Enhancement of spatial coherence by surface plasmons

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We report on a method to generate a stationary interference pattern from two independent optical sources, each illuminating a single slit in Young's interference experiment. The pattern arises as a result of the action of surface plasmons traveling between subwavelength slits milled in a metal film. The visibility of the interference pattern can be manipulated by tuning the wavelength of one of the optical sources. © 2007 Optical Society of America

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It is well known that the visibility of the interference fringe pattern observable in Young's double-slit experiment is determined by the spatial and temporal coherence properties of the light incident on the slits.[1] For a stationary light field, these properties are described by the mutual coherence[1–3] function

$$\Gamma(P_1,P_2,\tau) = \langle E^*(P_1,t)E(P_2,t+\tau)\rangle, \tag{1}$$

with E the complex amplitude of the field, assumed here to be scalar; P_1 and P_2 denote the positions of the slits, τ a delay time, and the brackets a time average. For our purpose it is useful to employ the normalized mutual coherence function (the so-called complex degree of coherence), defined as

$$\gamma(P_1,P_2,\tau) = \Gamma(P_1,P_2,\tau)/[I(P_1)I(P_2)]^{1/2}, \tag{2}$$

where $I(P_i)$ is the averaged intensity at slit i. Under typical circumstances, the visibility $\mathcal{V}$ of the interference fringes near a point P in the far zone is equal to the modulus of the complex degree of coherence, i.e.,

$$\mathcal{V} = |\gamma(P_1,P_2,\tau)|, \tag{3}$$

with τ equal to the time difference $(\overline{P_1P}-\overline{P_2P})/c$, c being the speed of light in air. If one slit is illuminated by a light source radiating at frequency ω_1 while the other slit is illuminated by a separate source radiating at frequency ω_2, it is easily seen that then $\gamma(P_1,P_2,\tau)=0$. Under these illumination conditions the fringe visibility should thus be zero across the entire interference pattern for sufficiently long integration times.

In this line of reasoning it is assumed that the radiative field *emerging* from a slit is simply, up to some factor, equal to the radiative field *incident* on that slit. When surface plasmons propagate between the two slits this assumption is no longer valid.[4,5] Consequently, a stationary interference pattern should be observed even if the frequencies of the lasers illuminating the individual slits are very different. Here we confirm this idea in an experiment where the two lasers run at frequencies differing by as much as 1.8 THz. Furthermore, we show that an interference pattern is also observed when only *one* slit is illuminated. When the polarization of the incident light is chosen such that no surface plasmons can be excited, the stationary interference pattern is observed to be absent.

The experimental setup is shown in Fig. 1. Two separate lasers, a tunable narrowband Ti:sapphire laser and a semiconductor diode laser operating at 812 nm, each illuminate a single subwavelength slit in a 200 nm thick gold film. Each laser is focused to a spot of approximately 5 μm FWHM. The two parallel slits, ~25 μm apart, are 50 μm long and 0.2 μm wide. The gold film is evaporated on top of a 0.5 mm thick fused-quartz substrate with a 10 nm thick titanium adhesion layer between the gold and the quartz. A CCD camera is used to record the far-field pattern.

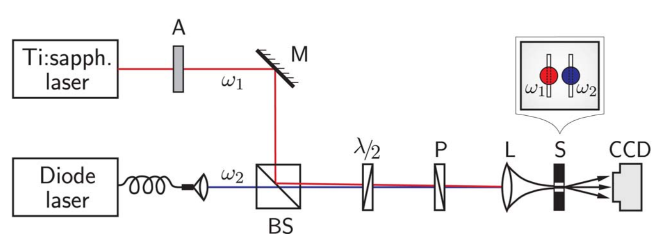

Fig. 1. (Color online) Sketch of the experimental setup. The outputs of a fiber-coupled diode and a Ti:sapphire laser are individually focused on one of a pair of 200 nm wide slits, separated by ≈25 μm, in a thin gold film. The light diffracted at the two parallel slits is imaged onto a CCD camera. A, attenuator; M, mirror; BS, beam splitter; $\lambda/2$, half-wave plate; P, polarizer; L, lens; S, gold sample. The inset shows the illumination of the double slit.

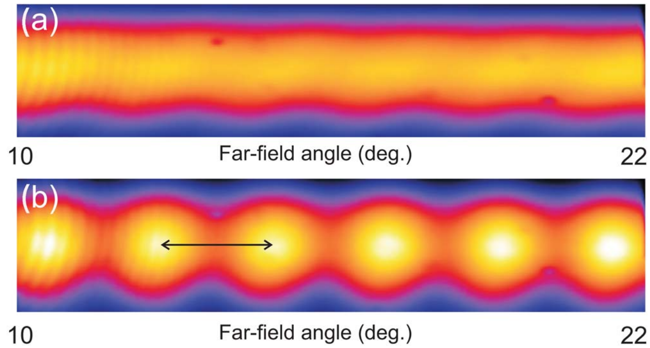

Fig. 2. (Color online) (a) Far-field pattern for the case when both laser beams are TE-polarized (polarization parallel to the slits). The semiconductor laser emits at 812 nm, while the Ti:sapphire laser is tuned to 808 nm. (b) Experimental far-field pattern when the polarization of both laser beams is perpendicular to the two slits (TM-polarization). Large-period fringes with a visibility $\mathcal{V}\approx 20\%$ are easily discerned. The arrow indicates the period of the fringes.

When the polarization of the two beams is parallel to the two slits (TE-polarization), the resulting far-field pattern exhibits no fringes (see the top of Fig. 2), thereby confirming that the fields emerging from the two slits are completely uncorrelated [$\gamma(P_1,P_2,\tau)=0$]. However, when the polarization is changed to be perpendicular to the slits (TM-polarization), a stationary interference pattern is obtained $\gamma(P_1,P_2,\tau)\neq 0$. This is shown in the bottom part of Fig. 2, with a fringe visibility $\mathcal{V}=20\%$. The fact that the appearance of interference depends on the polarization of the incident beams demonstrates that the interference phenomenon cannot be attributed to one or both of the input beams illuminating the two slits to some extent.

Because the frequency difference between the two laser beams is so large, the mutual coherence [Eq. (1)] of the light fields incident on slit 1 and slit 2 is identical to zero, independent of the polarization. The fact that we, nevertheless, observe interference fringes for the case of TM-polarized illumination indicates that the fields emerging from slits 1 and 2 must, in that case, be at least partially mutually coherent. This mutual coherence is acquired by traversing the sample and, in view of the wavelength range of our study and the separation of the slits, we attribute it to the action of surface plasmons.[6,7] Only when the incident light is TM-polarized can they be excited at the slits. In the geometry of our sample they travel from one slit to the other with little loss, the slit separation ($\sim 25\ \mu$m) being smaller than their attenuation length ($\sim 40\ \mu$m).[8] At the second slit the surface plasmons are partially converted back into a propagating light field.[4,9] The consequence is that, while we illuminate slit 1 with a laser operating at frequency ω_1 and slit 2 with a laser operating at frequency ω_2, both slits will scatter at frequencies ω_1 and ω_2. Moreover, since the processes of scattering free-space radiation into a surface plasmon and vice versa are phase coherent, the plasmon-mediated emission at frequency ω_2 from slit 1 is fully coherent with the direct emission by slit 2 at that frequency. Similarly, the plasmon-mediated emission by slit 2 and the direct emission by slit 1 at frequency ω_1 are fully coherent. Therefore, each frequency generates its own interference pattern with nonzero visibility.

To corroborate the proposed explanation we have switched off one of the lasers so that only a single slit is illuminated (by a single laser). One then expects to again observe an interference pattern when the incident light is TM-polarized and none when it is TE-polarized. This is confirmed by the experiment, with Fig. 3 showing the results for the case of TM-polarized illumination. Here, the fringe visibility, of the order of 0.2, does not provide a measure for the phase correlation between the fields emitted by the two slits; it rather reflects the imbalance of the intensities of the fields emerging from the two slits (ratio ≈ 170). This imbalance can be tuned by adjusting the widths of the individual slits. High-visibility fringes are observed only when subwavelength slits as narrow as the ones in the current experiment (200 nm) are used.

Additional support for our interpretation in terms of surface-plasmon-enhanced spatial coherence comes from measuring the shift of the interference pattern upon changing the wavelength of the incident radiation. As shown in Fig. 3 we record the interference pattern for far-field angles ranging between 12° and 22° at the right side of the z-axis. If the left slit is illuminated and the wavelength is increased from 767 to 784 nm, the fringes shift to the left by approximately half a fringe, as shown in the figure. Actually, all the fringes that can be recorded shift to the left. However, when the right slit is illuminated, one observes that all the fringes shift to the right. This is not possible in a traditional Young's-type experiment where the interference arises as a result of both slits being illuminated by a single source. In that case the pattern expands symmetrically around the z-axis.

Because the surface plasmon has to propagate from one slit to the other, the field emitted by the nonilluminated slit is delayed relative to that of the directly illuminated slit, the phase delay $\Delta\phi(\omega)$ being equal to

$$\Delta\phi(\omega)=k_{\mathrm{sp}}(\omega)d+\psi. \tag{4}$$

Here $k_{\mathrm{sp}}(\omega)$ is the surface-plasmon propagation constant, d the slit separation, and ψ a scattering-induced phase jump. The angular position of an interference maximum is then given by

$$k_0 d\sin\theta\pm\Delta\phi(\omega)=2\pi m, \tag{5}$$

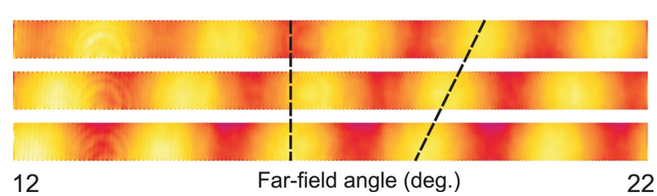

Fig. 3. (Color online) Interference patterns recorded with only a single slit illuminated by the TM-polarized output of the Ti:sapphire laser for, from top to bottom, $\lambda=767$ nm, $\lambda=775$ nm, and $\lambda=784$ nm.

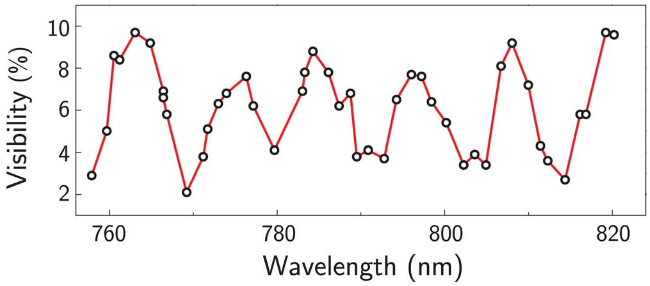

Fig. 4. (Color online) Fringe visibility of the recorded pattern (for TM-polarization) as a function of the wavelength of the Ti:sapphire lasers.

the sign depending on which slit is being illuminated. Here k_0 represents the free-space wavenumber of the incident radiation, and m is an integer. From this expression one calculates that the pattern shifts by half a fringe spacing for a wavelength change of 17 nm, in excellent agreement with the experimental result shown in Fig. 3.

In the case that both slits are illuminated (as in Fig. 2), albeit at different frequencies, we expect to observe an incoherent superposition of two fringe patterns. If ω_1 and ω_2 are not vastly different, as in the present experiment, these patterns have very similar fringe spacings. However, because of the frequency-dependent phase delay of Eq. (4), these interference patterns can be aligned in different ways. In the case that the two patterns are perfectly aligned, the observed interference pattern will have good visibility, while the visibility of the observed pattern can become close to zero when the two wavelengths are chosen so that the nodes of the pattern at one frequency overlap the antinodes of the pattern at the other frequency. Consequently, one expects the visibility of the fringe pattern to go up and down when tuning, for instance, ω_1. Figure 4 shows our experimental results, taken in a setup using two synchronously tuned Ti:sapphire laser beams, which confirm this picture.

A peculiar situation arises when the frequencies of the two incident beams are almost equal. Let us suppose that, at this frequency, $\Delta\phi(\omega) \approx (2m+1)\pi$, so that the fringe pattern at each of the frequencies shows a minimum in the center ($\theta=0$). One then would observe an intensity minimum at the center of the fringe pattern. However, when the two lasers have equal frequencies and are phase locked, one should observe an intensity maximum at the center, as explained in any textbook on optics.[2]

In conclusion, we have demonstrated that interference fringes can arise in Young's double-slit experiment under conditions where they are not usually found. In particular, we have shown that such fringes can appear when the illumination of one of the slits is completely spatially incoherent with that of the other. We attribute this effect to the action of surface plasmons generated at, and traveling between, the two slits. Using a variety of experimental approaches, we have shown this picture of surface-plasmon-enhanced coherence to be consistent. Whereas the vast majority of recent work on surface plasmons focuses on enhancement of the field or its transmission, i.e., on an effect involving the intensity of the light field, our work demonstrates that surface plasmons also have a profound influence on its coherence properties, leaving much territory to be explored.[5]

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