Enhanced THz Permeability in Non-Magnetic Drude Conductors

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Abstract: The permittivity and the permeability of Al and Cu thin films have been measured through THz time domain spectroscopy. The unusually very high permeability values indicate the onset of strong coupling between electronic plasma and spins.

Non-magnetic metallic films are generally not expected to exhibit any magnetic response when probed with electromagnetic (EM) radiation. In fact, a large number of studies on EM simulations, particularly those involving metals, such as in the realization of metasurfaces [1], model them by setting $\tilde{\mu} = \mu_0$, where μ_0 represents the vacuum permeability. Veselago himself in his pioneering paper [2] on the negative refractive index (NRI) materials assumed that electronic plasma (Drude-like materials), being non-magnetic, could exhibit NRI phenomena only in the presence of ferromagnetic moments.

Time domain THz spectroscopy has been used to measure the permittivity ($\tilde{\varepsilon}$) and permeability of aluminum and copper thin films. Results indicate that the electrical response is consistent with the Drude model characteristic of plasmonic media, whereas the permeability of the two materials exhibits slightly different behaviors. Specifically, the Al films are diamagnetic while the Cu films are paramagnetic.

Such results arise from a rigorous self-consistent retrieval process that exploits both transmission and reflection measurements [3]. This computational routine defines a narrow interval within which the true value of each electrodynamic parameter lies. The complex refractive index $\tilde{n}$ and the optical impedance $\tilde{z}$ are first retrieved through Fresnel's equations. Subsequently, the permittivity and the permeability are obtained through $\tilde{\varepsilon} = \tilde{n}/\tilde{z}$ and $\tilde{\mu} = \tilde{n}\,\tilde{z}$, respectively. Fig.1 displays the four electrodynamic parameters of a 10nm-thick Al film.

It is important to emphasize that the spectroscopic $\tilde{\mu}$, shown in Fig.1(d) is inherently constrained to exhibit a positive real part whereas its imaginary part may be either positive or negative. This behavior arises from the adopted sign conventions of $\tilde{n}$ ($n > 0$, $k > 0$) and from the requirement that ε_i remains positive. It can be demonstrated that a spectroscopic permeability characterized by $\mu_r > 0$ and $\mu_i < 0$ corresponds to a diamagnetic response, which is theoretically expected to assume the opposite behavior, namely $\mu_r < 0$ and $\mu_i > 0$. The observed phenomenology is consistent with the electronic plasma-spin theory [2] according to which the EM confinement in the metallic film induces the onset of spin waves that oscillate coherently with plasma waves.

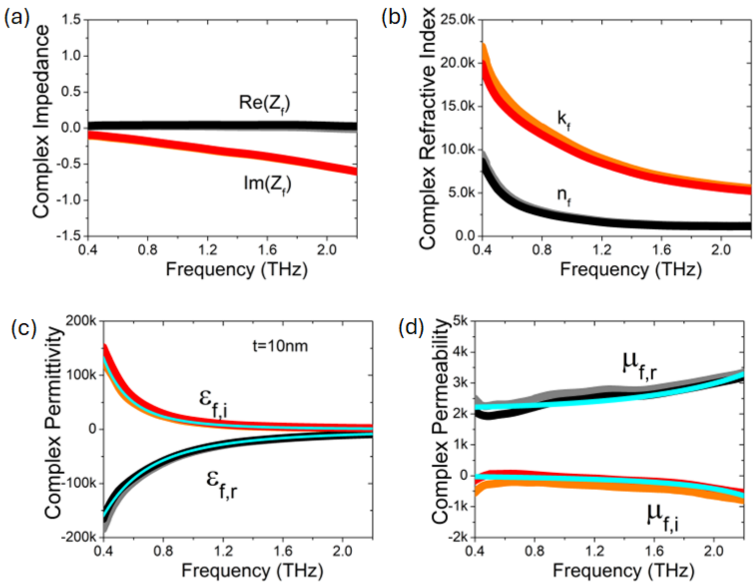

Fig.1: (a), (b), (c) and (d) show the optical impedance, the complex refractive index, the permittivity and the permeability of an aluminum thin film, respectively.

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