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Implications of high resolution to near-field optical microscopy

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Abstract

This paper presents problems inherent to high-resolution near-field optical microscopy. It is shown on an easily understandable level, that high lateral confinement of optical fields (a prerequisite for high-resolution microscopy) leads to a fast decay of the fields. Consequently, the optical probe has to be brought very close to the sample surface, increasing the sensitivity to artifacts. Highly confined optical fields are strongly sensitive to variations in the probe-sample separation. The resulting optical images are, therefore, dominated by topographical variations and do not represent the optical properties of the sample surface. © 1998 Published by Elsevier Science B.V. All rights reserved.

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1. Introduction

The goal of near-field optical microscopy is to image the optical properties on an unknown sample with resolutions beyond the diffraction limit. However, it is well known that the images obtained by the various forms of scanning near-field microscopy (SNOM) do not only represent the desired optical properties of the sample, but also contain topographical information. Without any prior knowledge about the sample, it is extremely difficult to distinguish between topographical contrast and true optical contrast in the obtained im-

ages. Many published near-field optical images are closely related to the simultaneously recorded shear-force images. In other cases it can be shown that the optical image simply represents artifacts. A recent paper by Hecht et al. illustrates the various forms of artifacts and discusses the reliability of near-field optical imaging [1].

The reconstruction of the properties of a sample surface using the information encoded in the recorded data is an inverse scattering problem. Unfortunately, this reconstruction is never unique, i.e. there are always different samples which provide the same image. As a consequence, prior knowledge about the sample is needed in order to pin down the right interpretation. It was recently shown that optical information cannot be distinguished from topography if no prior knowledge is provided

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[2, 3]. A sample with a topographical elevation (depression) can lead to the same image as a flat sample where the elevation (depression) is replaced by a buried region with a higher (lower) refractive index.

The present paper is intended to discuss these issues on the basis of a qualitative theoretical picture. It is not intended to provide a rigorous theoretical analysis. Instead, the implications related to high-resolution near-field optical imaging shall be discussed in simple terms which are valid for a broad range of configurations.

With near-field optical imaging we refer to all techniques that use the same wavelength for illumination and detection in the optical near field. This excludes spectroscopic methods using fluorescence, Raman, or nonlinear signals.

2. Theory

Near-field optical microscopy relies on the confined optical fields between a local probe and a sample surface. The higher the lateral confinement, the higher the resolution will be. According to Fig. 1 the light field under consideration shall be laterally confined to the characteristic size d by some artificial structure. At a distance z_0 beneath that structure the field can be represented by an angular spectrum consisting of plane and evanescent waves with \mathbf{k} vectors in all possible directions in the lower half-space [4]

$$\mathbf{E}(x, y; z_0) = \frac{1}{2\pi} \iint_{-\infty}^{\infty} \hat{\mathbf{E}}(k_x, k_y) e^{i(k_x x + k_y y + k_z z_0)} dk_x dk_y. \quad (1)$$

The term $\hat{\mathbf{E}}(k_x, k_y)$ denotes the spatial spectrum (Fourier transform) of the field immediately beneath the confining structure ($z_0 = 0$). The spatial dependence of each component in Eq. (1) is given by an exponential function, which can be split into a transverse and a longitudinal part

$$e^{i\mathbf{k} \cdot \mathbf{r}} = e^{i\mathbf{k}_t \cdot \mathbf{r}_t} e^{ik_z z_0}, \quad (2)$$

where k_t and k_z denote the transverse and longitudinal wave number, respectively. Similarly, the

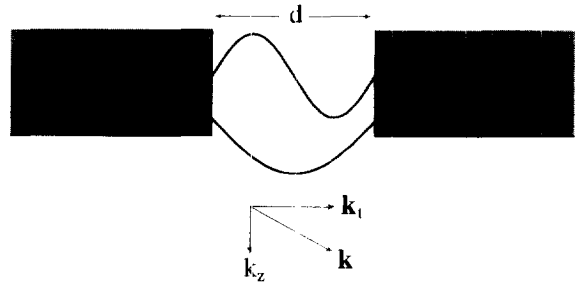


Fig. 1. Lateral confinement of the optical fields to the characteristic size d . The \mathbf{k} -vectors can be split into a transverse and a longitudinal part.

spatial coordinates are decomposed into a transverse (r_t) and a longitudinal part (z_0).

The longitudinal wave number of each component of the angular spectrum Eq. (1) can be expressed in terms of the transverse wave number and the wavelength λ as

$$k_z = \sqrt{(2\pi/\lambda)^2 - k_t^2}. \quad (3)$$

The absolute value of the transverse wave number depends on the characteristic dimension of the confining structure

$$k_t \approx j(n\pi/d) \quad (j = 1, 2, \dots), \quad (4)$$

when n designates the index of refraction of the medium inside the structure (cf. Fig. 1). It then turns out, that the longitudinal wave number can be either real or imaginary, depending on the mode j and the spatial confinement d . According to Eq. (2) the waves do either propagate (plane waves) or decay (evanescent waves) in the z -direction.

2.1. Field decay and probe-sample coupling

From the above considerations it follows that a certain field mode j is evanescent, if the following inequality holds:

$$d < j(n\lambda/2) \quad (j = 1, 2, \dots). \quad (5)$$

If the optical field is laterally confined to dimensions smaller than $(n\lambda/2)$, all field modes are evanescent. In the absence of a sample, no propagation to the far-field takes place in this

oversimplified picture. In the presence of a sample, the evanescent fields can be converted into propagating modes by refraction at the sample surface [5, 6] or by scattering at sample features. Notice, that in reality the plane-wave components cannot be entirely suppressed (even in the Bethe/Bouwkamp model). However, with increasing lateral confinement their amplitudes tend to zero. In real situations, the fields also cannot be abruptly confined as in the present model.

The 1/e decay length of the electric field strength ($|E|^2$) of an evanescent mode is given by

$$\frac{1}{2k_z} = \frac{\lambda}{2\pi\sqrt{(jn\lambda/d)^2 - 4}} \quad (6)$$

The slowest decay is obtained for the $j = 1$ mode which is shown in Fig. 2. A refractive index of $n = 1.485$ has been chosen. The main point of the figure is that the more the field is confined laterally, the faster it decays in forward direction. Assuming a wavelength of $\lambda = 500$ nm and a confinement of $d = 10$ nm the decay length turns out to be ≈ 1 nm. In other words, within 1 nm the field energy drops to approximately one-third. This has important experimental implications: The higher the confinement is, the closer the probe has to be moved to the sample surface and the higher the probe-sample coupling will be. High-resolution images will, therefore, be strongly influenced by

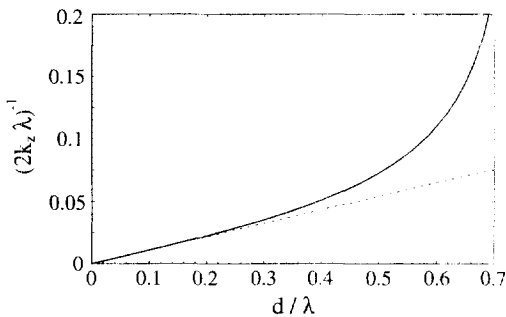


Fig. 2. Decay length ($1/2k_z$) versus lateral confinement (d). A normalization with the wavelength λ is used. The higher the confinement is, the faster the fields decay in forward direction and the closer the probe must be moved to the sample surface. Higher resolution is opposed by stronger probe-sample coupling.

topographical variations of the sample (artifacts) due to the dramatically enhanced coupling. This leads to screening of real optical information such as refractive index variations or local absorption changes [1].

2.2. Sensitivity to probe-sample separation

Variation of the probe-sample separation (e.g. due to the tip trying to follow the surface in constant gapwidth mode) modulate the optical signal. The sensitivity of the optical field (S_z) to a variation Δz_o in forward direction can be represented by

$$S_z = A \left| \frac{\partial e^{2ik_z z_o}}{\partial z_o} \right|_{z_o = (2k_z)^{-1}} \quad (7)$$

where A is a proportionality constant. As indicated, the expression is evaluated at the 1/e decay length given by Eq. (6). It turns out, that the sensitivity is simply proportional to the longitudinal wave number k_z (inversely proportional to the decay length). The dependence of S_z on the confinement d is shown in Fig. 3. While for large d there is a linear relationship, a strong increase in sensitivity can be observed for small d . Assuming a wavelength of $\lambda = 500$ nm, the sensitivity for a confinement of $d = 10$ nm is more than 10 times higher than for a confinement of $d = 100$ nm. This result suggests

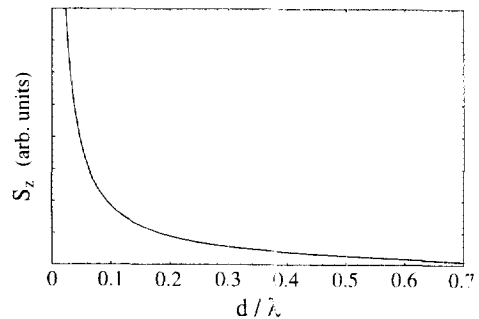


Fig. 3. Sensitivity to variations of the probe-sample separation (S_z) versus lateral confinement (d). The sensitivity increases strongly for small d . Higher resolution is opposed by stronger sensitivity to topographical variations.

that it is extremely difficult to obtain high-resolution near-field optical images which are free of artifacts in the sense of Ref. [1] and uncorrelated to topography.

3. Conclusions

High resolution in near-field optical microscopy requires small probe-sample separations. Because of the increasing probe-sample interactions at small separations, the optical images can become dominated by artifacts. Furthermore, highly confined light sources cause the optical signal to be very sensitive to variations of the probe-sample separation. It is, therefore, difficult to retrieve optical information at high resolution without coupling to topographical variations. Substantial prior knowledge about the sample is needed in order to correctly interpret the optical images. It seems that high resolution is opposed by loss of true optical information! Although contrast/absorption imaging (same wavelength for illumination and detection) becomes intractable at very high resolutions, reliable images can still be provided by fluorescence

or nonlinear imaging (detection and illumination at different wavelengths).

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