Photon-pair generation in a heterogeneous silicon photonic chip

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Abstract: We perform photon-pair generation in a heterogenous multi-layer silicon photonic chip consisting of SiN_x and a-Si:H waveguides. Record high CAR value of 1632.6 (± 260.4) is achieved in a-Si:H waveguides from the heterogeneous design.

The rapid advancement of the field of silicon photonics has resulted in a growing density of optical components on an integrated photonic chip. The increase of components has coincided with an increase in functionality on a single chip. Each silicon photonic material platform comes with both strengths and weaknesses for any given function. By combining different materials through heterogeneous integration, the weaknesses of one material can be overcome by the strengths of another [1, 2].

Correlated photon-pair sources are of great interest due to their applications in quantum computing, quantum teleportation, and others [3]. The generation of correlated photons through spontaneous four-wave mixing (SFWM) requires a material platform that has both a high Kerr nonlinearity and low linear losses. Silicon nitride (SiN_x) is a common platform that has shown losses below 1 dB/m [4]. Although the nonlinearity of SiN_x is about 10 times larger than that of optical fibers [5], efficient spontaneous SFWM requires resonant structures which limit the speed and bandwidth of the photon-pair generation. Hydrogenated amorphous silicon (a-Si:H) has been shown to have the highest reported Kerr nonlinearity for silicon-based material platforms ($n_2 = 7.43 \pm 0.87\text{x}10^{-13}$ cm^2/W) [6]. This exceptionally high Kerr coefficient allows for highly efficient SFWM over only millimeters of waveguide propagation. Because the lowest reported a-Si:H linear propagation losses are about an order of magnitude higher than SiN_x [7], here we show a multi-layer heterogeneous platform of a-Si:H/SiN_x waveguides used as a photon-pair source that can benefit from both the low linear losses of SiN_x and high Kerr nonlinearity of a-Si:H.

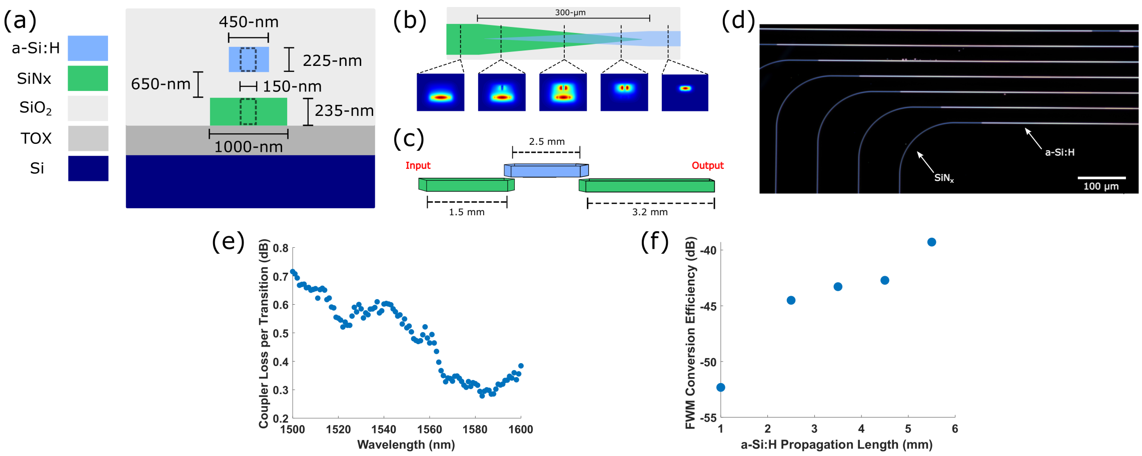

Fig. 1. (a) Cross-section of multi-layer platform. (b) Top-down view of evanescent interlayer coupler. (c) Side view of device showing propagation lengths in SiN_x (green) and a-Si:H (blue) waveguides. (d) Dark-field microscope image of SiN_x/a-Si:H waveguides and interlayer coupling region. (e) Interlayer coupler loss per wavelength. (f) FWM conversion efficiency for different propagation lengths of a-Si:H waveguides.

The layout of our multi-layer chip is shown in Figure 1 (a-d). Figure 1 (d) shows a dark-field microscope image of SiN_x and a-Si:H waveguides and interlayer coupling region. The fabrication process described in detail in [2]. We first perform classic degenerate FWM in our multi-layer devices. Light is coupled on/off chip via inverse taper couplers in the SiN_x layer as shown in Figure 1 (c). In addition to the low propagation losses that SiN_x offers, it also provides improved fiber-to-chip coupling efficiency compared to a-Si:H due to better mode-matching with optical fibers. After propagating for 1.5 mm in the SiN_x layer, on-chip light is coupled to the a-Si:H layer via evanescent inverse taper couplers and propagates for varying a-Si:H lengths between 1 mm and 5.5 mm. Light is then coupled back down to the SiN_x layer and propagates for 3.2 mm before being output via the SiN_x layer. We measure on-chip interlayer coupling losses of less than 1 dB per transition over a 100 nm bandwidth as shown in Figure 1 (e). Conversion efficiency is measured using multiple devices with varying propagation lengths in the

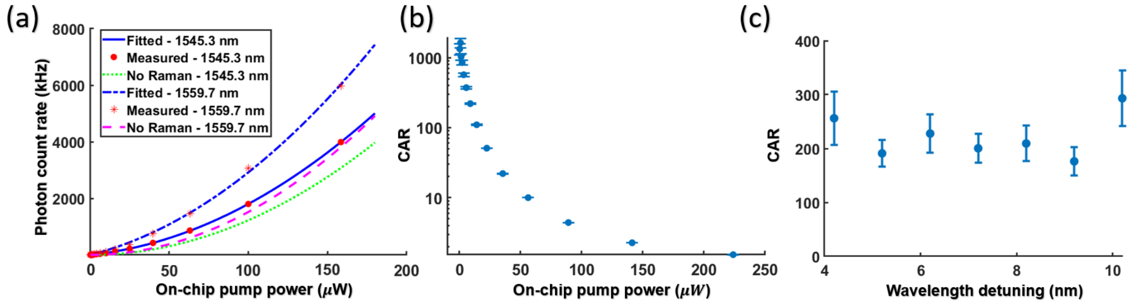

Fig. 2. (a) Single photon counts of Stokes and anti-Stokes channels versus the on-chip pump power. (b) CAR versus the on-chip pump power. (c) CAR measurement for multiple wavelength channels

a-Si:H layer. The results are shown in Figure 1 (d). The classic FWM results indicate a Kerr coefficient of ~ 5 x 10^{-13} cm^2/W, which is comparable to the state-of-the-art value [6].

The photon-pair source is generated through SFWM in the multi-layer device. The input pump at 1552.5 nm is selected using four cascaded wavelength division multiplexers (WDM) from a mode locked laser with a repetition rate of 50 MHz. The laser is then coupled to the SiN_x waveguide through a lensed fiber. After propagating in the SiN_x waveguide, light is coupled through an interlayer coupler to the 2.5 mm long a-Si:H waveguide where the photon-pair source is generated through SFWM. Light is then coupled back to a low-loss SiNx length and coupled off-chip. The generated photon-pairs are collected by the lensed fiber. The fiber-to-fiber transmission loss is ~9 dB. The generated photon-pairs are collected by the lensed fiber. Next, two WDMs are used to reject the remaining pump power. The Stokes and anti-Stokes photons are separately selected at 1545.2 nm and 1559.7 nm with 2 cascaded WDMs. The bandwidth for the WDM filters are aligned to be 200 GHz. The selected photon-pairs are finally sent into superconducting nanowire single photon detectors.

The stimulated Raman scattering (SRS) noise is first characterized by measuring the power-dependent single photon counts. In the waveguide, the SRS generated photons are linearly proportional to the on-chip pump power P_{in} while the SFWM generated photons are proportional to P_{in}^2. Therefore, SRS noise can be characterized at Stokes and anti-Stokes channels by fitting the curves as shown in figure 2 (a).

Figure 2 (b) shows the coincidence-to-accidental ratios (CAR) versus on-chip pump power. The dark count has been subtracted from coincidence and accidental counts to eliminate dark-count noise, which may significantly decrease CAR in the low count rate regime. The highest CAR is achieved at 1632.6 ($\pm$ 260.4) with on-chip pump power at about -30.5 dBm. The CAR then drops to 1335.3 ($\pm$ 240.9) when further lowering on-chip pump power. This is because the background noise contributes more to the result when the count rates of Stokes and anti-Stokes photons are closer to the dark-count level. Figure 2 (c) depicts CAR measurement for multi-channel photon-pairs. With on-chip pump power at -20.5 dBm, the CAR remains about 200 for the wavelength detuning from 4.2 nm to 10.2 nm. This showcases the wide bandwidth for photon-pair generation that can be dispersion engineered into these devices.

We experimentally demonstrate photon-pair generation with a record CAR of 1632.6 ($\pm$ 260.4) for non-resonant a-Si:H waveguides, which shows improvement compared to the single a-Si:H platform [8]. We also demonstrate multi-channel photon-pair sources with CAR around 200 across 10-nm bandwidth.

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