Nonlinear transmission properties of hydrogenated amorphous silicon core optical fibers

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Abstract: The nonlinear properties of a low loss hydrogenated amorphous silicon core fiber have been characterized for transmission of high power pulses at 1540 nm. Numerical modelling of the pulse propagation in the amorphous core material was used to establish the two-photon absorption, free-carrier absorption and the nonlinear refractive index, which were found to be larger than the values typical for crystalline silicon. Calculation of a nonlinear figure of merit demonstrates the potential for these hydrogenated amorphous silicon core fibers to be used in nonlinear silicon photonics applications.

OCIS codes: (060.2290) Fiber materials; (160.6000) Semiconductor materials; (190.4370) Nonlinear optics, fibers.

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1. Introduction

Highly nonlinear silicon waveguides have played a central role in the recent advancements in semiconductor photonics forming the basis of a number of important optoelectronic devices [1]. To date, many of these device demonstrators have been developed on photolithographically defined single crystal silicon-on-insulator (SOI) waveguides to leverage off the well established on-chip processing capabilities. However, a new class of semiconductor waveguide that is currently gaining increased interest is the silicon optical fiber [2, 3, 4]. Silicon fibers offer a number of advantages over their on-chip counterparts in that they are robust, flexible, cylindrically symmetric and can be fabricated over long lengths. Furthermore, the incorporation of the active semiconductor component into the fiber geometry provides an important step towards seamlessly linking silicon photonics with existing fiber infrastructures, with the potential to reduce the complexity and improve the efficiency of future communication networks.

Silicon-core, silica-clad fibers have been fabricated using various methods to obtain single crystal, polycrystalline and amorphous core materials. Using a high pressure chemical processing technique we have routinely deposited high quality polycrystalline and amorphous silicon core materials over lengths of several centimeters into the internal holes of pure silica capillaries [2, 5]. This simple low cost deposition technique can be easily modified to fill a range of capillary sizes, from tens of microns down to hundreds of nanometers, so that the core dimensions can be optimized for the specific application. At present, the lowest loss reported in a silicon fiber for transmission around 1550 nm has been measured in a hydrogenated amorphous silicon (a-Si:H) core [5]. Whilst a-Si:H has always been a strong candidate for low loss interconnects, recent characterization of its enhanced nonlinear properties has identified it as a promising material for nonlinear optical applications [6, 7].

In this paper we investigate the nonlinear properties of a low loss hydrogenated amorphous silicon optical fiber. By comparing the nonlinear transmission measurements with numerical models describing pulse evolution in the fiber we have characterized both the nonlinear absorption and refractive index. The values obtained for the two-photon absorption (TPA) parameter, the free-carrier absorption (FCA) and the nonlinear refractive index are found to be large compared to those typical for crystalline silicon, in agreement with what has been reported for a-Si:H waveguides fabricated on-chip. We anticipate that further enhancement of the nonlinear properties of the a-Si:H fibers could be obtained by modifying the deposition conditions.

2. Fabrication and material characterization

The fiber used in our experiments was fabricated by depositing the amorphous silicon inside a 5.6 μm silica capillary using a high pressure microfluidic chemical technique [2]. This process involves a mixture of silane and helium (SiH_4/He) being forced to flow through the central

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hole of the capillary under high pressures $\sim 35\,\mathrm{MPa}$, whilst being heated in a tube furnace. The deposition of the amorphous material occurred over a relatively low temperature range of $360-440\,^\circ\mathrm{C}$. We have found that by keeping the deposition temperatures below $450\,^\circ\mathrm{C}$ the out diffusion of hydrogen can be suppressed [5], which is consistent with previous observations of sample fabrication via plasma enhanced chemical vapor deposition (PECVD) [8]. Importantly, the incorporation of hydrogen into the amorphous silicon material is known to saturate the dangling bonds [9], and can thus reduce the absorption losses as we demonstrated in Ref. [5].

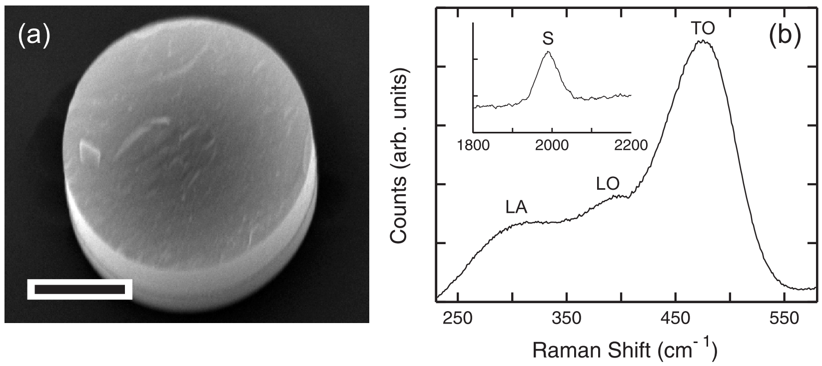

Fig. 1. (a) SEM micrograph of the silicon fiber with the cladding etched from the core to facilitate imaging; scale bar $2\,\mu\mathrm{m}$. (b) Raman spectrum for the amorphous silicon core labelled with the phonon modes. Inset shows the Si-H stretching mode.

Figure 1(a) shows a SEM micrograph of the silicon core from which it is clear that the material has deposited smoothly onto the silica walls, conformally filling the capillary hole until complete closure. A completely filled length of 1.2 cm was obtained for our transmission measurements and modal analysis was used to calculate the effective area $A_{\mathrm{eff}} \sim 14\,\mu\mathrm{m}^2$ and the group velocity dispersion (GVD) $\beta_2 \sim 1\,\mathrm{ps}^2/\mathrm{m}$ at 1540 nm. The quality of the deposited core material was determined via micro-Raman measurements conducted at 633 nm using a HeNe excitation laser. A $50\times$ objective was used to focus the source onto the silicon core through the side of the transparent silica cladding, with a spot size of $2\,\mu\mathrm{m}$ and 3 mW of power at the outer surface, and the backscattered radiation was recorded on a thermoelectrically cooled CCD detector. The Raman spectrum plotted in Fig. 1(b) exhibits a strong broad peak around $480\,\mathrm{cm}^{-1}$ corresponding to the transverse optical (TO) mode and two weaker subsidiary peaks associated with the longitudinal acoustic (LA) and longitudinal optical (LO) modes of amorphous silicon [10]. The presence of hydrogen in the core material is confirmed by the observation of the Si-H stretching (S) mode seen in the inset at $\sim 2000\,\mathrm{cm}^{-1}$ [10].

3. Description of pulse propagation in a silicon core fiber

Nonlinear pulse propagation in silicon fibers can be described by a modified form of the nonlinear Schrödinger equation (NLSE) [6, 11]:

$$\frac{\partial A(z,t)}{\partial z} = -\frac{i\beta_2}{2}\frac{\partial^2 A(z,t)}{\partial t^2} + i\gamma |A(z,t)|^2 A(z,t) - \frac{1}{2}\left(\sigma_f + \alpha_l\right) A(z,t), \tag{1}$$

where $A(z,t)$ is the pulse envelope, β_2 is the GVD and γ is the nonlinearity parameter. Owing to the effects of TPA, the nonlinear parameter is complex and is defined as, $\gamma = k_0 n_2/A_{\mathrm{eff}} + i\beta_{\mathrm{TPA}}/2A_{\mathrm{eff}}$, where n_2 is the Kerr coefficient and β_{TPA} is the TPA coefficient. The remaining terms are the linear loss α_l and the free carrier contribution $\sigma_f = \sigma(1+i\mu)N_c$, where σ is the

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FCA coefficient, μ governs the free-carrier dispersion (FCD), and the free carrier density N_c is determined by the rate equation [11]:

$$\frac{\partial N_c(z,t)}{\partial t} = \frac{\beta_{\mathrm{TPA}}}{2h\nu_0}\frac{|A(z,t)|^4}{A_{\mathrm{eff}}^2} - \frac{N_c(z,t)}{\tau_c}, \tag{2}$$

where τ_c is the carrier lifetime. Using the value for the GVD parameter we can calculate the dispersion length $L_D = T_0^2/|\beta_2|$, which for a hyperbolic secant input pulse with a full width half maximum (FWHM) duration of 720 fs, as used in the nonlinear absorption experiments described below, $L_D \sim 17$ cm. This length is considerably longer than the length of the fiber used in the transmission measurements so that the GVD contribution is negligible in our simulations.

Ignoring the effects of dispersion in Eq. (1), it is possible to define a simplified propagation equation describing the temporal evolution of the intensity profile, which can be expressed as [12]:

$$\frac{dI(z,t)}{dz} = -\alpha_l I(z,t) - \beta_{\mathrm{TPA}} I^2(z,t) - \sigma N_c(z,t) I(z,t), \tag{3}$$

where $I(z,t) = |A(z,t)|^2/A_{\mathrm{eff}}$ and N_c is the same as that described by Eq. (2). Although this equation does not provide any information about the spectral evolution of the pulse, which is governed by n_2, it isolates the effects of the losses on the pulse propagation so that, given the linear loss α_l, we can determine the TPA and FCA parameters. Finally, we note that both Eq. (1) and (3) assume that the individual pulses are well separated in time so that free carriers generated by a previous pulse are negligible. This is a reasonable assumption in our experiments as a-Si:H waveguides have been shown to exhibit short carrier lifetimes ($\tau_c \sim 400$ ps [7]), much less than the 40 MHz repetition rate used in our nonlinear experiments.

4. Characterization of the optical transmission properties

To characterize the transmission properties of our a-Si:H fiber we first determine the linear losses as a function of wavelength over the broad telecommunications band $1.3 - 1.8\,\mu$m. A Ti:sapphire laser was used to pump an optical parameteric oscillator (OPO) to provide 250 fs (FWHM) pulses at 80 MHz over this wavelength range. Due to the high peak powers of the femtosecond pulses, low average input powers of less than 100 μW were maintained to avoid the effects of TPA and FCA. The light was launched into the silicon core via free space coupling using a 40× microscope objective lens and a second 40× objective was used to capture the transmitted light and focus it onto a power meter. To avoid shortening the fiber length, the losses were calculated using a non-destructive single pass measurement technique. After accounting for the coupling and reflection losses, the linear loss values are shown in Fig. 2(a). These results follow the same trend of decreasing loss for increasing wavelength observed in our earlier silicon fibers, which we have previously attributed to scattering losses [5]. The loss values determined here (3 dB/cm at 1550 nm) are slightly lower than reported for the a-Si:H core fiber in Ref. [5] (5 dB/cm at 1550 nm) and this reduction in loss is likely to be due to an increase in the hydrogen content leading to a greater saturation of dangling bonds. It is worth noting that these loss values are at the lower end of the range measured in a-Si:H waveguides on-chip ($2 - 14$ dB/cm [8, 13]), and are lower than the 7 dB/cm loss of a nanowire waveguide in which cross-phase and cross-absorption modulation have recently been demonstrated [13].

Nonlinear absorption measurements were then conducted to investigate the roles of TPA and FCA on the high power pulse propagation. For this investigation we used a fiber laser to generate hyperbolic secant pulses with a 720 fs (FWHM) duration operating at 1540 nm and a repetition rate of 40 MHz. As before, the light was free space launched into the silicon core using a 40× microscope objective lens, with a second 40× objective used to focus the output

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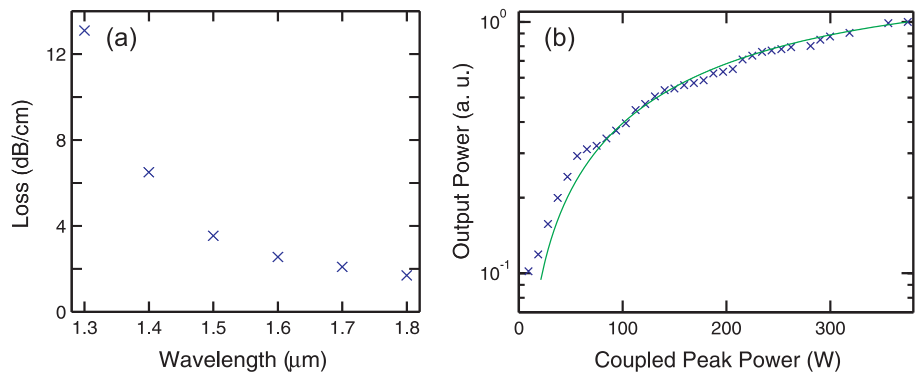

Fig. 2. (a) Linear loss measurements as a function of wavelength. (b) Normalized output power as a function of coupled input peak power showing the onset of nonlinear absorption. The solid green curve is the simulated fit obtained via solving Eqs. (2) and (3).

onto the power meter. A plot of the normalized output power as a function of coupled input peak power is given in Fig. 2(b), clearly showing the onset of nonlinear absorption. A fit to this data is obtained by solving Eq. (3), in conjunction with Eq. (2), with $\alpha_l = 3.5\,\text{dB/cm}$ and β_{TPA} and σ as free parameters, where we expect TPA to be the dominant nonlinear loss at the lower input powers. The simulations reveal the best fit values of $\beta_{\text{TPA}} \sim 0.8\,\text{cm/GW}$ and $\sigma \sim 1 \times 10^{-16}\,\text{cm}^2$ with the resulting curve plotted as the solid green line in Fig. 2(b). The value found for the TPA parameter is slightly lower than what has been reported in other a-Si:H materials [6, 14], however, it is at the upper end of the range reported for crystalline silicon ($\beta_{\text{TPA}} \sim 0.5 - 0.9\,\text{cm/GW}$ [15, 16]). The estimated FCA coefficient is also slightly lower than the value recently obtained for an a-Si:H strip waveguide [6], but is close to the value calculated via the Drude model [17], which using the parameters for a-Si:H in Ref. [18] yields $\sigma = 1.6 \times 10^{-16}\,\text{cm}^2$. Similar to the linear loss values, we anticipate that the precise values of the nonlinear absorption parameters depend on the quality of the deposited material and this is currently the subject of further investigations.

Characterization of the nonlinear transmission was completed by studying the spectral evolution of the pulses to determine the nonlinear refractive index n_2. Figure 3 shows the output spectra recorded on an optical spectrum analyzer at a selection of coupled input powers, clearly illustrating the spectral broadening of the pulses due to self-phase modulation (SPM). Using the values of A_{eff}, β_2, α_l, β_{TPA} and σ already obtained above, and estimating the FCD term as $\mu = 2k_c k_0/\sigma$, with $k_c = 1.35 \times 10^{-27}\,\text{cm}^{-3}$ [11], we now solve Eqs. (1) and (2) with n_2 as the free parameter. Comparing the simulated spectral widths with the measured spectra we find the best fit value of $n_2 \sim 1.8 \times 10^{-13}\,\text{cm}^2/\text{W}$ and the corresponding simulated results are plotted as the red curves in Fig. 3, showing a good qualitative agreement between the spectral shapes. Interestingly, this value of the nonlinear index is of the same magnitude as that measured in Ref. [6] and at least two times larger than that measured for crystalline silicon [15, 16].

Finally, as in previous studies of the nonlinear properties of silicon waveguides, it is useful to calculate a nonlinear figure of merit, which we define as [19]:

$$T_{\text{FOM}} = \frac{2\lambda \beta_{\text{TPA}}}{n_2}. \tag{4}$$

Using this equation, values of $T_{\text{FOM}} < 1$ are necessary for applications requiring a 4π phase shift (e.g. directional couplers) and $T_{\text{FOM}} < 4$ for applications only requiring a π phase shift (e.g. Mach-Zehnder interferometers) [15, 19]. Importantly, owing to the relatively modest β_{TPA}

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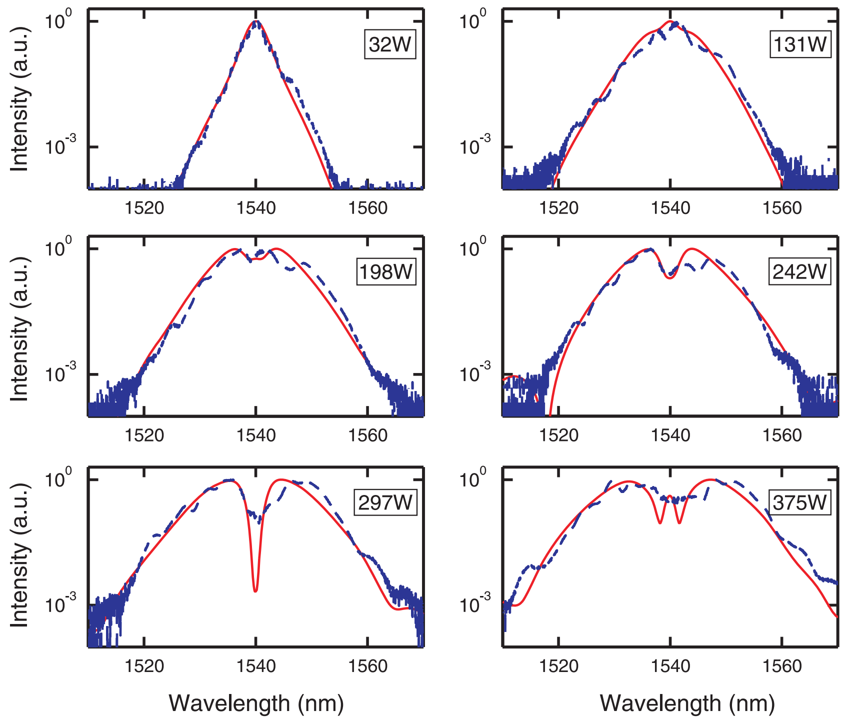

Fig. 3. Spectral evolution as a function of peak input coupled power (dashed blue curves). The red curves are the simulated fits obtained via solving Eqs. (1) and (2).

measured in our a-Si:H fiber and the high n_2, we calculate $T_{\mathrm{FOM}} = 1.54$, which is much lower than typically reported in silicon waveguides on-chip [6, 15, 16]. Thus we anticipate that a-Si:H core fibers have great potential for use in future nonlinear switching devices.

5. Conclusion

We have characterized the nonlinear transmission properties of a low loss hydrogenated amorphous silicon core fiber. By comparing the evolution of high power pulses with numerical modelling describing propagation in the semiconductor core we have determined both the nonlinear absorption parameters associated with TPA and FCA and the refractive index n_2. The results indicate that a-Si:H has enhanced nonlinear properties compared to crystalline silicon, in agreement with recent results obtained on-chip [6, 14], and on-going investigations are being conducted to establish the dependence of the nonlinear parameters on the material quality. The calculated nonlinear figure of merit suggests that a-Si:H core fibers are a suitable platform for a range of applications in nonlinear silicon photonics.

Acknowledgments

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