On-chip parametric amplification with 26.5 dB gain at telecommunication wavelengths using CMOS-compatible hydrogenated amorphous silicon waveguides

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We present what we believe to be the first study of parametric amplification in hydrogenated amorphous silicon waveguides. Broadband on/off amplification up to 26.5 dB at telecom wavelength is reported. Measured nonlinear parameter is $770\,\mathrm{W^{-1}\,m^{-1}}$, nonlinear absorption $28\,\mathrm{W^{-1}\,m^{-1}}$, bandgap 1.61 eV.

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An important goal in photonics is to realize high-performance parametric amplifiers in integrated waveguide circuits. Ideally, this requires low-loss waveguides manufactured in materials with high Kerr nonlinearity, operating in the telecommunication window, realized using a complementary-metal-oxide-semiconductor (CMOS)-compatible fabrication platform. In this context, crystalline silicon (c-Si) waveguides have been studied extensively. However, their performance is limited by nonlinear absorption, resulting in wavelength conversion and parametric amplification gains limited to +5.2 dB and +4.2 dB, respectively [1], in this wavelength range. In order to overcome this problem, a first possibility is to use a cladding layer with a high figure of merit (FOM) [2,3]. FOM is the ratio of the nonlinear response to the nonlinear absorption: $\mathrm{FOM} = \mathrm{Re}[\gamma]/(4\pi \mathrm{Im}[\gamma])$, with γ being the nonlinear parameter of the waveguide. However, the required evanescent coupling implies stringent design constraints that preclude good phase matching. A second approach is for the waveguide core itself to consist of a material with good FOM [4–6], but these realizations suffer either from lower linear and nonlinear refractive indices or from incompatibility with CMOS fabrication. One can also step away from the telecommunication wavelength range and work above the c-Si two-photon absorption threshold wavelength of $2.2\,\mu$m [7]. Although this approach effectively improves the FOM of the c-Si waveguides, the use for telecommunication applications is not straightforward.

Silicon-on-insulator (SOI) waveguides with a hydrogenated amorphous silicon (a-Si:H) waveguide core are an alternative to the standard crystalline SOI high-index contrast waveguide platform. An appealing feature of this solution is that a-Si:H is deposited at relatively low temperatures and can thus be integrated on a finished CMOS wafer in the back end. Recently, the nonlinear response of a-Si:H waveguides was studied [8,9], and the measured FOM was no better (0.40–0.66) than that of c-Si waveguides (0.4–0.7 [10]). Building on our previous work on low-loss a-Si:H waveguides [11,12], we present in this Letter engineered a-Si:H waveguides with a FOM of 2.1 ± 0.4 at telecommunication wavelengths. A similarly high FOM value was reported in [13] in an amorphous silicon core fiber. The difference from previous work [8,9] is presumably due to the fact that a-Si:H is a material with considerable freedom in chemical structure. Therefore different fabrication procedures can give rise to different material properties. The high linear refractive index of a-Si:H allows high optical confinement, which not only enhances the nonlinear response of the waveguide, but also allows for dispersion engineering. By carefully designing the dimensions of the a-Si:H waveguide it is possible to bring the dispersion of the waveguide into the anomalous regime, which allows for nonlinear effects such as soliton propagation and modulation instability (MI) [14]. In this Letter we make use of the latter effect to construct a nonlinear parametric amplifier.

The circuit is built in 220-nm-thick hydrogenated amorphous silicon deposited on top of a 1950-nm-thick polished high-density silicon dioxide layer. The 220-nm-thick a-Si:H film is deposited by plasma-enhanced chemical vapor deposition. The film was formed using silane (SiH4) as a precursor gas along with helium (He) dilution. In order to achieve low losses, we used a gas ratio (He/SiH4) of 9 and a plasma power of 180 W at a pressure of 2.6 Torr. These typical parameters were obtained from extensive process optimizations [11]. After forming the waveguide core layer, 500-nm-wide photonic wires were patterned using CMOS fabrication technology [12]. The bandgap of our a-Si:H films is measured using spectroscopic ellipsometry (in the 300–1600 nm range). The optical constants were extracted from a multilayer model using the Cody–Lorentz model [15] and the recommendations of Ferlauto *et al.* [16]. In order to have an accurate result, the interface roughness was also taken into account as well as the film thickness measured independently by cross-section scanning-electron microscopy. By using seven fitting parameters, we obtained a bandgap of 1.613 ± 0.022 eV (while c-Si has a gap of 1.12 eV). The half-bandgap is thus approximately 0.8 eV, corresponding to $\lambda \simeq 1550$ nm. Working around the half-bandgap gives rise to a high FOM. The single-mode waveguides we use are 500 nm wide, and TE-polarized light is used in the experiments. Incoupling and outcoupling of light is realized using diffractive grating couplers, each inducing 7.5–8 dB loss, depending on the wavelength. Waveguides with a variety of lengths were fabricated. Except where mentioned explicitly, all results are for waveguides with a length of 1.1 cm. The fiber-to-fiber loss was measured for different waveguide lengths ranging from 6 mm to 6 cm at low input powers to extract the linear loss and the incoupling and outcoupling loss, which are assumed to be identical. The linear waveguide propagation loss at 1535 nm is 4.8 dB/cm. The dispersion of the waveguides was estimated from a four-wave-mixing-based conversion efficiency spectrum we measured at low power. Indeed, its bandwidth depends only on the propagation length and the group-velocity dispersion, $|\beta_2| = 2.0\,\mathrm{ps^2\,m^{-1}}$. The negative sign of β_2 (anomalous regime) is deduced from the existence of MI (see below). These values are confirmed by numerical simulation using the commercial software Fimmwave (Photon Design, Oxford, UK), which predicts $\beta_2 = -2.6\,\mathrm{ps^2\,m^{-1}}$. The imaginary part of the nonlinear parameter, estimated by measuring the nonlinear dependence of the absorption, is $\mathrm{Im}[\gamma] = 28 \pm 3\,\mathrm{W^{-1}\,m^{-1}}$. The real part of the nonlinear parameter, determined by comparing the dependence of the self-phase modulation fringes on input power with a simulation that takes into account dispersion, nonlinear absorption, and the presence of free carriers, is $\mathrm{Re}[\gamma] = 770 \pm 100\,\mathrm{W^{-1}\,m^{-1}}$, in agreement with the value obtained by studying photon pair production in these waveguides [17]. Assuming a nonlinear modal area $A_{\mathrm{eff}} = 0.07\,\mu\mathrm{m}^2$, the nonlinear index is $n_2 = (1.3 \pm 0.2) \times 10^{-17}\,\mathrm{m^2/W}$. During our measurements, we found that the nonlinear properties of our waveguides degrade with time, rapidly during the first minutes and then more slowly. Annealing the sample at 200 °C for 1/2 h restores the FOM to its initial value (and this can be done multiple times). This suggests that with proper further optimization of the a-Si:H material, thermal excitation can compensate for photon-induced decay at moderate operating temperatures, possibly down to room temperature. All results reported in this Letter were taken after a few hours of operation, when the properties of the waveguides change slowly, and without annealing the sample. We intend to report on the decay properties for different temperatures in more detail in a future publication.

Parametric amplification occurs in waveguides with Kerr nonlinearity and anomalous dispersion. When the phase-matching conditions are satisfied, a small signal detuned from the pump frequency by a frequency difference, Ω, is exponentially amplified, while simultaneously an idler signal is created at detuning $-\Omega$ [14]. This process can be used for both signal amplification and frequency conversion. We studied parametric amplification in an a-Si:H waveguide using a pump–probe experiment; see Fig. 1. The pump was produced by a fiber laser emitting pulses at 1535 nm with a spectral width of 0.67 nm (FWHM), a duration of 3.8 ps (FWHM) at a 10 MHz repetition rate. The peak power in the waveguide was adjusted from 0 to 5.3 W thanks to a variable attenuator. Signal pulses are obtained from the secondary output of the laser: they are spectrally broadened using the optical nonlinearities in an erbium-doped fiber amplifier (EDFA), and then selected by a 1.2 nm tunable passband filter to generate (signal) pulses at arbitrary wavelengths ranging from 1550 to 1590 nm. The coupled peak power of the signal was always kept below 100 μW. An optical delay line was used to synchronize or desynchronize the signal and the pulse. After passing polarization controllers, the combined pump and signal were coupled into the waveguide. At the output of the waveguide, the light is sent to an optical spectrum analyzer. The parametric gain as a function of input pump power and signal wavelength was calculated after removing the effect of spontaneous MI. This was done by subtracting the MI spectrum when signal and pump are not synchronized from the output spectrum when they are synchronized. The on/off gain was calculated in a similar way as in [7] by integrating the power in the sideband caused by the amplification of the signal pulse. We obtained a maximum on/off gain of 26.5 dB and an on/off conversion efficiency of 27 dB for a signal at 1562 nm and an on-chip pump peak power of 5.3 W. Taking into account propagation losses, this corresponds to a net on-chip amplification of 21.2 dB, resulting in enough gain to overcome the high incoupling and outcoupling losses, giving rise to 6.2 dB net offchip amplification. The amplification as a

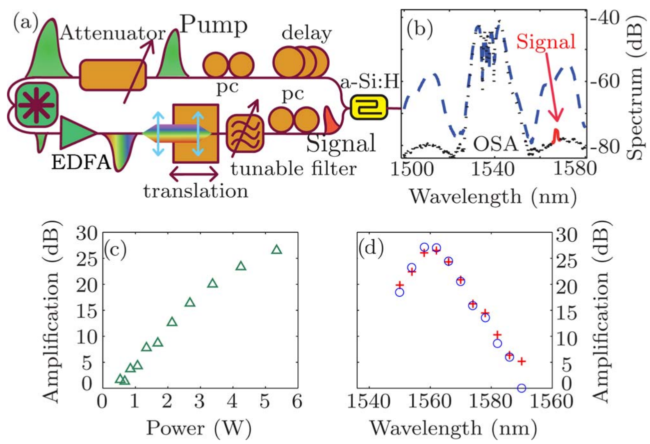

Fig. 1. (Color online) Pump probe experiment. (a) Experimental setup combines an intense pump pulse with a signal pulse whose polarization (pc), frequency, and time delay can be adjusted. (b) When the pump (dotted curve) and signal (short dashed curve) pulses are not synchronized, the signal is very small in comparison to the pump pulse. If both pulses are synchronized (long dashed curve), signal pulses are amplified by more than 20 dB and are converted into idler pulses. Note that the pump pulse is broadened spectrally due to self-phase-modulation, which in turn induces a broadening of the signal pulse. (c) On/off gain as a function of peak power (Δ). (d) On/off gain (resp. frequency conversion efficiency) as a function of wavelength (+, resp. $\bigcirc$).

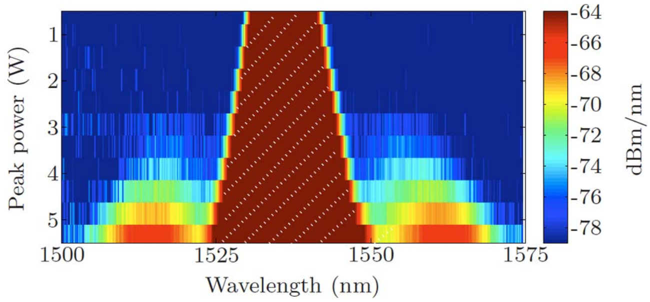

Fig. 2. (Color online) MI spectra as a function of the input power, which is outside the range of the color coding at approximately −30 dBm/nm.

function of the pump power at wavelength 1562 nm is plotted in Fig. 1(c). This amplification is to be compared with the 4.2 dB on/off amplification that was observed in crystalline silicon waveguide structures [1]. Figure 1(d) shows gain and conversion efficiency spectra for the peak pump power of 5.3 W. On/off gain in excess of 20 dB was observed in the band 1550–1570 nm, and on/off gain in excess of 10 dB was observed in the band 1550–1582 nm.

In the absence of a signal beam, the quasi-continuous nature of the pump pulse is broken by spontaneous MI [14]. The spectra when only the pump pulse travels through the a-Si:H waveguide are shown in Fig. 2 for various pump power levels. The bandwidth and strength of the MI sidebands increase with coupled peak input power, while the pump itself also broadens due to self-phase-modulation. Note that MI peak can be related to amplification by comparison with the spectral density in the absence of MI. Spectral density at the MI-peak wavelength before a-Si:H chip is less than −80 dB/nm and experiences 20 dB fiber-to-fiber loss afterwards. The typical value of MI peak, above −70 dBm/nm, should thus be compared with background level below −100 dB/nm, giving an amplification significantly greater than 30 dB. The difference from the maximum gain reported in Fig. 1(c) is presumably because in the pump probe experiment, at maximum power, the pump starts to become depleted, which limits the gain.

In summary, CMOS-compatible hydrogenated amorphous silicon waveguides provide on-chip parametric amplification at telecommunication wavelengths. Optimization of the fabrication process could lead to further increases in the nonlinear figure of merit.

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