Waveguided sources of consistent, single-temporal-mode squeezed light: the good, the bad, and the ugly

Martin Houde, Nicolás Quesada

Department of Engineering Physics, École Polytechnique de Montréal, Montréal, Québec, H3T 1J4, Canada
{martin.houde, nicolas.quesada}@polymtl.ca

Abstract: We study how variations in pump brightness, for identical profiles, affect the temporal-mode structure of squeezed states generated by three different waveguided sources. Double-pass structures give optimal results in terms of indistinguishability and spectral purity. © 2023 The Author(s)

1. Introduction

We study how driving three different commonly used parametric waveguided sources with pumps at different brightness but identical Gaussian profiles gives rise to partial distinguishability between squeezed states of different brightness. In the high-gain regime, we highlight the non-trivial nature of the joint spectral amplitudes (JSAs) which is no longer simply related to the product of the pump amplitude and the phase-matching function (PMF).

As stated in Ref. [1], for a source to be practically useful for scalable continuous variable quantum computing it must produce indistinguishable states over a large range of squeezing. It is thus important to characterize how partial distinguishability may arise. Furthermore, these results are important for Gaussian boson sampling [2–4] as well as heralding [5] where one requires indistinguishable states [6, 7].

We first consider an unfiltered, unapodized source, with an unpoled nonlinear profile shown in Fig.1(a), where the low-gain regime JSA is the product of a Sinc function and the Gaussian pump envelope. In this case, the signal and idler modes are correlated to begin with which is undesirable. By studying the frequency content of the JSA as the energy in the pump pulse is increased, we find that the overlap between the brightest ($\langle N_S \rangle \sim 10.5$) and lowest ($\langle N_S \rangle \ll 1$) modes considered drops to below 90% ($\langle N_S \rangle$ is the average number of signal photons).

We then consider an unfiltered apodized source, with a poled nonlinear profile shown in Fig.1(b), where the low-gain regime JSA is the product of two symmetric Gaussians. We find that the signal and idler modes are mostly uncorrelated and our state can be approximated as separable even in the high-gain. However, similarly to the unapodized source, we find that the overlap between brightest and lowest modes considered also drops to below 90%.

Finally, we consider a double pass structure where both sources are apodized (by poling the crystals) and the modes pass through a half-wave plate to swap the polarizations between sources, shown in Fig.1(c). In this setup, we find that the signal and idler modes are even less correlated, compared to only one apodized source, for all levels of gain. The state is separable to an even better approximation. Furthermore, unlike the two previous sources, we find that overlap between brightest and lowest modes only drops by a little more than 1%.

2. Methods

We solve for the two-mode squeezed states (TMSS) generated by pumping a waveguided source outlined in Ref. [8] and implemented and benchmarked in Ref. [9]. We assume that we can treat the pump classically and ignore pump depletion, self-phase modulation, and cross-phase modulation. We focus on spontaneous parametric down conversion processes and assume that the central frequencies $\omega_\mu$ ($\mu = P, I, S$ for pump, signal, and idler modes) and associated wave vectors $\vec{k}_\mu$ satisfy $\omega_P = \omega_S + \omega_\delta$ and $\vec{k}_P = \vec{k}_I + \vec{k}_S$ respectively. Finally, we work in the symmetric group-velocity matching regime and assume that group velocity dispersion can be neglected. For the apodized sources, we pole our crystal using 1000 domains and optimize to obtain an approximately Gaussian PMF using the Python library Custom-Poling [10, 11].

3. Results and Discussion

The results are summarized in Fig.1. The second row shows the first temporal mode in the low-gain ($\langle N_S \rangle = 3.17 \cdot 10^{-3}$) and high-gain ($\langle N_S \rangle = 10.5$) regimes for all sources. Fig.1(g) shows the fidelity, $F(L,H) =$
Fig. 1. a) Unapodized single pass setup. b) Apodized single pass setup where the crystal is poled (represented by the lines in the crystal). c) Apodized double pass setup where the modes pass through a half-wave plate (HWP) to swap polarizations. Real(dark blue(light blue)) and imaginary(fuchsia(orange)) parts of the low(high)-gain temporal mode for average signal photon number $3.17 \cdot 10^{-4}(10.5)$ for the (d) unapodized single pass, (e) apodized single pass, and (f) apodized double pass structure. g) The fidelity, $F(L,H)$, between the first temporal mode at fixed low-gain, $\rho^S_L(\omega)$, and the first temporal mode at variable-gain, $\rho^S_H(\omega)$, as a function of gain for all three setups. h) The Schmidt number, $K$, for all three setups.

For the unapodized source, we see that the first temporal mode differs in the low and high-gain regimes. The real part varies slightly and an imaginary part is acquired. The first temporal mode is thus partially distinguishable at different levels of gain. Looking at the fidelity, we see that it decreases as a function of gain and drops to slightly below 90%. The Schmidt number starts well above unity ($K \approx 1.17$) and only increasing to $K \approx 1.06$. The squeezed state is thus never spectrally pure and the signal and idler modes are always correlated. The unapodized source is therefore far from optimal.

For the single apodized source, the temporal mode structure of the main mode and the fidelity as a function of gain behave similarly to the unapodized source. As gain increases, the temporal mode increasingly picks up a phase and we again have partial distinguishability. The fidelity also drops to slightly below 90%. The Schmidt number on the other hand fares much better. Initially measured at $K \approx 1.006$ and only increasing to $K \approx 1.02$, this tells us that even in the high-gain regime our state remains spectrally pure to an excellent approximation.

Finally, the apodized double-pass source tells a completely different story. The imaginary phase that the temporal mode picks up as a function of gain is much less pronounced. Indeed, when considering the fidelity as a function of gain, it only drops by a little over 1%. This is well above the threshold needed for quantum computational advantage and quantum processing [7]. The Schmidt number also decreases as a function of gain and remains much closer to unity than the two previous cases. The generated states are spectrally pure to an even better approximation. The double apodized source is thus practically useful for scalable continuous variable quantum computation.

Our work is the first exploration of the effects of varying pump intensities on the distinguishability of generated squeezed states in parametric waveguided sources, a vital component in quantum photonic architectures.
References

1. Z Vern et al. Scalable squeezed-light source for continuous-variable quantum sampling. *Phys. Rev. Applied*, 12(6):064024, 2019.
2. C. S. Hamilton et al. Gaussian boson sampling. *Phys. Rev. Lett.*, 119(17):170501, 2017.
3. N. Quesada et al. Gaussian boson sampling using threshold detectors. *Phys. Rev. A*, 98(6):062322, 2018.
4. Daniel Grier, Daniel J Brod, Juan Miguel Arrazola, Marcos Benicio de Andrade Alonso, and Nicolás Quesada. The complexity of bipartite gaussian boson sampling. *arXiv:2110.06964*, 2021.
5. Agata M Branczyk, T C Ralph, Wolfram Helwig, and Christine Silberhorn. Optimized generation of heralded fock states using parametric down-conversion. *New Journal of Physics*, 12(6):063001, Jun 2010.
6. Valery Shchesnovich. Distinguishability in quantum interference with multimode squeezed states. *Phys. Rev. A*, 105:063703, Jun 2022.
7. Junheng Shi and Tim Byrnes. Gaussian boson sampling with partial distinguishability. *arXiv:2105.09583*.
8. N. Quesada et al. Theory of high-gain twin-beam generation in waveguides: From Maxwell’s equations to efficient simulation. *Phys. Rev. A*, 102:033519, 2020.
9. Martin Houde and Nicolás Quesada. Waveguided sources of consistent, single-temporal-mode squeezed light: the good, the bad, and the ugly. *arXiv preprint arXiv:2209.13491*, 2022.
10. Agata Branczyk. Custom-Poling. [https://github.com/abranczyk/custom-poling](https://github.com/abranczyk/custom-poling), 2022.
11. Francesco Graffitti, Dmytro Kundys, Derryck T Reid, Agata M Brańczyk, and Alessandro Fedrizzi. Pure down-conversion photons through sub-coherence-length domain engineering. *Quantum Science and Technology*, 2(3):035001, Jul 2017.