# Microwave Imaging by Alternating Magnetic Force Microscopy

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**Introduction:** Alternating Magnetic Force Microscopy (A-MFM) has been successfully applied to image high frequency magnetic fields up to GHz range with high spatial resolution in ambient condition [1, 2]. The purpose of the current work is to extend the measurable frequency of the A-MFM beyond 10 GHz range to apply the evaluation of microwave frequency materials, such as for electromagnetic shielding and microwave absorption.

**Experimental:** A-MFM uses frequency modulation (FM) of cantilever oscillation caused by low frequency off-resonant alternating force gradient $F_z'$ and lock-in detects the $F_z'$ after frequency demodulation of the cantilever oscillation signal. In the present study, we generated the $F_z'$ by using the interaction between A-MFM tip and the amplitude modulated microwave which is irradiated to the tip.

$$F_z' = \frac{\partial}{\partial z}\left(-\frac{\partial U}{\partial z}\right) = \frac{1}{2}\int_{V_{tip}}\left(\varepsilon\frac{\partial^2 E^2}{\partial z^2} + \mu\frac{\partial^2 H^2}{\partial z^2}\right)dV_{tip} \qquad \left(\begin{array}{l} E = E_0(1+\alpha\cos(\omega_m t))\cos(\omega_c t) \\ H = H_0(1+\alpha\cos(\omega_m t))\cos(\omega_c t) \end{array}\right)$$

Here we set the values as $\alpha$ =0.9, $\omega_m$ =89 Hz, $\omega_c$ =12–25 GHz. The microwave source is home-made traveling rectangular waveguide antenna with impedance matching. We observed Au particles on glass substrate by irradiating microwave from the back-side of the substrate. We used several tips coated by different materials and evaluated the imaging performance.

**Results:** The right panel of Fig. 1 shows the amplitude signal of lock-in amplifier ($R$) of the $\omega_m$ component. In the top, signal of pristine Si tip does not differ on Au particle and glass substrate. However, tips coated with conducting materials (non-magnetic (Pd) and superparamagnetic (SP) Co-GdO$_x$ granular alloy film) show darker spots at the Au nanoparticles in $R$ images, which makes possible the detection of local microwave absorption of Au particle from transmitted microwave through the particle. The measured intensity correlated with particle size which allowed to estimate the relative absorption values. The tips with conducting coatings have high concentration of microwave at the tip-end due to the small skin depth, which increases the spatial resolution of the microwave energy gradient. This method was also applied to other materials such as ferromagnets. We expect that microwave imaging can be useful for the studies of electromagnetic shielding materials as well as for the non-contact estimation of local conductance.

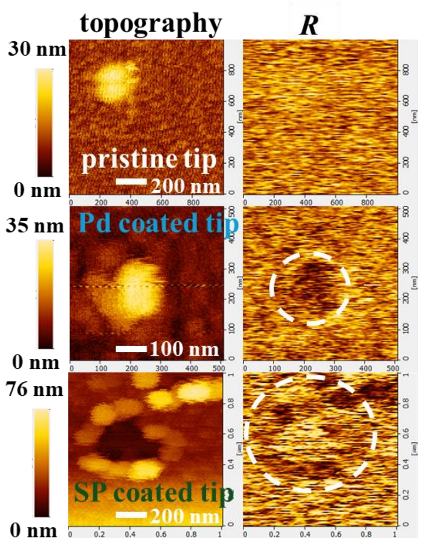


Fig.1 A-MFM image of $\omega_m$ amplitude modulated microwave transmission ($R$) through gold nanoparticles/ glass obtained by pristine Si tip (top), Pd- (middle) and SP film- coated tips (bottom).

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**References**

1) D. V. Christensen et al, J. Phys. Mater., 7, 03501, 2024

2) M. Makarova et al, Appl. Sci. ,13, 4843, 2023