Generation of correlated photons in hydrogenated amorphous silicon waveguides

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We report the first observation of correlated photon emission in hydrogenated amorphous silicon waveguides. We compare this to photon generation in crystalline silicon waveguides with 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
The traditional way of producing photon pairs is based on parametric downconversion in optical materials with a $\chi^{(2)}$ 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 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 two 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. Secondly, as a-Si:H can be deposited at relatively low temperatures, it could be deposited on many different substrates while
keeping compatibility with the CMOS process. Furthermore, a-Si:H waveguides can be stacked into 3-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 the present work 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 $\mu$m of SiO$_2$. The amorphous silicona was deposited using low temperature ($300^\circ$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. On the other hand, the waveguide made of crystalline silicon was fabricated with same section on top of a 2 $\mu$m layer of SiO$_2$. Measurements made for amorphous (resp. crystalline) silicon waveguides revealed in/out-coupling losses of 8±1 dB (resp. 6±0.5 dB) and propagation loss of 4.5±0.5 dB (resp. 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 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 exceed 2 mW in the waveguide so that 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 DWDM add & drop filters (100 GHz on ITU grid and centered at 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 BP 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 band: 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±0.1% and 5±1% [14] 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 Acquiris system) so that the entire detection system can resolve coincidences with 80 ps resolution (fwhm of a coincidence peak). 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 requires thus 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 convertor 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:

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

where \(\gamma\) is the third order nonlinearity coefficient of the waveguide (around 200 W\(^{-1}\)m\(^{-1}\) for c-Si), \(\beta_2\) is the group velocity dispersion parameter of the waveguide (estimated to be \(-2 \pm 0.2\) ps\(^2\)m\(^{-1}\) for both waveguides via a four-wave mixing 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 in presented in Fig. 2. As expected, the pair flux \(\Phi\) 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 detection rate should be reduced by 12 dB for a given input power. Fig. 2 indicates that the photon pair generation is around 1.6
times lower in the amorphous silicon waveguide in comparison to c-Si waveguide. This implies a Kerr nonlinearity coefficient in a-Si:H higher by a factor 2.2. This is compatible with results obtained independently [11, 13]. In Fig. 3, the coincidences to accidental ratio (CAR) for c-Si and a-Si:H are compared. CAR is the number of events in the peak of the coincidences histogram divided by the number of events in the background of this histogramme 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 CAR by up to one order of magnitude which can be explained by additional loss in a-Si:H waveguide. Fig. 4 compares the fluxes generated in a-Si:H and c-Si in anti-Stokes band. The higher flux generated in 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 study 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 a rather wide spectral band (±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 which 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 CMOS process, and as it allows for 3-dimensional architectures.

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10. Y. Shoji, T. Ogawara, T. Kamei, Y. Sakakibara, S. Suda, K. Kintaka, H.


14. Higher uncertainty on second detector’s efficiency is due to absence of polarization controller before the superconducting chip.
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 & drop filter for the pump band; bbf: bandblock filter; dmux2: Stokes/anti-Stokes selector; sspd: superconductor single photon detectors; tdc: time-to-digital converter provides result as a histogram.
Fig. 2. (Color online) Detected coincidence rate versus pump power before incoupling 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) Coincidences-to-accidental detections ratio (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 statistic.
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.