Flexible engineering of quantum state using nonlinear interferometer

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Abstract

Using an N-stage nonlinear interferometer scheme consisting of N pieces of nonlinear media with $N-1$ pieces of dispersive media, photon pairs with near ideal modal purity and heralding efficiency are realized.

The availability of photon states with well-defined temporal modes and high heralding efficiency is crucial for photonic quantum technologies. Tremendous efforts were spent through the years on generating photon pairs with factorable joint spectral function (JSF). Many spectral engineering techniques have been deployed by manipulating the dispersion of the nonlinear media [1]. While most were successful to some extend, many are limited to the specific wavelengths of operation due to strict requirement on dispersion and phase matching and are therefore lack of tunability.

Here we resort to a totally different approach in which we separate the nonlinear gain control from linear dispersion engineering by using an SU(1,1)-type nonlinear interferometer (NLI). The NLI (Fig. 1(a)) achieves quantum interference between the nonlinear interaction processes taken place in the nonlinear media (NMs), so the outcome depends on the phases induced by the dispersive media (DMs). With a Gaussian-shaped pump, the JSF of photon pairs at the output of an N-stage ($N \geq 2$) NLI can be expressed as [2]

$$F^{(N)}_{NLI}(\omega_s, \omega_i) = \exp\left[-\frac{(\omega_s + \omega_i - 2\omega_{p0})^2}{4\sigma_p^2}\right] \times \mathrm{sinc}\left(\frac{\Delta k L}{2}\right) \times H(\theta), \tag{1}$$

with the modulation function $H(\theta) = 1 + \sum_{n=1}^{N-1} e^{2jn\theta} = \frac{\sin N\theta}{\sin\theta} e^{j(N-1)\theta}$, where Δk is the wave vector mismatch in the NMs each having a length of L, and $\theta = \frac{1}{2}\Delta k L + \frac{1}{2}\Delta\phi_{DM}$ with $\Delta\phi_{DM}$ being the phase difference induced by the DMs. $H(\theta)$ is similar to the interference factor of multi-slit interferometer in classical optics and can be seen as a result of the two-photon quantum interference.

Using dispersion-shifted fibers (each of length 50 m) and conventional single-mode fibers (each of length 7 m) as the NMs and DMs, respectively, we simulate the JSFs for the non-NLI and NLI cases in Fig. 1(b). One sees the JSFs for the NLI cases follows a quasi-periodically varying interference profile and exhibits some kind of "islands" pattern due to the interference factor $H(\theta)$. If we carve out one island by using a proper dual-channel filter, higher modal purity and collection efficiency can be achieved. We calculate the second-order intensity correlation function $g_s^{(2)}$ and heralding efficiency h_s of the signal photons when both passbands of the signal and idler filters have a common bandwidth of $\Delta\lambda_f$. From Fig. 1(c), one sees the modal purity ($g_s^{(2)}$) and heralding efficiency of the NLI cases are significantly higher than that of the non-NLI case and close to the ideal value.

We experimentally test the two- and three-stage NLI schemes based on fiber system and the improvements are confirmed. Our interferometric approach can also be applied to high gain situation for modal purity, thus provides more flexibility in engineering quantum states.

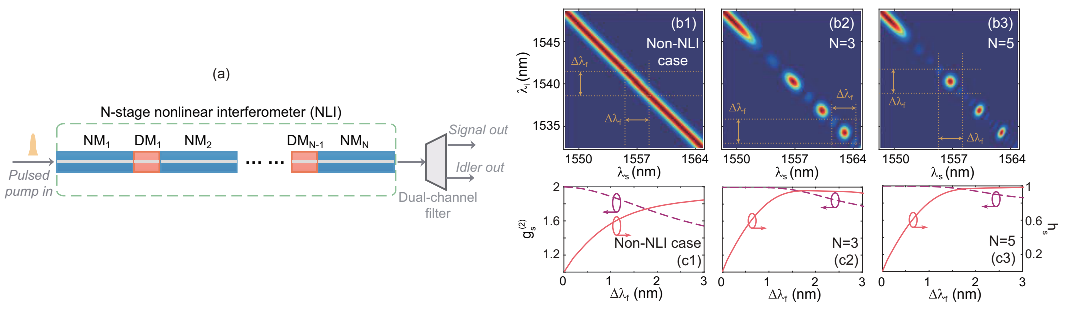

Figure 1: (a) N-stage nonlinear interferometer (NLI) scheme. (b) Calculated joint spectral function, (c) second-order correlation function (modal purity) and collection efficiency for the Non-NLI and NLI cases.

[1] P. J. Mosley et al, Phys. Rev. Lett. **100**, 133601 (2008).
[2] J. Su et al, arXiv:1811.07646 (2018).