WD2.5 (Contributed)
11:45 – 12:00

Low-Noise Frequency Downconversion for Long-Distance Distribution of Entangled Atomic Qubits

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Distribution of quantum resources such as entanglement over distances beyond a few fiber attenuation lengths requires realization of quantum repeaters that utilize entanglement swapping to extend the distance between the entangled qubit pairs [1]. A quantum repeater is a small quantum computer capable of generating entangled qubit pairs with its neighboring repeaters and storing them in stable quantum memories. Once the entangled pairs are generated, it will perform Bell basis measurements, classical communication with appropriate repeaters, and single qubit gates necessary for entanglement swapping. For high fidelity operation, it might perform local operations and classical communications (LOCC) such as entanglement distillation [2] and/or quantum error correction [3,4]. Generation of remote entangled ion pairs mediated by photonic qubits has been demonstrated [5] but their reach is limited since the photons used in the experiment are in the UV part of the spectrum. Coherent conversion of the photons emitted by Yb ion at 369.5nm to a photon at 1310 nm would enable entanglement generation over long distances [6].

We adopt a cascade of second-order nonlinear processes (difference frequency generation, DFG) to convert 369.5nm input photon to an intermediate photon at 708 nm, and then to a 1310 nm photon with pump field generated from a 1544nm laser. This scheme reduces the possibility of background Raman and downconversion processes that add noise photons at the target wavelength [7]. The first stage is designed to convert the 369.5nm photon to a 708nm photon using a 772 nm pump beam, and the second stage will convert the 708 nm photon to the final 1310nm photon with a 1544 nm pump beam. Here we report the successful first-stage conversion of the 369.5nm photon to 708nm with low background noise.

Figure 1a shows the experimental setup. The output of a narrow linewidth laser at 1544nm is amplified by a 5W erbium doped fiber amplifier to generate the pump beam. This is frequency-doubled to generate 772 nm pump beam (with up to 325mW of pump power) using a single-pass second harmonic generation (SHG) setup with magnesium oxide doped periodically poled lithium niobate (MgO:PPLN) crystal. In the current experiment, 369.5nm photons emitted by a $^{171}Yb^+$ ion is replaced by an attenuated 369.5nm laser frequency-stabilized to the Yb ion transition. The pump beam and the signal photons are fed into another MgO:PPLN crystal for the DFG process. Since the 369.5nm photon experiences a large dispersion in the lithium niobate crystal, the poling period of the PPLN crystal required to satisfy the quasi-phase matching condition for the DFG process (1.84μm) cannot be obtained using commercially available technologies. We used a 3rd order poling period of 5.52μm, which reduces the efficiency of the DFG process by a factor of 9. The generated 708nm photons are spectrally separated by a narrow bandpass filter (Semrock, 6.8nm) and detected using either a photon-counting detector or a power meter.

Figure 1b shows the (normalized) converted power at 708nm as a function of crystal temperature, tracing the tuning curve for the DFG process. Plane wave theory predicts a symmetric curve (solid blue line), but our beam is focused at the center of the crystal and should feature an asymmetric one due to the phase matching constraints (dotted blue line). Actual experimental data (red dots) features a tuning curve slightly broader than the predicted one. Figure 1d shows the overall conversion efficiency as a function of the pump power at 708nm. The low conversion efficiency is due to third-order phase matching in the crystal and limited availability of the pump power. We expect ~100% conversion with ~20W of pump power. We achieve conversion efficiency that is about 70% of the predicted value, due to the duty cycle and periodicity errors in the PPLN crystal that lead to fluctuation in the phase matching condition.

Since the pump wavelength is chosen to be longer than both the input signal (369.5nm) and generated idler (708nm) channels, the background noise at the idler channel is mostly contributed by the anti-Stokes Raman scattering of the strong pump laser as the Stokes Raman and spontaneous parametric processes cannot contribute photons in this band. Figure 1c shows the measured background photon counts (in the absence of the input signal) near the idler band, as a function of temperature and pump power at various center frequencies. The bandwidth of the detected noise photons is determined by the transmission characteristics of the bandpass filter, and the total count is proportional to the bandwidth. Using narrower bandpass filters such as volume holographic grating or Fabry-Perot etalon filters, we should be able to achieve low background counts in the 100 counts per second (cps) range.

If the qubit is encoded in either the frequency or the time bin (phase) of the photon, the DFG process is expected to preserve the qubit coherence during the frequency conversion. If the qubit is encoded in the polarization, one must ensure the simultaneous conversion of both polarizations without distinguishing them. All three qubits are viable candidates for the generation of remote ion entanglement that can be utilized for the quantum repeater realization. We will discuss the experimental prospect of practical quantum repeater realization using trapped ion systems.

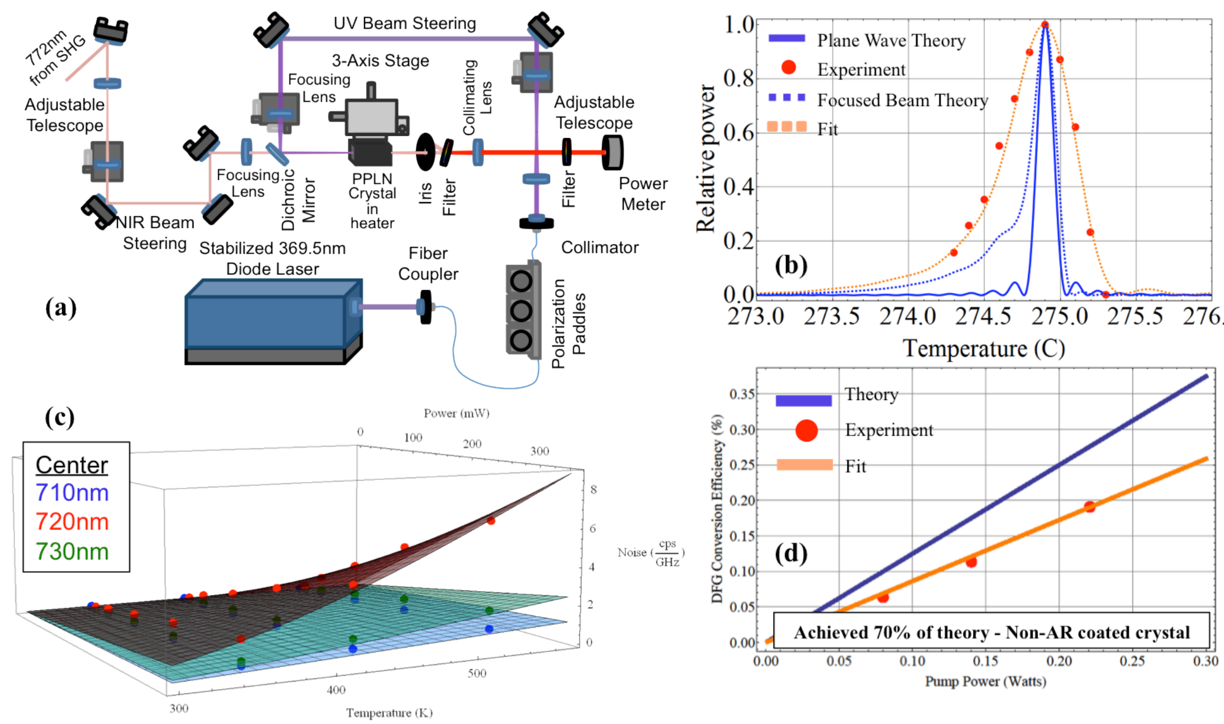

Figure 1: (a) Experimental setup. (b) Temperature tuning curve for the DFG process. (c) Background noise counts as a function of temperature, pump power and center frequency. (d) Conversion efficiency of the DFG process.

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