Realization of double resonance for a bright frequency-tunable source of narrowband entangled photons*

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In this paper, we report an interesting phenomenon when precisely adjust the tuning crystal for double-resonance of a type-II configured parametric amplifier cavity, which is later verified as a cavity-enhanced effect in optics alignment. The theoretical result indicates that an angle accuracy error within 0.09° is necessary to achieve a high contrast ratio of 100:1 for a cavity with a finesse of about 205, which is crucial but high-demanding to get a high-quality narrowband entanglement source. Meanwhile, we figure out a method to release such a high requirement and get high visibility in a moderate-accuracy alignment.

Keywords: optics alignment, double-resonance, cavity-enhanced, narrowband entanglement

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1. Introduction

A true narrowband entanglement source[1] is one of the two building blocks[2] for long-distance quantum communication (LDQC)[3,4] and linear optical quantum computation (LOQC).[5,6] Pursuing the efficient interaction with atomic-ensemble based quantum memories,[7] a series of significant works[1,8−11] have been done to suppress the originally broad bandwidth of spontaneous-parametric down conversion (SPDC) source[12] into ∼ MHz level by cavity-enhanced SPDC method. In those works, a double-resonant cavity for both horizontal ($|H\rangle$) and vertical ($|V\rangle$) down-converted photons is exploited to get an enhancement factor proportional to the square of the cavity's finesse. However, the sources are either of multi-mode output[9,11] due to the identical cavity length of $|H\rangle$ and $|V\rangle$ polarization, without entanglement[8] or with non-tunable working wavelength due to the lack of the tuning crystal.[1,10] Only recently by employing a tuning crystal with axes consistent with the nonlinear crystal have we realized a single-mode narrowband entanglement source which is approximately 20 times[2] as bright as the previous true narrowband entanglement source.[1] However, such an improvement is not that straightforward because a highly enhanced noise would appear if the axes of the crystals are not precisely adjusted and it would result in a rather poor visibility and ruin the generation of the source.

In this paper, at first we present an interesting noise amplification phenomenon when double-resonance of the cavity is approaching. And then we analyse the phenomenon both theoretically and experimentally from which a precision requirement is derived for aligning the axes of nonlinear and tuning crystals. At last we figure out a method to release such a high-demanding requirement and circumvent the problem with a moderate accuracy alignment.

2. Analysis

As shown in Fig. 1, the source cavity mainly consists of three parts in sequence, i.e. a PPKTP crystal as a nonlinear crystal, a KTP crystal for double-resonance tuning and a concave output coupler attached to a piezoelectric ceramic (PZT). The first side of the PPKTP crystal is of high-reflection coating ($R_1 \sim 100\%$) while the output coupler is coated

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with a reflectivity of $R_2 = 97\%$, which results in a theoretical finesse of about 205. A locking beam for cavity locking is polarized at $|H\rangle$ and coupled into the cavity. Without loss of generality, we assume that the PPKTP crystal is perfectly aligned, i.e. the axes are perfectly along $|H\rangle$ and $|V\rangle$ directions, because the input polarization can be adjusted to be perfectly along the crystal's axes with wave plates. When KTP crystal is roughly aligned (the angle $\theta > 0.5°$), the output intensities of $|H\rangle$ and $|V\rangle$ are comparable at double-resonance! It directly results in a distorted error signal[13] for cavity locking and low visibility for the further generation of the entanglement source.

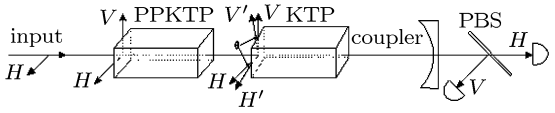


Fig. 1. Schematic of a narrowband type-II configured double-resonant cavity. The input beam polarized at $|H\rangle$. The axes of PPKTP crystal are along $|H\rangle$ and $|V\rangle$ directions, while the axes of KTP crystal are along $|H'\rangle$ and $|V'\rangle$ directions. There is a small angle difference of θ between their axes. PBS denotes polarizing beam splitter, which transmits $|H\rangle$ polarization and reflects $|V\rangle$ polarization respectively.

To interpret this giant amplification effect, we consider the intensity variation of input $|H\rangle$ photons during a round-trip inside the cavity, of which procedure can be described as follows:

$$\begin{aligned}
|H\rangle &\rightarrow \mathrm{PPKTP}(|H\rangle = \cos\theta \times |H'\rangle - \sin\theta \times |V'\rangle) \\
&\rightarrow \mathrm{KTP}(\cos\theta \times |H'\rangle - \sin\theta \times \mathrm{e}^{\mathrm{i}\,\varphi_{\mathrm{KTP}}} \times |V'\rangle) \\
&\rightarrow \mathrm{KTP}\begin{pmatrix} \cos\theta \times |H'\rangle - \sin\theta \times \mathrm{e}^{2\,\mathrm{i}\,\varphi_{\mathrm{KTP}}} \times |V'\rangle \\ = (\cos^2\theta + \sin^2\theta \times \mathrm{e}^{2\,\mathrm{i}\,\varphi_{\mathrm{KTP}}})|H\rangle + \cos\theta\sin\theta(1 - \mathrm{e}^{2\,\mathrm{i}\,\varphi_{\mathrm{KTP}}})|V\rangle \end{pmatrix} \\
&\rightarrow \mathrm{PPKTP}((\cos^2\theta + \sin^2\theta \times \mathrm{e}^{2\,\mathrm{i}\,\varphi_{\mathrm{KTP}}})|H\rangle + \mathrm{e}^{\mathrm{i}\,\varphi_{\mathrm{PPKTP}}}\cos\theta\sin\theta(1 - \mathrm{e}^{2\,\mathrm{i}\,\varphi_{\mathrm{KTP}}})|V\rangle), \qquad (1)
\end{aligned}$$

where $|H'\rangle$ and $|V'\rangle$ denote the horizontal and vertical axes of the KTP crystal, θ is the angle between the two crystals' axes, and φ_{KTP} (φ_{PPKTP}) denotes the accumulated phase difference between polarizations along KTP (PPKTP) crystal's two perpendicular axes when photons travel through. For calculation simplicity, we set up a model that for every round-trip $|H\rangle$ photons have a probability, $P = \sin^2\theta$, falling into the $|V\rangle$ resonant cavity and never converts back. This is reasonable, because the angle θ is typically smaller than 1°. In that case, for every round-trip, the loss of $|V\rangle$ photons due to the re-conversion back into the $|H\rangle$ polarization is less than $|\cos\theta\sin\theta|^2 \sim 3 \times 10^{-4}$ which is two orders smaller than the loss of cavity output of 3% and is thus negligible. Since the photons have an average round trip times of F inside the cavity, where F is the cavity's finesse, then the output $|V\rangle$ photons would be accumulated and its intensity I_V^{out} can be intuitively estimated as $I_V^{\mathrm{out}} \propto I_H^{\mathrm{ins}} \times P \times F$, where I_H^{ins} is the intensity of the $|H\rangle$ photons inside the cavity. A more detailed calculation exploiting the multi-beam interference[14] of a one-sided cavity is as follows:

$$\begin{aligned}
I_V^{\mathrm{out}} &= |E_H^{\mathrm{ins}} \times p \times t_2 + E_H^{\mathrm{ins}} \\
&\quad \times p \times r_2 \times r_1 \times t_2 + \cdots|^2 \\
&= I_H^{\mathrm{ins}} \times P \times \left|\frac{t_2}{1 - r_1 r_2}\right|^2 \\
&= I_H^{\mathrm{ins}} \sin^2\theta \times \left|\frac{\sqrt{1 - R_2}}{1 - \sqrt{R_2}}\right|^2 \\
&= I_H^{\mathrm{ins}} \sin^2\theta \times \frac{F^2}{\pi} \times \frac{1 - R_2}{\pi\sqrt{R_2}}, \qquad (2)
\end{aligned}$$

where $E_H^{\mathrm{ins}} = \sqrt{I_H^{\mathrm{ins}}}$ is the amplitude of $|H\rangle$ photons inside the cavity which has neglected the constant coefficient, $p = \sqrt{P} = \sin\theta$ is the probability amplitude that $|H\rangle$ photons can convert into $|V\rangle$ photons in a round trip, $r_1 = 1$ is the reflection coefficient of the first side of PPKTP, r_2 and t_2 are the reflection and transmission coefficient of the output coupler respectively, and $F = \pi(\sqrt{R_2})^{1/2}/(1 - \sqrt{R_2})$ is the finesse of a one-sided cavity. Since the term of $(1 - R_2)/(\pi\sqrt{R_2})$ is the reciprocal of finesse for a two-sided cavity with both sides coated with a reflectivity of R_2, the total enhancement factor is proportional the first power of cavity's finesse, which is consistent with our intuitive estimation. So for a cavity with the coating described above and an angle difference of 1°, the output intensity of the generated $|V\rangle$ photons is $0.04 \times I_H$ which is comparable with the $|H\rangle$ output of $T_2 \times I_H$, where $T_2 = 0.03$ is the transmissivity of the output coupler. Meanwhile, when far from double-resonance $|V\rangle$ pho-

tons are out of phase and the accumulated effect due to constructive interference disappears, so the polarization of light is well preserved. Figure 2 shows the theoretical result of enhancement factors for the $|V\rangle$ photons versus the round trip phase.

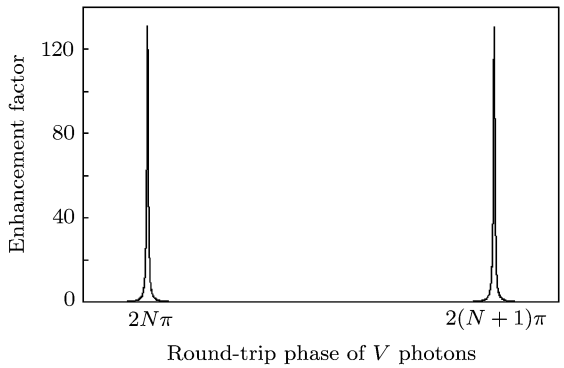


Fig. 2. Theoretical plot of enhancement factor versus round-trip phase of $|V\rangle$ photons. The enhancement factor equals 131 at resonance.

3. Experiment

To experimentally confirm this, we dither the PZT and meanwhile utilize a polarizing beam splitter (PBS) placed following the cavity to monitor the variation of output $|H\rangle$ and $|V\rangle$ intensities with two photon diodes respectively. The measured curve is shown in Fig. 3, which is well consistent with the theoretical result.

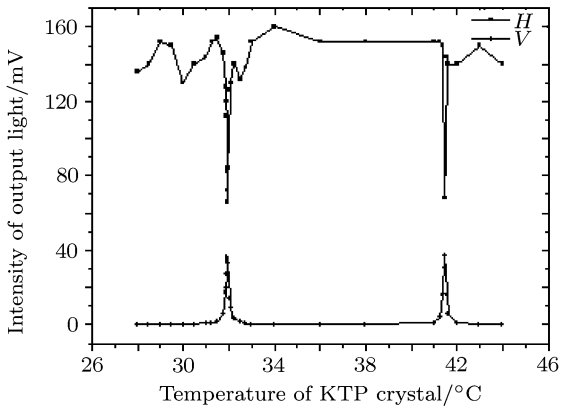


Fig. 3. Measured transformation between $|H\rangle$ and $|V\rangle$ photons inside a cavity. At double-resonance, the intensity of $|V\rangle$ photons is highly enhanced and comparable with that of $|H\rangle$ photons.

For a small amount of conversion, the contrast ratio can be defined as $I_H^{\rm out}/I_V^{\rm out}$, where $I_H^{\rm out}$ is the output intensity of $|H\rangle$ photons, and it equals $T_2 \times I_H^{\rm ins}$ for a one-sided cavity. Therefore the contrast ratio yields

$$C \equiv \frac{I_H^{\rm out}}{I_V^{\rm out}} = \frac{\pi^2\sqrt{R_2}}{\sin^2\theta} \times \frac{1}{F^2}. \qquad (3)$$

For a high finesse cavity, R_2 is also $\sim 100\%$, so the contrast ratio is reduced by a factor proportional to the square of finesse which indeed agrees with the result of Ou[8] which calculates the enhancement factor for photon pair generation.

From this equation we can determine the precision requirement of the angle θ to get high visibility. Some simple calculation indicates that a high contrast ratio of 100:1 requires an angle precision of about 0.09°. So an accurate loading device is necessary to fulfill this requirement.

However, since the contrast ratio reduces as the square of finesse increases, it will become extremely difficult to meet the precision requirement for large finesses. For example, if a cavity has a finesse of 10000 (A cavity of 1-cm length needs a finesse of 10000 to get a bandwidth of 1.5 MHz.), the angle precision becomes about 0.0017° to get a contrast ratio of 100:1. Therefore it limits the improvement of the system to have higher finesse which is crucial to get more efficient interaction between narrowband photons and atomic quantum memory.[7] So are there any methods to release this requirement and make use of a moderate angle accuracy aligned cavity? Here we figure out a method to solve this problem. It can be seen from Eq. (1) that when $\mathrm{e}^{2\,\mathrm{i}\,\varphi_{\rm KTP}} = 1$, the $|V\rangle$ photons disappear due to destructive interference. This can be achieved by precisely tuning the temperature of KTP crystal. In this way, a contrast ratio larger than 100:1 has been achieved in our experiment. Now back to the case of a 10000-finesse cavity, suppose the temperature-control precision is 0.001 K and the angle precision is 0.09°, combining with Eqs. (1), (3) and thermal–optical coefficients of KTP crystal,[15] and then we obtain a theoretical contrast ratio larger than 2000.

4. Conclusion

In summary, we have analysed an interesting double-resonance phenomenon in crystals' axes alignment. By efficiently eliminating the intra-cavity generated $|V\rangle$ photons, we have achieved a high contrast of the cavity output. And it enables the possibility to embed a tuning crystal inside cavity. As a result, the wavelength of the narrowband source is tunable by tuning the temperature of PPKTP for phase matching and meanwhile tuning the temperature of KTP for double-resonance. Therefore we generate an ultrabright narrowband source which is nearly 20 times as

bright as the previous true narrowband entanglement source. Besides, the giant amplification effect due to double-resonance may have important applications in signal amplification.

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