# Force-detected wideband probe magnetic resonance optical imaging

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**Introduction**: We present motivation, theoretical aspects and experimental program for using magnetic force microscopy (MFM) techniques for MR imaging. Massively parallel analysis and the advantages of highest sensitivity per unit cost motivate a reduction in sample size accessible by NMR. Optical detection can overcome cable losses, parasitic coupling and improved signal extraction from existing NMR coils, especially for parallel imaging. Here we discuss how this can be done.

**Method**: A force detection method based on application of magnetic force resonantly coupled to a harmonic oscillator, increases the interaction time of the sample with the detector and minimizes thermal noise. Lithographically structured, micron-scale current loops attached to microfabricated cantilevers induce magnetic dipole moments in samples, which in turn produce a magnetic dipole forces on the cantilever to cause mechanical oscillation at the cantilever's resonant frequency. The dipole-dipole force, which is the product of the magnetic moment on the cantilever coil and the spatial gradient of the sample's magnetic field, results in a modulated force at the sum and difference of frequencies of the sample's response and the current on the cantilever. A significant response occurs when this difference is the mechanical resonant frequency of the cantilever. Controlling the frequency of the current on the cantilever can locally control the detected frequency.

Expressed mathematically:

$$F(t) =(M*\cos(\omega_{loop}t)*grad(\sum B_{sample} \cos(\omega_{sample}t)) = M*\cos(\omega_{loop}t)*d/dt(\sum B_{sample} \cos(\omega_{sample}t))*(dt/dz)$$

$$F (t) = M*\sum (\omega_{sample}/2)* B_{sample} *\{\cos (\omega_{sample}t - \omega_{loop}t )* \cos (\omega_{sample}t \ \omega_{loop}t \}*(\sqrt{\mu * \varepsilon})_{diel} , \ldots\ldots\ldots\ldots \quad \mathbf{(1)}$$

where 'F(t)' is the time varying force at time 't', 'M' denotes the time harmonic magnetic moment on cantilever with frequency '$\omega_{loop}$', '$B_{sample}$' designates the time harmonic sample magnetic field of frequency '$\omega_{sample}$', and 'dz/dt' gives the velocity of the electromagnetic wave along z axis.

At resonance, the deflection of the cantilever is measured with a laser shining on the cantilever and reflecting back to a photodiode. In our experiment, we have a primary coil of diameter 6cm, serving as a pick up coil, and a secondary coil of diameter 1cm, oriented orthogonal to the primary one. This orientation results in negligible mutual coupling, giving undistorted fields. Working like a transformer, the same current flows through both coils, the larger primary coil improving far field detection while the secondary coil excites the cantilever. The cantilever probe, held above the tiny secondary loop containing a dielectric core, concentrates the magnetic field at its tip. A low mass and temperature stable small ceramic piece of high dielectric constant and quality factor becomes the energy storage device. The surrounding air makes the dielectric–air interface an open circuit causing internal reflection and thereby confining fields in the dielectric core, creating a resonant structure. This surface thus works as a perfect magnetic conductor. Another important feature is that the core with height to radius ratio less than 2.03 supports the dominant $TE_{01}$ mode. We calculated that the attenuation coefficient for the $TE_{01}$ mode decreases monotonically with increasing frequency, which is a highly desirable characteristic for high frequency operation. The force acting on the cantilever is equal to the magnetic moment on the cantilever times the spatial gradient of the magnetic field from the sample, which, in our case, is the time gradient times the reciprocal of the velocity of propagation of the force in the medium. Thus, the magnetic force magnifies by square root of permittivity of the medium by increasing its dielectric constant (Eq 1)**.**

**Results**: The experimental results obtained from measuring the amplitude change of the photodiode current by changing the frequency of the cantilever's current, give sharp change only at the cantilever's resonant frequency. The 'Q' of the coil is that of the cantilever. The well-predicted fall off of signal with distance is also seen where the distance is comparable to the diameter of the outer coil. Lastly, as predicted by Eqn 1, a linear increase of the force on the cantilever with the rise in sample frequency is reflected in rise in the amplitude of the current at resonance.

**Conclusion**: Though dominated by thermal noise, our coil offers potential advantages over conventional NMR detector coils, such as optical detection, detection of multiple frequencies by the same coil, analysis of sub-micron particles, etc. Our future goal is to implement multiple secondary coils having phased locked cantilever probes with different frequency current coils on them for extracting multiple frequency information for parallel imaging. Moreover, further reduction of noise will be aimed employing cryogenic cooling of the cantilever system.

**References:** Rugar D, Budakian R. Single spin detection by magnetic resonance force microscopy. *Letters to nature* 2004;Vol 430:329-332

Balanis C, Advanced engineering electromagnetics

Matsuda Y, Super-parallel MR microscope *Magn Reson Med* 2003; 50(1): 183-9