

The Numerical Analysis of Quantum Scattering Characteristics of Nanostructures Under Two Independent Photon Irradiation

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The fast development of the quantum technologies and applications makes it important to employ the theoretical and numerical methods for the analysis of realistic quantum systems. Notably, the interactions among the quantum emitters with nanostructures is a fundamental concern in the quantum nanophotonics. Furthermore, quantum optical concepts have been extended to alternative applications involving wave scattering and diffraction. The novel degrees of freedom introduced by the ability to control the quantum statistics of light results in the distinction between classical scattering and quantum scattering. Therefore, the special quantum effects such as the Hong-Ou-Mandel (HOM) effect referring to the suppression of single-photon contributions via two-photon interference can be observed, which arise from the quantum correlations.

In this work, we calculate the second-order correlation function of the scattered field, which unveils the angular distribution of the HOM interference for the dielectric nanostructures acting as the beam splitter. Different from the classical optics, the Maxwell equations for quantum light are reformulated in terms of the operators. The photodetection correlation functions are expressed through the local and cross densities of states of the electromagnetic field, creating a direct connection to classical quantities. We consider two single-photon emitters, an i -polarized photon at a position $\mathbf{r}_1$ and a j -polarized photon at a position $\mathbf{r}_2$. The joint detection probability is proportional to the second-order correlation function $G_{ij}^2(\mathbf{r}_1, \mathbf{r}_2) = \langle \hat{E}_i^-(\mathbf{r}_1) \hat{E}_j^-(\mathbf{r}_2) \hat{E}_j^+(\mathbf{r}_2) \hat{E}_i^+(\mathbf{r}_1) \rangle$, where $\hat{E}_i^+(\mathbf{r}) = [\hat{\mathbf{E}}^+(\mathbf{r})] \cdot \mathbf{e}_i = [\hat{E}_i^-(\mathbf{r})]^\dagger$ is the projection of the positive frequency part of the electric field operator. The normalized second-order correlation function is defined as $g_{ij}^2(\mathbf{r}_1, \mathbf{r}_2) = \frac{G_{ij}^2(\mathbf{r}_1, \mathbf{r}_2)}{G_i^1(\mathbf{r}_1)G_j^1(\mathbf{r}_2)}$, the first-order correlation function is defined as $G_i^1(\mathbf{r}) = \langle \hat{E}_i^-(\mathbf{r}) \hat{E}_i^+(\mathbf{r}) \rangle$. Each photon is assumed to reside in an outgoing normalized scattering eigenmode, with different mode indices κ_1 and κ_2 . Thus the normalized second-order correlation function could be evaluated

$$g_{ij}^2(\mathbf{r}_1, \mathbf{r}_2) = \frac{\omega_{\kappa_1} \omega_{\kappa_2} |F_{ik_1}(\mathbf{r}_1) F_{jk_2}(\mathbf{r}_2) + F_{ik_2}(\mathbf{r}_1) F_{jk_1}(\mathbf{r}_2)|^2}{\sum_{n=1,2} \omega_{\kappa_n} |F_{i\kappa_n}(\mathbf{r}_1)|^2 \sum_{n=1,2} \omega_{\kappa_n} |F_{j\kappa_n}(\mathbf{r}_2)|^2} \quad (1)$$

where $F_{ik}(\mathbf{r}) = \mathbf{F}_\kappa^{\text{out}}(\mathbf{r}) \cdot \mathbf{e}_i$ is the projection of the outgoing normalized scattering eigenmode on the polarization vector, two modes hold the equal frequency $\omega_{\kappa_n} = ck$. The far-field detectors are set to be not susceptible to the polarization of the incident plane-wave part, i.e., $i = j = z$. The calculation of the far-field could be achieved by the rich set of analytic and numerical tools of classical electrodynamics. Considering the dimension and the plane-wave mode of single frequency, we employ the volume integral equation method in conjunction with the method of moments. The matrix equation is established as follows: $\frac{\mathbf{J}^s(\mathbf{r})}{j\omega(\epsilon - \epsilon_0)} + j\omega\mu_0 \int_V \vec{\mathbf{G}}(\mathbf{r}, \mathbf{r}') \cdot \mathbf{J}^s(\mathbf{r}') dv' = \mathbf{E}^{\text{inc}}$. Compared with the existing eigenmode expansion method, the numerical method demonstrates superiority for the modeling of more intricate nanostructures.

We fix two different polar position θ_1 and θ_2 , and calculate the $g_{zz}^2(\phi_1, \phi_2)$ as a function of the detector's azimuthal positions ϕ_1 and ϕ_2 . For the example of the dielectric sphere, there are some pairs (θ_1, θ_2) resulting in a vanishing correlation function that correspond to HOM destructive interference. Our numerical results match well with the analysis results in the reference (Maurer, C. Gonzalez-Ballester, and O. Romero-Isart, J. Opt. Soc. Am. B, 40, 3137-3155, 2023). Also, the metasurface deflecting the incident light into different output directions $\pm 10^\circ$ is simulated, which generates the path-entangled NOON states. The HOM interference could also be observed.