Spectral compression of biphotons using time-varying cavities for quantum networking

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Abstract: We propose and analyze the use of linear, time-variant cavities for spectral compression of broadband frequency correlated photon pairs, with potential applications in quantum networking. Our time-varying cavity relies on rapid electro-optic switching of input coupling to the cavity.

Quantum networks generally consist of different platforms like matter-based systems for memory and photons for long-distance transportation. The efficient interfacing of these disparate systems is vital for the functioning of quantum networks. Generally, photons generated from spontaneous parametric downconversion (SPDC) sources are broadband (a few hundred GHz or more), whereas the memory nodes are narrowband (a few hundred MHz or less). Hence, spectral compression of broadband photons is inevitable for their efficient interaction. The conventional approaches to spectral compression include nonlinearity and time-lens based schemes. In our recent work [1], we proposed a novel scheme of using linear, time-variant cavities as a new route to spectral compression. Our scheme is based on rapid switching of input coupling to the cavity, violating the time-invariance consequently resulting in spectral compression. Time-varying cavities have been explored for various applications like wavelength conversion [2], and non-reciprocal devices [3]. Unlike these works based on intracavity phase modulation, we exploit switching of input coupling thereby widening the breadth of time-varying photonic systems.

In our previous work, we analyzed the spectral compression of single photons. Here, we explore and analyze the spectral compression of broadband frequency correlated photon pairs (biphotons) to generate biphoton frequency combs (BFCs). BFCs have fueled the attention to quantum information processing in the frequency domain owing to its inherent high-dimensionality and compatibility with fiber-optic networks. BFCs are generally produced either using spectral filtering of broadband biphotons from SPDC ($\chi^{(2)}$) waveguide sources or through spontaneous four-wave mixing (SFWM) in integrated $\chi^{(3)}$ microrings [4]. $\chi^{(2)}$ sources are typically brighter than the $\chi^{(3)}$ counterparts. However, spectral filtering of broadband SPDC biphotons to produce BFCs suffers strong insertion loss. We propose to avoid these losses by rapidly switching the input coupling to the cavity from unity to zero just after the biphoton enters the cavity. This also allows for indistinguishability between such spectrally compressed broadband biphotons and BFCs from integrated microrings, enabling the prospective of hybrid quantum networks.

Fig. 1(a) illustrates the concept of our scheme for single photons, yet extendable to biphotons. In the discussions, we consider a Fabry-Perot (FP) cavity without loss of generality. We switch the reflectivity of the input mirror from zero to one once the input photon enters the cavity. Now, the entire biphoton is captured inside the cavity, avoiding any reflection losses onto the input side. The captured biphoton has to eventually exit through the partially reflecting output mirror. The output temporal biphoton wavefunction contains multiple copies of the input biphoton wavefunction with exponentially decreasing amplitude. The temporal copies have fixed relative delay—equal to cavity roundtrip time—in both signal and idler times. These copies are also phase-locked to each other, resulting in spectral compression. In Fig. 1(b), we also show a possible implementation on an integrated platform using a ring resonator cavity that is configured with a Mach-Zehnder interferometer (MZM). MZM on the input side allows for modifying the input coupling and the drop port is analogous to the output mirror of the FP cavity.

Consider an FP cavity, with the input and output field reflection (transmission) coefficients given by $r_1(t_1)$ and $r_2(t_2)$, respectively. r_1 is rapidly switched from 0 to 1 at $t = T_R$, where T_R represents the roundtrip time. r_2 is partially reflecting and time-invariant. The intracavity loss is assumed to be 0. Lets consider an input biphoton characterized by its spectral wavefunction $\psi_{in}(\omega_s, \omega_i)$, where $\omega_s(\omega_i)$ represents the signal (idler) frequencies. The output biphoton wavefunction $\psi_{out}(\omega_s, \omega_i)$ of our time varying cavity is given by:

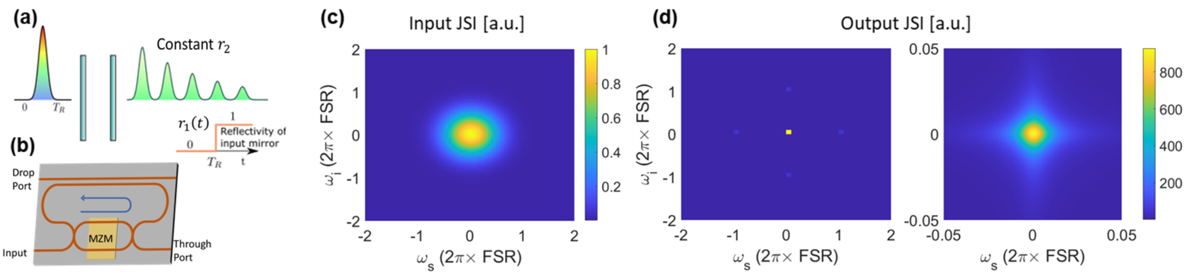

Fig. 1. (a) Schematic of our time-varying cavity. (b) Integrated photonics implementation. (c) Input and (d) output JSI for $\psi_{in} \propto e^{[(\omega_s+\omega_i)/2\pi]^2} e^{[(\omega_s-\omega_i)/2\pi]^2} \times e^{-j(\omega_s+\omega_i)T_R/2}$. In (d), both zoomed-out (left) and zoomed-in (right) versions are shown. Plots are normalized to peak input spectral intensity.

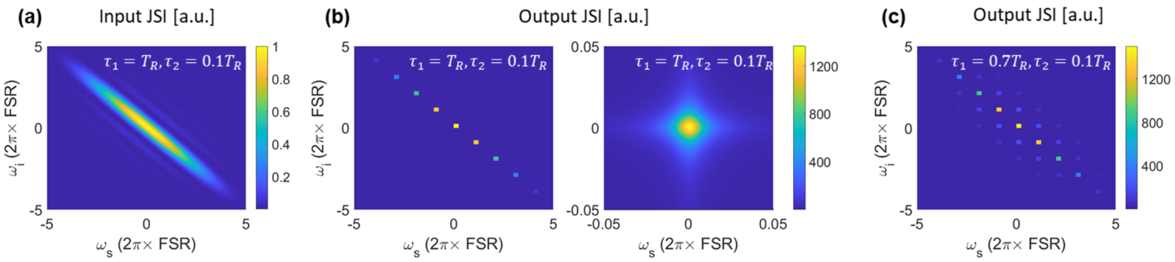

Fig. 2. $\psi_{in} \propto sinc[(\omega_s+\omega_i)\tau_1/2]sinc[(\omega_s-\omega_i)\tau_2/2] \times e^{-j(\omega_s+\omega_i)T_R/2}$. (a) Input and (b) output JSIs shown for $\tau_1 = 1, \tau_2 = 0.1$. (c) Output JSI for $\tau_1 = 0.7, \tau_2 = 0.1$. Plots are normalized to peak input spectral intensity.

$$\psi_{out}(\omega_s,\omega_i) = \int_{-\infty}^{\infty}\int_{-\infty}^{\infty} H(\omega_s,\omega_s')H(\omega_i,\omega_i')\psi_{in}(\omega_s',\omega_i')d\omega_s'd\omega_i'$$
$$H(\omega,\omega') = \left(\frac{T_R}{2\pi}\right)\frac{t_2 e^{-j\omega\frac{T_R}{2}}}{1-r_2 e^{-j\omega T_R}} e^{-j(\omega-\omega')\frac{T_R}{2}}\,sinc\left[(\omega-\omega')\frac{T_R}{2}\right] \tag{1}$$

We here note that $H(\omega,\omega')$ is the impulse response of our linear time-variant system, which describes the transfer of input frequency content at ω' to ω at the output [5]. This frequency transfer between the input and output is indeed stemming from the time variance of the linear cavity.

We illustrate this concept by considering different examples of biphoton wavefunctions. Previous works have explored the engineering of pump pulses and phase-matching for producing spectrally separable biphotons [6]. The input and output joint spectral intensities (JSIs) are plotted in Fig. 1(c) and (d), respectively, for a spectrally factorable $\psi_{in} \propto e^{-[(\omega_s+\omega_i)T_R/2\pi]^2} e^{-[(\omega_s-\omega_i)T_R/2\pi]^2} \times e^{-j(\omega_s+\omega_i)\tau_s}$. The central frequencies of the signal and idler are assumed to coincide with different cavity resonances to facilitate maximum spectral compression. We set $\tau_s = T_R/2$ to better localize the input between $t=0$ and $t=T_R$. $r_2 = 0.95$ is assumed. We can notice that the majority of the input wavefunction gets compressed into the resonance at $\omega_s = \omega_i = 0$ (spectral narrowing along with peak enhancement). In the left column of Fig. 1(d), a poorer resolution is chosen for the clear visibility of peaks. The plot on the right zooms in on the spectral compression peak at $\omega_s = \omega_i = 0$. The spectral compression (ratio of input FWHM to output FWHM) of each of the individual photons is ≈ 53, which is essentially dictated by the cavity linewidth. The corresponding peak enhancement in the biphoton JSI is ≈ 930.

We next consider time-energy entangled biphotons of the form $\psi_{in} \propto sinc[(\omega_s+\omega_i)\tau_1/2]sinc[(\omega_s-\omega_i)\tau_2/2] \times e^{-j(\omega_s+\omega_i)\tau_s}$ to produce BFCs. Here, τ_1 and τ_2 determine the spread of the biphoton wavefunction, and $\tau_s = T_R/2$ sets the input arrival time. τ_1 is related to the temporal width of the pump pulse. For $\tau_1 = T_R$ and $\tau_2 = 0.1T_R$, we have shown the input and output wavefunctions in Fig. 2(a) and (b), respectively. In Fig. 2(b), the plot on the right zooms in on the peak at $\omega_s = \omega_i = 0$. We can clearly see that the input broadband biphoton gets compressed into multiple resonance peaks forming a BFC. The coincidence-to-accidental ratio (CAR), defined as the ratio between the mean of diagonal peaks to that of anti-diagonal peaks, is ≈ 255. Also from the zoomed-in version shown in Fig. 2(b), we note that the peaks assume a spectrally factorable form with their widths identically equal to the cavity linewidth in both ω_s and ω_i axes, whereas the input biphoton is not spectrally factorable. This is in accordance with erasing the time-energy entanglement using narrow spectral filters [7]. However in our work, instead of discarding the energy blocked by the spectral filters, all the energy is retained but is spectrally compressed. For $\tau_1 = 0.7T_R$ and $\tau_2 = 0.1T_R$, the output is shown in Fig. 2(c). In addition to the diagonal peaks, spectral compression also occurs at off-diagonal locations reducing the CAR to 20. Hence, we would like to roughly match τ_1 to the roundtrip time so that energy is primarily compressed into diagonal peaks.

In our earlier work [1], we have analyzed the performance of our system considering various practical scenarios including cavity losses and finite rise-time for switching input coupling for single photons. We anticipate presenting a more comprehensive analysis for the case of biphoton compression at the conference talk if selected. Our concept is implementation-agnostic and should apply to any resonance with rapidly switchable coupling - ranging from electro-optic microring resonators to time-varying metamaterials.

Funding. National Science Foundation (ECCS-1809784); Air Force Office of Scientific Research (FA9550-20-1-0283)

References

1. K. V. Myilswamy and A. M. Weiner, Opt. Lett. **45**, 5688 (2020).
2. S. F. Preble, Q. Xu, and M. Lipson, Nat. Photonics **1**, 293 (2007).
3. H. Lira, Z. Yu, S. Fan, and M. Lipson, Phys. Rev. Lett. **109**, 033901 (2012).
4. M. Kues, C. Reimer, J. M. Lukens, W. J. Munro, A. M. Weiner, D. J. Moss, and R. Morandotti, Nat. Photonics **13**, 170-179 (2019).
5. L. A. Zadeh, Proceedings of the IRE **38**, 291-299 (1950).
6. F. Laudenbach, H. Hübel, M. Hentschel, P. Walther, and A. Poppe, Opt. express **24**, 2712-27 (2016).
7. K. Laiho, K. N. Cassemiro, and C. Silberhorn, Opt. express **17**, 22823-22837 (2009).