Photonic Hyperentanglement in Polarisation and Frequency via Joint Spectrum Shaping

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Hyperentanglement is a valuable resource for enhancing the capacity and efficiency of quantum communication and computing protocols. Encoding quantum information in frequency bins at telecom wavelengths is particularly attractive for its robustness and natural compatibility with fibre-optic networks, but typical approaches rely on spectral filtering or optical cavities [1], which limits the source heralding efficiency.

Building on our recent work on optimised pump and nonlinearity shaping for spectrally pure photon pairs [2], we extend the approach to a two-dimensional shaping of the joint spectral amplitude by combining domain engineering in spontaneous parametric down-conversion KTP crystals with dynamic shaping of the pump laser spectrum via a programmable pulse shaper (see Fig. 1(a)-(b)). This distributes frequency modes in both diagonal and anti-diagonal directions, giving access to rich spectral structures (see Fig. 1(c)). Enclosed within a Sagnac interferometer (see Fig. 1(d)), the source generates photon pairs hyperentangled in polarisation and frequency-bin degrees of freedom without filtering, with flexible tunability of the frequency-bin structure, and with polarisation fidelities exceeding 99%. We verify the hyperentanglement through polarisation-resolved time-of-flight spectrometry and Hong-Ou-Mandel interference (~90% visibility), providing unambiguous evidence of simultaneous entanglement in both degrees of freedom [3].

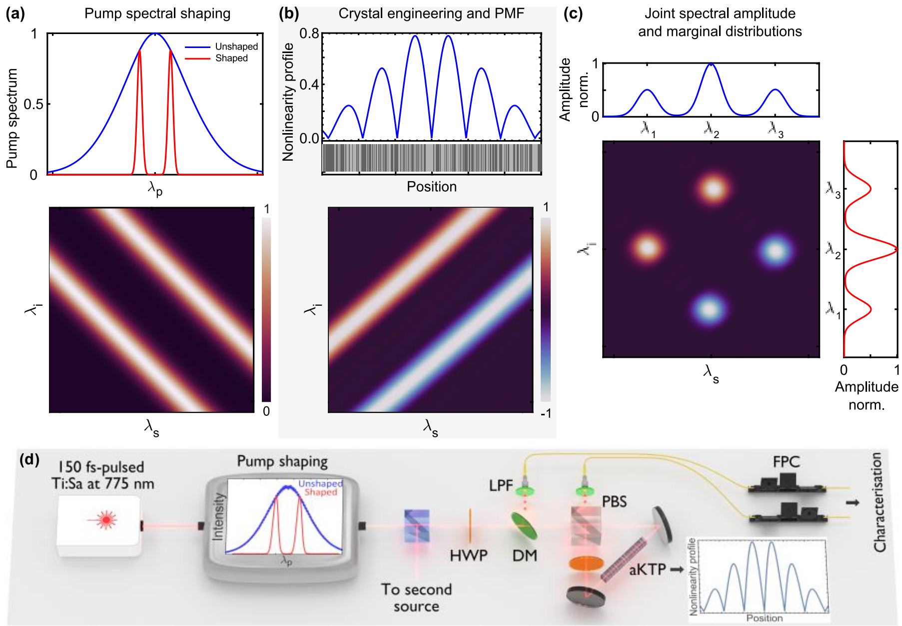

Fig. 1: *(a)-(b) Double Gaussian shaping of the pump spectrum and of the phase-matching function. (c) Resulting 2-by-2 rotational-symmetric joint spectral amplitude and spectral marginals (two-qutrit state). (d) Hyperentanglement generation setup composed of a broadband pump laser, the pump shaping, and of an aperiodically-poled nonlinear crystal inside a Sagnac interferometer.*

References

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[2] T. Faleo, *et al.*, e-print arXiv:2510.06196 (2025).

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