Recovery of Permittivity and Depth from Near-Field Data as a Step toward Infrared Nanotomography

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Scattering-type scanning near-field optical microscopy (s-SNOM) is a powerful optical technique for nondestructive spectroscopic imaging with deep subwavelength resolution [1]. In s-SNOM, images are recorded by scanning a sharp illuminated probe along the sample surface and detecting the backscattering. This scattering depends on the near-field interaction between the probe and the sample, thus revealing the dielectric properties of the sample in the image contrast. While s-SNOM has demonstrated the ability of quantitative analysis of such images for samples with structure varying in two dimensions [2], the elucidation of sample structure in all three dimensions (3D) has proved elusive.

The main obstacle to inferring the 3D sample structure from s-SNOM images is the complicated nature of near-field interaction that intermixes (couples) the dielectric properties of sample constituents/features with their distance to the tip. Thus the same image contrast could result from the variation of the dielectric permittivity of the feature or its depth below the sample surface, i.e. from the sample geometry. The lack of simple image interpretation method resulted in s-SNOM being traditionally regarded as a technique for surface studies.

In this work we break the traditional view at s-SNOM and open the door to the third dimension for near-field techniques by introducing and providing the first experimental demonstration of a method for performing a rapid recovery of the thickness and permittivity of simple 3D objects, such as thin films and polymer nanostructures [3]. This is accomplished by taking advantage of the near-field data recorded at multiple harmonics of the oscillation frequency of near-field probe as depicted in Figure 1. A complete set of such harmonics serves as a proxy for an approach curve that measures the near-field interaction as a function of tip-sample distance. Thus multiple harmonics of the demodulated signal encode information about the volumetric composition of the sample.

To recover this volumetric information, we developed a novel nonlinear model that describes the near-field interaction of the s-SNOM tip with a film deposited on a substrate. The key advantage of our model is that it allows for an analytic inversion of the associated scattering problem with respect to the sample permittivity, parameterized by a single depth/thickness variable. The correct film thickness is then obtained by enforcing the consistency of the results derived from different harmonics of the scattered signal. Mathematically, this formulates a simple one-dimensional minimization problem that decouples the dielectric properties from the sample geometry, thus allowing for the unique interpretation of near-field images. In conjunction with the simplicity of obtaining the necessary data (the signal harmonics are routinely recorded as a part of the background suppression in s-SNOM) our technique presents a humble, practical method of recovering the subsurface sample structure from near-field measurements.

Our work enables the quantitative nondestructive nanoscale-resolved optical studies of thin films, coatings and functionalization layers, as well as the structural analysis of multiphase materials and other samples in which the topography does not correlate with the chemical or optical properties. It opens new frontiers for chemometrics, materials and bio sciences and represents a major step towards the further goal of the near-field nanotomography.

References

[1] T. Taubner, R. Hillenbrand, and F. Keilmann, Appl. Phys. Lett. 85, 5064 (2004),

[2] A. Govyadinov, I. Amenabar, F. Huth et al, J. Phys. Chem. Lett. 4, 1562 (2013),

[3] A. Govyadinov, S. Mastel, F. Golmar et al, ACS Nano, in Just Accepted (2014).

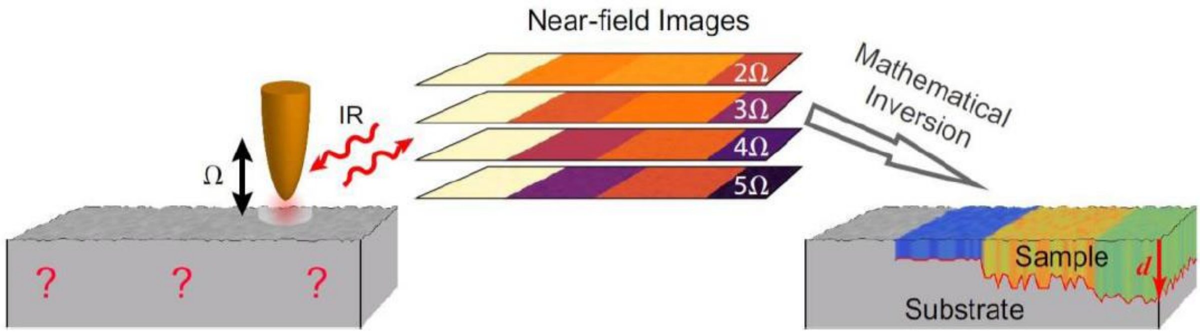

Figure 1. Schematics of the s-SNOM experiment and the conceptual representation of the reconstruction procedure that yields the sample structure. The field scattered by an oscillating AFM tip is detected interferometrically and demodulated at higher harmonics of the tip oscillation frequency. By scanning the sample surface, a set of near-field images is recorded. A mathematical inversion procedure is then applied at each pixel to recover the sample structure, i.e., thickness (represented by red curve) and dielectric permittivity (represented by fill color) of the sample layer.