Generation of correlated photons in hydrogenated amorphous-silicon waveguides

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We report the first (to our knowledge) observation of correlated photon emission in hydrogenated amorphous-silicon waveguides. We compare this to photon generation in crystalline silicon waveguides with the same geometry. In particular, we show that amorphous silicon has a higher nonlinearity and competes with crystalline silicon in spite of higher loss. © 2010 Optical Society of America

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The traditional way of producing photon pairs is based on parametric downconversion in optical materials with $\chi^{(2)}$ nonlinearity. During the past decade, there has been increasing interest in photon pair generation based on four-wave mixing (FWM). The latter types of sources were initially demonstrated in standard optical fibers [1] and microstructured fibers [2]. However, except when special precautions are taken, such as cooling the fibers, these sources suffer from a high noise level due to Raman scattering. More recently, photon pair sources based on FWM in crystalline silicon (c-Si) nanophotonic waveguides have been reported [3–7]. One would expect a c-Si source of pairs to be noise free, as Raman gain in bulk silicon at the wavelength at which photon pairs are generated is negligible. However, a careful study [7,8] shows that uncorrelated photons constitute a source of noise in this case also but almost 2 orders of magnitude smaller than in the case of fibers. Recent work has shown that hydrogenated amorphous-silicon (a-Si:H) nanophotonics has a number of potential advantages with respect to c-Si. First of all, the material properties of deposited a-Si:H can be tuned by adjusting the deposition parameters, which could affect Raman scattering as well as the bandgap energy. This flexibility makes a-Si:H an attractive platform for nonlinear applications. Second, as a-Si:H can be deposited at relatively low temperatures, it could be deposited on many different substrates while keeping compatibility with the complementary metal-oxide-semiconductor (CMOS) process. Furthermore, a-Si:H waveguides can be stacked into three-dimensional optical circuits, whereas c-Si waveguides are restricted to planar architectures. Finally, a-Si:H waveguides can now be manufactured with losses comparable to c-Si waveguides [9]. As a-Si:H waveguides have typically the same size as c-Si waveguides, and as a-Si:H material has $\chi^{(3)}$ nonlinearity comparable to c-Si [10,11], the efficiency of the photon pair generation process should be comparable in both structures. In this Letter, we report the observation of photon pair generation in a-Si:H nanophotonic waveguides at telecommunication wavelengths. In particular, we carry out a comparison

between the rate of photon pair generation in c-Si and a-Si:H waveguides.

The a-Si:H (c-Si) waveguides used in the present experiment were fabricated on a silicon wafer with 220-nm-thick a-Si:H (c-Si) on top of 2 μm of SiO_2 . The amorphous silicon was deposited using a low temperature (300 °C) plasma-enhanced chemical vapor deposition process [9]. After the a-Si:H layer deposition phase, single-mode 500-nm-wide and 11.2-mm-long waveguides were defined using 193 nm optical lithography and dry etching [12]. Identical grating couplers were defined for in and out light coupling. As mentioned above, the waveguide made of crystalline silicon was fabricated with the same section on top of a 2 μm layer of SiO_2 . Measurements made for amorphous (respectively, crystalline) silicon waveguides revealed in/out-coupling losses of 8 ± 1 dB (respectively, 6 ± 0.5 dB) and propagation loss of 4.5 ± 0.5 dB (respectively, 2.5 ± 0.5 dB). Propagation losses are estimated by comparison with very short waveguides on the same chips. The experimental setup relies on a coincidence measurement; see Fig. 1. Photon pairs are generated while pumping the waveguides with a

Fig. 1. (Color online) Coincidence measurement: laser, cw beam at 1539.8 nm amplified by an EDFA; Atn, tunable attenuator; pc, polarization controller; bpf, bandpass filter centered at pump wavelength; ff, switch mirror; col, collimation package; dmux1, demultiplexer add and drop filter for the pump band; bbf, bandblock filter; dmux2, Stokes/anti-Stokes selector; ssdp, superconductor single photon detectors; tdc, time-to-digital converter provides result as a histogram.

cw beam at telecom wavelength. The power of the pump beam can be adjusted with a tunable attenuator so that, for 0 dB attenuation, the power before incoupling is 10 mW and never exceeds 2 mW in the waveguide; hence, nonlinear losses can be neglected. A bandpass filter (BPF) ensures absolute darkness at Stokes and anti-Stokes frequencies. This BPF is made of fiber Bragg gratings, circulators, and commercial dense wavelength division multiplexing (DWDM) add and drop filters (100 GHz on ITU grid 1539.8 nm). Overall, the BPF provides extinction greater than 150 dB outside of the pump band 1538.9–1540.6 nm (pump band). The last DWDM filter of the BPF has a short pigtail (10 cm) to limit Raman scattering in the fiber.

Correlated pairs are exhibited by deterministically splitting the photon pairs and optically delaying one of the photons. A first demultiplexer separates the pump beam from the pairs. A second demultiplexer selects two spectral bands: Stokes from 1541.5 to 1558.5 nm and anti-Stokes from 1523 to 1538.5 nm. Photons are detected thanks to superconducting single photon detectors (from Scontel) cooled down to 1.8 ± 0.1 K. Efficiencies of detectors are $6.1 \pm 0.1\%$ and $5 \pm 1\%$ [13], while dark counts are 80 ± 20 Hz and 25 ± 12 Hz. The time difference between both detections is measured with a time-to-digital converter (TDC—Agilent Acquis system) so that the entire detection system can resolve coincidences with 80 ps resolution (FWHM of a coincidence peak). The TDC system collects all events, including single detection events, and sends them to a computer. This limits the rate at which coincidences can be measured by the TDC system and therefore requires a calibration of the system for obtaining an absolute rate of coincidences. To this end, the absolute flux at anti-Stokes frequency is measured by replacing the time-to-digital converter by an auxiliary counter. Stokes and anti-Stokes bands are chosen so that the pair flux is spectrally flat over the selected bandwidth. Indeed, theory predicts that the pair flux is given by a sinc function, which is flat for low values of its argument:

$$\Phi = \frac{1}{2\pi} \int_{\Delta\omega} \left| \gamma P L \text{sinc} \left[L \left(\frac{(\beta_2 \omega^2)^2}{4} + \beta_2 \omega^2 \gamma P \right)^{1/2} \right] \right|^2 d\omega, \quad (1)$$

Fig. 2. (Color online) Detected coincidence rate versus pump power in the c-Si waveguide (blue, top curve) and in the a-Si:H waveguide (red, bottom curve). Error bars come from Poisson statistics. Curves are quadratic fits following Eq. (1).

Fig. 3. (Color online) CAR versus the measured pair flux in the a-Si:H waveguide (red, bottom) and in the c-Si waveguide (blue, top). Error bars come from Poisson statistics.

where γ is the third-order nonlinearity coefficient of the waveguide (around $200 \text{ W}^{-1} \text{ m}^{-1}$ for c-Si), β_2 is the group-velocity dispersion parameter of the waveguide (estimated to be $-2 \pm 0.2 \text{ ps}^2 \text{ m}^{-1}$ for both waveguides via an FWM experiment), $\Delta\omega$ is the bandwidth of the demultiplexer used to collect Stokes and anti-Stokes photons, P is the pump power in the waveguide, and L is the waveguide's length.

Comparison of pair fluxes generated in a-Si:H and c-Si is presented in Fig. 2. As expected, the pair flux Φ grows quadratically with pump power P . We expected the pair flux generated in a-Si:H silicon to be lower than in c-Si because of higher losses. Indeed, as incoupling, propagation, and outcoupling losses are each 2 dB higher in a-Si:H waveguides, we expect that the detection rate should be reduced by 12 dB for a given input power. Figure 2 indicates that the photon pair generation is around 1.6 times lower in the amorphous-silicon waveguide in comparison to the c-Si waveguide. This implies a Kerr nonlinearity coefficient in a-Si:H higher by a factor of 2.2. This is compatible with results obtained independently [11,14]. In Fig. 3, the coincidences-to-accidental ratio (CAR) for c-Si and a-Si:H are compared. The CAR is the number of events in the peak of the coincidences histogram divided by the number of events in the background of this histogram over the same time-bin duration. In Fig. 3, dark counts are so low that the main sources of accidental coincidences are either broken pairs or noise from the source itself. We find a reduction of the CAR by

Fig. 4. (Color online) Measured photon flux versus input power in a-Si:H (red, circles) and c-Si (blue, stars) in the anti-Stokes band. The flux generated is slightly higher in a-Si:H despite higher propagation and coupling losses. Error bars come from Poisson statistics.

up to 1 order of magnitude, which can be explained by additional loss in a-Si:H waveguide. Figure 4 compares the fluxes generated in a-Si:H and c-Si in the anti-Stokes band. The higher flux generated in an a-Si:H waveguide despite higher propagation loss clearly indicates either a higher nonlinearity or a higher source of noise, or both. Elsewhere [8], we studied the origin of the weak noise that arises in c-Si and demonstrated that this noise is not due to carrier dynamics but is related to a thermal population of phonons, probably Raman scattering. Note that we are able to observe and quantify the noise in Fig. 3, because we use detectors with very low dark count rates and we operate in a regime where $\gamma PL \ll 1$, and thus linear effect (noise) are not dominated by quadratic effect (pair generation). This was possible thanks to a continuous pumping (low peak power) and by collecting pairs over the relatively wide bandwidth of 15 nm.

In summary, we have shown that a-Si:H silicon, as well as c-Si, nanophotonics is an interesting platform for quantum optics, as it provides an efficient and low noise source of photon pairs. We have observed that amorphous silicon has a higher Kerr nonlinearity than c-Si but also suffers from higher loss, which results in an overall figure of merit that is not as good as in c-Si. Nevertheless, a-Si:H is more versatile, as it can be deposited on many substrates while keeping compatibility with the CMOS process, and as it allows for three-dimensional architectures.

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