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Review article

Dana C. Kohlgraf-Owens, Sergey Sukhov, Léo Greusard, Yannick De Wilde and Aristide Dogariu*

Optically induced forces in scanning probe microscopy

Abstract: Typical measurements of light in the near-field utilize a photodetector such as a photomultiplier tube or a photodiode, which is placed remotely from the region under test. This kind of detection has many draw-backs including the necessity to detect light in the far-field, the influence of background propagating radiation, the relatively narrowband operation of photodetectors which complicates the operation over a wide wavelength range, and the difficulty in detecting radiation in the far-IR and THz. Here we review an alternative near-field light measurement technique based on the detection of optically induced forces acting on the scanning probe. This type of detection overcomes some of the above limitations, permitting true broad-band detection of light directly in the near-field with a single detector. The physical origins and the main characteristics of optical force detection are reviewed. In addition, intrinsic effects of the inherent optical forces for certain operation modalities of scanning probe microscopy are discussed. Finally, we review practical applications of optical force detection of interest for the broader field of the scanning probe microscopy.

Keywords: scanning probe microscopy (SPM); near-field scanning optical microscopy (NSOM); scanning near-field optical microscopy (SNOM); atomic force microscopy (AFM); Kelvin probe force microscopy (KPFM); near-field optics; optical forces; opto-mechanics; opto-mechanical resonator.

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Edited by Aaron Lewis

1 Introduction

As technology relies more and more on the design and engineering of structures which are nanoscale in two or three dimensions, it becomes increasingly important to have metrology tools capable of characterizing the properties of the constituent materials at the relevant length scales. In the field of nano-optics and nano-photonics, an additional requirement is to measure properties of electromagnetic fields at scales much smaller than the wavelength. Such demands are usually met by scanning probe microscopy (SPM) which, in general, relies on detecting the consequences of the field-mediated interaction between a small probe and some physical surface. Depending on the properties of the probe and the sample as well as the operation modality, different interactions may be measured largely limited only by the imagination and ingenuity of the researcher. As a result, forces such as chemical, biological, magnetic and electrostatic are routinely measured [1–4].

Because SPMs are essentially interaction microscopies, understanding the phenomenology of the interaction is critical to appreciate the result of a measurement. The focus of this review is on the influence of optically induced effects in SPM and the contribution of optically induced forces on the total force acting on the probe.

Electromagnetic fields interact with a scanning probe by transferring energy or by imparting a momentum. Because these mechanisms may be inter-related, they both must be taken into account to properly describe the physical situation. In general, all interaction mechanisms result in forces acting on the scanning probe. These forces can either constitute the information to be measured or can be utilized as an auxiliary signal that provides the feedback for position control.

In practice, interactions are present on multiple length scales and from multiple sources. Thus, it becomes possible to use the interaction from one physical mechanism occurring at a given length scale for feedback control

while measuring the result of another interaction in a separate channel. Perhaps the most widely used SPM which takes advantage of this functionality is near-field scanning optical microscopy (NSOM), which relies on the interaction of a sharp probe or aperture with evanescent near-fields contained close to the sample surface to measure light distributions with sub-diffraction limited resolution.

The feedback mechanism of an NSOM allows the probe to follow the topography by maintaining the interaction force or force gradient between the probe and the sample at a constant preset value. In the meantime, the evanescent near-fields which are confined at the probe or at the sample surface are detected via tip and/or sample induced conversion of evanescent to propagating fields, which may then be detected in the far-field using sensitive photodetectors.

Here we review recent evidence that, at least for certain experimental configurations, the optical radiation influences the feedback control and therefore must be taken into account to properly interpret NSOM measurements. To understand the origin and the importance of this effect, we will briefly review the operation of feedback control in SPM in Section 2.

The electromagnetic field induces forces through a variety of mechanisms that can include energy transfer, which, most commonly, leads to heating of the probe. However, forces acting on the scanning probe can also be generated by direct momentum transfer. This phenomenon will be reviewed in Section 3, where we will discuss several experimental configurations where optically induced forces come into play. In Sections 4 and 5 we will show how one can capitalize upon this type of interaction to investigate properties of the local distributions of electromagnetic fields. Finally in Section 6 we discuss the applicability of the measurement of electromagnetic radiation via its interaction with a probe both within the SPM community as well as to the broader physics community.

2 Fundamental concepts in SPM

To understand the motivation for using SPM techniques to measure optical radiation, we recall that when fields interact with media, waves are scattered thus encoding information about the object into the field. Two types of waves are generated: propagating waves which may be measured in the far field by a detector and evanescent near-fields which unless disturbed will decay exponentially away from the surface. Such exponential decay occurs when $k^2 < k_x^2 + k_y^2$ where $k = 2\pi n/\lambda$ is the wavevector

of the light, with components (k_x, k_y, k_z) . It is assumed here that k_x, k_y are parallel to the surface of the sample, while k_z is perpendicular to it. Thus the action of propagating information about an object to a detector in the far-field causes the attainable resolution to be limited to the order of a wavelength [5]. Higher resolution may still be achieved in several ways with methods based on far-field microscopy: for example, using a shorter wavelength, imaging in a higher refractive index medium or using structured illumination. Particularly in the biological sciences, there has been considerable research involving the use of fluorescence tagging to generate images with better than diffraction limited resolution. Stochastic optical reconstruction microscopy (STORM), photoactivated localization microscopy (PALM), saturated structured illumination microscopy (SSIM), and stimulated emission depletion (STED) are a few examples of such methods [6–8].

Another possibility is NSOM, which is based on the direct detection of the evanescent fields. This may in general be accomplished by using a probe of subwavelength size, which is placed directly in the near-field at the surface of the sample [9]. High spatial frequency components are required to describe a subwavelength probe; therefore such an object can couple with the near-field to be detected. Placing the probe in the near-field practically requires the use of a feedback loop to maintain a fixed tip-sample separation while lateral scans of the tip at the surface are performed in order to map the spatial distribution of the near-field. This permits the probe to maintain a consistent imaging resolution both for topography and for near-field optical measurements and prevents it from crashing into the sample.

A schematic example of a NSOM set-up is shown in Figure 1. It consists of a sharp probe attached to a mechanical resonator such as a tuning fork or cantilever. Feedback can be achieved by oscillating the resonator close

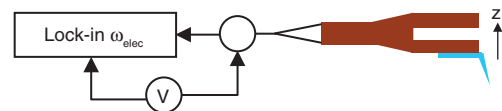


Figure 1 Typical intermittent contact SPM setup, here based on a tuning fork force detector. A sharp probe is rigidly attached to one arm of the tuning fork. A voltage generator is used to electrically drive the tuning fork near resonance. Due to the piezoelectric effect, the electrical driving is converted into a mechanical motion which dithers the probe. The reflected signal from this electrical driving is then fed into a lock-in and the amplitude and phase are measured. A feedback loop permits the probe to follow the sample topography by maintaining a constant force gradient induced phase shift on the probe due to tip-surface interaction forces.

to its resonance frequency and monitoring the changes in the resonator properties as it interacts with the sample surface. This allows one to maintain a prescribed tip-sample separation close to the sample surface. The surface topography is recorded in the standard AFM resonant mode using an oscillating quartz tuning fork having a sharp probe rigidly fixed to one of its arms. When the probe is brought close to an interface, the resonance frequency of the tuning fork and/or the dissipation rate are affected by surface forces, which change the amplitude and/or the phase of the induced oscillations measured by lock-in detection. A feedback loop maintains a constant phase or frequency shift of the piezoelectric signal relative to the driving voltage and thus establishes a constant tip-sample separation in the proximity of the sample.

3 Radiation forces in SPM

As we discuss in this review, the presence of an optical field induces additional forces acting on an SPM probe. When the strength of these optical forces is comparable to the surface forces, they can induce a measurable effect upon the feedback mechanism. Readout of the changes in cantilever properties may be performed using optical detection [10], piezoelectric [10, 11] or piezoresistive effects [12].

The optical field can perturb the cantilever in two different ways. First, the cantilever can be affected directly due to optically induced forces which compete with van der Waals/Casimir forces to alter the surface force profile that the AFM probe follows and act to “trick” the probe into thinking topography exists when it doesn’t. We refer to this effect as the “*topography of light*”, which will be discussed in the next section.

The electromagnetic radiation can also affect the cantilever indirectly. For instance, thermal heating due to absorption may occur and can induce lattice expansion in the sample or tip, in the latter case leading to many effects such as tip elongation. In general both effects are present and their relative contribution is strongly dependent on the probe, sample, and operation modality. The influence of direct and indirect optically induced effects is the subject of this review.

3.1 Indirect effects of optical fields

The optical forces acting on small particles, particularly when induced by evanescent fields excited in a TIR

illumination mode, have received considerable attention both theoretically and experimentally [13–17]. Because a small NSOM probe is often modeled as a small sphere and because TIR illumination is common for this microscopy, these studies can provide a useful framework to understand NSOM measurements.

To our knowledge, the prospect that an atomic force microscope probe may be sensitive to optically induced forces due to evanescent fields was first put forth in a theoretical article in 1992 [18], wherein the authors calculated the force on a sphere in an evanescent field from a totally internally reflected wave on a triangular prism. Based on their calculations, Depasse and Courjon concluded that for reasonable excitation intensities, a force should be measurable using a standard AFM. This idea was further refined theoretically [19–21]. Later, Iida and Ishihara studied the effect of light induced force microscopy of resonant quantum dot systems [22–24].

Some experiments have also been carried out to study this effect. In 1997, Zhu, et al. examined the shear force feedback signal as a function of tip-sample separation both when the laser light was coupled into the probe and when the probe was illuminated from the side [25]. In a subsequent publication they report that a somewhat higher optical force was induced on an aluminum coated tip than on a bare silicon dioxide tip and a significantly higher force was detected when using a substrate with high dielectric constant. These authors did not notice any effect when a metal substrate was used [26]. Likewise, Lienau et al., studied the thermal expansion of AFM probes, operated in shear-force feedback mode, as a function of incident power when the probes were placed over the face of an emitting quantum well laser [27]. Their topography images clearly demonstrate the influence of the light on the measurement. In their experiments, Lienau et al. found a linear dependence between the output power of the laser and the elongation of standard metal coated and fully metalized probes. However, no effect could be measured in the case for uncoated dielectric probes [27].

These observations and others can be traced directly to phenomena related to dissipation of electromagnetic energy. Thermal effects can impact the measurement in a number of ways, for example probe elongation or shortening [26, 28–34], widening of the probe aperture [31], expansion of a metal coating past the dielectric core of the probe [32], changes in the metal work function and thus the capacitance present between the tip and sample [35], and of course in extreme cases thermally induced damage [36].

For cantilever based systems, the influence of the beam-bounce laser cannot be ignored as it can itself affect the cantilever deflection [37, 38]. In one report, a 100 μW

laser caused the commercial uncoated probe studied to deflect by 30 nm when excited from one side as in a typical beam-bounce configuration whereas the standard metal coated probe deflected over 3 μm [37]. These studies found that radiation pressure dominates the optical effects on uncoated silicon nitride cantilevers whereas thermally induced bi-material effects dominate the contributions for metal coated silicon nitride cantilevers. In this study, the probe was excited below the bandgap for silicon nitride, thus only thermal effects result. If the cantilever is instead excited above the bandgap, the radiation induced mechanical stress is dominated by photoinduced stress [39].

A notable SPM technique relying on the dissipation of radiation is Kelvin probe force microscopy (KPFM), which relies on the measurement of local variations in the contact potential difference (CPD), a property depending on material work functions, surface impurities, oxide layers, humidity, dopant concentration for semiconductors and temperature. Because conductors or semiconductors are used, the thermally induced effects on the tip and/or sample are primarily due to absorption of the incident radiation [40].

The Kelvin technique used to measure the CPD for bulk materials relies on bringing two conducting materials together in close proximity in a parallel plate capacitor arrangement. To measure these properties locally, one of the plates is replaced by an AFM tip and the applied force as a function of applied external voltage between the tip and sample is measured [41]. This technique permits the measurement of local changes in the optical absorption of the tip-sample system [42–45]. Moreover, by modulating the external voltage and the cantilever oscillation at different frequencies, the topography and CPD maps may be simultaneously acquired [46].

As part of the probe-sample interaction, energy dissipation provides interesting opportunities for SPM. Thermal effects were used to optically modulate the cantilever with light [37], to optically increase [47] or decrease [48] the cantilever quality factor or even to change the cantilever spring constant [49]. The latter can, for example, improve the time response without sacrificing the force sensitivity [48] or even to increase the force sensitivity [49]. Furthermore photothermal cantilever actuation may be used to realize fast scanning rates or low noise scanning in low Q environments such as scanning in liquids [50–55].

3.2 Effect of optically induced forces

Recent developments prove that, in fact, the effect of electromagnetic radiation on the interaction between SPM probes and materials is more complex and does not

necessarily rely on energy dissipation. For instance, Satoh et al. measured optical force induced changes in the resonance frequency and dissipation on a probe scanning a checkerboard structure of chromium patches deposited on a glass prism and illuminated in total internal reflection, as shown in Figure 2 [56].

The specific feedback used in the experiment is critical to understanding the results. At typical irradiation, the optical radiation exerts a force on the probe of the order of a few pN [21, 57], and commercially available SPM probes are usually sensitive to forces of this order [21]. However, in order to be detected, the optically induced force (OIF) cannot be significantly weaker than the other interaction forces. Moreover, the strength of the surface forces acting on an SPM probe depends strongly on the measurement modality used. For example, when operating in intermittent contact mode using normal force feedback, relatively high oscillation amplitudes are used as was the case in the experiment illustrated in Figure 3. Consequently, the averaged surface-induced force is relatively small because the surface forces depend strongly on the tip-sample separation. Thus, in these conditions the magnitudes of OIF become comparable to the surface forces present in typical experimental conditions [11, 56, 58, 59].

On the other hand, when shear force feedback is used, the average surface force acting on the probe is much stronger since the probe spends most of its oscillation cycle very close to the sample surface. Likewise, surface forces can also dominate in contact mode, where the probe is brought into contact with the sample surface. Nevertheless, the presence of optical radiation can still

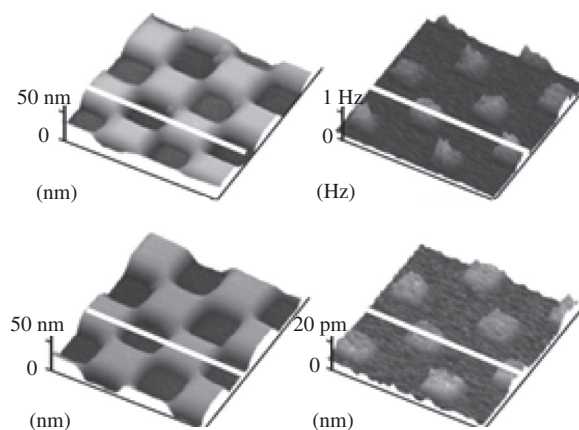


Figure 2 (A) Topography and (B) corresponding frequency shift measured over a Cr checkerboard structure deposited on a prism illuminated in total internal reflection. (C) Topography and (D) corresponding amplitude shift measured in dissipation mode for the same structure. Adapted from [56].

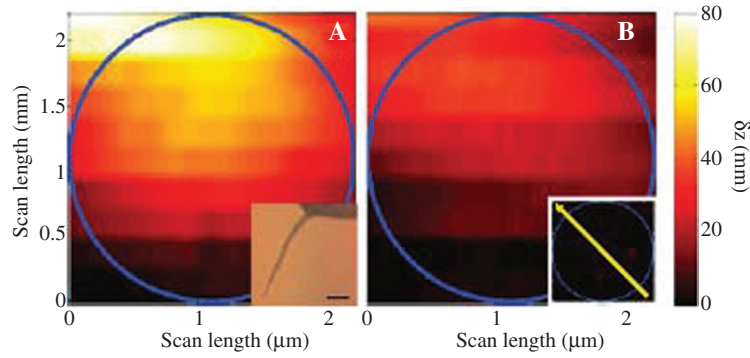


Figure 3 Perceived topography over the core of a single-mode optical fiber when (A) 24 and (B) 16 mW of 532-nm laser light is coupled into the fiber. The inset in (A) is the side view of the probe; the scale bar corresponds to 100 μm . The inset in (B) shows the measured topography of the fiber face. The circles indicate the location of the fiber core, which is approximately 2.2 μm in diameter. The arrow indicates the orientation of the tip during scanning. Adapted from [11].

affect the outcome of a measurement due to thermally induced probe elongation [26, 27, 60].

As mentioned at the beginning, the two mechanisms of interaction, the energy dissipation and the direct momentum transfer, may not be completely isolated. However, because thermal effects have a relatively low time constant on the order of milliseconds [31], the influence of thermal effects may be diminished if the optical radiation is modulated at a sufficiently high frequency. This aspect will be discussed in more detail later. Finally, we note that the strength of all possible thermal effects ultimately depends on the degree of light absorption. Thus the material properties of both the probe and the sample plays a key role in determining the strength of thermal effects [26, 27].

3.3 Direct optical forces on SPM probes

To better understand how optical radiation influences the feedback of a SPM probe, one can model the resonator to which the probe is attached as a damped, driven, harmonic oscillator. Depending on the exact system used, this resonator may either be a tuning fork or a cantilever. In this case, the probe's equation of motion is

$$m(\ddot{a} + i\gamma\dot{a} + \omega_0^2 a) = f_e(t) + \sum_n \int_0^t \frac{df_n}{dt} h_n(t-t') dt' \quad (1)$$

where m is the equivalent mass of the oscillator, ω_0 is the closest resonance frequency of the resonator, and $\gamma = \omega_0/Q$ is the damping of the system where Q is the quality factor of the closest resonance. The probe's position $z = z_0 + a$ around its undeflected position z_0 oscillates with amplitude $a = A \exp(i\omega t + i\phi)$ at the frequency of excitation ω . The

oscillator is driven electrically by a force $f_e = F_e \exp(i\omega_e t)$ which is applied to the tuning fork and by the sum of all other surface and optically induced force contributions f_n . The interaction between the probe and the sample results in different surface-induced forces such as van der Waals/Casimir forces, meniscus forces, etc. The optically-induced forces may be due to the direct action of the optical radiation or due to different indirect mechanisms of thermal origins. As we stated earlier, the direct influences include effects due to radiation pressure, gradient forces and optical binding. Thermally induced effects include influences such as probe elongation and bi-material effects.

In the equation of motion, the integral represents the convolution of the change in force acting on the probe with the temporal response function of the resonator, h_n , which may be modeled as $h_n = 1 - \exp(-t/\tau_n)$. Performing a Laplace transform of the convolution integral, one obtains

$$(\omega_{0_eff}^2 - \omega^2 + i\gamma_{eff}\omega) A \exp(i\phi) = \frac{F_e}{m} \quad (2)$$

where $\omega_{0_eff}^2$ and γ_{eff} are given by

$$\begin{aligned} \omega_{0_eff}^2 &= \omega_0^2 \left(1 - \sum_n \frac{K_n}{K} \frac{1}{1 + \omega^2 \tau_n^2} \right) \\ \gamma_{eff} &= \frac{\omega_0}{Q} \left(1 + \sum_n \frac{K_n}{K} \frac{\omega_0 \tau_n}{1 + \omega^2 \tau_n^2} \right) \end{aligned} \quad (3)$$

Here $K = m\omega_0^2$ is the spring constant of the tuning fork and $K_n = (\partial F_n / \partial z)|_{z=z_0}$ represents the effective spring constant of the external forces acting on the probe. A detailed description of the derivation for an analogous effect may be found in Refs. [61, 62].

These results are valid when the forces acting on the probe vary only slightly over the probe oscillation cycle such that one can use a two-term Taylor expansion of the surface and optically induced forces acting on the probe. This assumption is made for the sake of conceptual simplicity of the resulting equations. In some near-field experiments the variation of the field over the probe oscillation cycle may be quite strong. Thus performing a quantitative analysis of measured results may require a more rigorous computation of the forces over the probe oscillation cycle. However, the essential physics remain the same [63].

As can be seen from Eq. 3, in general, the effect of the surface and optically induced forces is to shift the resonance frequency and to modify the damping of the resonator. Importantly, this effect depends on the gradient of the force acting on the probe; in other words it is influenced by the probe's oscillation through a spatially varying force field. For effects which are quasi-instantaneous, such as surface forces and direct optically-induced forces, $\tau_n \rightarrow 0$ meaning that the force gradients shift the probe resonance frequency without modifying the damping.

The feedback in SPM systems commonly relies on maintaining a constant amplitude or phase shift on the probe, such that there is, at least in principle, a constant surface force gradient acting on the probe. Rearranging Eq. (2), the amplitude and phase measured by a lock-in demodulated at the electrical modulation frequency are given by:

$$A(\mathbf{r}) = \frac{F_e(\mathbf{r})}{m} \left[(\omega_{0_eff}^2 - \omega^2)^2 + (\gamma_{eff}\omega)^2 \right]^{-\frac{1}{2}}$$

$$\phi(\mathbf{r}) = \tan^{-1} \left(\frac{\gamma_{eff}\omega}{\omega_{0_eff}^2 - \omega^2} \right) \quad (4)$$

where ω_{0_eff} and γ_{eff} are given in Eq. (3).

Here we modeled the resonator as a point mass at the end of a spring, a simple representation that can be used to conceptually understand the result for either tuning forks or cantilever based systems. Physical SPM probes consist of either a single cantilever or a tuning fork. The tuning fork is effectively an ensemble of two coupled cantilevers having the mass distributed along the spring. Cantilevers are more accurately modeled using the Euler-Bernoulli equation [64]. Though a more rigorous model with two coupled equations of motion, one for each arm of the tuning fork, would more rigorously describe the physics for tuning fork systems, the single mass on a spring model is often sufficient to describe the system dynamics [65].

3.4 Optical topography

Direct mechanical action of radiation comes about as a result of momentum conservation during the interaction between the probe and the electromagnetic field. The ability of light to exert forces has been known for a long time and it is often used to manipulate small particles. In general, this force can be calculated using the Maxwell stress tensor approach [9]. When the probe is small and can be modeled as a dipole, the time averaged optical force acting on it is simply $\langle F_z \rangle = \frac{1}{2} \text{Re}(\alpha \mathbf{E} \cdot \partial \mathbf{E}^* / \partial z)$ where α is the probe polarizability [66]. The consequences of this force are sometimes discussed in terms of radiation pressure, gradient or optical binding forces. By finding the self-consistent solution for the fields, the direct influence of optical forces can be accounted for [17, 66]. In cases where the dipole approximation breaks down, higher order moments may be evaluated [67].

Thermal effects induce a physical change in the probe's characteristics which is subsequently detected during an SPM scan. Optically-induced forces (OIF) on the other hand do not produce physical changes in the size, shape or other properties of the probe. Rather, the observed effects are due to the feedback response to the additional force acting on the probe. This concept is illustrated schematically in Figure 4 where the surface of a prism is illuminated in total internal reflection by a focused laser spot. As the probe passes over the illuminated spot, it retracts away from the surface. We emphasize that this is not because the probe is pushed away by a repulsive optical forces. Indeed, as one might expect, the optical forces are actually attractive due to the strong

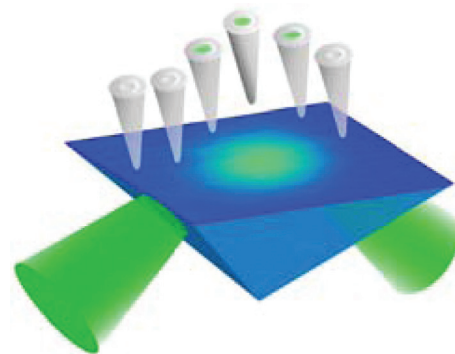


Figure 4 As the probe passes over the illumination spot, the system feedback causes the probe to retract. This occurs because the attractive optically induced force gradients compete with the attractive surface induced force gradients forcing the feedback to retract in order to maintain a constant force gradient acting on the probe. Adapted from [68].

gradient of the field in this configuration. However, the feedback is working to maintain a constant force gradient acting on the probe. Away from the spot of light, only the attractive surface force gradients are present. As the probe passes over the illumination, the total force gradient acting on the probe is increased because of the probe's exposure to the additional attractive contribution of the optical force gradient. The scanning system's feedback retracts the probe to reduce the contribution from the surface forces, thus maintaining a constant force gradient acting on the probe [11]. As a result, a topographic feature is recorded, which correlates with the field distribution across the surface.

4 Steady-state OIF

We presented experimental evidence demonstrating the sensitivity of SPM probes to optical radiation, and we briefly discussed how this effect can be quantitatively modeled. We now turn our attention to practical near-field experiments where such effects manifest. In this section we will examine the possibilities for novel measurements that can be based on optically-induced forces generated in conditions of steady-state illumination.

Experiments performed on structured media indicate that OIF effects are highly localized to sharp edges. This can, for example, be seen in Figure 5 [69]. To significantly reduce the thermal influences, this measurement was performed with an uncoated dielectric probe scanned across a structured dielectric gallium phosphide sample. The 3D relief shows the topography measured with the

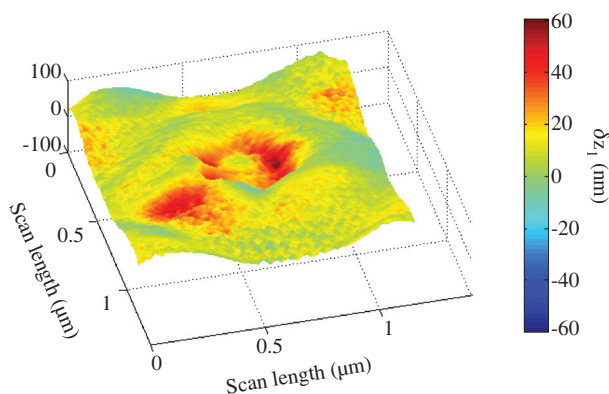


Figure 5 3D topography of a structured dielectric gallium phosphide sample as measured with an dielectric uncoated pulled fiber NSOM probe with no illumination. The color scale shows the “extra” topography induced due to irradiation with 532 nm light illuminated in total internal reflection. Adapted from [69].

light off and the color scale shows the extra topography induced when the sample is illuminated in total internal reflection with 532 nm laser light. One can clearly observe the strongest effects localized along the sharp edges of the sample.

To understand this effect, we recall that such sharp discontinuities in space require high spatial frequency components to accurately describe them, in other words a large spectrum of evanescent waves. These are the wave components of interest in near-field microscopy and, by their nature, they not only have strong amplitudes, but also strong gradients of their amplitudes. As mentioned before, the effects discussed here are sensitive to the gradient of the optically induced force acting on a probe. If the probe acts as a simple dipole, this force gradient can be written as

$$\langle \partial F_z / \partial z \rangle = \frac{1}{2} \text{Re}(\alpha(\partial |\mathbf{E}|^2 / \partial z) + \alpha \mathbf{E}(\partial^2 \mathbf{E}^* / \partial z^2)). \quad (5)$$

Thus, OIF are strongest where both the field and its gradient are important, which occurs in regions of strong evanescent fields. As a result, significant OIF effects are localized to precisely the regions one is interested in measuring. This can be a nuisance for standard near-field intensity scans as it can be regarded a source of measurement artifacts. However, intentionally detecting OIF is advantageous because of its inherent strong suppression of propagating waves components, which allows collecting high quality near-field force images without needing to lock-in on a higher harmonic of the oscillation as is done in the practice of scattering NSOM [70].

Several major applications may be envisioned for this type of force sensitivity. For instance, one can use the OIF's sensitivity to complement or to replace standard intensity based NSOM measurements. Because the force acting on the probe depends on a different combination of field components, measuring both NSOM and OIF simultaneously provides a more complete description of the electromagnetic field at the sample surface without increasing the complexity of the measurement [71]. Notably, force measurements on small probes give access to all three field components whereas intensity measurements with aperture and scattering NSOM give information about the field components through an anisotropic scattering cross section of the probe, which is not precisely known.

Mapping near-field distributions via force detection rather than intensity detection provides several advantages. In addition to the strong background suppression achieved by OIF measurements that we already mentioned, the additional principal advantage is the relative

lack of wavelength sensitivity to the measurement allowing for not only broadband force detection, but also detection in regions where standard photodetectors are impractical or impossible to use, such as in the far IR and THz [72–74].

Lastly, the use of force based SPM techniques could open up the possibility to measure aspects of the radiation that may otherwise not be possible. For example, it was shown that such approach can be used for a quantitative measurement of the tip-optical interaction force [11]. A by-product of this process is the possibility to determine the tip-sample separation, which can be simply determined by controllably varying the light intensity. This simple technique bypasses the need for complex external measurement schemes, a notorious difficulty in the practice of SPM [75, 76].

5 OIF in modulated fields

As described before, the SPM probe reacts to all existent force gradients. Consequently the influence of the optical and surface induced forces interacting on the probe are mixed together, typically in a complex topography signal or otherwise in the signal used for feedback regulation. This mixing is undesirable as the targeted force must then be extracted, usually based on the knowledge of all other components. Note that, in some practical circumstances, OIF may have to be isolated not only from all other types of surface forces acting on the probe but also from possible thermal effects that may be important under steady-state illumination.

Nevertheless, an interesting alternative is provided by modulating the electromagnetic fields acting on the probe. In principle, an SPM probe can be driven at different frequencies and, recently, there has been a surge in interest in simultaneously measuring multiple interactions or the same interactions on multiple scales using a technique called multi-frequency atomic force microscopy (MF-AFM) [77, 78]. This technique affords contrast enhancement and permits the quantitative determination of the complex tip-sample interaction force [79–82].

A similar approach can be implemented in OIF-based near-field imaging. The probe interacting with the electromagnetic field can be driven at two frequencies, one electrically for feedback control as in standard SPM measurements and another optically to measure the local optical force distribution acting on the probe. By modulating the light at a sufficiently high frequency (~ 50 kHz or more) and using separate lock-in detection at this

frequency, one can generate a separate channel with the OIF information, which significantly reduces the influence of thermal effects. The best choice for this modulation frequency is either near a resonance frequency of the tuning fork or cantilever [10] or selected such that a sum or difference of multiple excitation frequencies is near a resonance frequency [83]. In this case, the signal strength of the generated signal will be amplified by a factor of $\sim Q$ on resonance. The amplitude and phase of the signal demodulated at the optical frequency are given by Eq. (4) where F_e is replaced with F_{opt_AC} . Note that the contribution due to the finite average light impinging on the sample, F_{opt_DC} is included in the forces responsible for the effective value of the resonance frequency and loss.

Implementing this type of detection allows one to obtain high-resolution images of near-fields with strong intrinsic suppression of propagating waves. An example image is shown in Figure 6 where an array of gold triangles fabricated on a cover slip via nanosphere lithography was measured using a chromium coated AFM probe. A direct comparison of the topography in Figure 6A with the optical force image shown in Figure 6B clearly demonstrates that the force is higher over the open regions of the cover slip than over the particles and also that the largest values of the optical force are localized at the particle vertices [10].

Finally, we note that, because the signal collected from the oscillating probe can be demodulated at both the electrical and optical driving frequencies, this procedure provides means for separating the surface topography from the optical information.

6 Discussion

There are different ways in which light fields can be detected with high spatial resolution. For instance, near-field microscopy relies on the scattering of evanescent waves into propagating waves to be detected in the far-field using a single channel sensitive photodetector such as an avalanche photodiode or a photomultiplier tube. More details can be found in an excellent review of near-field light detection techniques for frequencies ranging from the microwave to the optical domain [84].

Alternatively, photonic force microscopy relies on monitoring Brownian motion induced fluctuations of the particle position within a three-dimensional standard Gaussian trap using a quadrant photodetector [85–89]. The potential well can be calibrated by measuring the statistics of these deflections and then used it to measure

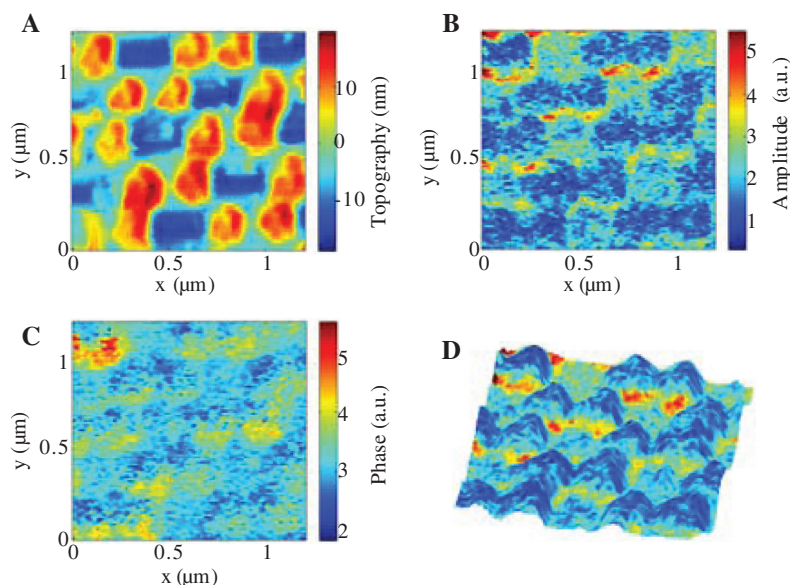


Figure 6 (A) Topography of an array of gold triangles fabricated on a cover slip using nanosphere lithography as measured by a chromium coated AFM probe. The sample is illuminated from beneath with 1550 nm light. (B) Optical force image measured by demodulating the signal from the tip at the optical modulation frequency. As expected, the optical force signal is higher over the coverslip than over the metal particles with peaks located the particle corners. From [10].

additional forces acting on the particles. By scanning the particle relative to the sample, the forces may be measured in a manner analogous to AFM [86, 88, 89]. A second laser probe can be used to detect the scattering off the particle in a manner analogous to NSOM [89].

For specific material systems, another possibility exists to indirectly detect light in the near-field by measuring permanent light induced changes to the sample topography, such as local oxide formation [90]. By performing standard AFM before and after light irradiation, the light intensity may be measured in locations where it is intense enough to cause said oxide formation. Similarly, by taking advantage of photopolymerization, the intensity of light in the near-field may be determined [91].

In this review we discussed a fundamentally different mechanism for detecting optical radiation with sub-wavelength resolution. In the context of scanning probe microscopy, we have shown that measurements of optically induced forces provide true near-field detection of the optical radiation with excellent inherent background suppression of propagating waves.

In this article we have reviewed recent research exploring the influences of optically induced forces acting on various scanning probes, and we have also discussed some of the applications relying on these effects. These included the ability to quantitatively extract the force acting on the probe, the possibility to collect additional

information about the complex electromagnetic field responsible for the probe-sample interaction as well as new prospects for detecting radiation via the force it exerts rather than by counting photons.

The optical force applied to a typical scanning probe has a rather broadband sensitivity, which makes it particularly suitable for measurements extended over large wavelength bands. Using a single probe for detecting radiation in the far-IR and THz can significantly simplify the experiments these regions where standard photodetectors are impractical or impossible to use. Indeed, sensitivity to far-IR radiation has been demonstrated.

We have assumed in our discussion that the optical force detector is a sharp probe connected to a cantilever or tuning fork. The purpose of the sharp probe is to increase the spatial resolution of the measurement such that near-field measurements may be made. However, we emphasize that the actual force detection is done by the resonator. Consequently, the equivalent of a large bucket detector may be realized by shining light directly on the tuning fork. This has been demonstrated in the visible to IR frequency regime [92, 93] and may find particular use in the far-IR and THz [72–74, 94].

In this review we have considered that the resonator is either a tuning fork or a cantilever. Because these resonators have relatively low Q factors in practical SPM use (–10–1000), the minimum detectable force is somewhat

high (on the order of pN). This can be improved by using more specialized resonators such as those based on whispering gallery modes, where the Q factor can reach values as high as 10^9 [95]. For a particular resonator, the force sensitivity may be further increased by engineering the probe

to exhibit a higher effective polarizability using strategies similar to the design of nano-antennas [96].

Received August 25, 2013; accepted March 14, 2014

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