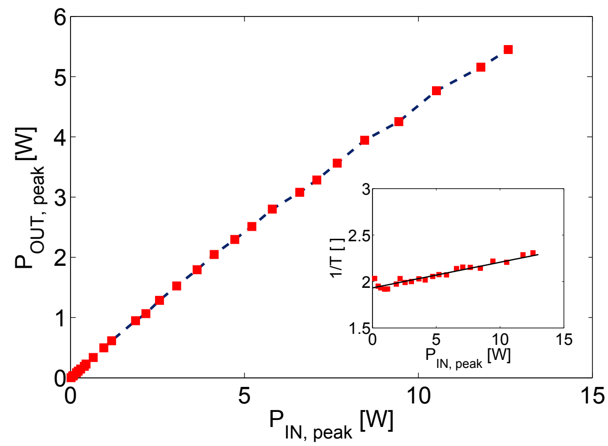

Fig. 3. The output power as a function of the coupled input peak power of the 1.2 ps pulse train at 1950 nm. The inset shows the reciprocal transmission as a function of the input peak power. The linear fit corresponds to a nonlinear absorption coefficient of $1.0 \pm 0.6\ W^{-1}m^{-1}$

Figure 3 shows that the output power is practically linear as a function of the coupled input power. Using the method described in [7], the imaginary part of the nonlinear parameter, γ_{Im} can be estimated from the transmission of the pulse through the waveguide. The inset of figure 3 shows the reciprocal of the transmission of the picosecond pulse train as a function of the input peak power. From the linear fit, a nonlinear absorption coefficient of $1.0 \pm 0.6\ W^{-1}m^{-1}$ is estimated.

IV. Conclusion

In summary, we have shown that a stable supercontinuum with a bandwidth of more than 1000 nm spanning from the telecom band to the mid-IR, can be generated by pumping a 1 cm hydrogenated amorphous silicon waveguide at a wavelength of 1950 nm, using a commercial Thullium-based fiber laser source. The stability of the material was demonstrated by an 11 hours stability experiment and is most likely related to the low nonlinear absorption coefficient $\gamma_{Im} = 1.0 \pm 0.6\ W^{-1}m^{-1}$. This shows that a-Si:H can be used as a stable highly nonlinear platform.

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