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Quantum–classical reciprocity for photon-triplet modelling

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Non-Gaussian optical resources are central to scalable quantum networks, precision sensing and photonic computing. A direct route is generating correlated photon triplets, yet optical third-order spontaneous parametric down-conversion (TOSPD) is difficult because $\chi(3)$ nonlinearities are weak and dispersion and phase-matching are complex. We introduce a general modelling framework that predicts TOSPD emission by exploiting a quantum–classical reciprocity: we reconstruct the photon-triplet amplitude and rate from the classically accessible three-wave sum-frequency generation (TSFG) field.

Using Lorentz reciprocity and Green-function formalism, we derive a closed relation linking the triplet wavefunction to TSFG. This enables rapid evaluation of spectra, angular correlations and collection efficiencies with standard electromagnetic solvers, avoiding full quantum simulations. The approach is geometry- and material-agnostic and applies across bulk media, waveguides and resonant photonic structures. It yields clear design rules that connect pump configuration, modal overlaps and resonance linewidths to brightness and directionality.

As an example, we apply the method to resonant $\chi(3)$ metasurfaces supporting quasi-bound-state resonances. Reciprocity-based reconstruction maps tunable collinear and non-collinear triplet emission and identifies collection-friendly, low-NA configurations. The same workflow supports k-space scanning, uncertainty analysis and inverse design, and can incorporate non-degenerate pumping and narrowband detection.

By reframing photon-triplet generation as a classical forward problem followed by reciprocity-based reconstruction, this work provides a broadly applicable, experimentally aligned toolkit to screen candidate platforms and interpret measurements, advancing prospects for optical triplet sources in both integrated and free-space systems.

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