A single non-linear directional coupler to generate N00N states

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Integrated optical devices have become important tools to generate photonic states useful for quantum information and computation tasks. The majority of the work has focussed on linear, passive devices where the process of state generation and manipulation are separate, which leads to losses when the two have to be combined.

Recently, several groups have investigated optical chips that also have a nonlinear process that allows for parametric down-conversion to occur within the chip itself, thereby combining state generation and manipulation. In our work, [1], we present such a device to generate a two-photon NOON state, a highly entangled state that has significant uses in quantum metrology and measurement protocols. Our system is directional coupler (two coupled waveguides) which is periodically poled and we illuminate one waveguide with a pump laser, as shown in Fig. 1.

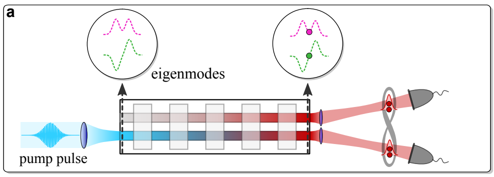

FIG. 1. Two coupled waveguides, one pumped by an external laser. When the pump frequency is tuned correctly a two-photon NOON state is created at the output.

The Hamiltonian of the system can be written as,

$$\hat{H} = \omega \sum_{j=1,2} \hat{a}_j^\dagger \hat{a}_j + C\, \hat{a}_1^\dagger \hat{a}_2 + \Gamma_p \hat{a}_1^{\dagger 2} e^{-i\omega_p t} + \text{h.c.}$$

The linear part of this Hamiltonian can be diagonalised to $\sum_\pm \Omega_\pm \hat{A}_\pm^\dagger \hat{A}_\pm$ with $\Omega_\pm = \omega \pm 2C$, with the transformation to the eigenmodes given by $\hat{A}_\pm = \frac{1}{\sqrt{2}}(\hat{a}_1 \pm \hat{a}_2)$. The down-conversion term can now be written as combinations of $\hat{A}_\pm^{\dagger 2}$ & $\hat{A}_+^\dagger \hat{A}_-^\dagger$. We can now choose the pump frequency, ω_p, to phase-match the latter term and, in the two-photon limit, we create the state $\hat{A}_+^\dagger \hat{A}_-^\dagger$ to a good approximation at the output of the waveguide system. When we transform back to the physical basis, using the inverse of the transform above, we obtain the state,

$$|\phi\rangle = \frac{1}{\sqrt{2}} \left(\hat{a}_1^{\dagger 2} - \hat{a}_2^{\dagger 2} \right) |0\rangle.$$

This transformation, from the eigenmodes to the physical modes, can be viewed as equivalent to the Hong-Ou-Mandel effect, even though the state never passes through a beam-splitter.

The experiment was performed and we were able to show the presence of such a NOON state. First, we determined the ideal point to phase-match at by varying the pump frequency and obtained a state fidelity of 84%. We then tested the coherence properties of the state by interfering the two output modes through an interferometer and successfully measured the double fringe pattern of a two-photon NOON state (Fig. 2b, red line). These results are shown in Fig. 2.

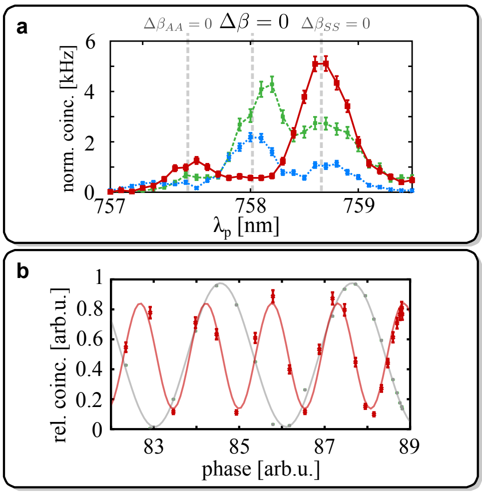

FIG. 2. Experimental results. a) By varying the pump frequency we can determine the optimum phase-matching point. The blue and green lines show two-photon rates in single waveguides and the red line shows the coincidence between waveguides. b) Directing the output state through an interferometer we can demonstrate the double interference fringe of the NOON state (red line) compared to classical light (grey line).

[1] R. Kruse et al., arXiv: 1412.0448 (2014)