Photons are generally believed to be good quantum information carriers for transmission and are dubbed the term “flying qubits” whereas atoms are best for storing and processing the quantum information. Therefore, a quantum network usually consists of nodes made of atoms and connected by photons [1]. In the network, quantum information is constantly transferred between photons and atoms. Because quantum information is sensitive to losses, minimum losses are required in the network. However, in current technology, atoms interact best with photons whereas optical communication system has low losses at 1.55 μm [3]. In contrast to some misunderstanding about parametric down-conversion, noise-free photon frequency down-conversion is achievable in this process. We implement a proof-of-principle experiment and show that quantum coherence is preserved in the process.

The parametric frequency down-conversion process is usually described by the Hamiltonian [20–23]:

\[
\hat{H}_{PA} = i\hbar \eta A_p \hat{a}_s^\dagger \hat{a}_i - i\hbar \eta^* \hat{a}_s \hat{a}_i A_p^*,
\]

where \( A_p \) is the strong pump field and usually is treated as a classical field. \( \hat{a}_s \) and \( \hat{a}_i \) stand for “signal” and “idler” fields for historic reason. This leads to the evolution equation for parametric amplifier:

\[
\hat{a}^{(out)}_s = G \hat{a}_s + \hat{g} \hat{a}_i^\dagger, \quad \hat{a}^{(out)}_i = G \hat{a}_i + \hat{g} \hat{a}_s^\dagger,
\]

where \( G \equiv \cosh|\eta A_p|\tau \) is the amplitude gain and \( g \equiv -e^{i\phi_s} \sinh|\eta A_p|\tau \). The appearance of the \( \hat{a}_s \)-terms in Eq.(2) leads to spontaneous quantum noise and the belief that frequency down-conversion is noisy and cannot preserve quantum coherence [12, 17].

On the other hand, there is another regime of operation in which we inject strong signal field. This regime is often ignored because of gain saturation: the amplification of the strong signal field requires more energy from the pump field which eventually will be depleted. In this regime of operation, the spontaneous emission for frequency down-conversion is negligible and we may achieve a noiseless frequency down-conversion of photons. We will demonstrate that contrary to some misunderstanding about parametric down-conversion, noise-free photon frequency down-conversion is achievable in this process. We implement a proof-of-principle experiment and show that quantum coherence is preserved in the process.

In this letter, we study a parametric down-conversion scheme for photon frequency down-conversion and quantum information transfer. We will demonstrate that contrary to some misunderstanding about parametric down-conversion, noise-free photon frequency down-conversion is achievable in this process. We implement a proof-of-principle experiment and show that quantum coherence is preserved in the process.

In this regime of operation, the spontaneous emission for frequency down-conversion is negligible and we may achieve a noiseless frequency down-conversion of photons. We will show this more rigorously in the following.

When the pump field is depleted, we can no longer use the evolution equations in Eq.(2). We need to start with a Hamiltonian for three-wave mixing:

\[
\hat{H}_{3W} = i\hbar \eta p \hat{a}_s^\dagger \hat{a}_i - i\hbar \eta^* \hat{a}_s \hat{a}_i \hat{a}_p^\dagger.
\]

Here the pump field is also treated quantum mechanically. If the “signal” field is very strong, as in our case
and it all depends on what the input field is. The transmissivity is simply a beam splitter equation, which mixes the two inputs together coherently. The transmissivity is simply a result of an inefficient nonlinear crystal that converts the pump and output power of the idler, we estimate the photon conversion efficiency is about 1%. The low efficiency is a result of an inefficient nonlinear crystal that we pulled out of shelf for the proof-of-principle experiment. More efficient nonlinear materials like PPLN can significantly improve the conversion efficiency. 

According to Eq.(5), the output-input relation is that for a beam splitter, which preserves the phase coherence. So, we check next the phase preservation in the conversion from the pump field to the “idler” field. Here, we use the original laser as a reference and beat the generated “idler” field with a small portion split from the “signal” field with a frequency difference (\(\omega_s = \omega_p - \omega_i\)) is generated at another direction. In the first experiment, we check the linearity of the detected “idler” field as a function of the attenuation factor on the incoming pump field, as predicted from Eq.(5). The result is shown in Fig.2 in logarithmic scale. It can be seen that in a range of 2 orders of magnitude, the detected signal follows well the linear dependence. The last point at the low end is due to the limit of the detector sensitivity. By a direct measurement of input power at the pump and output power of the idler, we estimate the photon conversion efficiency is about 1%. The low efficiency is a result of an inefficient nonlinear crystal that we pulled out of shelf for the proof-of-principle experiment. More efficient nonlinear materials like PPLN can significantly improve the conversion efficiency. 

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laser field but with a phase dependence from the pump field. This clearly demonstrates the coherent photon conversion from the pump field to the “idler” field. The frequency down-conversion scheme can be used to create a superposition of multiple frequency components from an input of single photon of one frequency component, equivalent to the wavelength division multiplexing scheme for multi-channel QKD, we need a single-photon source with corresponding frequency components from different lasers into one fiber. Such a technique combines multiple-wavelength components from different lasers into one fiber. The source so created has different channels that are independent of each other. So different information can be simultaneously transmitted over a single fiber, thus increasing the channel capacity of the fiber. In quantum communication, we may apply the same multiplexing technique on quantum information carriers, namely, photons. But since quantum information requires preservation of quantum superposition, different channels may not be independent to each other. Furthermore, in quantum key distribution (QKD) [25], a single-photon source is preferred to defeat the photon splitting attack. So, for multi-channel QKD, we need a single-photon source with WDM. In the WDM-QKD system, we can use multiple single-photon sources with different frequencies, just like in classical optical communication. However, single-photon sources are often from a single quantum system such as atom or ion, which gives rise to a single frequency. And sometimes we may also have only one such kind of system due to limited resources.

Using the frequency down-conversion scheme discussed earlier, we can create multiple frequency components from only one single-frequency source and implement the wavelength division multiplexing technique on single photons. The idea is to use light source of many wavelengths as the “signal” field to drive the three-wave mixing process (Fig.4). Due to energy conservation: $\omega_p = \omega_s + \omega_i$, the down-converted “idler” field will have different frequencies $\omega_1, \omega_2, \omega_3, ...$ corresponding to the different frequencies of the “signal” field. The system will behave like a multiple of beam splitters for the input pump field. If the input pump field is in a single-photon state $|1\rangle_p$, the output will be a superposition state of many frequencies: $|1\rangle_p \rightarrow \sum_k c_k |1_{\omega_k}\rangle$, realizing single-photon wavelength division multiplexing. The strong “signal” field of multiple wavelengths can be from a mode-locked laser [26] where all frequency components are coherent to each other so that the photon so-produced is in a superposition state of different frequencies. Such a wavelength division multiplexing scheme for quantum source preserves quantum entanglement.

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