Spontaneous photon pair generation at the nanoscale

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Abstract: Subwavelength resonators have recently emerged as promising sources of spontaneous parametric down-conversion. By modeling them with quasi-normal mode expansion, we reveal a nonlinear multimode interaction and assist the design of efficient metasurfaces for quantum technologies. © 2022 The Author(s)

Since its discovery several decades ago, spontaneous parametric down conversion (SPDC) has become a key process in quantum optics to generate photon pairs and is at the heart of many fundamental experiments. With the recent observations of photon-pair generation in nonlinear dielectric nanoresonators [1] and metasurfaces [2], subwavelength-sized resonators have emerged as a promising platform for compact and efficient SPDC sources with engineered properties. Their open-system nature provides indeed access to several degrees of freedom and therefore the opportunity to tailor the spectral, spatial and polarization properties of the down-converted photons. However, a description of SPDC in such arbitrarily complex nanoscale structures is needed to control this broadband generation in order to allow for quantum state engineering.

To this end, we firstly develop a model for SPDC in lossy systems. It integrates into a Green’s function (GF) formalism [3] the calculation of the natural modes of the system, the so-called quasinormal modes (QNMs) [4] that have recently been used in the nonlinear regime to describe the up-conversion process of second-harmonic generation [5]. We obtain the following photon-pair generation rate:

$$\frac{dN_{pair}}{dt} \propto \sum_{q_s,q_i,m,n} \xi_{m,n}(\omega_s, \omega_i) E_{m,q_s}(r_s)E_{n,q_i}(r_i)$$

(1)

with $\omega_s$ and $\omega_i$ the angular frequencies of the generated signal and idler photons, $r_s$ and $r_i$ their positions, $q_s$ and $q_i$ their polarization states, $E_m$ and $E_n$ their associated QNMs, and the mode coupling factor:

$$\xi_{m,n}(\omega_s, \omega_i) \propto \sum_{\alpha,\beta,y} \int d^3 r \chi_{\alpha\beta y}^{(2)}(r)E_{\alpha y}(r)E_{\beta m}(r)E_{n y}(r)$$

(2)

This quantity describes the overlap integral between the interacting fields in the nonlinear medium of second-order susceptibility $\chi_{\alpha\beta y}^{(2)}$, $(\alpha, \beta, y) \in \{x, y, z\}^3$.

To demonstrate its practicality, we apply this model to a (100)-grown AlGaAs nanocylinder with 220 nm radius and 400 nm height, see Fig.1(a). For the pump field we consider a linearly polarized a plane wave of 740 nm wavelength and $10^{13}$ W/cm$^2$ intensity, impinging along the nanocylinder revolution axis. Its near field is shown in the left panel of Fig.1(b). Its QNMs are calculated numerically just once using a finite-element method solver, and plugged into in the analytical formalism to infer the properties of the down-converted photons. Fig.1(c) depicts the spectrum of the mode-coupling factor and shows that only a few of these QNMs efficiently couple to the pump field in this nonlinear process, i.e. have a significant weight in the conversion efficiency. The near fields of the two main contributing modes are shown in the middle and right panels of Fig.1(b) and their far fields in the inset of Fig.1(c). This reduced number of modes makes our model physically insightful and its implementation computationally efficient to deal with SPDC in open systems.

Finally, the far fields of the down-converted photons are reconstructed and Fig.1(d) displays the angular distribution of the generation rate corresponding to the joint detection of degenerate and copropagating signal and idler photons.
Fig. 1. (a) Sketch of a nanocylinder generating signal and idler photons via SPDC. An x-polarized plane-wave pump at 740 nm is impinging along the $-z$ direction. (b) Near-field spatial distributions of the pump and the two QNMs that mainly contribute to photon-pair generation. The norms of the electric fields are normalized by the incident pump field. (c) Total mode coupling factor $\xi_{m,n}^2$ (grey shading) and main QNM contributions (colored lines) vs. signal frequency. Inset: far-field spatial pattern of the two most relevant modal contributions. (d) Spatial probability density of measuring signal and idler photons measured in the same direction, at spectral degeneracy ($\lambda_s = \lambda_i = 1480$ nm).

In conclusion, our formalism is a physically insightful and numerically efficient tool to describe the properties of photon pairs generated via SPDC, and thereby constitutes a valuable resource to engineer specific arbitrary biphoto quantum states by properly designing non-Hermitian systems such as single nanoresonators or metasurfaces.

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