Effective $\chi^{(2)}$ in a Rb-Filled Hollow-Core Photonic Bandgap Fiber for Coherent Photon Conversion

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Abstract: We demonstrate a large effective $\chi^{(2)}$ in a rubidium-filled photonic bandgap fiber by an spontaneous parametric down conversion process. This system can be used for the coherent photon conversion scheme in quantum information processing.
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The nonlinear process of coherent photon conversion (CPC) [1] offers a path to realizing a strong interaction between individual photons, a long standing goal for photonic quantum information processing. Variations of the CPC process can offer solutions for efficient photon sources, deterministic photon gates, and highly efficient photon detection. The key to efficient CPC is to have a large effective $\chi^{(2)}$ nonlinearity, which can be achieved in a $\chi^{(3)}$ medium by pumping one of the optical modes with a strong classical field. Such an effective $\chi^{(2)}$ can potentially exceed the $\chi^{(2)}$ of a conventional non-centrosymmetric material. Additionally, unlike most $\chi^{(2)}$ materials, $\chi^{(3)}$ platforms are far more readily available in micro- and nano-structures which provides extra enhancement to a nonlinear process. This effective $\chi^{(2)}$ is demonstrated in various bulk $\chi^{(3)}$ materials including photonic crystal fibers [1], chalcogenide nanofibers [2], silicon nitride [3], and silicon [4] and we have previously demonstrated this effective $\chi^{(2)}$ in a rubidium vapor cell [5]. If the latter system could be extended to a Rubidium-filled hollow core photonic bandgap fiber (PBGF) system with its strong field confinement, large atomic density, and long interaction lengths, then it would be possible to achieve even larger effective $\chi^{(2)}$ nonlinearity. This Rb-fiber platform has been used to develop quantum memory [6] and phase gates [7].

In this work, we demonstrate this large effective $\chi^{(2)}$ in our Rb-PBGF system by showing the analogous process of spontaneous parametric down conversion (SPDC) as seen in a $\chi^{(2)}$ material.

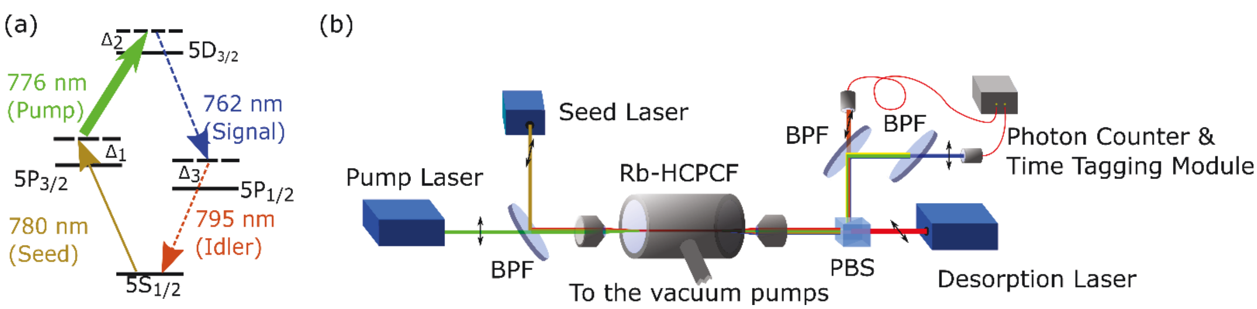

Fig. 1. (a) Level scheme for the effective SPDC process. (b) Experiment setup. BPF: bandpass filter, PBS: polarizing beam splitter.

In SPDC, one input photon is split into two lower frequency photons fulfilling energy conservation. A similar process in a $\chi^{(3)}$ material is spontaneous four wave mixing (SFWM) as shown in Fig 1(a). According to the original proposal of CPC, we can also regard this process as an effective $\chi^{(2)}$ process when one pump (776 nm) is much stronger than the other (780 nm) and the $\chi^{(2)}$ is provided by the $\chi^{(3)}$ of rubidium and the strong pump field. With its annihilation, one seed photon at 780 nm is then able to generate two photons at 762 nm (signal) and 795 nm (idler). The photon statistics from this effective SPDC process closely resemble that of an actual SPDC process.

In our experiment we use a 10-cm-long PBGF with a mode field diameter of 6 μm. It is placed in an ultra-high vacuum chamber as described in [8,9]. A long lasting OD of 30 is generated by light-induced desorption with a laser at 806 nm. In this experiment, the desorption power is set at 30 mW. The strong pump and the seed are red detuned from the 85Rb $5P_{3/2}\ F' = 2 \rightarrow 5D_{3/2}\ F'' = 2$ and blue detuned from the $5S_{1/2}\ F = 2 \rightarrow 5P_{3/2}\ F' = 2$ transitions by 1.4 GHz and 1.1 GHz respectively. The two lasers are combined by a bandpass filter and copropagate into the PBGF [Fig 1(b)]. Both the pump and the seed field are set to be vertically polarized while the desorption field is horizontally polarized. A polarizing beam splitter is used to separate the output interaction fields from the input desorption field, resulting in only the vertically polarized photons being measured. The signal and idler photons are selected with corresponding narrow linewidth (3 nm) bandpass filters and coupled into single mode fibers. The characterization is performed with single photon counters and a time tagging module. The total loss on each detection arm is 17 dB which includes filtering, coupling and detection.

We first study the generated photons by measuring the second order cross correlation function $g_{si}^{(2)}(\tau)$ as shown in Fig 2(a). The measured $g_{si}^{(2)}(0)$ is larger than 2 which is a feature of nonclassical light. The Gaussian shape of the $g_{si}^{(2)}(\tau)$ is a result of the time jitter of the photon counters rather than a result of the joint spectrum of the photons. Similar to SPDC, the individual signal and idler photons are expected to have thermal statistics, which is shown by an autocorrelation measurement of the idler photons $g_{ii}^{(2)}(\tau)$ (Fig 2(b)). A pure thermal state would have $g_{ii}^{(2)}(0) = 2$. We attribute the presence of noise photons for the smaller than expected $g_{ii}^{(2)}(0)$.

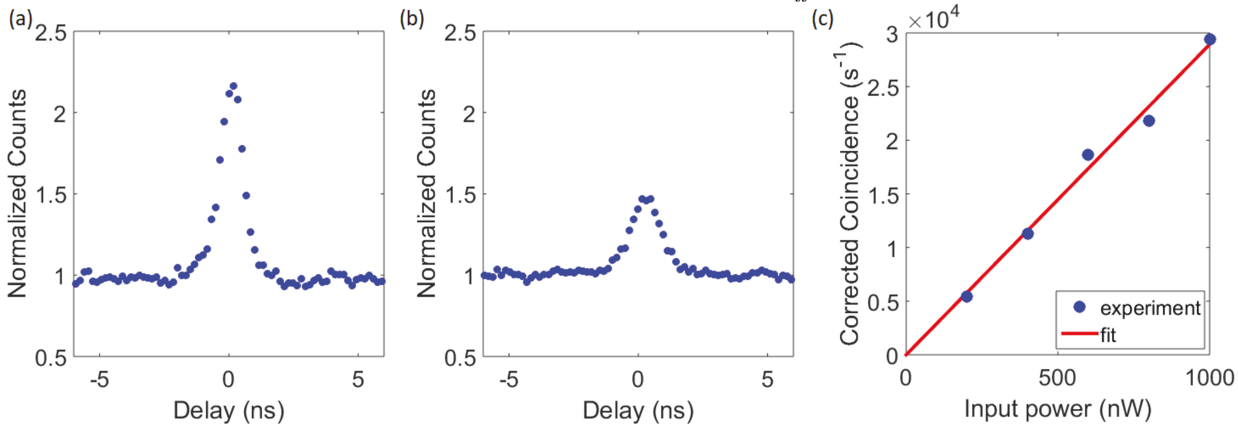

Fig. 2. (a) Crosscorrelation between the signal and the idler. (b) Autocorrelation of the signal. (c) Scaling of photon pair generation rate versus seed power.

We repeat the experiment with various seed powers while maintaining the pump power at 25 mW to study the efficiency of the effective SPDC process. At each seed power level, we sum up the coincidence events within the ± 1 ns window near zero delay and then infer the ideal lossless coincidence rate according to the detection efficiency mentioned above. The result is shown in Fig 2(c), and as expected, the photon pair generation rate is proportional to the seed power. The efficiency is calculated to be on the order of 5×10^{-7} W^{-1}, where the dimension is pairs per input seed photon per watt pump power. As a comparison, Langford *et al.* achieved an efficiency of $\sim 10^{-11}$ W^{-1} (peak power) in a photonic crystal fiber [1] and Donvalkar *et al.* achieved $\sim 6 \times 10^{-11}$ W^{-1} in a rubidium vapor cell [5]. This nonlinearity is comparable to that in a silicon nitride microresonator platform [3] where an effective second harmonic process is demonstrated.

The low signal to noise ratio of $g_{si}^{(2)}(\tau)$ is due to the inelastically scattered photons from the far detuned strong desorption laser. A similar effect is also seen in far-off-resonance atom trapping [10]. This noise issue can be solved by using a pulsed desorption laser. As the Rb density decays very slowly when the desorption laser is absent, the desired process can be timed to occur between the desorption pulses without losing efficiency.

In conclusion, we demonstrated a large effective second order nonlinearity in a Rb-PBGF system by showing an effective SPDC process. With a pump power 5 orders smaller, we observe an efficiency comparable to that in a photonic crystal fiber. The efficiency can be further boosted by increasing the optical density with a higher desorption power, or by using a stronger pump than what was available in the current experiment.

[1] N. K. Langford, S. Ramelow, R. Prevedel, W. J. Munro, G. J. Milburn, and A. Zeilinger, Nature **478,** 360 (2011).
[2] A. Dot, E. Meyer-Scott, R. Ahmad, M. Rochette, and T. Jennewein, Phys. Rev. A **90**, 043808 (2014).
[3] A. Farsi, S. Ramelow, S. Clemmen, X. Ji, M. Lipson, and A. L. Gaeta, *Conference on Lasers and Electro-Optics*, paper FTu3D.5 (2017).
[4] E.Timurdogan, C. V. Poulton, M. J. Byrd, and M. R. Watts, Nature Photonics, **11**, 200 (2017).
[5] P. Donvalkar, C. Joshi, S. Ramelow, and A. L. Gaeta, *Conference on Lasers and Electro-Optics*, paper FTu1C.7 (2016).
[6] M.R .Sprague, *et al*, Nature Photonics **8,** 91 (2014).
[7] V. Venkataraman, S. Kasturi, and A. L. Gaeta. Nature Photonics **7,** 138 (2013).
[8] A. D. Slepkov, A. R. Bhagwat, V. Venkataraman, P. Londero, and A. L. Gaeta, Phys. Rev. A **81**, 053825 (2010).
[9] P. S. Donvalkar, S. Ramelow, S. Clemmen, and A. L. Gaeta, Opt. Lett. **40**, 5379 (2015).
[10] D. Miller, R. A. Cline, and D. J. Heinzen, Phys. Rev. A 47, R4567(R) (1993)