Enhancing the Quantum Correlation of Biphotons via Coherent Energy Redistribution

Benjamin Crockett[1], Nicola Montaut[1], James van Howe[1,2], Piotr Roztocki[1,3], Yang Liu[1,4,5], Robin Helsten[1], Wei Zhao[4,5], Roberto Morandotti[1], José Azaña[1]

[1]Institut national de la recherche scientifique, centre Énergie Matériaux Télécommunications (INRS-EMT), Montréal, Québec, Canada
[2]Augustana College, Department of Physics and Astronomy, Rock Island, IL, USA
[3]Ki3 Photonics Technologies Inc., Montréal, Québec, Canada
[4]State Key Laboratory of Transient Optics and Photonics, Xi'an Institute of Optics and Precision Mechanics (XIOPM), Chinese Academy of Sciences, Xi'an 710119, China
[5]University of Chinese Academy of Sciences, Beijing 100049, China
Benjamin.crockett@inrs.ca

Abstract: Towards meeting the strict demands of practical quantum networks, we leverage coherent energy redistribution for noise-tolerant quantum signal processing. We demonstrate the enhancement of noisy biphoton coincidence-to-accidental ratios by up to 3.8 times.

1. Introduction

The rapid growth of quantum technologies is expected to bring considerable social and economic impact through the advent of a quantum internet, which will enable a wide range of major functionalities including secure communication, clock synchronization, quantum sensor networks, and remote-access quantum computing [1]. Photonics will play a principal role towards this goal, although a variety of systems needed for quantum networks remain underdeveloped. These include, for example, quantum repeaters, memories, processors, as well as efficient schemes for transferring quantum states between photons and matter-based units [2,3]. A major hurdle that plagues the development of all of such units is noise robustness, as quantum states are extremely sensitive to parasitic photons that degrade signal-to-noise ratios (SNRs) below the levels required to carry out the intended functionality. For instance, quantum key distribution (QKD), arguably one of the most popular quantum photonic network technologies, is still fundamentally limited by noise. This has caused the vast majority of experimental demonstrations of quantum communication links to be done under impractical and ideal conditions to avoid the injection of unwanted photons. In fiber optic links, most experiments are done in so-called "dark fibers" [4], which are communication links devoid of any classical signals, in order to reduce the impact of amplified spontaneous emission (ASE) noise generated from erbium-doped fiber amplifiers (EDFAs), as well as parasitic spontaneous four-wave mixing (SFWM) noise caused by the propagation of classical signals in optical fiber, even at moderate powers [5]. In free-space satellite communication links, stray light from the sun forces transmissions to occur mostly at night [6], severely limiting the operation time unless sophisticated setups are implemented to increase the SNR [7]. As such, there continues to be a sustained effort to develop mitigation techniques for improving the noise tolerance of quantum communication schemes, such as using ultrafast temporal

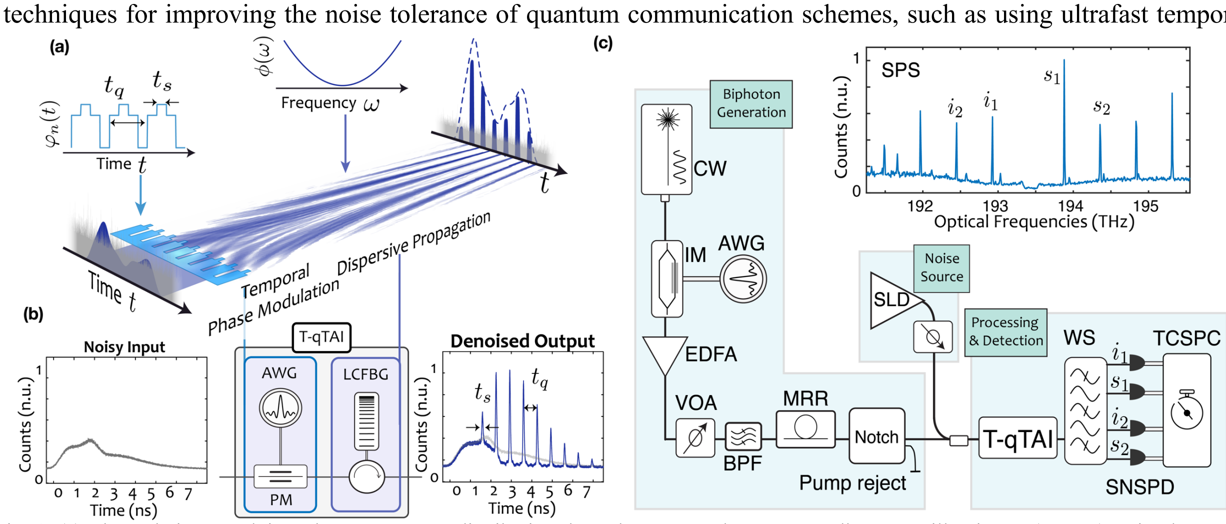

Fig. 1. (a) The technique exploits coherent energy redistribution through a temporal quantum Talbot array illuminator (t-qTAI) to implement a denoising process on the photon's wavefunction. (b) The scheme is comprised of multi-level phase modulation followed by dispersion to redistribute the wavefunction into peaks following the input waveform's envelope, allowing for efficient time filtering in post-processing. (c) Experimental setup and single-photon spectrum (SPS) measured from our silicon nitride micro-ring resonator, showing the resonances of the two signal-idler pairs employed here. Acronyms are defined in the main text.

gating [8], high-dimensional states [9], and multicore optical fibers [10]. Whereas some of these techniques are appropriate in specific systems, none of them offer a broad solution for a practical, general quantum network. Many are either too complex and have stringent demands on stability that limit their use outside well-controlled laboratories [8,9] or they would require significant modifications to existing telecommunications infrastructure [10].

Here we present a novel approach for enhancing the SNR of quantum states, based on passive energy redistribution implemented via a temporal quantum Talbot array illuminator (T-qTAI). Based on the Talbot effect, this framework has been recently employed to improve the SNR and bit error rate of classical data telecommunication signals [11]. Its noise mitigation capabilities are demonstrated for quantum states here for the first time. Specifically, we demonstrate a notable SNR improvement for a heralded single photon source based on a silicon nitride (SiN) microring resonator (MRR, procured from Ki3 Photonics Technologies). In particular, we show a significant increase of the coincidence-to-accidental ratio (CAR, analogous to classical SNR), a key metric intimately related to the quantum bit error rates of QKD protocols [12,13]. Our work paves the way towards noise-tolerant processes as required for practical realizations of quantum networking.

2. Operation Principle and Experimental Results

As depicted in Fig. 1(a), the T-qTAI implements a coherent energy redistribution on the temporal profile of the photons. By exploiting phase modulation and dispersion, the continuous profile of the input waveform is transformed into temporal peaks discretizing the envelope of the original waveform but with an increased count rate. Since this technique relies on the coherence of the underlying waveform, the input signal is processed while the noise, which is incoherent, is left unaltered [11]. As a result, a significant portion of the background noise can be discarded by temporally filtering the output peaks in post-processing. As shown in the experimental implementation of the T-qTAI in Fig. 1(b), the signal is redistributed into a series of peaks of width t_s separated by $t_q = qt_s$, where q is the enhancement factor, which is an integer number proportional to the compression (and height) of the output peaks. Therefore, the key requirement for enhancement of a given quantum state is that the temporal profile should extend over a duration longer than t_q, and the detection scheme should have sufficient resolution to resolve the output peaks for optimal denoising. Otherwise, the proposed scheme can process most, if not all, quantum states (i.e., single-, entangled-, high-dimensional, etc.).

The T-qTAI is achieved by first modulating the temporal phase following a multi-level step function, where each level has a duration t_s. The n^{th} level satisfies $\varphi_n(t) = -n^2\pi(q-1)/q$, for $n = 1 \ldots q$, forming a periodic sequence of length t_q. The modulated waveform then undergoes dispersive propagation where the second-order dispersion $\ddot{\phi}$ satisfies $2\pi\ddot{\phi} = qt_s^2$. Here, we experimentally implement the phase function by using a 92-GSa/s electronic arbitrary waveform generator (AWG) driving a 40-GHz electro-optic phase modulator (PM) to generate a phase function with $t_s = 47.8$ ps and an enhancement factor of $q = 14$. The dispersive propagation is realized through a linearly-chirped fiber Bragg grating (LCFBG) providing ~-5,082 ps^2, equivalent to ~240 km of single-mode fiber.

In the experiment shown here, we employ a carved continuous wave (CW) pumping scheme to generate the biphotons from a SiN MRR. As shown in Fig. 1(c), the pump beam is generated by shaping a CW laser into 640-ps wide sinc pulses at a repetition rate of 51.5 MHz using an electro-optic intensity modulator (IM) driven by an AWG, producing a flat-top spectrum to ensure stable pumping operation. This signal is then amplified using an EDFA, and a variable optical attenuator (VOA) is employed to adjust the pump power. A high-rejection bandpass filter (BPF) is used to remove the noise in the pump beam prior to entering the SiN MRR. The pump is then suppressed using a high-rejection notch filter, granting access to a total of four signal-idler pairs, each with a resonance width of ~160 MHz (full-width at half maximum) separated by 500 GHz. The two pairs employed in this study are labeled by $s_{1,2}$ and $i_{1,2}$ in the inset of Fig. 1(c) depicting the single photon spectrum (SPS). The biphoton correlations are then purposedly deteriorated by injecting ASE noise generated by a superluminescent diode (SLD), whose contribution is controlled by a second VOA. We note that additional noise comes from parasitic SFWM generated by the pump propagating in the short length of fiber between the BPF and the notch filter. The noisy biphotons are processed by the T-qTAI, and each resonance is separated by a waveshaper (WS) and individually detected via four superconducting nanowire single-photon detectors (SNSPDs) connected to a time-correlated single-photon counter (TCSPC).

We show the measurement outcomes in Fig. 2 for the first signal-idler pair, set for a pump power of 0.3 mW and a noise count rate of 129.7 kHz. To analyze the enhancement effect of the proposed scheme, we compare the processed signal obtained with the phase modulator turned on (PM on) vs the phase modulator turned off (PM off), effectively neglecting the insertion losses of the T-qTAI scheme, estimated to be ~7.5 dB (2.5 dB for the PM, 5 dB for the LCFBG). We note that a loss-optimized implementation of these components could reduce the insertion loss to ~4 dB, while the dispersion from the fiber employed in a quantum network could be harnessed to avoid the use of LCFBGs and allow for even lower insertion loss values. The unprocessed (i.e., PM off) waveform is shown in Fig.

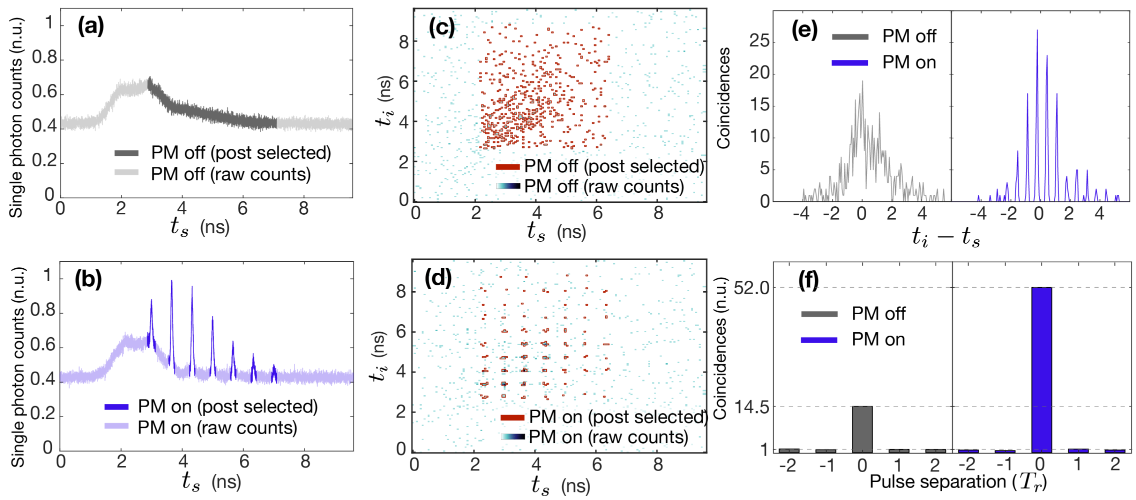

Fig. 2. (a) Temporal profile of the noisy idler with a pump power of 0.3 mW and a noise count rate of 129.7 kHz, with the phase modulator turned off (PM off). It is not possible to directly resolve the biphoton counts from the noisy background. (b) Temporal profile of the processed waveform (PM on), allowing for temporal filtering. (c) 2D temporal distribution of the signal-idler pair with the PM off and (d) with the PM on. (e) The observed enhancement can also be seen through the temporal correlations. (f) Improvement in the CAR by a factor of 3.8 using the T-qTAI.

2(a). Notice a visible noise bump near the 2-ns mark resulting from parasitic SFWM generated in the short fiber length outside the cavity mentioned above, along with a significant noise background present throughout. As such, during post-processing, it is not possible to isolate the biphoton waveform from the noise. In contrast, with the phase modulator turned on, Fig. 2(b), the coherent signal is redistributed into peaks, such that only the counts within this region need to be considered, allowing to remove a significant portion of the background noise. The corresponding 2D representation of the correlated counts are shown in Figs. 2(c)-(d), with all counts shown in shades of blue and the post-selected counts shown in red. Here, the biphoton is redistributed into an array of smaller distributions comprising higher photon events above the background noise level (when compared to the input waveform), while following the temporal mode profile of the input state. We show the temporal correlations in Fig. 2(e), demonstrating that the pulse formation and related noise mitigation was effectively transferred to the biphoton. Finally, we present the coincidence distribution as a function of pulse separation in Fig. 2(e) normalized to the accidental counts (*AC*), where we can observe a clear increase in the coincidence counts (*CC*). This demonstrates a clear improvement in the *CAR*, defined as *CAR=(CC-AC)/AC* [14], namely a CAR of 51 for PM-on vs 13.5 for PM-off, corresponding to a 3.8-fold improvement. The second resonance pair, which was processed simultaneously, showed a similar improvement, namely a CAR of 8.2 for PM on vs 2.4 for PM off, representing a 3.5-fold increase and demonstrating the versatility of the method. We predict that higher enhancement factors can be obtained using larger dispersions to have a broader peak separation, as well as by using high-resolution single photon detectors to further decrease the output pulse width.

In conclusion, we demonstrated a novel approach based on the Talbot effect to enhance the SNR of quantum states as demonstrated through a significant improvement in the CAR. We predict that the observed enhancement could be employed to improve the robustness and viability of entanglement-based communication schemes under realistic conditions, as well as for other noise-sensitive processes required for the deployment of the quantum internet.

3. References

1. S. Wehner, D. Elkouss, and R. Hanson, "Quantum internet: A vision for the road ahead," Science **362**, eaam9288 (2018).
2. A. Singh, *et al.*, "Quantum Internet—Applications, Functionalities, Enabling Technologies, Challenges, and Research Directions," IEEE Communications Surveys & Tutorials **23**, 2218–2247 (2021).
3. S. Pirandola, *et al.*, "Advances in quantum cryptography," Adv. Opt. Photon. **12**, 1012 (2020).
4. Y. Mao, *et al.*, "Integrating quantum key distribution with classical communications in backbone fiber network," Opt. Express **26**, 6010 (2018).
5. S. Du, Y. Tian, and Y. Li, "Impact of Four-Wave-Mixing Noise from Dense Wavelength-Division-Multiplexing Systems on Entangled-State Continuous-Variable Quantum key Distribution," Phys. Rev. Applied **14**, 024013 (2020).
6. R. Bedington, *et al.*, "Long-distance free-space quantum key distribution in daylight towards inter-satellite communication," Nature Photon **11**, 509–513 (2017).
8. F. Bouchard, *et al.*, "Achieving Ultimate Noise Tolerance in Quantum Communication," Phys. Rev. Applied **15**, 024027 (2021).
9. N. T. Islam, *et al.* "Provably secure and high-rate quantum key distribution with time-bin qudits," Sci Adv **3**, e1701491 (2017).
10. R. Lin, *et al.* "Telecommunication Compatibility Evaluation for Co-existing Quantum Key Distribution in Homogenous Multicore Fiber," IEEE Access **8**, 78836–78846 (2020).
11. B. Crockett, *et al.,* "Optical signal denoising through temporal passive amplification," Optica **9**, 130 (2022).
12. Q. Zhang, *et al.* "Generation of 10-GHz clock sequential time-bin entanglement," Opt. Express **16**, 3293 (2008).
13. J.-H. Kim, *et al.*, "Quantum communication with time-bin entanglement over a wavelength-multiplexed fiber network," APL Photonics **7**, 016106 (2022).
14. E. Meyer-Scott, C. Silberhorn, and A. Migdall, "Single-photon sources: Approaching the ideal through multiplexing," Review of Scientific Instruments **91**, 041101 (2020).