Non-perturbative solution to quantum parametric down-conversion in open optical systems

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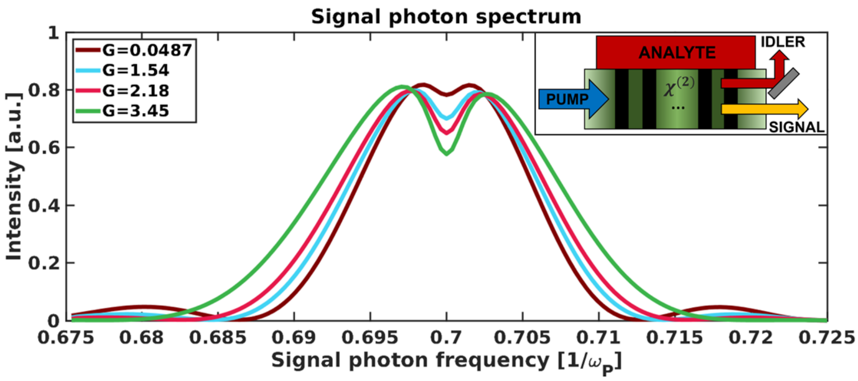
With the growing use of nanostructured nonlinear sources of photon pairs in optical quantum technologies, there is need for new analytical frameworks to describe pair generation in open (lossy) nanostructured systems with highly complex spatial/spectral properties. The Green's function (GF) quantization method [1] has been used for this purpose, as it naturally takes into account arbitrary amounts of loss and dispersion [2]. However, the existing formalism treats pair generation perturbatively (in the low-gain regime), where the output state has negligible contribution from multiple photon-pair states. Although sources of such states are of importance in many areas of quantum technologies, development of sources operating in the high-gain regime, is also of interest for generation of squeezed states of light, with wide applications in continuous variable (CV) quantum computation [3], communication, and sensing [4].



In this work, we extend the use of the GF quantization method for pair generation into the high-gain regime. Our non-perturbative formalism allows the calculation of field correlation functions in high-gain photon-pair generation, while intrinsically taking into account arbitrary dispersion and losses of a nanostructured system. This method can be of special interest for the description of engineered squeezed-light generation in nanostructured systems, where losses cannot be treated perturbatively (e.g. metasurfaces), as well as high-gain quantum sensing and imaging applications, where loss is not necessarily a weak effect. As an example, we numerically investigate quantum spectroscopy with undetected photons (QSUP) in a nonlinear waveguide in the high-gain regime and discover new behaviour compared to previous low-gain regime results [4]. The output spectra of QSUP at different values of gain are shown in the figure above with the schematic of the process shown in the inset.

[1] Gruner, T. and Welsch, D.G., *Phys. Rev. A* **53**(3), 1818–1829 (1996).

[2] Poddubny, A. N., Iorsh, I. V. and Sukhorukov, A. A., *Phys. Rev. Lett.* **117**, 123901 (2016).

[3] Arrazola, J. M., Bergholm, V., Brádler, K., Bromley, T. R. et al., *Nature* **591**(7848), 54–60. (2021).

[4] Kumar, P., Saravi, S., Pertsch, T., and Setzpfandt, F., *Phys. Rev. A* **101**(5), 053860 (2020).