An Integrated Silicon Photonic Nonlinear Interferometer

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ABSTRACT

We construct a nonlinear interferometer on a silicon photonic chip, where interference occurs between the production of photon pairs generated from two different spontaneous four-wave mixing waveguide sources. Nonlinear interferometers have demonstrated an improvement in measurement sensitivity beyond the shot-noise limit and offer the ability to sense and detect using light at different wavelengths. This demonstration of nonlinear interferometry on a silicon photonic chip establishes this important technology in a scalable and manufacturable chip-scale platform for the first time.

Keywords: Optical interferometry, Silicon photonics, Nonlinear optical devices

1 INTRODUCTION

Interferometric measurement of an unknown phase is of fundamental technological significance and has been the focus of much research in both the classical and quantum photonic communities. The sensitivity of a classical interferometer is fundamentally limited by the discrete photonic nature of light, leading to shot-noise limited sensitivity often called the *Standard Quantum Limit* (SQL). Several techniques have been proposed to increase the sensitivity of interferometers beyond the SQL, most noteably, by reducing the noise of the measured signal using squeezed states of light [1] and by increasing the resolution of the measurement using photon-number entangled states [2]. An alternative approach aims to increase the measured signal strength, while leaving the noise level unchanged, by replacing the beamsplitters of a conventional interferometer with parametric amplifiers [3]. This approach, referred to as a *Nonlinear Interferometer* (NLI) also finds application in the classical photonics community, due to the ability to perform phase measurement and signal detection using different wavelenghts of light [4].

Here we construct an on-chip nonlinear interferometer, composed of two spiral-waveguide photon-pair sources [6] ($1.4\,\mathrm{cm}$ long) which are pumped by a continuous-wave laser at $1544.5\,\mathrm{nm}$. The relative phase and intensity of each pump field can be controlled using the on-chip Mach-Zehnder Interferometer (MZI) and pump thermal phase-shifter. Pump 1 is demultiplexed from the photon pairs generated in source 1 by the on-chip filter (AMZI-1) and pump 2 is multiplexed into the input of source 2 by the filter AMZI-2. By adjusting the relative phase and brightness of each pump, a frustration of the photon pair generation process [5] can be demonstrated. Filtering and detection of the output photon flux is performed off-chip using two cascaded commerically available Dense Wavelength Division Multiplexers (Opneti) and superconducting nanowire single-photon detectors (Photon Spot).

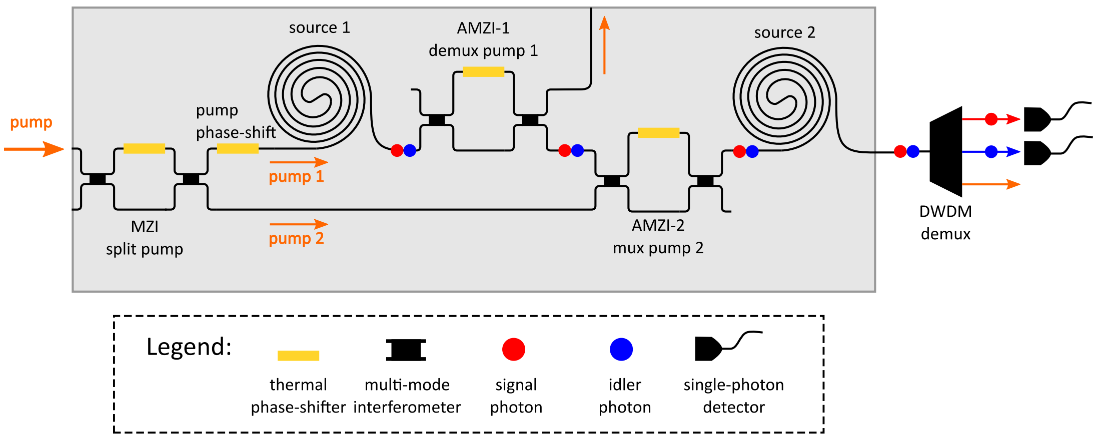

Figure 1. Layout of the on-chip nonlinear interferometer. Interference occurs between photon-pairs generated in source 1 and source 2, which are pumped by a continuous-wave laser with a controllable relative intensity and phase between each source. Single photon-detection occurs off-chip using superconducting nanowire single photon-detectors (PhotonSpot Inc).

2 RESULTS AND ANALYSIS

At the output of the NLI the state of the signal and idler modes is given by the concatenation of the two photon-pair generation processes [7], performed by source 1 and 2 with independent pumps:

$$|\psi_{\text{out}}\rangle = \left(\mathbb{1} + i\gamma P_2 e^{2i\Delta\phi_p} \int dz \int dt e^{i\Delta\beta z} \hat{A}_i^\dagger(z,t)\hat{A}_s^\dagger(z,t) + \cdots\right) \times \quad (1)$$

$$\left(\mathbb{1} + i\eta\gamma P_1 \int dz \int dt e^{i\Delta\beta z} \hat{A}_i^\dagger(z,t)\hat{A}_s^\dagger(z,t) + \cdots\right) |\text{vac}\rangle, \quad (2)$$

where γ is the waveguide nonlinearity parameter, P_n is the power of pump n, $\Delta\phi_p$ is the phase of pump 2 relative to pump 1, $\Delta\beta = 2\beta_p - \beta_s - \beta_i$ is the phase-matching term, $\hat{A}_{s|i}^\dagger$ are the creation operators acting on the signal and idler modes and η is the intermediate loss between sources 1 and 2. The spatial integrals are taken over the length of each source ($\{0, \text{L}\}$ for source 1 and $\{z_0, z_0 + L\}$ for source 2) and the temporal integrals extend over $t \in \{-\infty, \infty\}$. If we neglect events in which more than one photon-pair is generated in either source and we find the coincidence count rate between the signal and idler modes is,

$$\Gamma = \gamma^2 L^2 (\eta^2 P_1^2 + P_2^2) \,\text{sinc}^2 (\Delta\beta_0 L/2) \left\{1 + \left(\frac{2R}{1+R^2}\right)\cos[2\Delta\phi_p - \theta_0]\right\}, \quad (3)$$

where $R^2 = (\eta P_1/P_2)^2$ is the ratio of the probability of detecting a photon pair generated in source 1 over source 2 and $\theta_0 = \Delta\beta z_0$ is a constant in our experiment. We note that the fringe visbility is given by $V = (\Gamma^{\max} - \Gamma^{\min})/(\Gamma^{\max} + \Gamma^{\min}) = 2R/(1 + R^2)$. By adjust the pump powers such that the probability of detecting a photon pair from source 1 and 2 are equal ($R = 1$) we observe a maximum two-photon fringe visibility of $96.8\,\%$. We attribute the non-ideal fringe visibility to variations of the chip temperature, which result in fluctuations of the relative phase of both source pump fields.

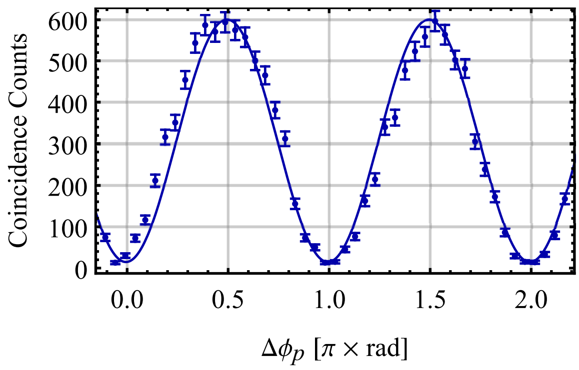

Figure 2. Coincidence counts (3 s integration time) as a function of the relative pump phase $\Delta\phi_p$.

3 CONCLUSIONS

We have constructed an nonlinear interferometer integrated on a silicon photonic chip for the first time. By adjusting the relative pump phase between each source we demonstrate frustrated photon-pair generation between both sources [5], with a maximum visibility of $96.8\,\%$, which we believe is limited by small (<2 mK) fluctuations in chip temperature. Nonlinear inteferometry has been proposed as means of increasing the sensitivity of quantum-enhanced sensors and of separating the sensing and detection wavelength of classical and quantum devices. We believe our demonstration of on-chip interferometry is an important step in bringing this highly applicable technology to the commerically and technologically promising silicon photonics platform.

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