Abstract—Entangled photonic states known as “NOON” states are manipulated within monolithic waveguide circuitry. The resulting quantum interference has sufficient visibility to measure phase beyond the shot noise limit using integrated waveguide. We also demonstrate a scheme for heralding two- and four-photon entangled states which can be generalized to arbitrarily large NOON states.

Keywords-component; quantum metrology; integrated waveguides; single photons

I. INTRODUCTION

Harnessing quantum superposition and quantum entanglement of single photon is already providing enhanced security with quantum cryptography [1] and is one of the leading platforms for other technologies derived from quantum information science, including quantum computation [2], quantum lithography [3] and quantum metrology [4].

In each of these technologies, quantum mechanics offers additional improvement over what can be achieved by applying classical physics alone. Quantum metrology uses large superposition states of photons, entangled in number and one other type of (typically path or polarization), known as “NOON” states. Related to so-called “Schrödinger cat states”, NOON states of photon number \( N \) are mathematically defined by

\[
|N\otimes 0\rangle = \frac{1}{\sqrt{2}} \left(|N\rangle_a |0\rangle_b + |0\rangle_a |N\rangle_b\right)
\]

where \( |n\rangle \) represents the Fock state of \( n \) photons populating a mode labeled \( j \). These states have an increased sensitivity to relative phase relative to un-entangled light, allowing a precision in phase measurement towards the Heisenberg limit (HL) \( \Delta \phi \sim 1/N \), beyond the classical shot noise limit (SHL) of \( \Delta \phi \sim 1/\sqrt{N} [4] \).

Previous experiments to demonstrate the increased resolution in phase sensitivity gained by NOON states have been demonstrated using bulk optics by encoding the quantum states in polarization and path (for example [5] and [6])

This work was supported by IARPA, EPSRC, QIP IRC and the Leverhulme Trust

II. MANIPULATING NOON STATES

A. Method

The waveguide circuit for manipulating path entanglement is a Mach-Zehnder interferometer with lithographically patterned thermal resistor to control the internal phase as shown in figure 1. The 3.5\( \mu \)m core waveguides are lithographically patterned from doped Silica fabricated on a Silicon substrate using standard methods and are designed for single mode operation in the 780nm region. On applying a voltage across the thermal resistor, the relative optical phase of quantum states guided through the interferometer is varied in a stable, controlled manner.

Multi photon states of two- and four-photons are produced by pumping spontaneous parametric down conversion (SPDC). A Ti:sapphire pulsed laser (157fs) laser is tuned to 780nm and upconverted to 390nm via second harmonic generation in a 2mm thick nonlinear Bismuth Borate \( \text{BiB}_2\text{O}_6 \) (BiBO) crystal. This is then focused onto a second BiBO crystal cut for non-collinear down-conversion to produce pairs of signal and idler photons with wavelength 780nm. The pairs are filtered spectrally using high transmission interference filters and spatially into two modes by focusing onto polarization maintaining fibres (PMF). The photons are injected into the chip using butt-coupled arrays of PMF pitched to match those of the waveguide. Coincidental events are then detected using

![Figure 1: An integrated waveguide Mach-Zehnder interferometer used to manipulate entangled states of light using a resistive heater (labeled \( \square \)).](image)
commercially available silicon avalanche photo diode single photon counting modules (SPCM).

B. Results

Figure 1A displays the single photon interference fringe obtained on inputting single photons into mode \(a\) and detecting them independently at modes \(g\) and \(h\) with respect to variation of phase inside the interferometer. While this interference pattern is equivalent to the pattern observed from inputting classical light, the contrast of 0.98\(\pm\)0.003 indicates an average fidelity of 0.99984\(\pm\)0.00004 for manipulating single bits of quantum information (qubits) encoded across two spatial modes—the natural encoding for integrated waveguide circuitry[cite integrated quantum circuits].

On inputting two coherent identical photons on inputs \(a\) and \(b\) deterministically yields a two photon NOON state; varying the phase of the device by \(\square\) causes the two photon NOON state to be shifted in phase by \(\bigtriangleup\). On post selecting two photon coincidences across the outputs of \(g\) and \(h\) allows an interference pattern of twice the resolution of the single photon case to be observed. The fringe given in figure 2B has a contrast of 0.972\(\pm\)0.004, sufficient to beat the standard quantum limit (assuming high efficiency detectors and photon sources).

Producing four photon NOON states is not so straightforward as the two photon case and cannot be achieved by using non-classical interference of Fock states alone. To observe a four-fold interference fringe, we use a method to post select the presence of a four photon NOON state inside the interferometer, hence allowing the observation of a four-photon interference fringe with four times the resolution of the single photon case [6]. The plot given in figure 2C has a contrast of 0.92\(\pm\)0.04, which despite the detection scheme required to post select the four photon NOON state, is sufficient to beat the standard quantum limit (again, assuming high efficiency detectors and photon sources).

III. HERALDING NOON STATES

The generation of large photon number NOON states is unlikely to be achieved by using non-classical interference alone. It has been theoretically proposed [8] that using linear optics and projective measurements, large photon number NOON states can be constructed from Fock states. Demonstrate this experimentally in waveguide circuit designed to herald the presence of two- and four-photon NOON states with, in principle, perfect fidelity. This requires two extra ancillary photons for each case. Using projective measurements in this manner can also be generalized to yield arbitrarily large NOON states [9].

IV. CONCLUDING REMARKS

The inherent stability and near perfect mode-overlap of lithographic waveguide architecture is ideal for the application to quantum metrology. They have already been demonstrated to yield high levels of non-classical interference for components for quantum computation [10,11,12], and the results presented here highlight their potential for quantum metrology realized in an integrated optics platform.

ACKNOWLEDGMENT

We thank A. Laing, T. Nagata, S. Takeuchi, X. Q. Zhou, J. P. Hadden, A. Lynch and J. G. Rarity for helpful discussion.

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