Mesoscopic effect of spectral modulation for the light transmitted by a SNOM tip

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Abstract

The effect of a tapered metal-coated optical fiber terminated by a sub-wavelength aperture (SWA) on the spectrum of the transmitted light is investigated experimentally. Under certain conditions a remarkable spectral modulation of the transmitted light can be observed. This effect is of a mesoscopic origin, occurring only for a certain interval of SWA diameters. One can conclude that a noticeable modulation appears when the number of the transmitted fiber modes is small but exceeds unity, thus indicating the presence of a phase shift between different modes. To discern between two possible sources of such phase shift, the fiber length dependence of the output spectrum has been studied. According to the results obtained for the used sample of 200 nm SNOM tip, the observed phase shift is mostly caused rather by the inherent modal dispersion of the multimode fiber than by the mode-dependent light slowdown in the tapered region close to SWA due to the coupling to surface plasmons of the metal coating. The SWA acts here mainly as an effective mode filter.

1. Introduction

Tapered metal-coated optical fiber tips terminated by a sub-wavelength aperture (SWA) have found a wide application as aperture probes for scanning near-field optical microscopy (SNOM) [1]. Possible applications in plasmonics [2] have also been considered, stimulating the research of the near-field light interaction with surface plasmon polaritons of the metal coating of SNOM tips [3–5]. Such kind of coupling could result in nonlinear effects, possibly affecting the spectrum of the transmitted light. The spectrum can also be affected by an interference of different optical modes propagating in a multimode fiber.

In this work we consider the mode filtering effect of a SNOM tip. It has been shown theoretically by Novotny and Hafner [6] that the number of different light modes propagating in a metal-coated optical fiber is gradually reduced with decreasing the fiber’s subwavelength core diameter. Most of the modes have a cutoff frequency, below which they become evanescent – the wave number becomes imaginary and the propagation of such mode is forbidden. This cutoff frequency depends on the fiber core diameter, and below some diameter value only the fundamental mode remains, allowing the single-mode operation of the fiber. Thus, a metal-coated SNOM tip terminating an optical waveguide can serve as an effective mode filter, with the output mode structure depending on the optical wavelength $\lambda$ and on the SWA diameter $d$ (along with other tip parameters) [1]. An interesting question one can ask is whether the number of output modes can affect the output light spectrum.

Recently sub-wavelength optical wires have been applied in combination with multimode waveguides for mode filtering [7]; in the same work an effect of spectral modulation has been observed in the transmission spectrum of a multimode waveguide combined with a thin optical wire of 70 μm diameter.

We introduce here our first experimental results concerning the influence of a SNOM tip and of its SWA diameter on the transmitted light spectrum.

2. Experimental

As a room-temperature light source with a relatively narrow well-defined emission spectrum we used a diamond sample with silicon-vacancy (Si-V) centers [8,9]. Some micrometers thick film of an ultra-nanocrystalline diamond [10], deposited on a Si substrate, was excited by a strongly-focused 532 nm or 658 nm laser radiation. The Si-V room-temperature fluorescence zero-phonon line is about 9 nm broad (FWHM), with the maximum at $\lambda \approx 738$ nm (see Fig. 1). This emission was collected by a confocal microscope and, after passing a red-pass filter, directed into a multimode optical fiber with an optional SNOM tip formed on its output tail. We used Nanonics bent-type SuperSensor™ NSOM/AFM Probes with SWA diameters of 100 nm and 200 nm: their multimode fibers have core and cladding diameters of 50 and 125 μm, respectively, while the tapered tips are covered with metal layers of Cr and Al with respective thicknesses of ~20 and ~200 nm.

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The bending radii of the fiber probes exceed λ by at least an order of magnitude, thus the bends (located in a multimode region close to the tapered tips) should not significantly affect the transmitted light mode structure. For comparison purposes we used an ordinary multimode fiber with two identical tails (without a SNOM tip). The light transmitted by the SNOM tips or by the ordinary multimode fiber was collected by using an objective (32× magnification, NA = 0.4) and directed into a spectrograph (Andor Shamrock SR-303i).

3. Results and discussion

The spectra of the light transmitted by the ordinary multimode fiber and by the two fibers terminated by SWAs are shown in Fig. 2. As one could expect, the spectrum is virtually unaffected by the ordinary fiber. The shape of the light spectrum after passing the 100 nm SWA seems also to be quite similar to the initial one. However, the spectrum of the light transmitted by the 200 nm SWA is noticeably modified, exhibiting a strong modulation.

We attribute the observed spectral modulation to the interference, which can occur if the fiber introduces a phase shift between its different optical modes. Indeed, supposing that the field \( E(t) \) of the transmitted light is the sum of the fields of different modes of the fiber, one gets

\[
E(t) = \sum_k \alpha_k E_0(t - t_k),
\]

where \( E_0(t) \) is the field of the initial light entering the fiber, \( \alpha_k \) is the relative amplitude and \( t_k \) – the phase shift of the transmitted field originating from the mode \( k \). In this case, the spectrum of the transmitted light reads:

\[
I(\omega) = \left| \int_{-\infty}^{\infty} e^{i\omega t} E(t) dt \right|^2 = I_0(\omega) \sum_k \alpha_k^2 e^{i\omega t_k}.
\]

Here

\[
I_0(\omega) = \int_{-\infty}^{\infty} e^{i\omega t} E_0(t) dt
\]

is the spectrum of the initial light. No interference occurs if only one term is present in the sum in Eq. (1). Obviously, this corresponds to a single output mode, which can be the case of the fiber with 100 nm SWA if we take into account the effect of mode filtering [6]. In the case of an ordinary multimode fiber many output modes interfere with each other. However, no remarkable modulation can be observed in the output spectrum due to the phase averaging (in this case \( \sum_k \alpha_k^2 e^{i\omega t_k} \approx \sum \alpha_k^2 = \text{Const} \)).

The spectral modulation is well observable if only a few modes are interfering at the output, which can be the case of the fiber with 200 nm SWA. The observed regularity of spectral interference fringes allows us to assume that a two-mode interference model can be used for this fiber, which simplifies the analysis. Indeed, in this case the output spectrum is modulated with a single period:

\[
I(\omega) \propto I_0(\omega) (1 + \beta \cos(\omega \tau)),
\]

where \( \tau = t_1 - t_2 \) is the relative phase shift of the two modes, determining the period of modulation \( \Delta \omega = 2\pi \tau / \tau \); the depth of the modulation is determined by \( \beta = 2 \alpha_1 \alpha_2 / (\alpha_1^2 + \alpha_2^2) \). Here an analogy can be drawn with the Fourier transform spectroscopy or with the two-pulse interferometry [11,12] where the spectrum of the resulting light field is modulated with \( \cos(\omega \tau) \), where \( \tau \) is the phase difference of two modes determined by the optical pass difference of the two shoulders of an interferometer. The modulation period \( \Delta \omega \) can easily be determined from the measured spectrum, allowing one to estimate the phase shift \( \tau = 2\pi / \Delta \omega \). For our fiber with 200 nm SWA this two-mode approach yields \( \tau = 0.58 \text{ ps} \).

Two major mechanisms can contribute to the generation of phase shifts between different modes. First, the multimode fiber generates the phase shifts that are proportional to the fiber length \( l \) due to the inevitably existing modal dispersion. Second, one can assume that phase shifts can be generated in the close proximity to SWA, therefore being virtually independent of \( l \), due to the light coupling to surface plasmon polaritons of the metal coating of the SNOM tip. This coupling can result in a mode-dependent propagation slowdown or acceleration at the tip. Thus, by finding the fiber length dependence of the phase shift \( \tau(l) \), one could be able to estimate the relative role of these two contributions.

With such a goal in mind, the output spectrum of a 200 nm SNOM tip attached to a multimode fiber of an initial length \( l = 1.075 \text{ m} \) has been repeatedly measured while gradually shortening the fiber. Due to the specifics of our experimental setup the fiber could not be cut shorter than \( l = 0.765 \text{ m} \), and the obtained \( \tau(l) \) dependence on \( l \) consists of only three experimental points (the three spectra shown in Fig. 3).

Assuming the two-mode model, the corresponding \( \tau(l) \) dependence is shown in Fig. 4 along with the linear fit. An extrapolation of the linear dependence, which represents the first mechanism of

Fig. 1. Room-temperature emission spectrum of silicon-vacancy (Si-V) centers in diamond. The Si-V fluorescence is excited by a strongly-focused 532 nm laser radiation, which is filtered out by a red-pass filter.

Fig. 2. Spectra of the light transmitted by different samples of a multimode fiber, with the Si-V fluorescence (spectrum shown in Fig. 1) at their input. Baselines of the spectra are shifted for clarity; vertical scales are changed for an easier comparison. (A) An ordinary fiber (without a SNOM tip), signal collection time \( t_c = 180 \text{ s} \); (B) fiber terminated with a 200 nm SNOM tip, \( t_c = 900 \text{ s} \), vertical scale relative magnification \( \times 18 \); (C) fiber terminated with a 100 nm SNOM tip, \( t_c = 27000 \text{ s} \), vertical scale relative magnification \( \times 35 \).
the phase shift generation, to the zero fiber length yields the phase shift due to the second mechanism: \( s_0 = -0.026(18) \) ps. Here the \( s_0 \) error is calculated by our least squares fitting program and does not account for the estimated errors shown in Fig. 4 – thus the actual uncertainty is larger and our obtained value of \( s_0 \) should not in fact be distinguished from zero. We conclude that the entire phase shift estimated by our simple experimental technique can be accounted for the modal dispersion of the multimode fiber. More sophisticated measurements should be performed to study the possible spectral effects due to the light coupling to surface plasmon polaritons in a SNOM tip.

First, when using the described experimental technique, the measurement precision should be improved. A larger range of output SWA diameters has to be tested to ensure the selecting of an SWA with an appropriate \( d \) for the two-mode operation; this would also allow one to observe the spectral interference patterns for more than two modes and the gradual disappearance of the mesoscopic modulation with further augmenting the number of transmitted modes. A larger range of fiber lengths is to be used, with smaller steps between the selected \( l \) values for a better statistics necessary to improve the precision of the results. It is important to reach as small values of \( l \) as possible, because for smaller \( l \) and non-zero \( \tau_0 \) its ratio to \( \tau \) has to increase, improving the chances of detecting \( \tau_0 \). Taking into account the low possible values of \( \tau_0 \), a source of light with a shorter coherence length (and broader spectrum) should be applied. Although no significant output spectrum dependence on the fiber bending conditions could be detected, we admit that unsharp SNOM probes should be used to eliminate any possible bending effects. An obvious demerit of this technique is an inherent irreproducibility of the past measurements after each fiber cut and an eventual destruction of the functional SNOM tip; different samples of SNOM tips can hardly be considered identical.

Another approach in studying the possible role of nonlinear interactions could be the use of SNOM tips coated with different metals. For example, light propagation through single-mode SNOM tips with different strengths of the photon-plasmon nonlinear interaction could be investigated.

Note finally that optical fibers can also be used to study the nonlinear optical effects on the single-photon level. In a recent experimental study [13] a photonic crystal fiber was applied as a nonlinear Kerr medium, which allowed one to observe the phase shifts of probe laser pulses due to the influence of single pumping photons. We anticipate a possible experimental application of SNOM tips to observe the effects of the mutual interaction of single photons. The evanescent waves of surface plasmon polaritons generated in the metal coating of a single-mode SNOM tip have a strongly reduced group velocity resulting in a strongly enhanced local field, which in turn can result in strong nonlinear interaction of plasmon polariton particles. According to our estimations, for pairs of such single particles the interaction effect may become apparent.

4. Conclusion

In this communication we present our first experimental findings on the effect of a SNOM tip, attached to a multimode fiber and terminated by SWA, on the spectrum of the transmitted light. A mesoscopic effect of spectral modulation is reported for certain SWA diameters. We conclude that a SNOM tip with SWA works as a mode filter, and the spectral modulation indicates the presence of only a few (but more than one) modes in the transmitted light. The modulation is caused by the interference between different modes, indicating the occurrence of their mutual phase shift. An experimental method is proposed, which allows one to study the origin of the observed phase shifts by comparing the transmitted light spectra for different fiber lengths. The application of this technique to a sample of 200 nm SNOM tip yielded the results allowing us to conclude that the observed phase shift can entirely be accounted for the modal dispersion of the multimode fiber. No indication of a phase shift generated in the tapered metal-coated region (or in the bend region) in the vicinity of SWA could be detected for the time being. This result might be caused by the low accuracy of our measurements or apply to the specific sample of a SNOM tip. Discussed are the ways of improving the sensitivity of the described experimental technique to the phase shift generated in the vicinity of SWA. We also propose to use a SNOM tip-based technique to study the mutual nonlinear interaction of single photons.

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References