Phase-Sensitive Nonlinear Near-Field Microwave Microscopy on MgB_2 Thin Films

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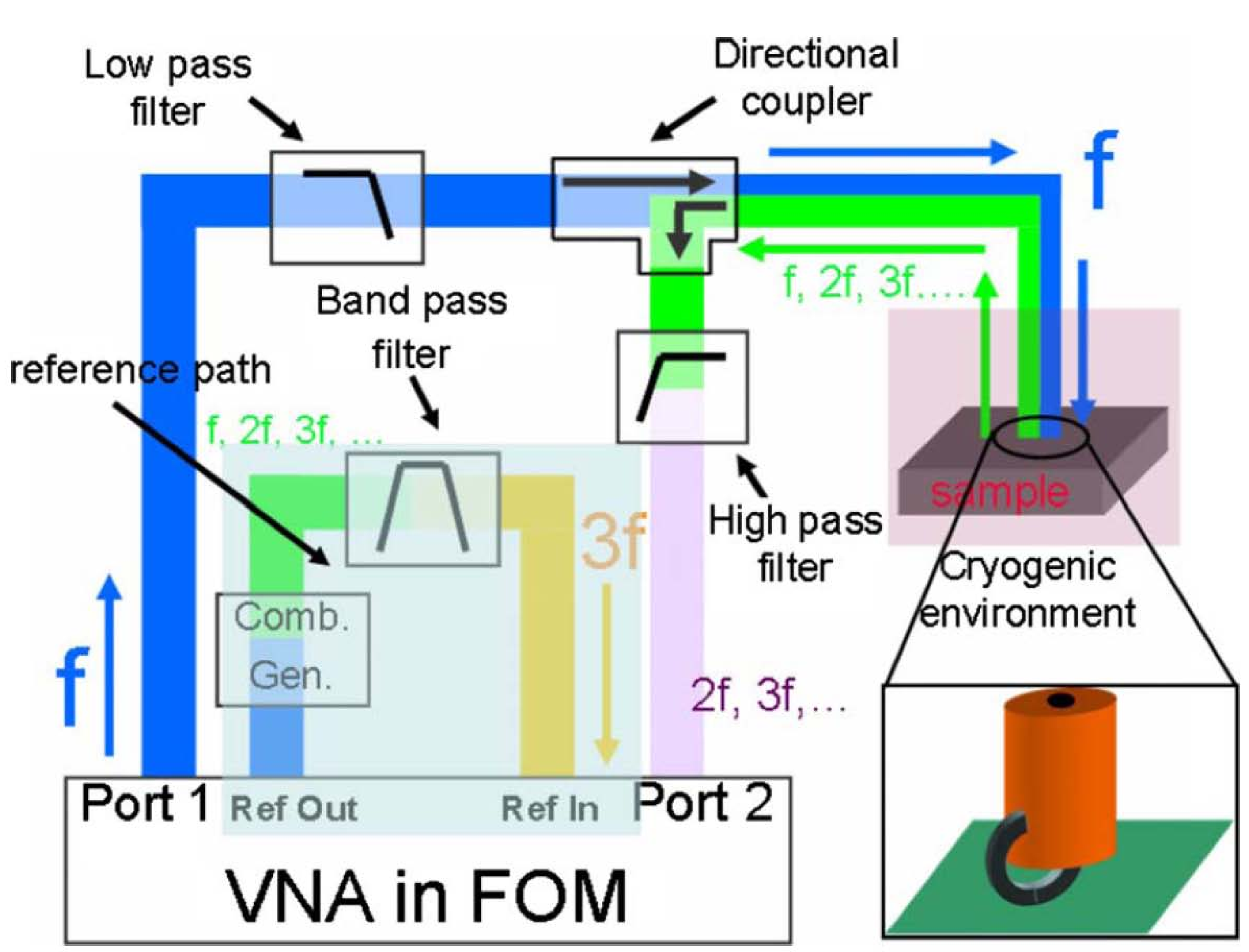
Abstract

Near-Field Microwave Microscopy (NFMM) is an accurate and precise experimental technique for measuring the local RF/microwave properties of materials and devices with sub-micron resolution. In general, a magnetic/electric probe induces a strong and highly localized RF/microwave field on the sample's surface and the response is measured in terms of the reflected signal and/or the resonance shift in an external cavity. In this work, a magnetic write-head excites MgB_2 thin films with a magnetic field parallel to the surface at a fundamental frequency, f, and measures the amplitude and phase of the 3rd harmonic signal , at 3f, generated by the local intrinsic/extrinsic nonlinearities.

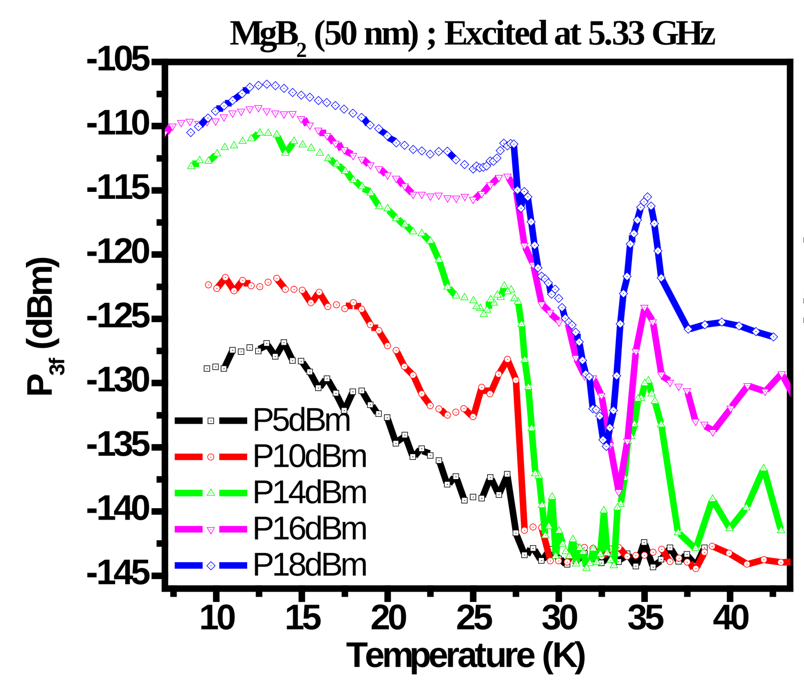
Experimental Method

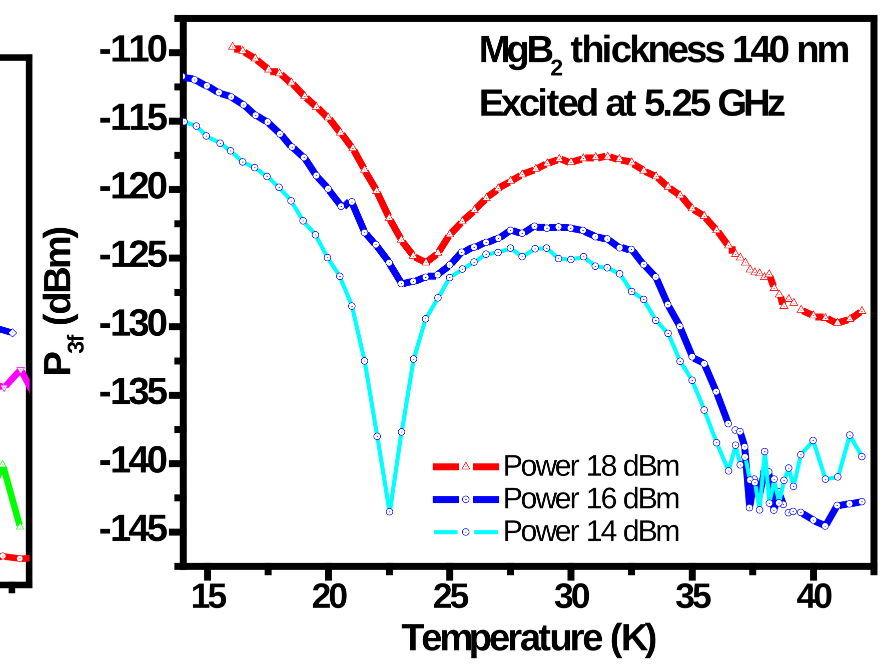


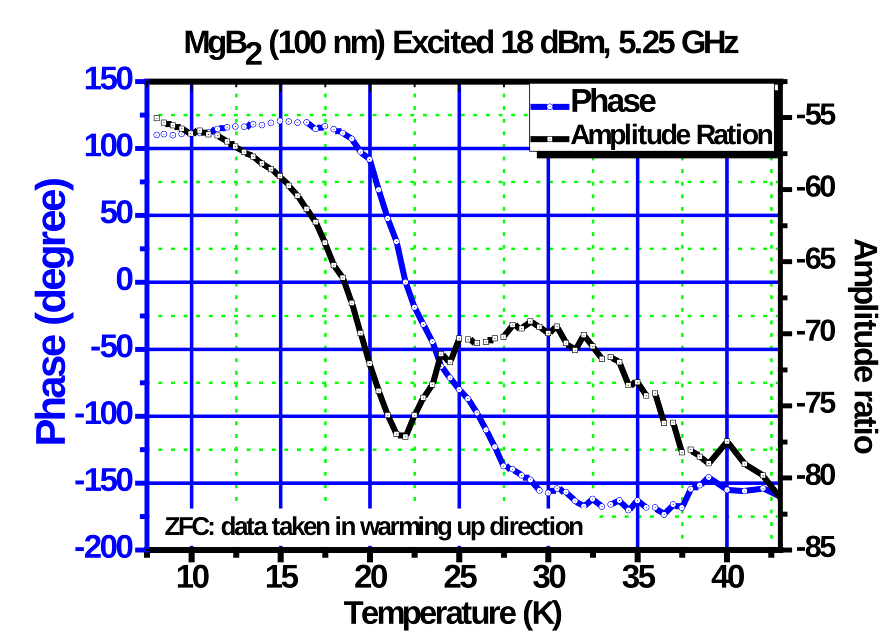
Dragos I. Mircea, Hua Xu, and Steven M. Anlage, Phys. Rev. B, **80**, 144505 (2009).

Harmonics of the fundamental frequency are produced by means of a comb-generator, and the harmonic of interest is selected using a bandpass filter, which will be used as the reference signal. The nonlinear response of the sample is directed toward the VNA, through a directional coupler and a high-pass filter, where it's amplitude and phase, with respect to the reference signal, are measured.

Third Harmonic Measurements on MgB_2





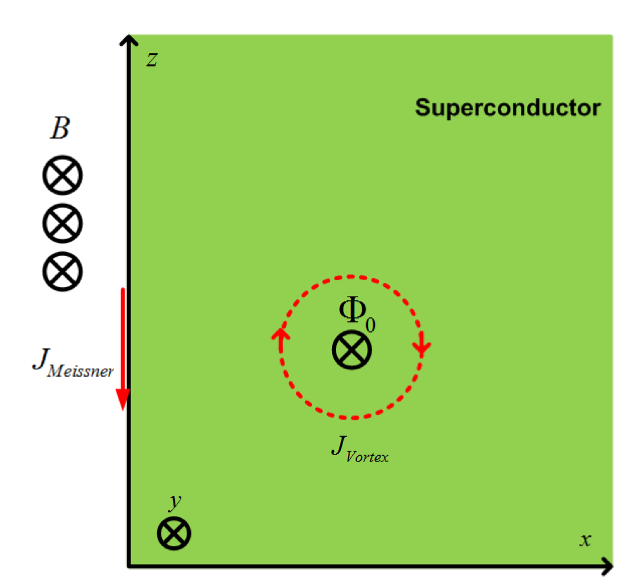


Near the critical temperature, the nonlinear Meissner response is observed.

At low temperatures, a third harmonic plateau with strong amplitude is measured.

At the border of the two aforementioned regimes, the third harmonic response is considerably suppressed.

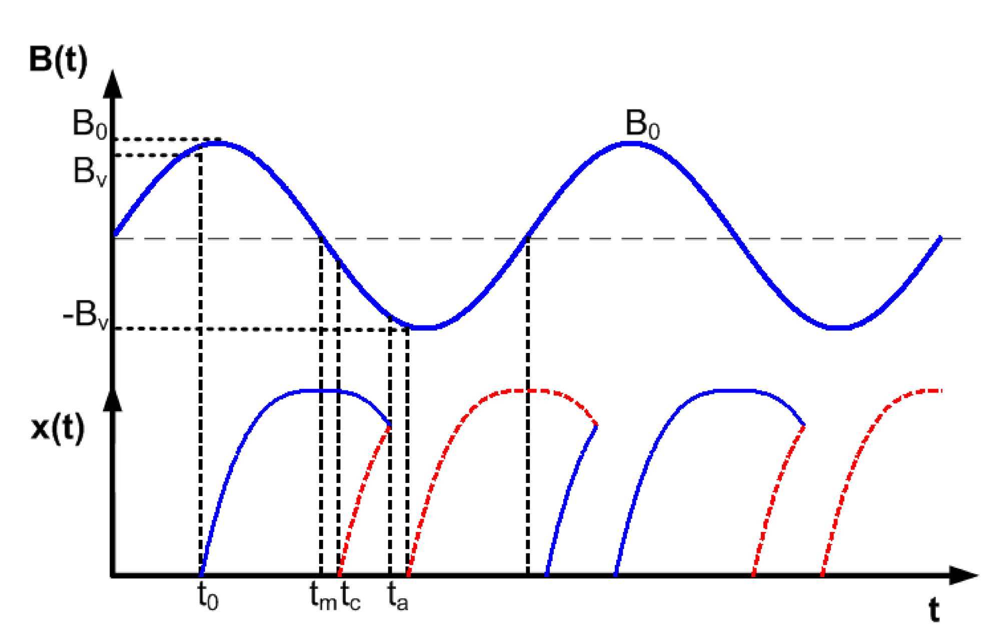
Vortex Dynamics in a Parallel Magnetic Field



$$\eta\,\dot{x} = \frac{\Phi_0 B_0}{\mu_0 \lambda} e^{-x/\lambda} \sin(\omega t) - \frac{\Phi_0^2}{2\pi\mu_0\lambda^3} K_1\left(\frac{2}{\lambda}\sqrt{x^2+\xi_s^2}\right)$$

A. Gurevich and G. Ciovati, Phys. Rev. B, **77**, 104501(2008)

$$\begin{cases}\lambda_{MgB_2} \approx 100\ nm \\ B_0 = 200\ mT\end{cases} : \quad n\Phi_0 = B_0\lambda^2 \Rightarrow n \cong 1$$



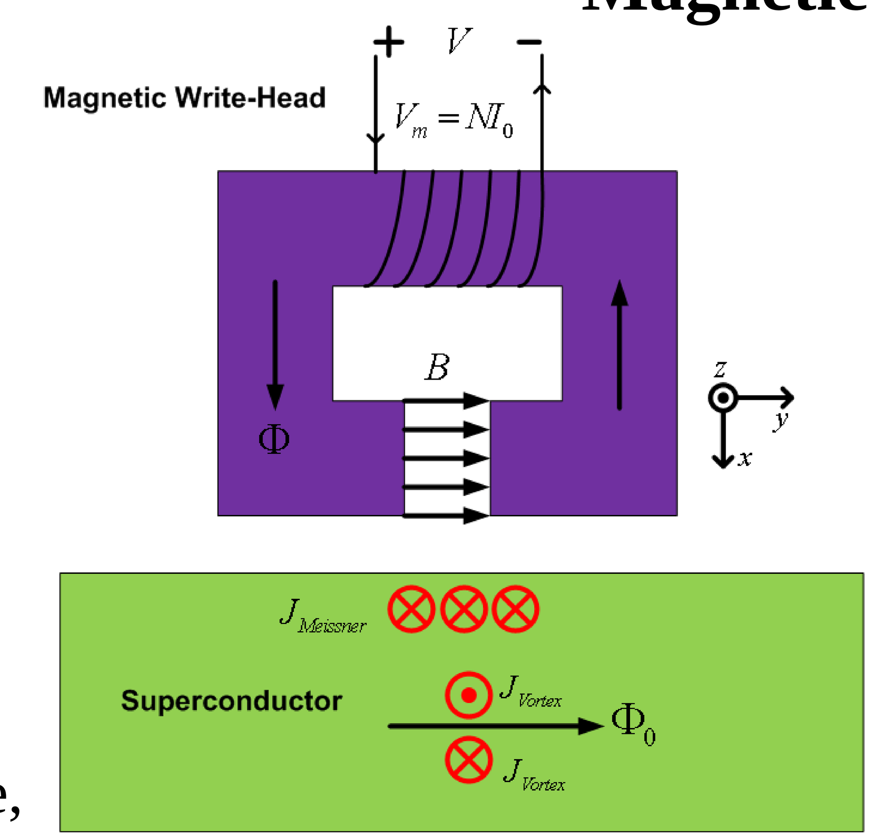
t_0: magnetic field exceeds the Bean-Livingston barrier and the first vortex nucleates.

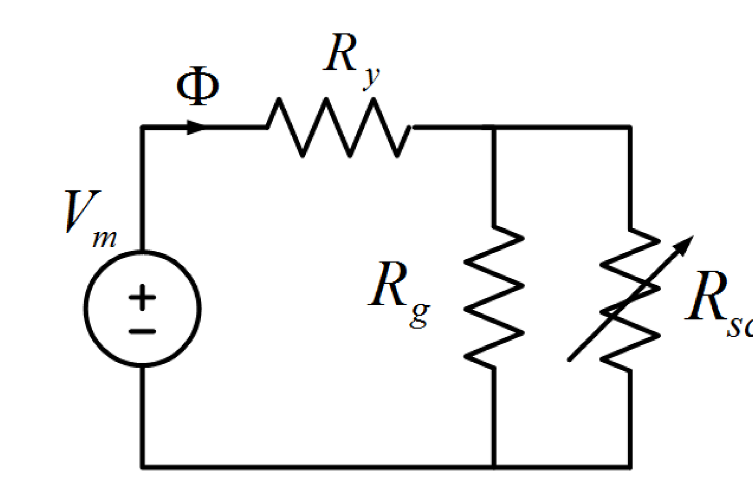
t_m: the vortex reaches its maximum distance from the surface.

t_c : an anti-vortex nucleates at the surface.

t_a : the vortex and anti-vortex collide and annihilate.

Probe-Sample Interaction as a Magnetic Circuit





$$R = \frac{\ell}{\mu A}\ (H^{-1})$$

$$\nabla\times\vec{H} = \vec{J} \Rightarrow \oint_c \vec{H}.d\vec{\ell} = NI = V_m$$

$$\begin{cases} V = \dfrac{d\Phi}{dt} \\ \Phi = \dfrac{V_m}{R_{eq}} \end{cases} \Rightarrow V = \frac{d}{dt}\left(\frac{NI}{R_{eq}}\right) = \frac{N}{R_{eq}}\frac{dI}{dt} - \frac{NI}{R_{eq}^2}\frac{dR_{eq}}{dt}$$

Although the amplitude of fluctuations in the reluctance may be small, the time rate of the changes is not small.

Meissner State

$$\begin{cases} \Phi_g = B_0(w.d) \\ \Phi_s = B_0(w.\lambda) \Rightarrow R_s = \left(\dfrac{d}{\lambda}\right)R_g \\ \Phi_s R_s = \Phi_g R_g \end{cases}$$

$$R_{eq} = R_y + R_g \| R_s = R_y + R_g\left(\frac{d}{d+\lambda}\right)$$

Vortex State

$$\begin{cases} \Phi_0 R_v = \dfrac{B_0 \ell_g}{\mu_0} \Rightarrow R_v = \dfrac{\ell_g}{\mu_0 \lambda^2} \\ \Phi_0 = B_0 \lambda^2 \end{cases}$$

$$R_{eq} = R_y + R_g \| R_s \| R_v$$

Conclusion

We have observed a strongly temperature-dependent RF nonlinear response in MgB_2 thin films. At the low-temperature limit, the nonlinearity is attributed to the vortex dynamics, where the switching between the Meissner and vortex states generates a third harmonic. As the temperature increases, so that the penetration depth exceeds the film's thickness, no vortices can nucleate and the third harmonic response is significantly suppressed. Near T_c, the usual non-linear Meissner effect is observed.

Acknowledgement

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