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INVERSE SCATTERING PROBLEMS IN NEAR-FIELD OPTICS

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ABSTRACT

We consider the inverse scattering problem for wave fields with evanescent components. Our results establish a method for three-dimensional tomographic imaging with subwavelength resolution.

Scanning near-field optical microscopy (SNOM) has attracted considerable attention as an experimental technique to obtain images of surfaces with subwavelength resolution. This achievement is particularly important for imaging structures where spectroscopic concerns or sample handling requirements dictate the use of lower frequency fields and yet high spatial resolution is still required. Applications range from the inspection of biological samples to semiconductors. Various experimental modalities are in practical use. Two prominent examples are collection mode SNOM and illumination mode SNOM. In illumination mode SNOM, a tapered fiber probe with a sub-wavelength size aperture serves as a source of illumination in the near-zone of the sample. The scattered field intensity is then measured and recorded as a function of the probe position while the probe is scanned over the sample. In collection mode SNOM, the fiber probe serves to detect the total field in the near-zone as the sample is illuminated by a source in the far zone.

There are certain limitations of SNOM as currently practiced. Despite the fact that the sample may present a complicated three-dimensional structure, SNOM produces only a two-dimensional image. Indeed, rather than being an imaging method, it is more accurate to say that SNOM maps the sub-wavelength structure of the optical near-field intensity in some plane above the sample. Under certain simplifying assumptions, such as homogeneity of the bulk optical properties of the sample, the images produced in these experiments may be related to the sample structure. However, for the more general case in which the topography of the sample and the bulk optical properties both vary, the connection between the near-field intensity and the sample structure has proven ambiguous To resolve this ambiguity it is desirable to solve the inverse scattering problem (ISP) for wave fields with evanescent components. The ISP consists of reconstructing the three-dimensional object structure, in this case the spatial dependence of the dielectric susceptibility of the sample, from measurements of the scattered field. By solving the ISP we thus resolve two issues. We remove the ambiguity in connecting the sample properties and the measured data, and simultaneously we obtain three-dimensional, tomographic images of the sample.

Historically, solution of the ISP for various scattering modalities has greatly expanded the functionality of existing methods. The ISP of SNOM is of great interest because it offers the possibility to obtain sub-wavelength resolved three-dimensional reconstructions. To this end it was recently demonstrated that when both the phase and amplitude of the optical near-field are available, the near-field ISP may be solved, and an inversion formula was presented. In that work, which treated only the case of scalar waves, an analysis of a collection mode SNOM experiment with phase measurement capability was presented. Validation of the results was demonstrated by numerical simulation.

In this paper we expand upon and extend our results. We discuss three experimental modalities and present analyses of the near-field ISP for both scalar and vector waves. A treatment of the vector case is particularly important in the near-field ISP because polarization effects are somewhat more complicated than for the far-field problem and, in fact, the scalar approximation may not be appropriate when the sample presents subwavelength variations in structure. The solution to the near-field ISP in all cases will be derived by a singular value decomposition (SVD) analysis of the linearized scattering problem. The SVD is a generalized mode decomposition that offers considerable insight into the scattering problem.

The analysis of the ISP for SNOM proceeds as follows. First, we consider the theory of near-field scattering for wave-fields obeying the scalar reduced wave equation. Specifically we obtain expressions for the scattered field as measured in three distinct modalities. In all cases we assume that the field may be measured, that is the measurements are phase sensitive. The first two modalities are variations on the illumination mode and collection mode experiments. The third modality we discuss is conceptually novel and requires the use of two near-field probes. The three expressions derived for the scattered fields are shown to be special cases of a single expression relating the measured data to the structure of the scattering object to be imaged. We take advantage of the unified form for all three modalities to develop the SVD for the scattering kernel and obtain the inversion formula for the ISP.

The vector theory of near-field scattering is developed analogously. We consider the three modalities and find a common underlying form so that we can again develop the SVD. Although the vector nature of light makes asignificant difference in the physics of the problem, the mathematical form is much like the scalar case and the results follow from the scalar case in a straight forward manner.

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