Journal of Quantitative Spectroscopy & Radiative Transfer 136 (2014) 1–15

Contents lists available at ScienceDirect

Journal of Quantitative Spectroscopy & Radiative Transfer

journal homepage: www.elsevier.com/locate/jqsrt

Strong tip–sample coupling in thermal radiation scanning tunneling microscopy

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ARTICLE INFO

Article history:
Received 15 July 2013
Received in revised form
9 November 2013
Accepted 11 December 2013
Available online 22 December 2013

Keywords:
Near-field thermal radiation
Infrared radiation
Local density of states
Scanning near-field optical microscopy
Tip–sample interactions
Local spectroscopy

ABSTRACT

We analyze how a probing particle modifies the infrared electromagnetic near field of a sample. The particle, described by electric and magnetic polarizabilities, represents the tip of an apertureless scanning optical near-field microscope (SNOM). We show that the interaction with the sample can be accounted for by ascribing to the particle dressed polarizabilities that combine the effects of image dipoles with retardation. When calculated from these polarizabilities, the SNOM signal depends only on the fields without the perturbing tip. If the studied surface is not illuminated by an external source but heated instead, the signal is closely related to the projected electromagnetic local density of states (EM-LDOS). Our calculations provide the link between the measured far-field spectra and the sample's optical properties. We also analyze the case where the probing particle is hotter than the sample and evaluate the impact of the dressed polarizabilities on near-field radiative heat transfer. We show that such a heated probe above a surface performs a surface spectroscopy, in the sense that the spectrum of the heat current is closely related to the local electromagnetic density of states. The calculations agree well with available experimental data.

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1. Introduction

Since the seminal work of Rytov and co-workers [1], it is known that thermal radiation has a different behavior when the involved characteristic lengths are large or small compared to the thermal wavelength [2–4]. For example, the heat flux transferred between bodies separated by a subwavelength distance can exceed by far the one between black bodies [5,6]. Energy density [7] and coherence properties [8] are also strongly affected in the near field, especially close to materials exhibiting resonances such as polaritons. Knowing precisely how the electromagnetic field behaves close to a surface is therefore an important issue in order to address potential applications involving near-field heat transfer.

From an experimental point of view, the coherence properties of near-field radiation have been utilized to produce directional and monochromatic thermal sources [9–11]. The enhancement of radiative heat transfer at short distances has been demonstrated recently between two macroscopic surfaces [12,13], but probe microscopy techniques are still playing a prominent role [14–16]. Near-field thermal flux imaging has been operated with a scanning thermal microscope [17,18]. A scanning near-field optical microscope (SNOM) without external illumination, termed thermal radiation scanning tunneling microscope (TRSTM), has also been used to image surfaces [19–21]. Very recently, local spectra have also been measured [22,23].

Most of these experimental techniques use a small probe brought in the vicinity of the sample surface. Its response to the sample's near field is given by a polarizability. The induced multipoles are sources that radiate

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0022-4073/$ - see front matter © 2013 Elsevier Ltd. All rights reserved.
http://dx.doi.org/10.1016/j.jqsrt.2013.12.006

into the far field, thus providing the TRSTM signal. At short (sub-wavelength) distances however, the mutual interaction between the probe and the surface modifies the local electromagnetic field [24–27], and this actually changes the probe's optical properties such as the polarizability. These interactions also complicate the data analysis for the near-field techniques mentioned above. In particular, one is often interested in the sample's optical properties, as encoded in the electromagnetic local density of states (EM-LDOS) [28,17]. Due to the tip–sample interaction, it is no longer obvious how the TRSTM signal scattered by the tip into the far field is related to the EM-LDOS. In particular, can a SNOM detecting thermal radiation be the electromagnetic equivalent of the scanning tunneling microscope detecting the electronic LDOS [29]? Moreover, one can ask what information can be extracted from the exchanged heat flux between the probe and the sample.

If some of these questions have already been addressed in the past [28,30], our goal is here to clarify remaining interrogations. Following previous similar works [31,32], we will first see how the particle polarizability can be replaced by an effective or *dressed* polarizability taking into account multiple reflections between the probe and the surface. This is more general than the image-dipole model [31] whose range of validity is very restricted in the infrared. We will then use the theory to calculate the signal detected in the far field when the near field is scattered by a probe dipole. An expression for the SNOM signal is calculated and illustrated by scanning a surface excited either by a plasmon or by broadband thermal radiation (TRSTM mode). In this paper, the probe tip is modeled by both electric and magnetic dipoles. This approach fails to capture field inhomogeneities across the tip that occur at short distances (comparable to the tip size) and excite higher multipoles. It has the advantage, however, of providing relatively simple expressions that can be physically interpreted. The model has also been shown to reproduce the main physical ingredients in the case of a TRSTM tip [22]. It is powerful since the analysis of the results based on analytical expressions is straightforward. It is sure that a more accurate modeling of the tip, e.g., with a cone, would be better. However, the analysis of the various detected components (polarization, electric vs magnetic, etc.) may be much more complicated in this case. The dipole approach could also be included as a building block into more flexible numerical schemes like the coupled dipole method [33,34,24], the multiple multipole method [35] or the discrete dipole approximation [36,37] that has been very recently adapted to thermal near field radiation [38]. It is also an alternative to more complicated but exact numerical methods such as surface-integral methods [39].

We conclude the paper by analyzing the signal detected in far field due to a heated probe when accounting for probe–surface interactions. Finally, the radiative cooling of a particle in the near field and the spectrum of the heat flux are analyzed.

2. Dressed polarizabilities

We propose here to calculate the *dressed* polarizability of a dipolar particle when it is placed in an environment

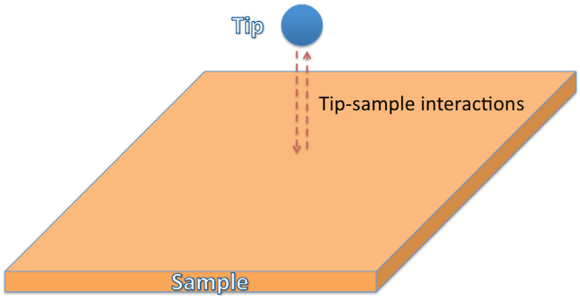

Fig. 1. Sketch of the system.

which is different from free space. Indeed, when a particle is added to a system, the electromagnetic field present in the system illuminates the particle and induces a dipole moment (Fig. 1). This dipole radiates a field everywhere that scatters back to the particle position. This interaction between the particle and the system modifies the total electromagnetic field, which is no longer given by the field in the absence of the perturbing probe. In other words, the probe is no longer a passive test dipole. Our aim is to show that we can work with the unperturbed electromagnetic field if we ascribe to the particle a dressed polarizability.

Let us call $\mathbf{E}^0$ the electromagnetic field in the system without the particle (i.e., the "non-perturbed field"). When a particle (tip) is placed in the system at position $\mathbf{r}_t$, an electric dipole $\mathbf{p}$ and a magnetic dipole $\mathbf{m}$ will be induced in the particle (tip). These dipoles radiate a field: the total field $\mathbf{E}^{tot}$ is the sum of $\mathbf{E}^0$ and of the field radiated by the dipoles. In the following, we use Green tensors to express the field radiated by a dipole:

$$\mathbf{E}^{tot}(\mathbf{r}) = \mathbf{E}^0(\mathbf{r}) + \overleftrightarrow{\mathbf{G}}^{EE}(\mathbf{r},\mathbf{r}_t)\cdot\mathbf{p} + \overleftrightarrow{\mathbf{G}}^{EH}(\mathbf{r},\mathbf{r}_t)\cdot\mathbf{m} \tag{1}$$

where $\overleftrightarrow{\mathbf{G}}^{EE}$ and $\overleftrightarrow{\mathbf{G}}^{EH}$ take into account the reflection (scattering) by the sample. This can also be written as

$$\mathbf{E}^{tot}(\mathbf{r}) = \mathbf{E}^0(\mathbf{r}) + \overleftrightarrow{\mathbf{G}}^{EE}(\mathbf{r},\mathbf{r}_t)\cdot\alpha\mathbf{E}^{tot}(\mathbf{r}_t) + \overleftrightarrow{\mathbf{G}}^{EH}(\mathbf{r},\mathbf{r}_t)\cdot\beta\mathbf{H}^{tot}(\mathbf{r}_t) \tag{2}$$

where α and β are the "bare" electric and magnetic polarizabilities of the particle: they do not know about the surrounding sample and describe its reaction to the local field $\mathbf{E}^{tot}(\mathbf{r}_t)$, $\mathbf{H}^{tot}(\mathbf{r}_t)$. For a spherical particle, they are scalars. The generalization to anisotropic particles where α and β become tensors is straightforward, see, e.g., Ref. [40].

Analogous expressions exist for the magnetic field

$$\mathbf{H}^{tot}(\mathbf{r}) = \mathbf{H}^0(\mathbf{r}) + \overleftrightarrow{\mathbf{G}}^{HE}(\mathbf{r},\mathbf{r}_t)\cdot\mathbf{p} + \overleftrightarrow{\mathbf{G}}^{HH}(\mathbf{r},\mathbf{r}_t)\cdot\mathbf{m} \tag{3}$$

that can also be written as

$$\mathbf{H}^{tot}(\mathbf{r}) = \mathbf{H}^0(\mathbf{r}) + \overleftrightarrow{\mathbf{G}}^{HE}(\mathbf{r},\mathbf{r}_t)\cdot\alpha\mathbf{E}_{tot}(\mathbf{r}_t) + \overleftrightarrow{\mathbf{G}}^{HH}(\mathbf{r},\mathbf{r}_t)\cdot\beta\mathbf{H}^{tot}(\mathbf{r}_t) \tag{4}$$

The Green tensors used here come in four types: $\overleftrightarrow{\mathbf{G}}^{EE}(\mathbf{r},\mathbf{r}_t)$ gives the electric field at position $\mathbf{r}$ when an electric dipole source is placed at $\mathbf{r}_t$. In the same way, $\overleftrightarrow{\mathbf{G}}^{EH}(\mathbf{r},\mathbf{r}_t)$ gives the electric field at position $\mathbf{r}$ when a magnetic dipole is placed at $\mathbf{r}_t$. $\overleftrightarrow{\mathbf{G}}^{HE}$ and $\overleftrightarrow{\mathbf{G}}^{HH}$ respectively give the magnetic field of an electric and a magnetic dipole. These Green tensors, which

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