A low-noise frequency down-conversion to the telecommunication band for a quantum communication based on NV centers in diamond

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Abstract: We demonstrate a low-noise frequency down-conversion of photons at 637 nm to the telecommunication band at 1587 nm by the difference frequency generation in a periodically-poled lithium niobate. An internal conversion efficiency of the converter is estimated to be 0.44 at the maximum which is achieved by a pump power of 430 mW, whereas a rate of internal background photons caused by the strong cw pump laser is estimated to be 9 kHz/mW within a bandwidth of about 1 nm. By using the experimental values related to the intrinsic property of the converter, and using the intensity correlation and the average photon number of a 637-nm input light pulse, we derive the intensity correlation of a converted telecom light pulse. Then we discuss feasibility of a single-photon frequency conversion to the telecommunication band for a long-distance quantum communication based on NV centers in diamond.

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1. Introduction

Quantum repeaters for efficiently transmitting a quantum state through lossy and noisy quantum channels have been proposed [1] and actively studied for realizing long distance quantum communication [2]. In the quantum repeater protocols, photons entangled with quantum memories at remote parties are sent to relay points, and they are measured by the Bell measurement for establishing the entanglement between the quantum memories at the remote parties. The elementary part that creates entanglement between a quantum memory and a photon has been demonstrated in atomic systems [3, 4], trapped ion systems [5] and solid-state systems [6, 7]. In such systems, the wavelengths of the photons are strictly limited by the structure of their energy levels, which lie around visible range. On the other hand, when we look at optical-fiber networks, the photons at the telecommunication wavelengths are crucial for the efficient transmission of the photons. Thus a photonic quantum interface [8] for visible-to-telecommunication wavelength conversion is considered to be inevitable for a long distance quantum communication based on the quantum repeaters [9].

So far, in order to build such a quantum interface, the frequency down-conversion working at a single-photon level from visible to the telecommunication wavelengths has been actively studied by using nonlinear optical media [10–17]. In the first experimental demonstration employing a light field with a non-classical property, the wavelength of 795 nm which corresponds to the D1 line of the rubidium atoms are converted to 1367 nm by using a third-order optical nonlinearity in a rubidium atomic cloud [10, 11]. In Ref. [11], preservation of the entanglement between two photons after the frequency down-conversion was also observed. For a wide-band and a compact wavelength conversion, the difference frequency generation (DFG) via a second-order optical nonlinearity in a periodically-poled lithium niobate (PPLN) has been used and the preservation of the quantum state through the wavelength conversion from 780 nm which corresponds to the D2 line of the rubidium atom to 1522 nm has been demonstrated [15, 17]. The non-classical property of a light converted to 1313 nm from a 711-nm light emitted by a quantum dot has also been demonstrated [16]. In Ref. [14], the feasibility of the frequency down-conversion of a light at a single-photon level from 738 nm to 1557 nm by using the 1403-nm pump light has been shown for single-photon sources based on silicon-vacancy centers in diamond [18].

Another important wavelength which should be converted to the telecommunication bands for quantum communications is 637 nm corresponding to the resonant wavelength of the nitrogen-vacancy (NV) center in diamond [19]. The NV center in diamond is one of the promising candidates for the quantum memories with the ability to create the entanglement with photons [6]. In spite of a variety of demonstrations related to the NV centers in diamond in recent years [20–26], to the best of our knowledge, none of the demonstration of the frequency down-conversion from 637 nm to the telecommunication bands with the preservation of the non-classical property and/or the quantum information of the input light has been performed. In the experiment in Ref. [27], while the conversion from 633 nm to 1.56-μm has been observed with a 1.06-μm pump light, the signal-to-noise ratio (SNR) was not sufficient for the observation of the above mentioned properties.

In this paper, we demonstrate a low-noise wavelength conversion of a 637-nm light at a single-photon level to the telecommunication band by using a PPLN waveguide for realizing the efficient optical-fiber quantum communication based on NV centers in diamond [9]. The converted wavelength in this experiment is 1587 nm which is determined by the wavelength of 1064 nm of the cw pump light. In the experiment, we evaluate the performance of the wavelength converter, namely we clarify the overall conversion efficiency of the signal light and the amount of background photons induced by the conversion process. From the experimental results, we derive the intensity correlation and the average photon number of a converted telecom
light pulse which are decided by those of a 637-nm input light pulse and the intrinsic property of the converter. Then we discuss the feasibility of the observation of non-classical property of the telecom light after the frequency down-conversion from a 637-nm light pulse. We found that when the transform-limited light pulse from the NV centers in diamond with a lifetime of 13.7 ns reported in Refs. [22, 23] is prepared with a probability above $10^{-3}$, the intensity correlation of the converted telecom photon will be below 0.75 which indicates the non-classical property of the converted light.

2. Experiment

2.1. Experimental setup

The experimental setup is shown in Fig. 1. The 637-nm signal light is taken from a vertical (V-) polarized cw external cavity laser diode with the linewidth of $< 150$ MHz and a maximum power of 9 mW. The power of the signal light input to the PPLN waveguide is adjusted by using a variable attenuator (VA) within the range from $\approx 1$ mW to a photon rate of $\approx 40$ MHz. We use a cw pump laser with the center wavelength of 1064 nm and the linewidth of $< 100$ MHz for the wavelength conversion. The power of the pump laser coupled to the PPLN waveguide is varied up to $\approx 400$ mW by a polarization beamsplitter (PBS) and a half-wave plate (HWP). The pump beam is set to the vertical polarization by a HWP and then it is combined with the signal beam by a dichroic mirror. The two beams are coupled to the PPLN waveguide by using an aspheric lens (L1) of $f = 8$ mm with anti-reflective coating for both the signal light and the pump light.

The PPLN waveguide we used is a ridged-type waveguide, the cross section is square with 8-$\mu$m wide, and the length of the waveguide is 23 mm. The period of periodically-poled structure is 11.5 $\mu$m [28]. Due to the type-0 quasi-phase matching condition, the V-polarized signal photon at 637 nm is converted to the V-polarized telecom photon at 1587 nm with the V-polarized strong pump beam at 1064 nm. The temperature is controlled to be $\approx 20^\circ$C. The acceptable bandwidth for 637-nm signal light of this waveguide is calculated to be $\approx 0.1$ nm.

The output photons from the PPLN waveguide are collimated by an aspheric lens (L2) of $f = 8$ mm with anti-reflective coating for the signal light, pump light and telecom light. Two Bragg gratings (BG$_T$) with a bandwidth of 1 nm extract only the converted telecom light among them. The combined bandwidth of two BG$_T$ is $\Delta \approx 0.7$ nm. The telecom light is coupled to the single-mode fiber (D$_T$), and detected by a superconducting single-photon detector (SSPD) after passing through an attenuator of $\approx 10$ dB for preventing the saturation of the detection counts. The SSPD has a cavity structure and its quantum efficiency denoted by $\varepsilon$ is $\approx 60\%$ [29].
Fig. 2. (a) Conversion efficiency from 637 nm to 1587 nm as a function of the pump power $P$. The curve fitted to the experimental data is described by $T_{\text{conv}}^{\text{max}} \sin^2(\sqrt{\eta P})$ with $T_{\text{conv}}^{\text{max}} \approx 0.44$ and $\eta \approx 5.8/W$.

2.2. Experimental results

In order to estimate an internal conversion efficiency of the frequency down-converter and an amount of background photons generated by the conversion process, we first estimate the transmittance of the overall optical circuit by measuring the power of the light before and after the optical components. The coupling efficiency of the signal light to the PPLN waveguide is $T_{\text{in}} \approx 0.88$. The diffraction efficiency of each of BG$_T$ is $T_{\text{BG}} \approx 0.86$. The telecom photons diffracted by the last BG$_T$ pass through the HWP and PBS, and then enter D$_T$. The efficiency of these processes is estimated to be $\approx 0.42$. As a result, the transmittance of the optical circuit from the first BG$_T$ to the front of the fiber attenuator is $T_{\text{oc}} \approx 0.31$. The transmittance of the fiber attenuator is $T_{\text{att}} \approx 0.083$.

The internal conversion efficiency in the PPLN depending on the pump power is estimated by the observed output power of the converted light coupled to D$_T$ connected to a power meter instead of the fiber attenuator and the SSPD in Fig. 1. In this measurement, we set the power of the input light at 637 nm coupled to the PPLN waveguide to be $\approx 840\mu$W. From the observed values by the power meter and the estimated transmittance $T_{\text{oc}}$ of the optical components, we estimate the internal conversion efficiencies of the photon number. The result is shown in Fig. 2. The conversion efficiency of the DFG process with a strong pump light is expected to be proportional to $\sin^2(\sqrt{\eta P})$ [8], where $P$ represents the pump power. The best fit to the observed conversion efficiency with $T_{\text{conv}} = T_{\text{conv}}^{\text{max}} \sin^2(\sqrt{\eta P})$ gives $T_{\text{conv}}^{\text{max}} \approx 0.44$ and $\eta \approx 5.8/W$. The best conversion efficiency of 0.44 will be achieved at a pump power of $\approx 430$ mW.

We evaluate the amount of background photons at the down-converted wavelength of 1587 nm. The background photons were measured when we turned off the signal light and input only the pump light to the PPLN waveguide. Before we investigate the dependency of the background photons on the pump power, we first see the polarization property of the background photons, which was performed by measuring the background photon counts with various rotation angles of the HWP in front of the last PBS. This measurement was performed at 300-mW pump power. The experimental result of the count rate of the background photons depending on the rotation angle is shown in Fig. 3 (a). The degree of polarization of the background photons was $\approx 0.95$. The standard deviations of the observed values under the assumption of the Poisson statistics of the observed counts are less than 0.01. We note that when we measured the polarization property for the signal light, the degree of the polarization of the signal photons was over 0.99 by subtracting the effect of the background photons from the observed counts. From the result, we see that while the polarization of the background photons are almost V polarized, a small number of the background photons are orthogonal to V polarization. In the
Fig. 3. (a) The observed count rates of the background photons (orange circle) and the signal photons (red triangle) depending on the rotation angle of the HWP followed by the PBS and the detector. The degrees of polarization of the background photons and the signal photons were 0.95 and over 0.99, respectively. The result shows that the background photons include the H polarization. (b) The dependency of the background photon rate on the pump power. By using the dark count rate of \( d = 220 \) Hz, the background photon rate is fitted to the line described by \( BP + d \) with \( B \approx 135 \) Hz/mW.

following experiment, H polarization component of the background photons is reflected by the PBS in front of \( DT \).

The dependency of the background photon rate on the pump power is shown in Fig. 3 (b). We see that the background photon rate linearly increase with the pump power. From this, we infer that the main cause of the noises is the Raman scattering of the strong pump light as reported in the previous experiments of the frequency down-conversion [14, 17]. In order to fit the data, we use the linear function of the photon count rate written as \( N = BP + d \), where \( d = 220 \) Hz is determined by an observed value of the dark count rate of the SSPD. The coefficient \( B \) is estimated to be 135 Hz/mW. The internal background photon rate of the converter is \( B/(T_{oc}T_{att}\varepsilon) \approx 9 \times 10^3 \) Hz/mW. As a reference, we compare the intrinsic background photon generation rate due to the Raman scattering in this experiment with that in the demonstration for frequency down-conversion from 780 nm to 1522 nm in Refs. [15, 17] when these converters give the same internal conversion efficiency. The observed value of the Raman scattering in Ref. [17] was \( B_{780} = 80 \) Hz/mW which was detected by a photon detector with the quantum efficiency of 0.125. In the report, the overall conversion efficiency just before the photon detector was 0.005 which includes the internal conversion efficiency of 0.07. From these values, the internal background photon rate is roughly estimated to be \( \approx 9 \times 10^3 \) Hz/mW. The conversion efficiency for the cw signal light was \( T_{\text{conv,780}} = T_{\text{conv,780}}^{\text{max}} \sin^2(\sqrt{T_{780}P}) \) with \( T_{\text{conv,780}}^{\text{max}} \approx 0.71 \) and \( T_{780} = 3.6/W \) [15, 17]. When the conversion efficiencies of the two converters are the same, the ratio of the background photon rate of the converter for the 637-nm light to that for the 780-nm light takes a maximum for \( T_{\text{conv}} = T_{\text{conv,780}}^{\text{max}} \). For the converter in Refs. [15, 17], \( T_{\text{conv,780}} = T_{\text{conv}}^{\text{max}} \) is achieved at a pump power of \( \approx 230 \) mW, resulting in the background photon rate of \( \approx 2.1 \times 10^6 \) Hz. For the converter in this paper, \( T_{\text{conv}} = T_{\text{conv}}^{\text{max}} \) is given by the pump power of \( \approx 430 \) mW, resulting in the background photon rate of \( \approx 3.7 \times 10^6 \) Hz. By using these values, the background photon rate introduced by the conversion process in this experiment is, at the most, twice as large as that in Refs. [15, 17].

3. Discussion

In this section, we discuss the performance of the demonstrated frequency down-converter for a pseudo single photon pulse emitted from the NV center in diamond based on our experimental
results in the previous section. Here we estimate the well-known intensity correlation $g^{(2)}_0$ of the converted light pulse to see the ability of the frequency down-converter to preserve the non-classical property $g^{(2)}_0 < 1$. We regard a part of the optical circuit including the PPLN and the two BGs as an essential part of the converter, which is the region surrounded by dashed lines in Fig. 1. In the following, we derive the intensity correlation and the average photon number of a converted telecom light pulse from the converter when those of a 637-nm signal light pulse are given.

Let us first derive the intensity correlation of a light pulse $X$ which is a mixture of two statistically-independent light pulses $A$ and $B$ with the intensity correlation $g^{(2)}_{0,A}$ and $g^{(2)}_{0,B}$ and the average photon number $\langle \hat{n}_A \rangle$ and $\langle \hat{n}_B \rangle$, where $\hat{n}_{A(B)}$ represents the photon number operator. The intensity correlation of each pulse is given by $g^{(2)}_{0,i} = \langle \hat{n}_i(\hat{n}_i - 1) \rangle / \langle \hat{n}_i \rangle^2$ for $i = A, B, X$. We also define the Fano factor $F_i = \langle (\Delta \hat{n}_i)^2 \rangle / \langle \hat{n}_i \rangle$, where $\Delta \hat{n}_i = \hat{n}_i - \langle \hat{n}_i \rangle$. We then obtain $\langle \hat{n}_i \rangle (g^{(2)}_{0,i} - 1) = F_i - 1$. When the two light pulses $A$ and $B$ are statistically independent so that $\langle \Delta \hat{n}_A \Delta \hat{n}_B \rangle = 0$, the Fano factor of the light pulse $X$ is calculated to be $F_X = \langle (\Delta \hat{n}_A + \Delta \hat{n}_B)^2 \rangle / \langle \hat{n}_A + \hat{n}_B \rangle = F_A \langle \hat{n}_A \rangle / (\langle \hat{n}_A + \hat{n}_B \rangle) + F_B \langle \hat{n}_B \rangle / (\langle \hat{n}_A + \hat{n}_B \rangle)$. As a result, the intensity correlation of the light pulse $X$ is given by

$$g^{(2)}_{0,X} = \frac{1}{\langle \hat{n}_A + \hat{n}_B \rangle^2} \left( \langle \hat{n}_A \rangle^2 g^{(2)}_{0,A} + \langle \hat{n}_B \rangle^2 g^{(2)}_{0,B} + 2 \langle \hat{n}_A \rangle \langle \hat{n}_B \rangle \right)$$  \hspace{1cm} (1)

$$= \frac{1}{(1 + \zeta)^2} \left( \zeta^2 g^{(2)}_{0,A} + g^{(2)}_{0,B} + 2 \zeta \right),$$  \hspace{1cm} (2)

where $\zeta = \langle \hat{n}_A \rangle / \langle \hat{n}_B \rangle$ is the ratio between the average photon numbers of the two light pulses. As we have seen in the previous section, the frequency down-converter adds the background photons in the output mode. Therefore the above relation (2) is useful for the estimation of the output light pulse.

Suppose that the intensity correlation of a 637-nm input light pulse is $g^{(2)}_{0,in}$ and the average photon number of the light is $\bar{\hat{n}}_{in,sig}$. For simplicity, we assume that the spectral width of the input light is much narrower than the acceptable bandwidth $\approx 0.1$ nm of the frequency down-converter. We also assume that the background photons induced by the pump light fol-

![Fig. 4. The estimated $g^{(2)}_{0,out}$ of the converted telecom light as a function of $\Delta_{fil}$ in the cases of $g^{(2)}_{0,in} \approx 0.16$ (solid curves) and $g^{(2)}_{0,in} \approx 0$ (dotted curves). The measurement time is fixed to be $\tau_{time} = 52$ ns. The four curves show the intensity correlation in the cases of $\bar{\hat{n}}_{in,sig} = 1, 10^{-1}, 10^{-2}$ and $10^{-3}$ from the bottom.](image-url)
low the Poisson statistics, and are independent of the down-converted photons. It is convenient to replace these background photons by a noise source placed at the input of the down-converter. The average photon number \( \bar{n}_{\text{in,noise}} \) of this equivalent input noise is then given by \( \bar{n}_{\text{in,noise}} = B P A_{\text{fil}} T_{\text{time}} / (T_{\text{in}} T_{\text{conv}} T_{\text{oc}} T_{\text{att}} \varepsilon) \). Here \( T_{\text{time}} \) is a measurement time window, and \( \Delta_{\text{fil}} \) is a ratio of a filter bandwidth to the bandwidth of \( \lambda \approx 0.7 \) nm in the current experiment. Note that we assume that the bandwidth of the filter is much wider than the spectral width of the 637-nm signal light. The reason why the component of the background photons is proportional to \( T_{\text{time}} \) and \( \Delta_{\text{fil}} \) is that the background photons induced by the cw pump light for the wavelength conversion are temporally continuous and spectrally broad. From the observed values in the previous section as \( B \approx 135 \) Hz/mW, \( T_{\text{in}} \approx 0.88, T_{\text{oc}} \approx 0.31, T_{\text{att}} \approx 0.083, \varepsilon \approx 0.6 \) and \( T_{\text{conv}} = T_{\text{conv}}^{\text{max}} \sin^2(\sqrt{\pi P}) \) with \( T_{\text{conv}}^{\text{max}} \approx 0.44 \) and \( \eta \approx 5.8/W \), we calculate as \( \bar{n}_{\text{in,noise}} \approx 2.2 \times 10^4 \Delta_{\text{fil}} T_{\text{time}} P / \sin^2(\sqrt{5.8 P / W}) \). By substituting \( g_{\text{in}}^{(2)}(\bar{n}_{\text{A}}, \bar{n}_{\text{B}}) \) and \( g_{\text{in}}^{(2)}(\bar{n}_{\text{in,noise}}) \) in Eq. (2) by \( g_{\text{in}}^{(2)}(\bar{n}_{\text{in,sig}}) \) and \( (1, \bar{n}_{\text{in,noise}}) \), respectively, and by using \( \xi_{\text{in}} = \bar{n}_{\text{in,sig}} / \bar{n}_{\text{in,noise}} \), the intensity correlation \( g_{\text{0, out}}^{(2)} \) of the output light pulse is given by

\[
g_{\text{0, out}}^{(2)} = \frac{1}{1 + \xi_{\text{in}}} \left( \xi_{\text{in}} g_{\text{in}}^{(2)} + 1 + 2 \xi_{\text{in}} \right). \tag{3}\]

Because \( T_{\text{in}} T_{\text{conv}} T_{\text{BG}}^{\text{2}} \approx 0.3 \sin^2(\sqrt{5.8 P / W}) \) is the transmittance of the intrinsic part of the converter, we obtain the average photon number \( \bar{n}_{\text{out}} \) of the output light pulse to be

\[
\bar{n}_{\text{out}} = T_{\text{in}} T_{\text{conv}} T_{\text{BG}}^{\text{2}} (\bar{n}_{\text{in,sig}} + \bar{n}_{\text{in,noise}}). \tag{4}\]

Below we borrow the observed value of \( g_{\text{in}}^{(2)} \approx 0.16 \) and a lifetime of \( \tau \approx 13.7 \) ns for the 637-nm light pulse from the NV center in the diamond nanocrystal reported in Ref. [22], and then we estimate the expected value of \( g_{\text{0, out}}^{(2)} \) for the converted telecom light. We assume that the spectral width of the 637-nm light is close to the transform-limit so that it is much narrower than \( \Delta_{\text{fil}} \Lambda \). We choose \( T_{\text{time}} = 52 \) ns to collect the pulsed signal light over 99%, and use \( P \approx 430 \) mW which achieves the maximum conversion efficiency in our experiment. From Eq. (3) and \( g_{\text{in}}^{(2)} \approx 0.16 \), we can calculate \( g_{\text{0, out}}^{(2)} \) which is shown as a function of \( \Delta_{\text{fil}} \) for \( \bar{n}_{\text{in,sig}} = 10^{-3}, 10^{-2}, 10^{-1} \) in Fig. 4. As a reference, we also show \( g_{\text{0, out}}^{(2)} \) for the converted telecom light when the 637-nm signal light has \( g_{\text{0, in}}^{(2)} = 0 \) and the same lifetime.

In practice, the apparent intensity correlation of the light measured by the Hanbury-Brown and Twiss setup [30] is affected by the dark count of the detectors. We assume that coupling efficiencies to the single-mode fibers and two photon detectors for the Hanbury-Brown and Twiss setup are the same as those used in our experiment, namely the transmittance of the optical circuit after the PPLN is \( T_{\text{oc}} \approx 0.31 \), the quantum efficiency is \( \varepsilon \approx 0.6 \), and the dark count rate is \( \delta = 220 \) Hz. When a half BS is used for the measurement of \( g_{\text{0, out}}^{(2)} \), an expected observed value of \( g_{\text{0, out}}^{(2)} \) for the converted telecom light as a function of \( \Delta_{\text{fil}} \) is shown in Fig. 5 (a). From the figure, even for \( \bar{n}_{\text{in,sig}} = 10^{-3} \), we see a non-classical intensity correlation \( g_{\text{0, out}}^{(2)} \approx 0.74 \) of the converted telecom light at \( \Delta_{\text{fil}} = 1.2 \times 10^{-3} \) which corresponds to about 100 MHz. Using Eq. (2), we also calculate an expected SNR of the converted telecom light at each detector under the assumption that the 637-nm light is a mixture of two statistically-independent light sources composed of an ideal single photon and background photons that follow the Poisson statistics, and show the results in Fig. 5 (b).

In the above estimation, we assumed the spectral bandwidth of the 637-nm signal light is much smaller than the acceptable bandwidth \( \approx 0.1 \) nm of PPLN crystal and the filter bandwidth
Fig. 5. The expected observed values of $g_{\text{out}}^{(2)}$ and SNR of the converted telecom light as a function of $\Delta_{\text{fil}}$ in the cases of $g_{\text{in}}^{(2)} \approx 0.16$ (solid curves) and $g_{\text{in}}^{(2)} \approx 0$ (dotted curves). The measurement time is fixed to be $\tau_{\text{time}} = 52$ ns. (a) The four curves show the intensity correlation in the cases of $\bar{n}_{\text{in,sig}} = 1$, $10^{-1}$, $10^{-2}$ and $10^{-3}$ from the bottom. (b) The four curves show the SNR in the cases of $\bar{n}_{\text{in,sig}} = 1$, $10^{-1}$, $10^{-2}$ and $10^{-3}$ from the top.

$\Delta_{\text{fil}} \tilde{\Lambda}$, where $\tilde{\Lambda} \approx 0.7$ nm, while it was not satisfied in the experiment reported in Ref. [22] due to the inhomogeneous broadening at the room temperature. On the other hand, recently a transform-limited narrow bandwidth light pulse from the zero phonon line of a NV center in a bulk diamond at a low temperature has been reported in Ref. [20]. In addition, there are several studies for efficient collection of the light from NV center using a solid immersion lens [21] and a photonic crystal cavity [31]. When such experimental efforts will meet our requirements of the 637-nm signal light in the near future, the demonstrated low noise frequency down converter will achieve the conversion of the non-classical light from the NV centers to the telecom band.

4. Conclusion

In conclusion, we have demonstrated that the low noise frequency down-conversion of the photon at 637 nm which corresponds to a resonant wavelength of the NV center in diamond to the telecommunication band. The analysis based on our experimental results shows that if the transform-limited light pulse from the NV center in diamond is prepared even with a probability of $10^{-3}$, the intensity correlation of the telecom light after the frequency down-conversion with the proper frequency filtering will be well below 1. We believe that the result will lead to the efficient connection between solid-state devices composed of the NV center in diamond and telecom fiber networks.

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