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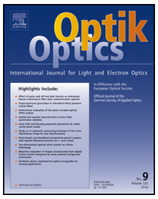

Sub-wavelength interference in the field assisted by surface plasmons

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ABSTRACT

We present a theoretical study of the optical transmission from a thin metallic double slit. The second-order correlation function as a function of the displacement of the detectors for different values of slit separation is studied. It is shown that surface plasmons excited at one slit and propagating to the other slit modulate the coincidence counts with the variation of slit separation. Sub-wavelength interference effect has also been observed for the field assisted by surface plasmons. It is also shown that the second order interference-diffraction pattern changes with slit separation and at some particular value of slit separation it changes into the Hanbury Brown and Twiss (HBT) effect.

1. Introduction

The interaction between the surface charges of a conductor (metal) and the incident electromagnetic field constitutes surface plasmons (SPs). SPs have many applications namely minimizing the size of the photonic circuits, enhanced optical transmission through sub-wavelength apertures in metal films etc. [1–3] and have attracted much attention in the last two decades [4–8]. SPs that are generated by the field incident on the slits in a Young's double slit setup travel from one slit to the other where they reappear as a freely propagating field. The interference between field produced by surface plasmons and the field that is directly transmitted modify the total transmission significantly [3]. In the same way the state of spatial coherence of the field that is radiated by two apertures can be changed by the surface plasmons that travel between the slits [7].

In the classical domain the de Broglie wavelength of a particle depends on its mass. When two particles of same mass combine, the de Broglie wavelength of the molecule reduces half of that of a single particle. This effect is known as sub-wavelength interference which has drawn much attention. Similar effect has been observed for photons, named as quantum sub-wavelength interference which has drawn much attention [9–16]. Hanbury Brown and Twiss in their landmark experiment considered the second-order intensity correlation to measure the angular diameter of stars [17]. By using such type of setup it has been shown that in a Young's double slit setup the joint intensity measurement of a thermal like light source shows sub-wavelength interference pattern at the detection plane [11]. It was also shown that the second-order correlation of the two independent pseudo thermal sources shows sub-wavelength interference which is explained by the quantum theory with no classical analogy [10]. Recently, it was shown that Young's interference fringes could be controlled with the slit separation and film thickness which is due to the additional phase retardation introduced by SPs [18].

In this paper we present the theoretical work of sub-wavelength interference in the field assisted by surface plasmons. In the Young's double slit interference setup, we studied the second-order correlation function of a thermal-like light assisted by surface plasmons at the detection plane. The change in the coincidence counts with displacement of the detectors for different values of slit separation is studied. We have also presented the comparison between the field assisted by surface plasmons and an ordinary field.

2. Theory

The principle of the setup to study the second-order correlation of the field emerging from the metallic double slit is shown in Fig. 1. It is similar as in [11] but in place of an ordinary slit we have assumed Au-double slit. We have assumed that a metallic double slit is illuminated by a Gaussian thermal TM polarized light of peak wavelength 600 nm. The SPs are generated at the interface between metal

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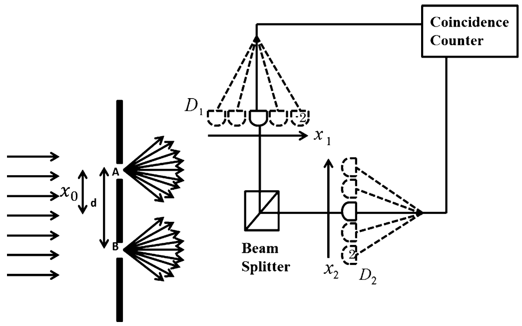

Fig. 1. Systematic diagram for studying second-order correlation measurement of the field emitted by Au- double slit. A and B are the slits, *d* is the separation between slits, is the distance of each slit from the centre point between them.

and dielectric. This field propagates from one slit to the other slit where it reappears as a freely propagating field and interferes with the incident field that is directly transmitted. The fields emerging from the two slits pass through a beam splitter and are detected by two single-photon detectors D_1 and D_2 respectively, which can be translated in the transverse direction of the field propagation. The outputs of the two detectors are sent to the coincidence counter where coincidence counts are recorded as a function of position of the detector.

We have assumed that the field incident on the two slits (each with width s and separated by a distance d) is the same. Let us assume that a fraction α of the incident field on each slit is directly transmitted, whereas a fraction $\alpha\beta$ is converted into SPs which travel to the other slit and reappears as a freely propagating field. Therefore, the fields emerging out of each slit are the sum of the transmitted field and the field due to SPs contribution and are given as [7],

$$U_{\mathrm{A}} = \alpha U_{\mathrm{A}}^{\mathrm{inc}} + \alpha\beta U_{\mathrm{B}}^{\mathrm{inc}} \exp(ik_{\mathrm{sp}}d), \tag{1}$$

$$U_{\mathrm{B}} = \alpha U_{\mathrm{B}}^{\mathrm{inc}} + \alpha\beta U_{\mathrm{A}}^{\mathrm{inc}} \exp(ik_{\mathrm{sp}}d), \tag{2}$$

where, k_{sp} is the wave number associated with SPs and it is a complex quantity given by [19],

$$k_{\mathrm{sp}} = \frac{2\pi}{\lambda_{\mathrm{sp}}} = \frac{\omega}{c}\sqrt{\frac{\varepsilon_{\mathrm{m}}\varepsilon_{\mathrm{d}}}{\varepsilon_{\mathrm{m}}+\varepsilon_{\mathrm{d}}}} = k'_{\mathrm{sp}} + ik''_{\mathrm{sp}},$$

where, ε_{m} and ε_{d} are the permittivity of the metal and the dielectric respectively.

The transmission function of the slit A can be written as

$$T_{\mathrm{A}}(x_0) = \begin{cases} \alpha\left[1+\beta\exp\left(ik_{\mathrm{sp}}d\right)\right], & (d-s)/2 \le x_0 \le (d+s)/2 \\ 0 & \text{otherwise} \end{cases}, \tag{3}$$

similarly for slit B

$$T_{\mathrm{B}}(x_0) = \begin{cases} \alpha\left[1+\beta\exp\left(ik_{sp}d\right)\right], & -(d-s)/2 \le x_0 \le -(d+s)/2 \\ 0 & \text{otherwise} \end{cases}, \tag{4}$$

where, is the distance of each slit from the centre point between them. The relation between the second-order correlation function and the first-order correlation function for Gaussian thermal light is given by [20],

$$\begin{aligned} G^{(2)}(x_1,x_2) &= \langle \hat{a}^{\dagger}(x_1)\hat{a}^{\dagger}(x_2)\hat{a}(x_2)\hat{a}(x_1)\rangle \\ &= |\langle \hat{a}^{\dagger}(x_1)\hat{a}(x_2)\rangle|^2 + \langle \hat{a}^{\dagger}(x_1)\hat{a}(x_1)\rangle\langle \hat{a}^{\dagger}(x_2)\hat{a}(x_2)\rangle \\ &= \left|G^{(1)}(x_1,x_2)\right|^2 + G^{(1)}(x_1,x_1)G^{(1)}(x_2,x_2), \end{aligned} \tag{5}$$

where, $\hat{a}^{\dagger}(x_i)$ and $\hat{a}(x_i)$ represent the creation and annihilation operators at detectors D_i located at x_i (i = 1,2) respectively.

The first-order correlation function for the field emerging from the slit A which is contributed by fraction of the incident field transmitted directly and contributed by SPs is calculated as [10], is given as

$$\begin{aligned} G_{\mathrm{A}}^{(1)}(x_1,x_2) = \frac{k}{2\pi z}\frac{1}{2\pi}\iiint T_{\mathrm{A}}^{*}\left(x'_0\right)T_{\mathrm{A}}(x_0)\,\delta\left(x'-x'_0\right)\times\delta\left(x'-x_0\right)\times \\ \exp\left[i\left(\frac{kx_1}{z}-q_1\right)x'_0 - i\left(\frac{kx_2}{z}-q_2\right)x_0\right]dq_1dx_0dx'_0 \end{aligned}. \tag{6}$$