A new platform for integrated quantum optics: the short-wave infrared

(Student paper)
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ABSTRACT

Integrated silicon photonic circuits are a promising candidate for large scale quantum optics experiments. Parasitic nonlinear absorption at near-IR (NIR) can be reduced or entirely eliminated by translating to the short-wave infrared (SWIR) band ca. 2.1 μm. We measure superconducting nanowire single photon detector efficiency, low loss multi-mode waveguides with 0.21 dB/cm attenuation and nonlinear absorption induced by a picosecond pulsed laser to be $\alpha_2 = 0.475 \times 10^{-12}$ m/W - an order of magnitude less than in NIR single-mode waveguides. This work demonstrates the feasibility for large scale integrated quantum photonics.

Keywords: Integrated photonics, mid-infrared optics, quantum optics, nonlinear optics

1. INTRODUCTION

Devices based on the properties of quantum mechanics—superposition and entanglement—stand to revolutionise how we gather, transmit, and process information. From quantum sensors, which overcome the shot noise limit to achieve exquisite sensitivity, to quantum key distribution systems, which allow cryptographic keys to be shared with unconditional secrecy, to tremendously powerful quantum computers, with applications from pharmaceutical and material design to machine learning and cryptography, quantum technology promises improvements across science, engineering, and society at large.
For photonic quantum technology to flourish, high performance is required at unprecedented scale. Silicon quantum photonics [1] offers the scale, mature fabrication capability, and much of the performance needed, and has facilitated exciting proof-of-concept devices from integrated functionality [2], and complex on-chip quantum light sources [3], through to inter-chip Bell tests [4]. Silicon photonics, however, has strong limitations in terms of scattering and nonlinear absorption. Subwavelength roughness on etched high-index-contrast waveguide sidewalls is the dominant source of propagation loss in silicon waveguides. Despite their excellent confinement and strong nonlinearity, silicon waveguides also suffer from strong deleterious two-photon absorption (TPA) at 1.55 μm. Quantum correlated photon-pairs can be generated in silicon via the nonlinear process, spontaneous four-wave mixing (SFWM). TPA limits the input power for nonlinear effects, such as parametric gain and supercontinuum generation, but it also subtly limits SFWM. As pointed out by Husko and colleagues [5], cross-TPA causes a bright pump to stimulate loss on copropagating single-photon channels, fundamentally limiting efficiency.

The short-wave infrared (SWIR) wavelength band, around 2.1 μm, mitigates side-wall scattering and nearly eliminates TPA, and greatly enhances silicon's dispersive nonlinearity (see Fig. 1a). Manufacturability is improved, bringing some subwavelength structures within reach of optical lithography, and free-carrier effects (attenuation, modulation) are enhanced.
With the manufacturing challenge of new TPA-free and lower-nonlinearity materials behind us, we must focus on the optical challenges presented by this new SWIR band.

2. RESULTS

The SWIR presents a number of opportunities, in addition to the suppression of TPA. We will discuss these, as well as the challenges, and outline our progress to date in exploiting this new band for SiQP. We will discuss the design and technical challenges of devices; show results on new passive structures, including waveguide couplers and delay lines; report on our progress towards generating and collecting photon pairs in the mid-IR; and finally outline our development of integrated SWIR-optimised single-photon detectors.

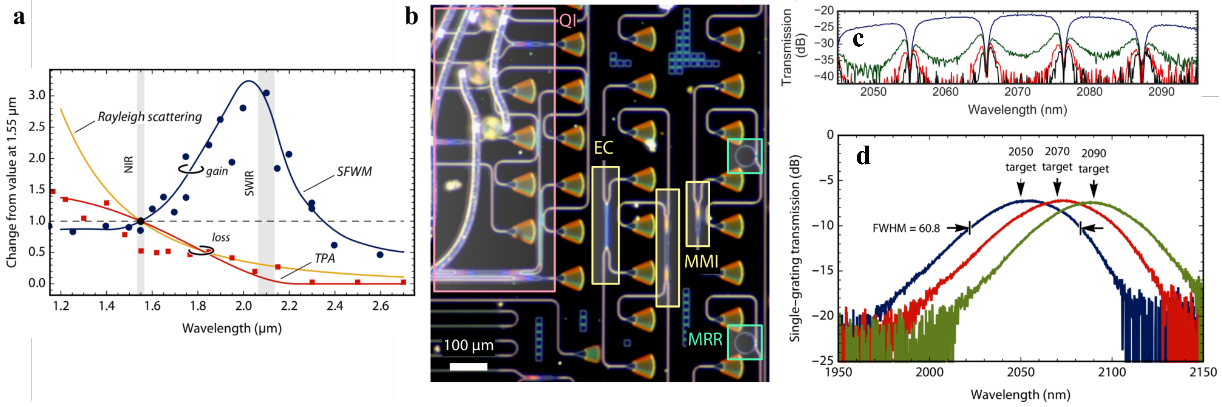

Figure 1a. *Linear, nonlinear loss and gain change in value from 1.55 µm.* ***b.*** *Micrograph of fabricated SWIR SiQP structures.* ***c.*** *Through port transmission spectra of a four stage cascaded racetrack filter.* ***d.*** *Measured single grating coupler transmission spectra.*

Linear loss contributions arise from waveguide wall roughness produced in during fabrication. A way to reduce this is to adiabatically taper between single-mode bends to less confined multi-mode waveguide straight sections, thereby reducing the overlap between the propagating light and the sidewalls. On a 220-nm top-silicon die, we design and fabricate strip waveguides in square spirals with single- and multi-mode bent and straight sections with 650 nm and 1500 nm widths, respectively. Figure 2b shows a cutback measurement of these waveguide spirals, probed with a narrow CW inter-subband quantum cascade laser (QCL) (Eblana Photonics) centred on 2.049 µm. Using linear regression fitting, we estimate the loss and standard error of the fit to be 0.21 ± 0.02 dB/cm with an insertion loss of 7.97 dB per grating.

To investigate the nonlinear response of the multi-mode waveguides spirals, we pump with a Thulium-Holmium doped fibre laser with a central wavelength of 2.07 µm, temporal width of 3 ps and peak power >10 kW. By varying the optical power launched into the waveguide and measuring the output on a InGaAs photodiode (PD), we use a nonlinear fit that accounts for linear loss, free carrier effects and TPA to estimate that the nonlinear absorption coefficient shown in Fig. 2a. The SWIR measurement of α_2 = 0.048 cm/GW is an order of magnitude lower than the measured NIR value, α_2 = 0.37 cm/GW, and much lower than the ~1 cm/GW reported elsewhere in the literature [6,7]. These comparison measurements were made in a single-mode waveguide spiral (cross-sectional area 500 × 220 nm^2) with a picosecond-pulsed laser operating at 1.55 µm. With the pulsed SWIR fibre laser, we compare the input and output pulses on an optical spectrum analyser (OSA) (Yokogawa AQ6375) and probe the nonlinear response of the longest (11.6 cm) square spiral to find ~3π self-phase accumulated during propagation through the waveguide.

To observe correlated photon pairs produced from SFWM that are co-propagating with a bright pump laser, measures to reject the pump are required. We demonstrate an on-chip filter using four cascaded racetrack resonators with the drop port of ring *i* connected to the input of the ring (*i*+1). We design these racetracks with a cavity length of 100 µm, corresponding to an experimentally measured group index n_g = 3.965 and FSR = 756.1 GHz. Characterisation of the device was performed with a supercontinuum source (NKT SuperK-Compact) and OSA the through port spectra is shown in Fig. 1c. Each ring in the filter provides up to 15 dB of extinction between the through and drop ports, giving us a maximum of 60 dB pump suppression - sufficient for observing single photons with additional off-chip bulk filtering.

Superconducting nanowire single photon detectors (SNSPDs) in the NIR are now capable of detection efficiencies around 90%. Single photon detection in the SWIR band is more challenging due to the lower photon energy. We take measurements of NIR SNSPD efficiency with an attenuated CW QCL laser with a central linewidth of 2.049 µm. By first measuring the transmission of several neutral density filters (NDFs) with the QCL, and separately the optical power transmitted from a knife-edge variable optical attenuator on an InGaAs PD, the laser beam is attenuated with the NDFs down to a regime where the SNSPDs are not latched and triggering events have photon arrival times much less than the dead time of the detectors.

The efficiency is estimated by fitting the incident photon to output photon fluxes. We find the best performance of a commercial NIR SNSPD to be up to 6% efficient with the mid-infrared fibre loops filters removed. To push the SWIR as a platform for quantum photonics, far higher detection efficiencies are desirable. Finite-difference time-domain (FDTD) and finite-difference eigenmode simulation results for WSi nanowires are shown in Fig. 2e and Fig. 2c and d respectively, showing the expected the absorption of light in SNSPD nanowire regions.

Development of superconducting WSi films on silicon waveguides are milestones for moving towards full integration of optical circuits, control electronics and detection on the same chip.

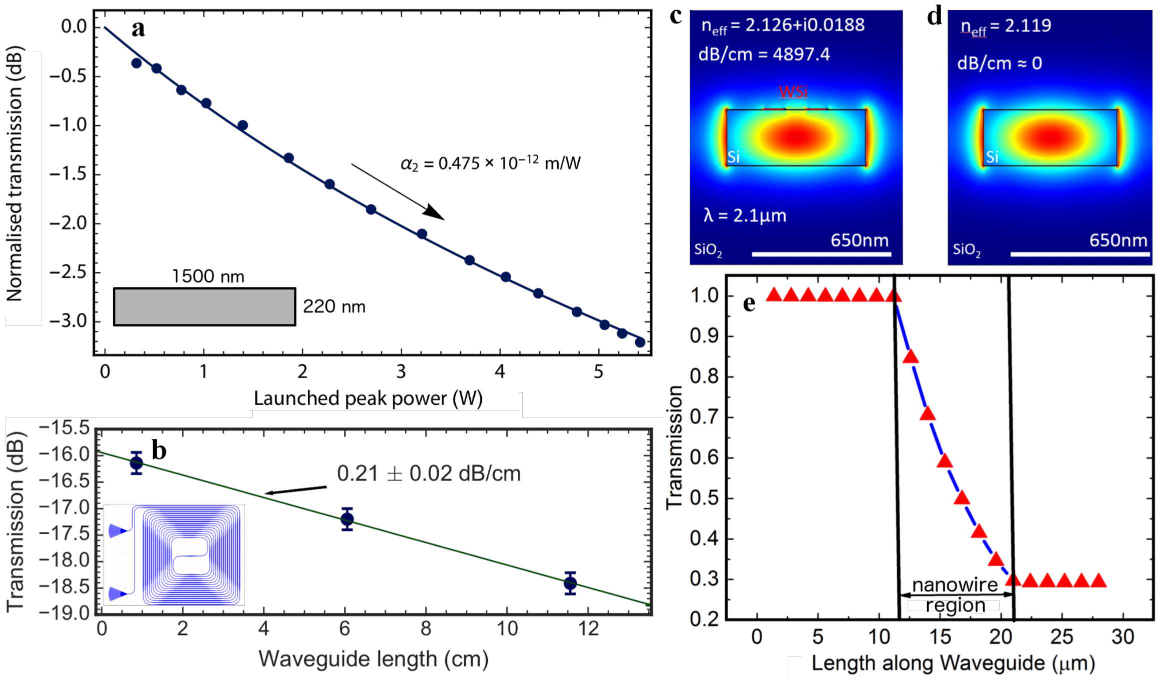

Figure 2a. *Measurement of the TPA coefficient α_2 in the SWIR band **b.** Cutback measurement of the propagation loss for multi-mode waveguides. **c.** FDE simulation of the electric field intensity for SWIR waveguides with 4nm thick WSi nanowires **d.** FDE simulation without WSi at a wavelength of 2.1 μm. **e.** FDTD simulations of a waveguide with a 10 μm WSi nanowire showing 70% absorption in this region.*

3. CONCLUSIONS

In summary, we have demonstrated the earliest stages of a new technology platform for integrated quantum photonics. First-generation designs of many passive structures perform well, with some showing state-of-the-art performance (e.g. propagation loss). Much remains to be done, however, and the next steps will be to robustly demonstrate photon-pair generation, while simultaneously improving our fibre- and chip-coupled single-photon detection capability.

This work opens the door to a new, fundamentally scalable quantum photonic technology platform, on which useful quantum devices can finally be realised.

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