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Hyperentanglement-empowered quantum waveguide optics

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Hyperentanglement, a sophisticated form of quantum entanglement across multiple degrees of freedom (DOFs), holds immense potential for revolutionizing quantum technologies in communication, sensing, and computing. This work presents a computational approach to generate hyperentanglement using waveguides, a method shown to be more efficient than traditional techniques and capable of producing a higher number of hyperentangled biphoton pairs. By acting as a tunnel for photons, waveguides minimize unwanted interactions with the environment \[1\], leading to a more robust and higher-fidelity hyperentangled state.

Our methodology is grounded in the theoretical framework of biphoton wavefunction dynamics \[2\], where we have expanded four equations to generate a set of 16 coupled differential equations with the basis equation shown below. These equations model the propagation of signal and idler photons through a system of two waveguides to generate Ψ_{n_s,n_i,p_s,p_i} wavefunctions for signal waveguide (n_s), idler waveguide (n_i), signal polarization (p_s), idler polarization (p_i) and consider key parameters to generate the 16 equations such as phase mismatch, effective refractive indices and coupling coefficients to determine the optimal conditions for hyperentanglement generation \[3\].

$$-id\frac{}{dz\Psi_{n_s,n_i,p_s,p_i}=-\left[C^{(s)}_{p_s}\Psi_{n_s,n_i,p_s,p_i}+C^{(i)}_{p_i}\Psi_{n_s,n_i,p_s,p_i}\right]+id_{eff}A_{n_s}\delta_{n_s,n_i}\exp(i\Delta\beta^{(0)}z)} \quad (1)$$

We numerically solve these equations using Python to simulate and calculate the final coupled states and biphoton correlations in a histogram and density matrix respectively to be presented. The simulations we are exploring show how varying system parameters, such as spatial (waveguide number) and polarization DOFs, affect the generation of hyperentangled states. Our waveguide platform is quite powerful, allowing the generation of various two-photon stages \[2\] and we are working on the extension to hyperentanglement where we are systematically exploring which hyperentangled states can be generated for which sets of parameters, and what the limits are in this context. This research represents a significant step forward in scaling these technologies toward practical quantum devices.

Authors: SOLNTSEV, Alexander (University of Technology Sydney); GOUNDER, Harshna Vithya Saahar (University of Technology ydney)

Presenter: GOUNDER, Harshna Vithya Saahar (University of Technology ydney)

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