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Suitability of AFM cantilevers as wideband acoustic point receivers for the characterization of acoustic sources

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***Abstract*— In Subsurface Scanning Probe Microscopy (SSPM), Atomic Force Microscopy (AFM) is combined with ultrasound. The AFM cantilever is used as a receiver. At low frequencies (O(MHz)) the method can be used to measure the stiffness contrast in a sample and at high frequencies (O(GHz)) to measure scattering based contrast. Both variants use modulated excitation signals in combination with the nonlinear tip-sample interaction to downmix the sample top surface displacement close to the resonance frequency of the cantilever. This concept has three advantages: 1) the resonance of the cantilever is used to boost the sensitivity, 2) the downmixing allows the system to record signals in an extremely wide range of carrier frequencies (kHz – GHz), and 3) the cantilever tip-sample contact diameter is usually much smaller than 10 nm. The latter implies that spatial averaging effects are negligible up to 100 GHz. Said advantages mean that AFM cantilevers could be useful to characterize acoustic sources. Here, we investigate the suitability of AFM cantilevers as acoustic point receivers to characterize acoustic sources. Investigation with an AFM setup and two sources - one O(MHz) and one O(GHz) – show a good match between the measured response, KLM simulations and the transducers bandwidth, which are promising results for the use of a cantilever as a wideband receiver for high resolution acoustic (transducer) characterization.**

Keywords—Atomic force microscopy, Scanning probe microscopy, transducer characterization, wideband

I. Introduction

For O(nm - µm) subsurface defect or crack detection, a promising technique is Subsurface Scanning Probe Microscopy (SSPM). SSPM combines Atomic Force Microscopy (AFM) and ultrasound excitation. SSPM is typically used to measure the viscoelastic contrast between a subsurface feature and its surrounding material(s) [1]. The vertical force applied to the cantilever needs to be sufficiently high (O(100s of nN)) to allow the tip of the cantilever to deform the sample top surface and generate a stress field that will be able to reach the subsurface layers and features. This method uses typically frequencies up to 10's of MHz. More recently, by increasing the frequency (typically >1 GHz), it has been showed that scattering could also be used as a contrast mechanism [3-4]. In this configuration, the tip of the cantilever is used as an acoustic receiver. In order to measure in the GHz range, the non-linear tip-sample interaction is used. Assuming the tip-sample interaction is approximated by a sphere/half-space interaction, Hertzian contact theory (1) dictates that the force and indentation are related with a power 3/2 relationship. The heterodyne frequencies generated from the frequency mixing at the tip-sample interface, allow to detect the incoming O(GHz) acoustical waves at much lower frequencies (O(100kHz)). The lower heterodyne frequencies are used for that purpose, the process of using the low heterodyne frequencies after mixing is referred to as downmixing in the remainder of this document. The driving signal used is an amplitude modulated sinusoidal wave and the modulation frequency is typically chosen such that the downmixed frequency matches the cantilever contact resonance frequency to allow maximum sensitivity.

Using an AFM cantilever as an acoustic receiver has a number of advantages: AFM cantilevers typically have small tip radii (10-100 nm) [5], thus the cantilever tip-sample contact radius is usually smaller than 10nm. This means that up to about 500 GHz in silicon (assuming a compressional sound speed of 10000 m/s), the spatial averaging effects are negligible. Additionally, an AFM cantilever essentially acts as a contact mode transducer, allowing it to interface well with solids without coupling liquids. Furthermore, by using the signal mixing of the non-linear sample-tip interaction, it is theoretically possible to test a broad frequency range (O(kHz to GHz)). However, a drawback is the fact that the choice in excitation signals is limited by the nonlinear tip-sample interaction. The GHz signal needs to be downmixed to frequencies close to the resonance frequency of the cantilever. This implies that the excitation signals should be semi-continuous modulated sine bursts.

Another technique traditionally used to characterize wave fields in solids is laser interferometry. Laser interferometers measure the interference pattern of a coherent source along a known optical path and a second optical path to the transducer or sample under test. The optical path difference is then converted into the out-of-plane displacement.

The main advantage of laser interferometry is that it is contactless. However, since it is not possible to use downmixing, very high sample frequencies are necessary in order to measure O(GHz) frequencies. Additionally, the optical reflection coefficient of the surface to be measured needs to be high enough. In that respect, dark material, roughness or dirt can be limiting.

Thus an AFM cantilever could be a suitable instrument to characterize transducers across an extremely broad frequency

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range. This could be achieved by sweeping the carrier frequency whilst keeping the modulation frequency constant.

In this study, we explore the use of AFM probes as wideband acoustic point receiver for direct transmission measurements and high resolution directivity measurements using both experiments and simulations.

II. TRANSDUCER CHARACTERIZATION SETUP

A schematic of a typical transducer characterisation setup using an AFM cantilever as a receiver is shown in Figure 1.

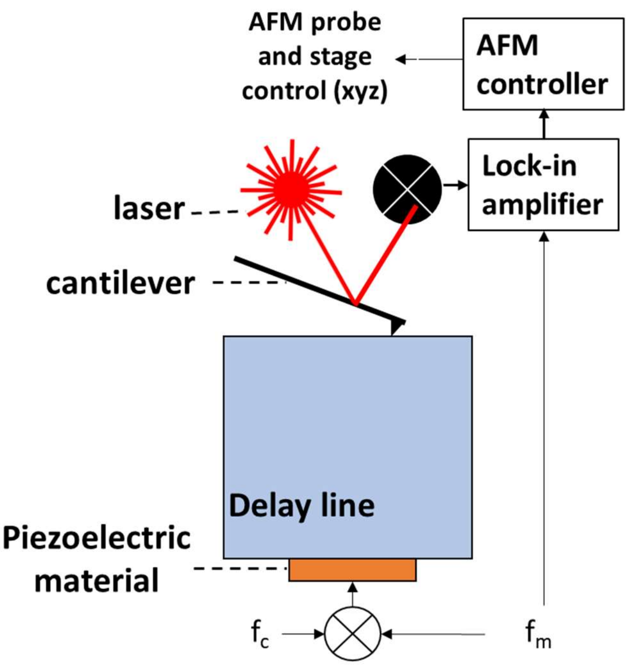

Figure 1: Schematic of a typical acoustical transducer characterization setup using an AFM cantilever as wideband point receiver.

A piezoelectric layer is driven by an amplitude modulated signal, characterized by its carrier frequency f_c and modulation frequency f_m, with $f_m < f_c$. The modulation frequency is typically chosen to match the contact resonance frequency at the interface between the tip and delay line for a maximum sensitivity. The force applied to the tip is chosen to be small enough to minimize the contact radius with the delay line (point source assumption) and just strong enough to remain in contact. Assuming a Hertzian contact between the tip and the delay-line:

$$F = 4/3\ E^{*} R^{1/2} d^{3/2}, \quad (1)$$

with

$$1/E^{*} = (1-\nu_1^2)/E_1 + (1-\nu_2^2)/E_2. \quad (2)$$

The applied force F and indentation d are linked with a power 3/2 relation (1). The other parameters of the equation are fixed: the reduced Young modulus E^{*} depends only of the tip and delay line material properties (2): the Young modulus E_1 and Poisson ratio ν_1 of the tip and the Young modulus E_2 and Poisson ratio ν_2 of the delay-line. The tip curvature radius R is also a fixed parameter. This non-linear interaction of the tip and delay line ensures that the acoustical signal is mixed. The downmixed part of the signal is measured by the AFM probe, extracted using a lock-in amplifier and further processed by the AFM controller and converted into a displacement as a function of the carrier frequency. Thus, by sweeping the carrier frequency, one can characterize a transducer in the considered frequency band.

The AFM controller can also be used to control horizontally in 2D the stage position where the stack is mounted, allowing high resolution 2D scans on top of the transducer delay-line.

III. METHODS

A. *Experimental setup GHz*

The amplitude modulated signals were generated using a frequency waveform generator (M8195A, Keysight, Santa Rosa, USA), amplified by a power amplifier (ZHL-2-8+, Mini-circuits, New-York, USA) and routed through a power splitter (ZFRSC-42S+, Mini-circuits, New-York, USA) to allow monitoring of the transmit signal. The signal was then send to a piezoelectric transducer (custom 3 GHz design, Kibero, Saarbrucken, Germany). The acoustic wave produced by the piezoelectric material travelled through the transducer's delay line, a water coupling layer of about 800 nm monitored using pulse-echo measurements as described in [4] and a sample consisting of 550 µm of silicon and 500 nm of resist. The out-of-plane sample surface displacements were recorded using an AFM probe (ScanAsyst-Air, 0.4 N/m, Bruker, Billerica, USA) connected to a lock-in amplifier (UHFLI, Zurich Instruments, Zurich, Switzerland) and an AFM (Bruker Dimension Icon, Bruker, Billerica, USA). The applied static force was 10 nN. The carrier frequency was varied between 3.2 GHz and 3.7 GHz and the modulation frequency was fixed at 280 kHz.

B. *Experimental setup MHz*

The MHz setup is very similar to the GHz setup, the amplitude modulated signals were generated using the same lock-in amplifier as in the GHz setup. The transducer was a custom design, a thin vaseline layer was used for the acoustical coupling between the transducer and the sample. The sample consisted of a 380 µm thick Si wafer with 360 nm of resist on top and 50nm of aluminium. The AFM probe used was a CONT40A (5 N/m, Bruker, Billerica, USA). The applied static force was a few 100's nN. The carrier frequency was varied between 10 MHz and 30 MHz and the modulation frequency was fixed at 220 kHz.

C. *Simulation setup*

A KLM model [6] MATLAB implementation was used to model the piezoelectric effect in the transducer and the acoustic wave propagation in the device under test. The transmit transfer function of the modelled acoustical stack is provided as a function of frequency.

For the GHz setup, the transmit transfer function in pressure p per volt are converted to displacement δ in meter assuming plane waves incoming at the receiver location. The conversion is done using:

$$\delta = p \,/\, \rho\, c\, \omega, \quad (3)$$

with ρ and c the density and compressional speed of the sample top layer and ω the carrier angular frequency. For the

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MHz setup, the plane wave assumption is not valid and only the transfer function in pressure per volt is provided.

IV. Results

Figure 2 shows the measured downmixed displacement on top of the sample used in the GHz setup compared to the KLM computed transmit transfer function converted to displacement according to equation (3). Please note that since the measured amplitude is related to the displacement with a power 3/2 according to Hertzian contact theory (1), a power 2/3 is applied to the measured signal in order to be able to compare the shape of the KLM model and the measurements quantitively.

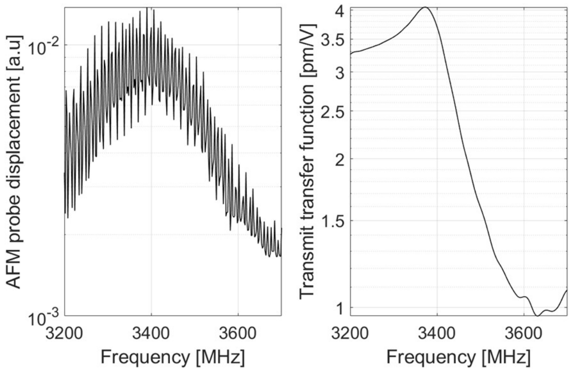

Figure 2: downmixed amplitude read by a cantilever and converted to out-of-plane displacement as a function of a carrier frequency sweep on a transducer-coupling-sample stack (left-hand-side). Corresponding transmit transfer function computed using a KLM model (right hand side).

The coupling layer has been monitored and kept below 1 µm using pulse-echo measurements [4]. The interference pattern visible in the measurement has a period of 8 MHz, which corresponds to previously measured interference from the standing wave in the coupling layer of similar thickness [4]. This interference is not visible in the KLM model output since the coupling later is not modelled there. The shape of the simulated transfer function globally agrees with the measurements. Some differences are still visible: in the beginning of the frequency band, the displacement is overestimated and at the end of the frequency band, a small rise in the displacement is not observed in the data.

Figure 3 shows the measured downmixed displacement on top of the sample used in the MHz setup compared to the KLM computed transmit transfer function. A power 2/3 is applied in order to be able to compare the shape of the KLM model and the measurements quantitively, in the same way as for the MHz measurement.

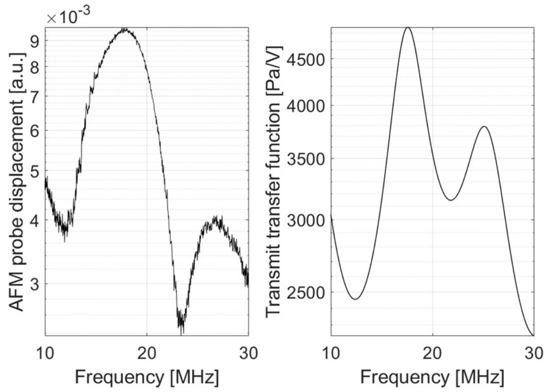

Figure 3: downmixed amplitude read by a cantilever and converted to out-of-plane displacement as a function of a carrier frequency sweep on a transducer-sample stack (left-hand-side). Corresponding transmit transfer function computed using a KLM model (right hand side).

The general shape of the measurement agrees with the shape of the KLM output. The peaks and dips are located at the same positions. Further, the peaks bandwidth is larger in the measurement data than in the KLM simulations. This is probably due to the uncertainties and assumptions about the material properties and geometry used as input in the KLM model. Please also note that no interference pattern is visible in this dataset, since the wavelengths at 10 MHz are much larger than the different stack thicknesses (1 mm in silicon for a compressional speed of 10000 m/s for instance).

V. Discussion

The measured and modelled transmit transfer functions show a reasonable qualitative agreement. These results are preliminary and should be completed and confirmed with more experiments. In particular (non-exhaustive):

- measurements directly on top of a single wideband transducer (with or without a delay-line) to demonstrate the wideband potential of this technique and to get rid of the coupling layer and samples uncertainties.
- Measurement with an identical measurement setup in different frequency regions. In particular a single AFM probe.
- AFM probe scans could also be performed to estimate the directivity of the acoustic source for several frequencies.

The disagreements observed are most probably due to a mismatch between the KLM model assumptions and the actual material properties or geometry. In particular:

- The KLM model outputs the out-of-plane displacement on top of the sample, excluding the tip-sample interaction and the cantilever contribution. See further the quantitative comparison discussion point below.
- The coupling layer, relevant in the GHz case, is further not modelled in the KLM model.
- The actual materials mechanical properties (Young modulus, Poisson ratio) are not accurately known.
- The coupling layer in the GHz case is not modelled in the KLM model.

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For these reasons, a quantitative comparison between the measurements and the KLM model is not possible with the described methodology. To allow a quantitative comparison, the cantilever including the mixing at the top of the sample-tip interface should be incorporated in the model. And even with a model including the interaction with the cantilever, uncertainties remain such as the exact tip shape or the roughness on top of the sample, these parameters will influence the sample-tip interaction such as the actual tip contact radius and thus also the frequency mixing behaviour.

Please note that the method is in principle not limited to piezoelectric acoustical sources, that the delay line may be removed for near field measurements and that additional layers, such as matching- or backing- layers may be added as well.

VI. CONCLUSION

In this work we have presented initial simulation and measurement results regarding the use of an AFM probe as a wideband point source receiver. Although the qualitative match was reasonable, considerable effort should be spent on the calibration of cantilever tips and the modelling of the tip-sample interaction to obtain true quantitative measurements.

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