Generation of Correlated Photons in a Silicon Chip

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Abstract: *We experimentally demonstrate the generation of correlated photon-pairs through parametric scattering in silicon waveguides. These measurements represent a first step towards developing tools for quantum information processing based on silicon-on-insulator technology.*

We report on a source of correlated pairs of photons that are generated within a silicon waveguide. Fabricated using CMOS-compatible technology, the nanoscale waveguide dimensions are tailored to allow for efficient four-wave mixing[1], which at the quantum level spontaneously creates pairs of photons, called signal and idler, whose energies are well defined with respect to one another. Similar four-wave parametric scattering (FPS) in optical fibres has been used to generate pairs of photons exhibiting polarization as well as time-bin entanglement[2,3] which are particularly useful for quantum communications applications. The work described here is the first demonstration of quantum-correlated photons in an integrated silicon system. It also represents a first step in the creation of a scaleable, silicon-based platform for quantum optical technology.

In the previous work on generating correlated and entangled photons using FPS in optical fibres, spontaneous Raman scattering (SRS) is the principal fundamental source of noise[4]. Uncorrelated photons are produced when pump photons couple with inhomogeneously-broadened vibrational Raman modes of the silica molecules. We are motivated to work with silicon because we expect the quantum noise due to SRS in silicon waveguides to behave differently than in silica glass because of the crystalline nature of the silicon material, which leads to significantly reduced broadening of the Raman vibrational modes.

The FPS process arises from the $\chi^{(3)}$ nonlinearity of the waveguide. Two pump photons of the same angular frequency ω_p are destroyed in order to create two other photons which are detuned in frequency from that of the pump by $\pm\Omega$. Energy is conserved in this process. Pump photons, which are confined mostly to the core of the waveguide, induce an electronic polarization in the material which then couples with photons of other optical frequencies. For nanoscale waveguides fabricated in silicon the relatively large susceptibility leads to $\gamma \approx 100{,}000$ $(\mathrm{W{\bullet}km})^{-1}$, meaning that significant nonlinear effects can be observed in device lengths of 1 cm or less. The strong mode-field confinement and large refractive-index contrast leads to dispersive properties that are extremely sensitive to the waveguide dimensions, so the waveguide must be carefully designed to obtain the anomalous dispersion required for phase matching the FPS process. One must also consider the presence of nearby excited energy levels in silicon. Individual photons with wavelengths of 1.5 μm do not carry sufficient energy to span the bandgap, but nonlinear, multi-photon absorption is possible. Additionally, once carriers are excited into the valence band, they can be further excited to a continuum of higher energy levels through excited state absorption which can be a loss process for the FPS photons.

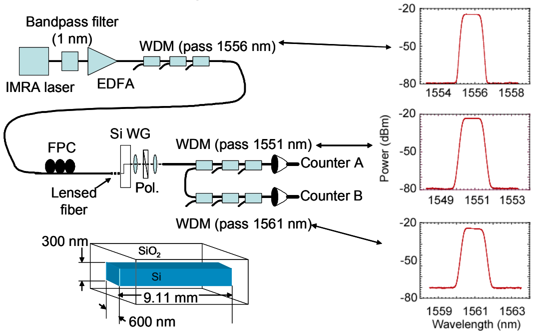

Figure 1: Schematic of the experimental setup. Shown at right are the pass bands for each of the sets of WDM filters. A schematic of the Si waveguide buried in SiO_2 is shown as an inset.

The experimental setup is illustrated schematically in Fig. 1. Pulses (5 ps, 50 MHz repetition rate) from a spectrally-filtered femtosecond fibre laser (IMRA, FemtoLite) are launched into a 9.33-mm long silicon-on-insulator waveguide whose cross section is 600 nm x 300 nm. The electric-field polarization is made parallel with the long dimension of the waveguide. The output is collected using a pair of short focal-length aspheric lenses where net collection efficiency is about 8%. A set of WDM filters (80% transmissivity) are used to spectrally separate the correlated pairs and to suppress leakage of the pump photons through to the photon counters.

Photon counting is performed by using InGaAs avalanche photodiodes operated in gated, Geiger mode. The quantum efficiency of these detectors is about 20% giving a total detection efficiency of 1.3% for the signal and idler photons. The counters are interrogated by a computer to obtain the signal counts and the idler counts as a function of time.

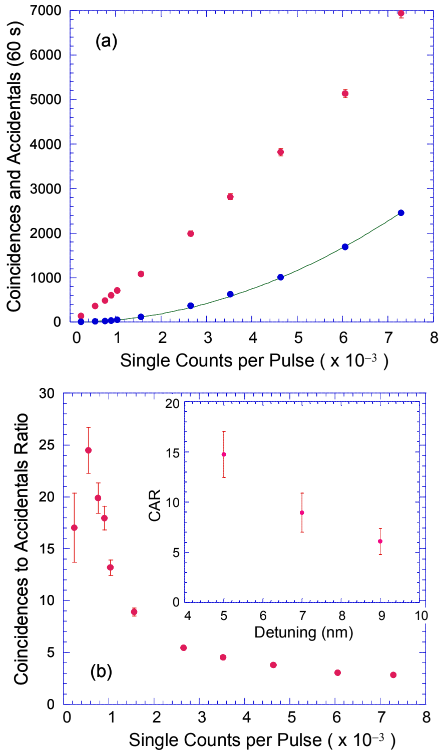

Figure 2: (a) Plots of total coincidences (red) and accidental coincidences (blue) versus single counts per pulse obtained as the pump power is increased. The latter plot fits very well to the expected quadratic dependence (solid line). (b) Plot of the ratio of coincidences to accidental coincidences (CAR) versus single counts per pulse. Inset in (b) is a plot of the CAR as a function of the detuning of the signal and idler filters from the pump wavelength.

Figure 2 presents the experimental photon-counting data showing how the coincidence-counting behaviour changes as the pump power is increased, in both the coincident time windows (coincidences) and the adjacent time windows (accidentals). The x-axis is expressed as the single counts per pulse (geometric average of the single counts in the signal and idler channels) and the contributions of the measured dark counts have been subtracted from the data. As shown in Fig. 2(a), both the coincidence rate and the accidentals rate grow as the power increases, but the coincidence rate shows a noticeably larger increase. In order to evaluate the degree of correlations in the generated light, we plot the coincidences-to-accidentals ratio (CAR). This is presented in Fig. 2(b) wherein we see that there is a rapid increase in the CAR to around 25 as the single-count rate increases to about 6×10^{-4}, corresponding to a photon-pair generation rate of $6 \times 10^{-4}/0.013$ = 0.05 in the waveguide. For larger single-count rates the CAR decreases. Interestingly, similar behaviour is observed in correlated-photon sources based on glass fibres[5]. The behaviour at low count rates, we presently believe, is caused by the increasing contribution of the detector dark counts, which cannot be reliably subtracted when the single-count rate becomes too low. Our recent measurements with superconducting single-photon detectors corroborate this hypothesis. The decrease in CAR for single-count rates greater than 0.001 is attributed to the increasing multi-photon scattering probability.

Measurements similar to those in Fig. 2 are also obtained when the polarizer in the free space path between the waveguide and the collection fibre is left out (see Fig. 1). In this case the measured CAR is slightly lower (about 17), suggesting that uncorrelated noise photons polarized orthogonally with respect to the pump are also produced. Since the FPS process is only phase matched for co-polarized pump, signal, and idler photons, the presence of noise in the other polarization suggests that there is another mechanism, such as SRS or some other process, which generates accidental counts.

The presence of excited energy levels and the dynamics of the generated carriers (electrons and holes) are important considerations when studying FPS in silicon waveguides. In order to gain further understanding into the source of the observed accidentals, we studied the CAR for different values of the pump to detection-filter separation. The data are plotted in the inset of Fig. 2(b) wherein one observes that the quality of the correlations decreases as the filters are tuned further from the pump. The CAR versus detuning data suggest that the source of noise photons does not arise from carrier dynamics, as it is unlikely that these mechanisms would have bandwidths exceeding a few hundred GHz.

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