

Polarization-preserving quantum frequency conversion to VIS via cross-band achromatic UV-NIR waveguide coupling

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Photons are essential for interconnecting quantum systems in quantum networks, where polarization is a widely used degree of freedom for encoding quantum information. However, frequency bands suitable for different quantum systems often do not align. While polarization-preserving quantum frequency conversion (PPQFC) is essential for interconnecting heterogeneous quantum systems, existing solutions lack cross-band capability between ultraviolet (UV) and near-infrared (NIR) regimes. Here, we experimentally demonstrated a PPQFC method that exploits the low-loss, self-phase stabilization of polarization and facilitates cross-band achromatic waveguide coupling. Specifically, we demonstrated the polarization-preserving quantum frequency conversion from UV 369.5 nm to visible 580 nm with infrared pumping at 1018 nm, achieving long-term fidelity of $97.6\% \pm 1.0\%$ at wavelengths relevant to trapped ions $^{171}\text{Yb}^+$ and solid-state $^{153}\text{Eu}^{3+}:\text{Y}_2\text{SiO}_5$ quantum systems. This work demonstrates a versatile PPQFC solution for future heterogeneous quantum networks.

Keywords: quantum frequency conversion; quantum network; quantum optics; nonlinear optics.

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1. Introduction

Quantum networks have promising applications^[1,2], such as distributed quantum computing^[3,4], quantum cryptography^[5], quantum sensing^[6], and clocks^[7]. The matter qubits in each quantum node are entangled via photons, so the quantum frequency conversion between different quantum systems is significant^[1]. The quantum information can be encoded into photons by several degrees of freedom, such as polarization, time-bin, and frequency. The polarization state of photons is commonly utilized as a flying qubit because of its simplicity. Therefore, polarization-preserving quantum frequency conversion (PPQFC) devices are critical for quantum networks and distributed quantum computing. Quantum frequency conversion is realized by a nonlinear effect. A cavity^[8–10] and a waveguide can enhance the nonlinear effect and obtain higher conversion efficiency. The PPQFC devices typically employ quasi-phase matching (QPM) on periodically poled crystals, involving beams of different wavelengths coupling into a waveguide simultaneously. Due to the significant

wavelength differences among these beams, chromatic effects must be carefully addressed in PPQFC.

Current PPQFC schemes include: 1) Mach-Zehnder configuration^[11,12], 2) cascaded crystals^[13,14] or dual-pass configuration^[15], and 3) Sagnac loop configuration^[16–18]. Within the Mach-Zehnder configuration, the photon designated for conversion traverses the nonlinear crystal a single time, resulting in a low loss. However, the polarization phase requires active stabilization^[12] or compact optical path design^[11]. The cascaded crystals or dual-pass configuration allows for phase stabilization without active feedback; however, it compels the photon to traverse the nonlinear crystal twice, thereby inducing increased loss. Among these, only the Sagnac loop configuration amalgamates the advantages of low loss and inherent phase stabilization. A key challenge across all three configurations is simultaneous multi-wavelength coupling into the waveguide. This is typically achieved using aspheric lenses or objectives. Nevertheless, chromatic aberrations cause focal-length mismatches for different wavelengths, resulting in the requirement of converging light beams

to achieve efficient coupling for each wavelength (e.g., transforming the incoming pumping or signal light into a diverging). This method has three notable limitations. First, the optical path design lacks universality and requires a redesign for varying wavelengths. Second, a considerable challenge exists to achieve effective coupling for waveguides operating at significantly different wavelengths. In particular, the refractive index grows dramatically in the ultraviolet (UV) band, leading to dramatic chromatic aberration. This results in the inability to achieve effective waveguide coupling by aspheric lenses or objectives. Third, there is a restriction in efficiently coupling waveguides with small mode field diameters, which require diffraction-limited focusing capabilities. The primary aim of reaching a small mode field diameter is to increase the power density, thus enhancing the efficiency of nonlinear conversion processes. This aim is essential for the advancement of the future high-efficiency interface of a quantum network.

In response to these challenges, this study introduces a method for PPQFC. We utilized the inherent phase self-stabilization and low-loss characteristics of the Sagnac loop configuration, and the achromatic feature of off-axis parabolic mirrors (OAPMs) for waveguide coupling. While OAPMs were previously employed for chromatic-aberration-free coupling^[13], our work integrated them with a Sagnac loop to achieve polarization preservation and enhanced waveguide coupling efficiencies (73% at 369.5 nm, 65.8% at 1018 nm), alongside long-term stability. This approach combines the benefits of both the Sagnac loop configuration and off-axis parabolic mirrors, offering a robust and universal solution for PPQFC to meet the cross-band interconnection requirements of quantum networks.

2. Experimental Setup

In this study, we experimentally achieved PPQFC from 369.5 to 580.0 nm, which coincides with the dipole radiation from a trapped $^{171}\text{Yb}^+$ ion and absorption wavelength of a quantum memory $^{153}\text{Eu}^{3+}:\text{Y}_2\text{SiO}_5$ crystal^[19]. This study establishes a substantial foundation for the integration between quantum processors and quantum memories, which is of pivotal importance in realizing the vision of advanced quantum networks^[2]. A Sagnac loop configuration is employed for PPQFC from 369.5 to 580.0 nm, as depicted in Fig. 1. A periodically poled MgO-doped stoichiometric LiTaO_3 (PPSLT) crystal with a poling period of $7.36\ \mu\text{m}$ is utilized for the third-order QPM in our difference-frequency-generation (DFG) process ($369.5\text{--}1018\ \text{nm} \rightarrow 580\ \text{nm}$). The key component of the system is the PPSLT crystal, which is mounted on a six-axis translation stage with thermoelectric cooling (TEC) temperature control ($115.090^\circ\text{C} \pm 0.005^\circ\text{C}$). The waveguide in the PPSLT crystal is inscribed by a femtosecond laser system. The mode field diameters of the waveguide are 8.7, 11, and $12.2\ \mu\text{m}$ at wavelengths of 369.5, 580, and 1018 nm, respectively. A comprehensive description of waveguide fabrication is provided by Zheng *et al.*^[11]. Two long-pass dichroic mirrors (DM1 and DM2) facilitate the

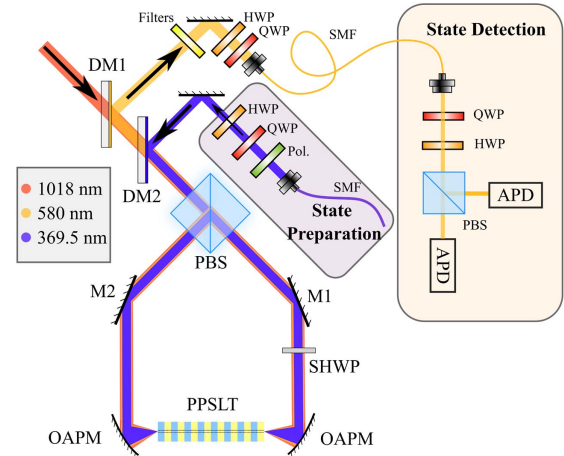


Fig. 1. Experimental setup for polarization-preserving quantum frequency conversion using a Sagnac loop with a PPSLT crystal for difference-frequency generation from 369.5 to 580.0 nm. Key components: dichroic mirrors (DM1, DM2) combine 369.5 nm/1018 nm beams and separate 580 nm output; polarization beam splitter (PBS) with super-achromatic waveplate (SHWP) enables polarization routing; off-axis parabolic mirrors (OAPMs) achieve achromatic coupling into waveguide. The output 580 nm photons are filtered out and coupled into a single-mode fiber (SMF). Its polarization phase shifts are compensated for by a half-wave plate (HWP) and a quarter-wave plate (QWP). The light purple shaded box denotes polarization preparation of 369.5 nm photons, generated via a polarizer (Pol.), an HWP, and a QWP. Polarization detection of 580 nm photons (light yellow shaded box) employs a QWP, an HWP, a PBS, and avalanche photodiodes (APDs).

integration of input photons at 369.5 nm with pump photons at 1018 nm, while simultaneously segregating the output photons at 580 nm. The input photons at 369.5 nm and the pump photons at 1018 nm enter the loop through a polarization beam splitter (PBS), where the horizontal polarization propagates in a clockwise direction arm, and the vertical polarization propagates in a counterclockwise arm. In our DFG process, type-0 QPM is utilized, where the maximum nonlinear coefficient is exclusively associated with vertical polarization. Consequently, the horizontally polarized photons propagating clockwise are converted into vertically polarized photons via a super-achromatic half-wave plate (SHWP, Thorlabs, SAHWP05M-700) before the waveguide. Two ultraviolet aluminum mirrors, M1 and M2 (Newport, 10Z40AL.2), are employed within the loop at an angle of incidence (AOI) of 67.5° to satisfy the incident angle specifications of the off-axis parabolic mirrors (OAPMs) (Thorlabs, MPD019-F01) and thereby establish a closed-loop configuration. The 369.5 and 1018 nm beams are achromatically coupled into the waveguide by OAPMs with efficiencies of 73.0% and 65.8%, respectively. The OAPMs are placed on a custom six-axis adjustment mount, while the mirrors M1 and M2 are placed on a three-axis mirror mount. The PPSLT crystal is mounted on a six-axis stage. As a result, there are enough degrees of freedom to optimize coupling efficiency. All 580 nm photons generated through DFG in the waveguide are vertically polarized and collimated by OAPMs. Vertically polarized 580 nm photons

traveling clockwise are reflected by the PBS, while those traveling counterclockwise pass through an SHWP, subsequently converting to horizontal polarization and transmitting through the PBS. The two separate arms are merged into a single path within the PBS. Thus, the polarization state of the output 580 nm photons is rotated by 90° relative to the input 369.5 nm photons. The 580 nm photons are separated from the input and residual pump photons by DM1, DM2, and 580 nm narrow bandpass filters. To compensate for polarization rotation and phase shift, a half-wave plate (HWP) and a quarter-wave plate (QWP) are utilized in the output 580 nm beam. However, it is worth reminding that phase compensation does not influence the concurrence of the ion-photon entangled state but makes it an expected right Bell state. The 580 nm photons are coupled into a single-mode fiber (SMF) with an efficiency of about 80%.

All optical components in the system were designed for cross-band operation. The component efficiencies are summarized in Table 1. The dichroic mirrors (DM1 and DM2) exhibited high efficiency: DM1 showed 94.5% transmission at 1018 nm and 98.8% reflection at 580 nm, while DM2 demonstrated 94.9% transmission at 1018 nm, 95.0% transmission at 580 nm, and 95.1% reflection at 369.5 nm. The custom PBS maintained efficiencies of 98.9% at 369.5 nm, 94.1% at 580 nm, and 98.8% at 1018 nm. The extinction ratios $\gamma_t = T_V/T_H$ for transmitted light and $\gamma_r = R_V/R_H$ for reflected light were measured at an AOI of 0° . The measured values were $\gamma_{t,369.5} = 1340$, $\gamma_{t,580} = 2120$, and $\gamma_{t,1018} = 2600$ for transmission, and $\gamma_{r,369.5} = 809$, $\gamma_{r,580} = 27$, and $\gamma_{r,1018} = 350$ for reflection. These extinction ratios affect only the conversion efficiency since the DFG process is inherently polarization selective. Implementation of an antireflection (AR) coating on the PPSLT crystal reduced Fresnel reflections from $\sim 14\%$ to $< 1\%$ at all wavelengths. This modification significantly improved system stability by minimizing unwanted polarization mixing effects and unstable interference that were observed in the uncoated crystal.

Table 1. Efficiency of Optical Components at Different Wavelengths.

Efficiency	369.5 nm	580 nm	1018 nm
DM1	—	98.8%	94.5%
DM2	95.1%	95.0%	94.9%
PBS	98.9%	94.1%	98.8%
Mirror	98.0%	83.1%	92.7%
OAPM	95.8%	82.6%	91.5%
Super-achromatic HWP	84.3%	94.3%	99.5%
580 nm bandpass filter	—	91.3%	—
Waveguide coupling efficiency	73.0%	—	65.8%
SMF coupling efficiency	—	80.0%	—

3. Results and Discussion

We used the quantum process tomography technique to quantify the process fidelity of this device. The coherent laser source of 369.5 nm is attenuated to a single-photon level to simulate ion fluorescence. The input states $|H\rangle$, $|V\rangle$, $|D\rangle$, $|A\rangle$, $|R\rangle$, $|L\rangle$ of 369.5 nm photons are generated by a horizontally placed polarizer, an HWP, and a QWP. The polarizer has an extinction ratio greater than 10^5 . This part is indicated by a light purple shaded box in Fig. 1. The state detection of 580 nm photons is made by a QWP, an HWP, a PBS, and two avalanche photodiodes (APDs). This part is indicated by a light yellow shaded box in Fig. 1. We performed tomography on each input state and then reconstructed the process matrix for this device. The fidelity of the process between the ideal process matrix χ_i and the measured process matrix χ_m is calculated by

$$\mathcal{F}(\chi_i, \chi_m) = \left[\text{Tr} \left(\sqrt{\sqrt{\chi_i} \chi_m \sqrt{\chi_i}} \right) \right]^2. \quad (1)$$

In Fig. 2, the measured process matrix χ_m (left) and the ideal process matrix χ_i (right) are displayed separately for a clearer comparison. Each matrix element is explicitly labeled with its complex value so that even the near-zero elements can be clearly identified. The ideal process matrix χ_i contains only one non-zero element $\chi_{00} = 1$, corresponding to the identity operation. Any unitary imperfection or decoherence leads to a reduction in χ_{00} and a corresponding increase in the other elements, as revealed by the experimentally measured χ_m . The PPQFC device maintained a fidelity of $97.6\% \pm 1.0\%$ over 10 h (Fig. 3), demonstrating long-term stability. Each data point was measured over approximately 222 s. Error bars represent $\pm 3\sigma$ obtained via Monte Carlo simulations. The stability of waveguide coupling was longer than 10 h. The temperature of PPSLT is stabilized at $115.090^\circ\text{C} \pm 0.005^\circ\text{C}$. Despite the presence of a gradual drift in the first 3 h as the air temperature reaches equilibrium, this result is adequate for establishing a connection between the trapped ion and the solid-state quantum memory.

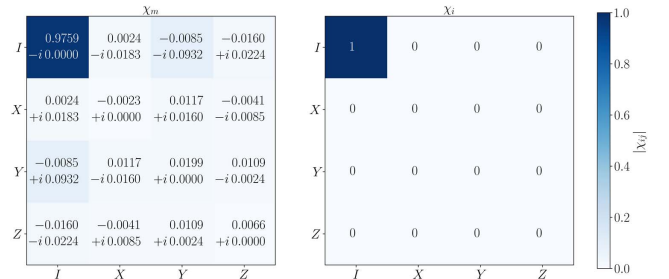


Fig. 2. Process matrices of the PPQFC device. The left panel shows the experimentally measured process matrix χ_m , and the right panel shows the ideal process matrix χ_i . Each matrix element is labeled with its complex value for clarity. The ideal process matrix χ_i has only one non-zero term $\chi_{00} = 1$, while deviations in the measured process matrix χ_m indicate the presence of unitary errors or decoherence.

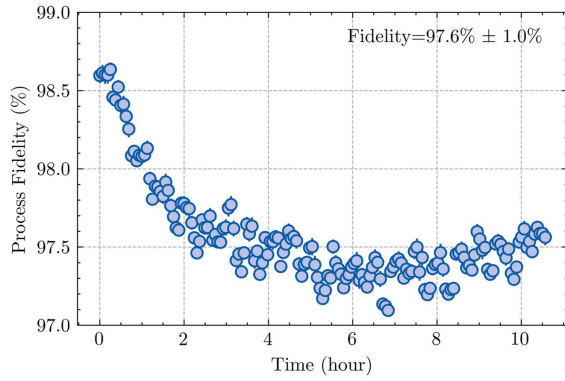


Fig. 3. Process fidelity maintains $97.6\% \pm 1.0\%$ over 10 h. Each data point was measured over approximately 222 s. Error bars represent $\pm 3\sigma$ obtained via Monte Carlo simulations.

Our waveguide coupling efficiencies (73% at 369.5 nm, 65.8% at 1018 nm) surpassed previous PPSLT-based designs^[11] by 13% and 40%, respectively. The SMF coupling efficiency for 580 nm was increased from 40% to 80%, attributed to improved collimation by the OAPMs. The waveguide coupling efficiencies are primarily limited by waveguide loss and scattering effects. The external device varies with the total input pump power as shown in Fig. 4, with error bars ($\pm 3\sigma$) derived from 1000 measurement repetitions. The solid curve represents the fitting curves of the experimental data. At a total input pump power of 1.412 W, the external device efficiency reaches $0.133\% \pm 0.011\%$, averaged over horizontal and vertical polarizations. Due to heating effects caused by the high pump power, the conversion efficiencies for horizontal and vertical polarizations exhibit a slight discrepancy as the pump power increases. This discrepancy can be compensated for by adjusting the pump power in the two arms.

Compared to other devices^[16,18] used for PPQFC, the efficiency of our device was relatively low due to three main reasons.

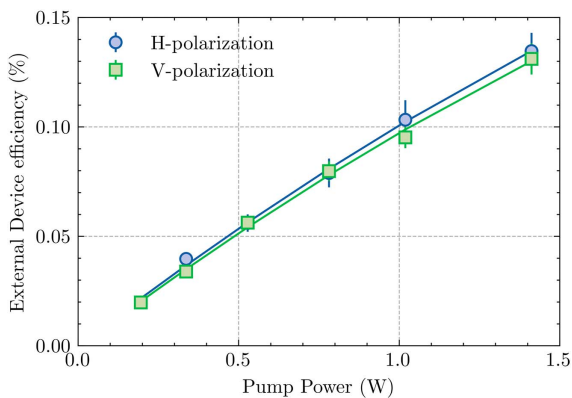


Fig. 4. External efficiency as a function of pump power. Peak efficiency reaches $0.133\% \pm 0.011\%$ at 1.412 W. Error bars: $\pm 3\sigma$ (1000 measurements). Solid lines indicate fitting results. The slight conversion efficiency imbalance between the two arms can be compensated for by rotating the polarization of the pump beam.

First, we employed the third-order QPM instead of the first-order (2.6 μm) due to its lower technical complexity; switching to the first-order QPM could enhance efficiency by a factor of 9. Because achieving effective poling in crystals with a poling period below 3 μm is technically challenging so far, realizing such poling requires the use of thin-film crystals in combination with advanced high-precision poling techniques. Furthermore, the targeted ultraviolet wavelength intrinsically exhibits higher propagation losses compared to infrared regimes. Second, the mode field diameter of the current waveguide is relatively large ($\sim 10 \mu\text{m}$). We are working on developing an on-chip waveguide that has a higher refractive index difference so that it can support a smaller mode field diameter and high power density of pumping. Reducing it to 1–2.5 μm is realistic, according to an efficiency improvement by a factor of $4^2 = 16$ under cautious estimation. Third, coating can be improved in the future. The anti-reflective coating we applied to the device has suffered some degradation under a high-power pump and UV light exposure, reducing its efficiency. Currently, we use ion-assisted deposition (IAD) for the coating, but we can later switch to ion beam sputtering (IBS), which offers higher coating quality. The ultraviolet aluminum mirror in the optical path has a relatively low reflectivity (83%) at a wavelength of 580 nm, which can be addressed by a custom high-reflection coating. By implementing a customized coating on the super-achromatic HWP to enhance 369.5 nm transmission efficiency to above 95%, and on the mirrors and OAPMs to enhance 580 nm reflection efficiency to above 95%, overall optical path efficiency of 369.5 and 580 nm can be improved from 23% to about 34%. Upon addressing the current technical limitations, the overall conversion efficiency can be enhanced to 28%. However, our PPQFC scheme provided a general solution to connecting a hybrid quantum system crossing different frequency bands in future quantum networks.

4. Conclusion and Outlook

In conclusion, we presented a universal scheme for PPQFC. This scheme mitigates chromatic aberration and ensures diffraction-limited focusing for waveguide coupling. Using this methodology, we experimentally achieved conversion from 369.5 to 580 nm utilizing 1018 nm pumping, maintaining the fidelity of the process at $97.6\% \pm 1.0\%$ over a duration of 10 h. The elevated efficiencies of waveguide coupling are facilitated by OAPMs, 73% for 369.5 nm and 65.8% for 1018 nm. The conversion efficiency has potential for enhancement through the first-order polarized PPSLT or PPLN. This work addresses the critical challenge of achieving effective ultraviolet-near-infrared (UV-NIR) cross-band waveguide coupling in Sagnac-loop-based PPQFC, which has previously hindered broader implementations. By developing an achromatic coupling solution spanning 250 nm to 20 μm , we established a universal platform for PPQFC in quantum networks. Currently, most PPQFC devices are dedicated to converting the wavelengths of ions or atoms to communication wavelengths. Nevertheless, direct short-distance

connections between two quantum systems are anticipated to have numerous applications in the future. This aspect is crucial for multinode quantum networks as it facilitates conversion to multiple distinct frequencies, thereby enhancing connectivity across more nodes.

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