

Spectral compression and frequency shifts of single photons by cascade modulation

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Spectral manipulation of single photons as an essential quantum technology provides a feasible method for highly efficient quantum interconnects between quantum systems with different transition linewidths via flying photons, which expands the capabilities of quantum networks. In this Letter, we propose a scalable scheme based on side-end cavity and time-dependent phase modulation, which allows the spectral compression of single photons by hundreds of times and even more, with an efficiency higher than active spectrum filtering. In addition, the achievable frequency shifts of single photons can reach hundreds of gigahertz. These techniques allow the implementation of a high-efficiency quantum interface between single photons and atomic quantum memories, as well as high-visibility quantum interference between two independent single photons. Our scheme opens up a way for hybrid quantum networks involving quantum systems with different transition linewidths.

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Introduction. Quantum interconnects [1] between distant quantum systems via flying photons are essential elements in the construction of hybrid quantum networks [2,3] which allow quantum information to be transmitted between separate network nodes and used in distributed quantum computing [4] and quantum sensing [5]. Quantum information processing platforms such as single atoms [6,7] or atom ensembles [8,9] are required to provide long storage times. The transition linewidth of these quantum systems is on the order of a few megahertz to tens of megahertz. Single photons are promising candidates for high-fidelity quantum information transmission [10] and can be emitted from a two-level quantum emitter, such as solid-state quantum dots [11]. To enhance the information-transfer capacity, short pulse durations are required to increase the repetition rate of single photons [12]. Typically, the spectral linewidth of high-performance single photons is on the order of gigahertz [13,14]. Matching the transition linewidth and wavelength between single photons and atom-based systems is an essential prerequisite for a highly efficient quantum interface [15–17]; one possible method is to compress the spectral linewidth of single photons.

Spectral manipulation of single photons has been demonstrated in recent years [18–25], based on the optical nonlinearities [18–21] or electro-optic time lens [22–24]. Frequency up-conversion or down-conversion, as the main nonlinear optical process, allows wavelength tuning over a wide range for single photons, but strong optical pumps are required and noise photons are inevitably generated at the same time. For electro-optic time lens schemes, stretching an optical pulse

from tens of picoseconds to hundreds of picoseconds, the amount of dispersion modulation needs to reach hundreds of ns nm^{-1} , which results in a significant photon loss for typical dispersion devices such as optical fibers and diffraction gratings [22–24]. On the other hand, the narrowband photons can be generated through coherent scattering processes [26–28], their spectral linewidth and wavelength depend on the excitation laser, but these scattered photons are nondeterministic during the generation process. Consequently, these approaches can hardly achieve the highly efficient spectral compression for deterministic single photons.

In this work, we propose a scalable scheme for spectral modulation of single photons using a side-end dispersive cavity and time-dependent phase modulation. The schematic diagram of single-level compression is illustrated in Fig. 1. In the first step, the single photons undergo chirping modulation in a dispersive cavity, and the wave packets are stretched in the time domain. Subsequently, a time-dependent phase modulation is applied to the chirped photons, which changes the energy distribution of the wave packets and concentrates more energy to the central frequency, thereby generating a narrowband spectrum. Finally, an effective compressed spectrum of single photons can be obtained using a filter cavity. Moreover, this technique can be easily extended from single-level to multilevel modulation, allowing a significant improvement in compression efficiency.

Chirping modulation by dispersive cavity. The single photons are emitted from a two-level quantum emitter, and the wave function can be represented as $\zeta_{\text{in}}[t] = \sqrt{\gamma} H(t) e^{-(i\omega_p + \gamma/2)t}$ in the time domain. Here, $\gamma(\omega_p)$ is the spectral linewidth (central frequency) of single photons and the Heaviside function $H(t)$ denotes that emission process of the two-level quantum emitter is on demand. Furthermore, the wave function of the single photons in the frequency domain is $\zeta_{\text{in}}[\omega] = \sqrt{\frac{\gamma}{2\pi}} \frac{1}{-i(\omega - \omega_p) + \gamma/2}$ via a Fourier transform.

The first step in spectral compression is to stretch the single-photon wave packets using dispersive devices so that

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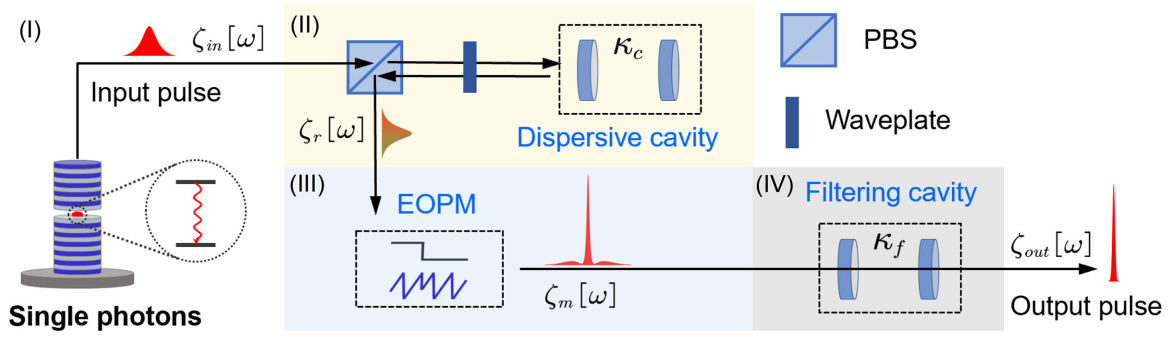


FIG. 1. The schematic diagram for spectral compression and frequency shifts of single photons under the single-level modulation. (I) Single photons are emitted from the two-level systems. (II) Chirping modulation of the single-photon wave packets is performed by a lossless dispersive cavity with the linewidth of κ_c . (III) A time-dependent phase modulation is applied by EOPM, which changes the spectral shape of chirped photons. (IV) The compressed spectrum of single photons is extracted by a filtering cavity with the linewidth of κ_f .

the different frequency components are spread out in the time domain. However, achieving a large spectral compression factor requires more dispersion modulation. For instance, compressing the spectral linewidth of single photons from approximately gigahertz to megahertz requires the amount of dispersion modulation up to $\sim 10^4 \text{ ns nm}^{-1}$, which results in an unbearable photon loss for typical dispersive devices such as optical fibers or diffraction gratings [22–24].

Optical cavities can also be utilized as dispersive medium and offer significantly large and tunable dispersion for optical pulses [29], as demonstrated in recently experiments [25,30]. In particular, a side-end optical cavity, in which the dissipation channel of light fields occurs only on the input coupling mirrors, is suitable to provide lossless dispersion modulation for single-photon wave packets, as shown in Fig. 1. The frequency response function of dispersive cavities is $\chi_c(\omega) = [-i(\omega - \omega_c) + \kappa_c/2]^{-1}$, where κ_c and ω_c are linewidth and central frequency of cavity mode, respectively. Only the frequency components of optical pulses that are near resonance with the cavity mode can enter the optical cavity, which generates chirped wave packets of single photons because the frequency components are spread out in time. Under the resonance conditions, i.e., $\omega_p = \omega_c$, the wave function of the chirped photons reflected from the lossless dispersive cavity is expressed as [25]

$$\zeta_r[\omega] = \sqrt{\frac{1}{2\pi}} \left(\frac{\kappa_c}{-i\omega + \kappa_c/2} - 1 \right) \frac{\sqrt{\gamma}}{-i\omega + \gamma/2}, \quad (1)$$

and the wave function in the time domain is written as

$$\zeta_r[t] = \frac{\sqrt{\gamma}}{\gamma - \kappa_c} [-(\gamma + \kappa_c)e^{-\gamma t/2} + 2\kappa_c e^{-\kappa_c t/2}] H(t). \quad (2)$$

This consists of two parts of the reflection field, one part is directly reflected from the input mirrors of the dispersive cavity, and the other is reflected from inner cavity, with a phase difference of π between the two parts. Therefore, a local minimum occurs at $\tau_{\min} = 2 \ln(\frac{\gamma + \kappa_c}{2\kappa_c}) / (\gamma - \kappa_c)$ in temporal intensity distribution $I_r(t) = |\zeta_r[t]|^2$ of the chirped photons, because of the destructive interference. This is shown in Fig. 2(a) with the red solid line.

Spectral shaping. To minimize the time-linewidth product of single-photon wave packets [25], a π phase jump at $\tau_{\min}$ is applied to the chirped photons by electro-optic phase modula-

tor (EOPM). The modulation signal [shown as the blue solid line in Fig. 2(a)] is represented by a step-type function

$$\phi(t) = -\pi H(t - \tau_{\min}). \quad (3)$$

In this case, the frequency components of the chirped photons are changed under the temporal phase modulation, and the sideband energy is shifted toward the central frequency. The resulting spectral shaping for single photons is generated, which is illustrated by the normalized spectral intensity $S_{m(\text{in})}[\omega] = |\zeta_{m(\text{in})}[\omega]|^2$ of the shaped (incoming) photons, as shown in red (gray) shadow area in Fig. 2(b). Here, $\zeta_m[\omega]$ is the wave function of the shaped photons in the frequency domain and is expressed as

$$\zeta_m[\omega] = \sqrt{\frac{1}{2\pi}} \frac{\sqrt{\gamma}}{\gamma - \kappa_c} \left\{ \frac{(\gamma + \kappa_c)[1 - 2e^{(i\omega - \gamma/2)\tau_{\min}}]}{i\omega - \gamma/2} - \frac{2\kappa_c[1 - 2e^{(i\omega - \kappa_c/2)\tau_{\min}}]}{i\omega - \kappa_c/2} \right\}. \quad (4)$$

To our knowledge, a linear temporal phase modulation signal [22,31] with the function of $\phi(t) = \alpha t$ is applied to the single-photon wave packets, and its central frequency is shifted from ω_p to $\omega_p + \alpha$. However, the amount of frequency shifts is limited by the achievable modulation depth of EOPM, especially for long-duration light pulses. To address this challenge, a sawtooth-shape phase modulation signal with a modulation depth of 2π is presented [32], which can be expressed as

$$\phi(t) = 2\pi f_m(t - nT_m) - \phi_0, \quad t \in [nT_m, (n+1)T_m], \quad n \in \mathbb{Z}. \quad (5)$$

Here, $f_m = 1/T_m$ is the modulation frequency of the EOPM, and the slope in each period is $\alpha = 2\pi f_m$. And ϕ_0 is the initial phase, as shown by the purple dotted line in Fig. 3(a).

Based on this periodic phase modulation scheme, a π phase jump is applied at the time point $\tau_{\min}$, and the phase modulation signal is depicted by the blue solid line in Fig. 3(a). Compared with the step-type phase modulation, our scheme allows simultaneous spectral shaping and frequency shifts of single photons [blue shadow area in Fig. 3(b)]. The maximal frequency shifts can reach hundreds of gigahertz for a high-speed EOPM with modulation frequency f_m of up to

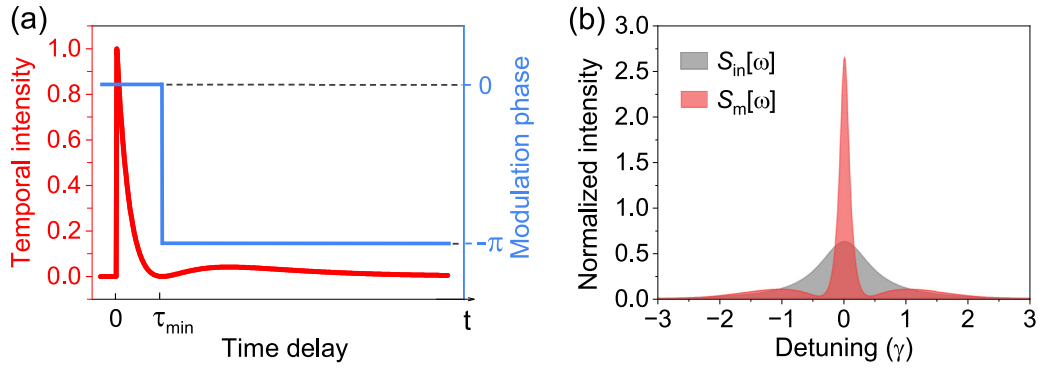


FIG. 2. Spectral shaping of single photons under temporal phase modulation, with the simulation parameter of $\kappa_c = 0.2\gamma$. (a) The temporal intensity distribution of single-photon wave packets after dispersion modulation (red solid line), where a local minimum appears at $\tau_{\min}$. A step-type temporal phase manipulation signal is then applied to single-photon wave packets (blue solid line). (b) The red (gray) shadow area represents the spectral intensity of the shaped (incoming) photons, which are normalized to the unit area.

several tens of gigahertz. Moreover, this scheme overcomes the inherent limitation imposed by the modulation depth of EOPM and is suitable for arbitrarily long-duration light pulses.

Spectral compression and extraction. The spectral envelope of the shaped photons consists of one narrow central peak and two broad sideband peaks, as shown in Fig. 2(b). Under the conditions of $\kappa_c \ll \gamma$, the insets in Fig. 4(a) show that the spectral envelop of the central peak is close to a standard Lorentz lineshape (red curve), with a full width at half maximum (FWHM) of κ_c . This means that a Lorentz-shape spectrum can be obtained by applying resonant cavity as a spectral filter to extract central peak from the shaped spectrum, and the filtered spectrum is shown by the blue shadow area in Fig. 4(a). Since the spectral lineshape of the filtered photons is identical to that of the initial incoming photons, the spectral compression factor of single photons can be defined as $\Lambda = \gamma/\kappa_c$.

Furthermore, the compression efficiency of the single-photon spectrum can be calculated as

$$\eta = \frac{\int_{-\infty}^{+\infty} S_m[\omega] \chi_f(\omega) d\omega}{\int_{-\infty}^{+\infty} S_m[\omega] d\omega}, \quad (6)$$

where $\chi_f(\omega) = \kappa_f^2/(4\omega^2 + \kappa_f^2)$ is the spectral response function of the resonant filter cavity with the linewidth of κ_f , which is typically five times of the linewidth of the central peak. Figure 4(b) plots the compression efficiency as a function of compression factor (blue solid line), which clearly shows that our scheme can achieve higher efficiency than direct spectrum filtering of the incoming photons (red solid line) under the same compression factor. That is because the sideband energy of the single-photon wave packets is concentrated to the central frequency by phase modulation, as shown in Fig. 2(c). However, when taking into account the insertion loss of phase modulator, with typical values of 2.4 dB [24], the practical compression efficiency decreases by a factor of 1.7, but remains higher than that of direct spectrum filtering, as shown in green solid line in Fig. 4(b). At the compression factor of $\Lambda = 10$, the compression efficiency of the single-photon spectrum without (with) insertion loss reaches 53.4% (31.4%), which is ~ 5.9 (~ 3.5) times that of direct spectrum filtering. For a larger compression factor of $\Lambda = 100$, the compression efficiency without (with) insertion loss reaches 8.1% (4.8%), which is ~ 8.1 (~ 4.8) times that of direct spectrum filtering.

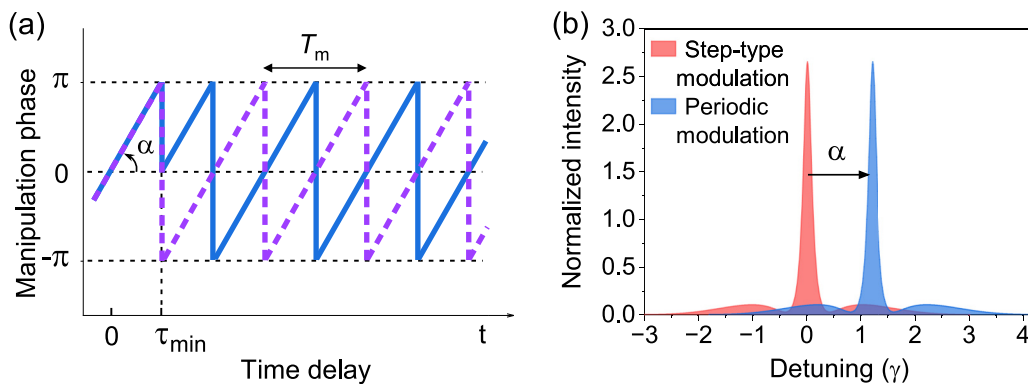


FIG. 3. The spectral shaping and frequency shifts of single photons under periodic temporal phase modulation. (a) The periodic phase modulation signal with a modulation depth of 2π and a period of T_m (purple dotted line). Based on this, an additional π phase jump at $\tau_{\min}$ is applied (blue solid line). (b) The spectral shaping and frequency shifts of single photons can be achieved, simultaneously, which is represented by the blue shadow area. The red shadow area shows the spectral shaping obtained under the step-type phase modulation.

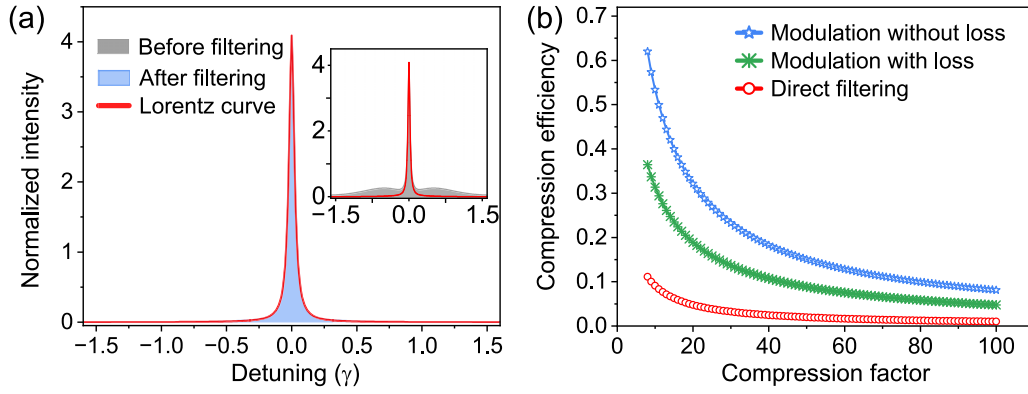


FIG. 4. Spectral compression of single photons. (a) The blue (gray) shadow area represents normalized spectral intensity of shaped photons after (before) an optical filtering cavity, with the simulation parameters of $\kappa_c = 0.05\gamma$ and $\kappa_f = 0.25\gamma$. The red solid line is a standard Lorentz curve with the linewidth of κ_c . (b) The compression efficiency of spectral linewidth as a function of the compression factor under the modulation schemes without loss (blue solid line), with loss (green solid line), and direct filtering (red solid line).

Cascade modulation for spectral compression. High-efficiency spectral compression of single photons is a critical prerequisite for quantum interconnects. Figure 4(b) shows that the compression efficiency rapidly decreases as the compression factor increases. This is because the chirping modulation range is focused toward the central frequency of the single photons as the linewidth of dispersive cavity decreases. As a result, most frequency components cannot be shifted to the central frequency of single photons under the time-dependent phase modulation and are ultimately filtered out through a filtering cavity.

To address this problem, we design a cascade method to implement multilevel modulation, as illustrated in Fig. 5(a). Each level of modulation undergoes a chirping modulation by a lossless dispersive cavity and a time-dependent π phase jump by an EOPM. For an N -level modulation scheme, the linewidth $\kappa_{c,n}^N$ ($n = 1, 2, \dots, N$) of n th dispersive cavity gradually decreases until it reaches a compression factor of $\Lambda = \gamma/\kappa_{c,N}^N$. Compared with single-level modulation under the same compression factor, most of the sideband energy of the single photons can be transported to central frequency under the cascade scheme. Therefore, the compression efficiency of single-photon spectrum is significantly improved by multilevel modulation, and the maximal compression efficiency occurs at $\kappa_{c,n}^N = \gamma\Lambda^{-n/N}$ for n th dispersive cavity. The π phase jump for n th level temporal phase modulation is applied at the time point

$$\tau_{\min,n}^N = \begin{cases} 2 \ln \left(\frac{\gamma + \kappa_{c,1}^N}{2\kappa_{c,1}^N} \right) / (\gamma - \kappa_{c,1}^N), & n = 1, \\ 2 \ln \left(\frac{\kappa_{c,n-1}^N + \kappa_{c,n}^N}{2\kappa_{c,n}^N} \right) / (\kappa_{c,n-1}^N - \kappa_{c,n}^N), & n \geq 2. \end{cases} \quad (7)$$

Figure 5(b) plots the normalized spectral intensity of single photons via single- (two-, three-) level modulation under the same compression factor of $\Lambda = 100$. As the modulation level increases, more and more energy of single photons is concentrated to central frequency, resulting in a significant improvement in the area proportion of central spectrum peak, as shown in the insets within of Fig. 5(b). Figure 5(c) depicts the compression efficiency of single-photon spectrum as a

function of compression factor. Under the three-level modulation, the compression efficiency reaches up to 54.3% for a compression factor of $\Lambda = 100$, which is ~ 6.7 (~ 1.9) times that of single- (two-) level modulation. More importantly, the advantages of cascade scheme become more noticeable at higher compression factors. At $\Lambda = 1000$, the compression efficiency of three-level modulation reaches 15.0%, which is ~ 18.5 (~ 3.1) times that of single- (two-) level modulation. This allows a highly efficient quantum interface between single photons with the spectral linewidth of approximately gigahertz and atomic quantum memories with the linewidth of approximately megahertz. Moreover, the compression efficiency can be further improved by adding more levels modulation.

Taking into account the current experimental technology, the advantages of multilevel modulation scheme are finitely limited by the practical insertion loss of the phase modulator within smaller range of spectral compression factor, as shown in Fig. 5(d). For a typical insertion loss of 2.4 dB in each level of modulation [24], the compression efficiency reaches 11.0% for three-level modulation at $\Lambda = 100$, which is ~ 2.3 (~ 1.4) times that of single- (two-) level modulation. However, the advantages of cascade scheme are still remarkable at large compression factor. For instance, at $\Lambda = 1000$, the compression efficiency of three-level modulation is ~ 6.4 (~ 1.8) times that of single- (two-) level modulation, and ~ 30.0 times higher than that of direct filtering.

Conclusions. In summary, we have presented a scalable modulation scheme for implementation of the spectral compression and frequency shifts of single photons. The proposed technique allows the spectral linewidth to be compressed from approximately gigahertz to megahertz with high efficiency by employing the multilevel modulation, which enables the linewidth matching between flying photons and atomic quantum memories. Our scheme also allows the amount of frequency shifts of single photons to reach the hundreds of gigahertz. These techniques can be used for high-visibility quantum interference between independent single photons [33,34] and for high-efficiency quantum interface between single photons and atom-based systems [35].

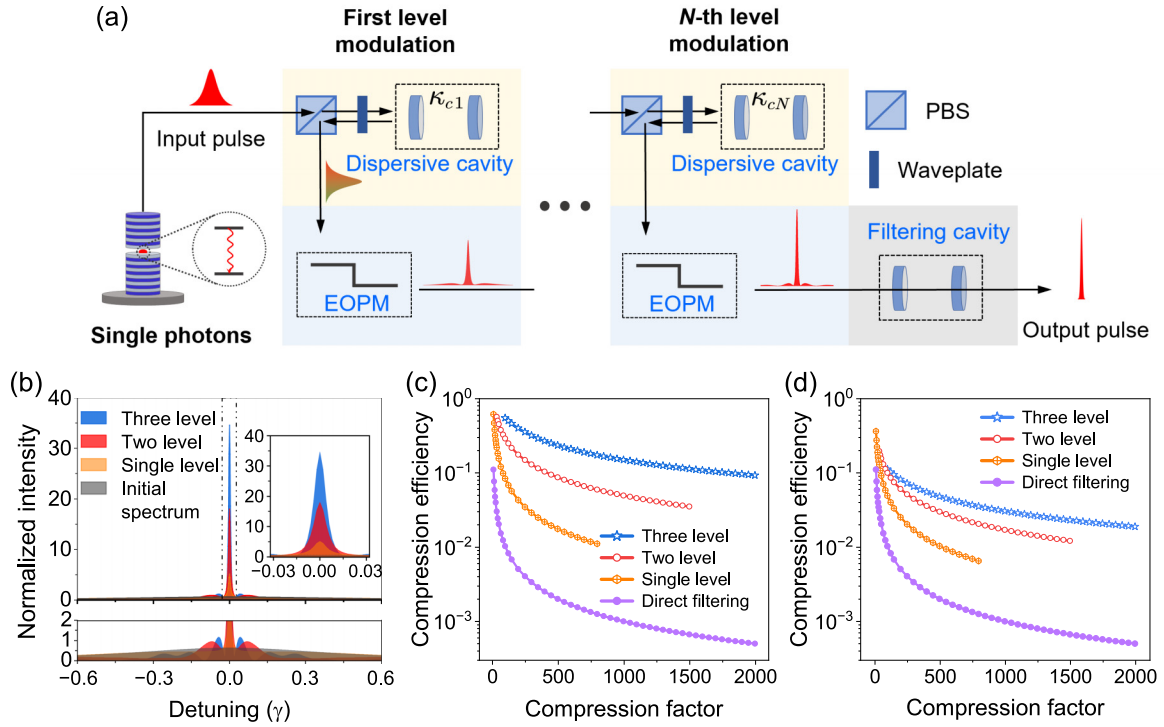


FIG. 5. (a) The schematic diagram of cascade modulation scheme for spectral compression of single photons. Each level of modulation undergoes a chirping modulation by a lossless dispersion cavity and a time-dependent π phase jump by an EOPM. (b) The spectral shaping of single photons under the single- (two-, three-) level modulation is represented by the orange (red, blue) shadow area, respectively. The compression efficiency as a function of compression factor is shown in panel (c) without insertion loss and in panel (d) with insertion loss of 2.4 dB for single phase modulator.

Compared with fiber-based dispersion devices, the side-end optical cavity allows a lossless chirping modulation for single-photon wave packets and significantly enhances the scalability of modulation scheme. More importantly, the side-end optical cavity can be used as a polarization-independent dispersive device; this technique is thus applicable to polarized-encoded entangled photons [36,37]. Although the advantages of the multilevel modulation strategy at smaller compression factor are currently limited by the insertion loss of phase modulator, the compression efficiency of single-photon spectrum still remains higher than that of direct filtering, especially for large compression factors. Looking ahead, the development of ultra-low-loss EOPMs will further improve the compression efficiency of single-photon spectrum.

Furthermore, our scheme is applicable to single photons over a wide range of wavelengths, from the near-infrared to the telecom band, requiring only an adjustment of the resonance frequency of the dispersive cavity. This technique is not limited to single photons with Lorentzian lineshape and can be also adapted to other spectral lineshape, including the Gaussian lineshape and so on. If there are multiple lineshape components in single-photon spectrum, the compression efficiency is limited when the spectral intensity or linewidth of lineshape components are different significantly.

But for high-performance quantum light sources in current experiments, such as quantum dots single-photon sources, which is nearly close to Fourier limited. Overall, our scheme provides a feasible way for implementing quantum interconnect with high efficiency and for use in hybrid quantum networks.

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Data availability. The data supporting this study's findings are available within the article.

Appendix: Spectral compression under the current experimental technology. The standard approach to generate temporal phase modulation signal is to use an arbitrary waveform generator (AWG) to drive an EOPM. Owing to the finite electronic bandwidth of EOPM and driving electronics, the output square waveform exhibits rising/falling edges. An imperfect step-type temporal phase modulation signal with a finite fall time τ_d is thus generated, and the falling edge at $\tau_{\min}$ can be approximatively expressed as a linear waveform with a slope of $\delta = -\pi/\tau_d$, shown as the blue solid line in Fig. 6(a). In this case, the wave function of shaped photons in the frequency domain can be

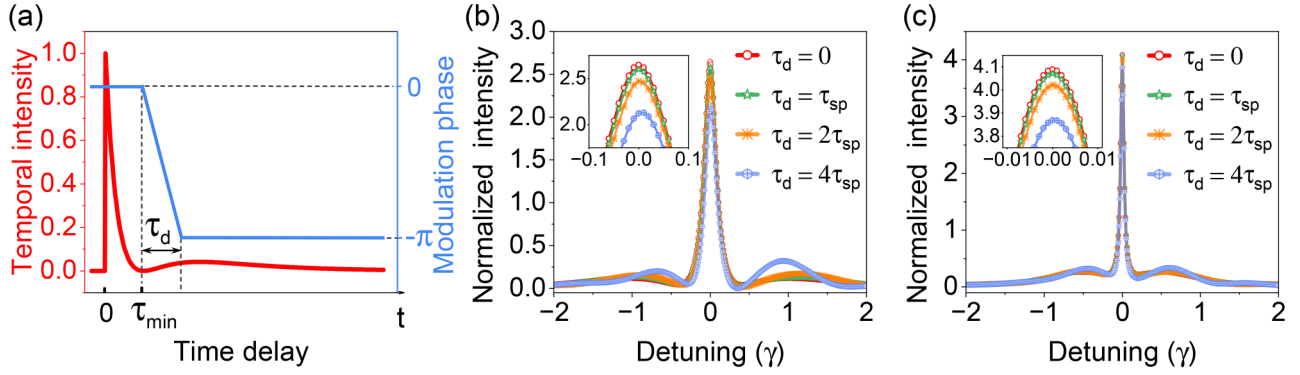


FIG. 6. Spectral shaping of single photons under the temporal phase modulation. (a) A step-type phase modulation signal with a finite fall duration τ_d is applied to chirped wave packets of single photons, with a π phase jump at $\tau_{\min}$. Normalized spectral intensity of the shaped photons (red, green, yellow, and blue solid line) under different fall durations $\tau_d = \{0, \tau_{\text{sp}}, 2\tau_{\text{sp}}, 4\tau_{\text{sp}}\}$ of the temporal phase modulation signal, using the simulation parameter of (b) $\kappa_c = 0.2\gamma$ and (c) $\kappa_c = 0.05\gamma$.

calculated as

$$\begin{aligned} \zeta'_m[\omega] &= \int_0^{\tau_{\min}} \zeta_r[t] e^{i\omega t} d\omega + \int_{\tau_{\min}}^{\tau_{\min}+\tau_d} \zeta_r[t] e^{-i\delta(t-\tau_{\min})} e^{i\omega t} d\omega + \int_{\tau_{\min}+\tau_d}^{+\infty} \zeta_r[t] e^{-i\pi} e^{i\omega t} d\omega \\ &= \sqrt{\frac{1}{2\pi}} \frac{\sqrt{\gamma}}{\gamma - \kappa_c} \left\{ \begin{aligned} &\frac{\gamma + \kappa_c}{i\omega - \gamma/2} [1 - (1 + e^{(i\omega - \gamma/2)\tau_d}) e^{(i\omega - \gamma/2)\tau_{\min}}] \\ &+ \frac{\gamma + \kappa_c}{i(\omega - \delta) - \gamma/2} (1 - e^{[i(\omega - \delta) - \gamma/2]\tau_d}) e^{(i\omega - \gamma/2)\tau_{\min}} \\ &- \frac{2\kappa_c}{i\omega - \kappa_c/2} [1 - (1 + e^{(i\omega - \kappa_c/2)\tau_d}) e^{(i\omega - \kappa_c/2)\tau_{\min}}] \\ &- \frac{2\kappa_c}{i(\omega - \delta) - \kappa_c/2} (1 - e^{[i(\omega - \delta) - \kappa_c/2]\tau_d}) e^{(i\omega - \kappa_c/2)\tau_{\min}} \end{aligned} \right\}. \end{aligned} \quad (\text{A1})$$

Figure 6(b) plots the normalized spectral intensity $S'_m[\omega] = |\zeta'_m[\omega]|^2$ of the shaped photons under temporal phase modulation signal with different fall times τ_d , using the simulation parameter of $\kappa_c = 0.2\gamma$. This shows that a finite falling edge at $\tau_{\min}$ has a negligible influence on the spectral shaping of single photons within the range of $\tau_d < 2\tau_{\text{sp}}$, where $\tau_{\text{sp}} = 1/\gamma$ is the lifetime of incoming photons. For a high-speed phase modulator and driving electronics with an electronic bandwidth of tens of gigahertz, the fall time τ_d is on the order

of ten to a few tens of picoseconds, which is shorter than the lifetime of the incoming photons, typically on the order of tens to a few hundred picoseconds. Especially for longer duration wave packets of chirped photons via significant dispersion modulation, the spectral shapes are hardly affected by the finite electronic bandwidth of high-speed phase modulator and driving electronics, which is illustrated in Fig. 6(c), using the simulation parameter of $\kappa_c = 0.05\gamma$. Therefore, our scheme is within reach of current experimental technology.

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