The nonlinear $\chi^{(2)}$ directional coupler: a versatile source for continuous variable quantum information

David Barral[1], Nadia Belabas[1], Kamel Bencheikh[1], Juan Ariel Levenson[1],
Virginia D'Auria[2], Sébastien Tanzilli[2]

[1] *Centre de Nanosciences et de Nanotechnologies C2N, CNRS UMR 9001, Université Paris-Saclay, Marcoussis, France*
[2] *Institut de Physique de Nice (INPHYNI), CNRS UMR 7010, Université Côte d'Azur, Nice, France*

Integrated quantum photonics has emerged over the last two decades as the most promising pathway towards disruptive information technologies. The processing of quantum information (QIP) with continuous variables (CV) is a thriving area of research that presents advantageous features such as deterministic resources, unconditional operations and highly efficient homodyne detection. Integrated optics (IO) is one of the main candidates of transferring current CV systems to a real-world technology due to its inherent features like stability, scalability and mode matching. Currently, generation of nonclassical features with Gaussian operations is carried out in bulk-optics by means of nonlinear crystals and beam splitters. The IO counterparts of these two elements are the nonlinear waveguides and the directional coupler. In IO, however, there is a third relevant device without bulk-optics analog: the nonlinear directional coupler (NDC). In this communication, we demonstrate the CV-QIP potential of this device in three regimes: spontaneous parametric down-conversion (SPDC), optical parametric amplification (OPA) and second harmonic generation (SHG) [1, 2].

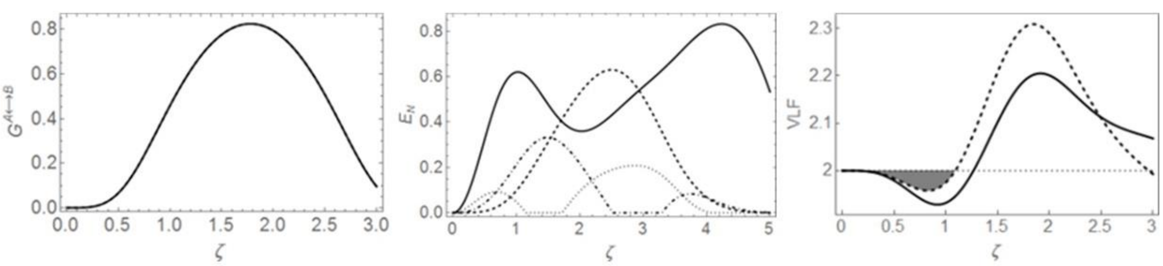

Figure 1: examples of CV-QIP features of the NDC. From left to right: Gaussian steering betwen fundamental modes in SPDC; single and two-color bipartite entanglement in OPA (fundamentals in solid, harmonics in dash, fundamental-harmonic in the same waveguide in dot, and fundamental-harmonic in different waveguide in dot-dash); and two-color quadripartite entanglement in SHG (in grey).

The NDC is made of two identical $\chi^{(2)}$ waveguides in which SPDC, OPA or SHG takes place depending on the initial conditions. The energy of the fundamental modes propagating in each waveguide is exchanged between the coupled waveguides through evanescent coupling, whereas the second harmonic waves remain confined for the considered propagation lengths. We focus here on three CV-QIP features: bipartite entanglement estimated via the logarithmic negativity E_N; quadripartite entanglement deduced from the violation of the van Loock - Furusawa inequalities (VLF) [3]; and Gaussian steering $G^{A\leftrightarrow B}$ [4]. Figure 1 shows three examples of the versatility of the NDC in terms of CV-QIP capabilities. These effects are based on the distributed combination of coupling and nonlinearity. Notably, in the SHG regime, we find fundamental fields entanglement without the need of ancillary pump beams at higher frequencies. This scheme minimizes resources opening the possibility to generate entanglement at mid-infrared frequencies using as a resource widely available telecom lasers and amplifiers [2].

The NDC can be realized with current technology, notably on lithium niobate with realistic parameters. Consequently, it stands as a good candidate for a source of multi-colour and/or multipartite entangled states for complex continuous variable - quantum information processing protocols.

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