Applications of negative-permittivity materials to sub-wavelength imaging and nanotechnologies

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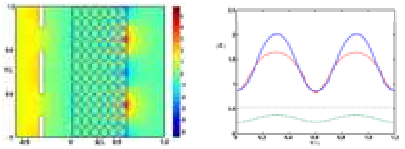
Outline

- **Motivation: why near field in mid-IR?**
- **Two approaches to sub-wavelength resolution:**

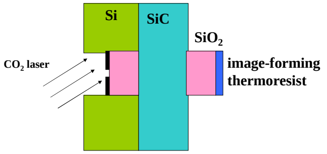
1. **Design of sub-micron "left-handed" metamaterials**

   (a) Sub-wavelength plasmonic crystals and their electromagnetic properties



2. **Near-field super-lens in mid-IR: using dielectric/semiconductor/dielectric "sandwich" for non-contact laser lithography**

   PENFIL: Phonon-Enhanced Near-Field Infrared Lithography with silicon carbide



Motivation

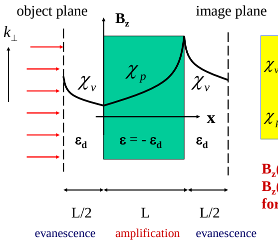
•Many materials (plastic, ceramics, polymers) strongly absorb in IR → "sculpting" various surfaces on a nanoscale by delivering IR to small (100 nm)^3 volumes (laser ablation)

•Nanoscale patterning of thermoresists using highly efficient carbon dioxide lasers

•Small biological objects (e.g., spores) can be imaged one at a time, by studying infrared Raman resonances.

•IR imaging and manipulation of biological molecules can be preferable to shorter wavelengths because it does not alter chemical composition.

Surface waves enable super-lensing



$$\chi_v = \sqrt{k_\perp^2 - \varepsilon_d \mu_d \frac{\omega_0^2}{c^2}}$$

$$\chi_p = \sqrt{k_\perp^2 - \varepsilon \mu \frac{\omega_0^2}{c^2}}$$

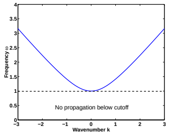
B_z(object plane) = B_z(image plane) for $\mu = -\mu_d$, $\varepsilon = -\varepsilon_d$

Choose a low-loss negative ε materials

•Plasma: $\varepsilon = 1 - \omega_p^2/\omega^2$

$\omega_p^2 = 4\pi e^2 n/m$

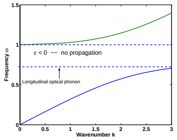
Typically, ω_p is in 10^{15} Hz range in metals



•Polaritonic crystals (ZnSe, SiC):

$$\varepsilon = \varepsilon(\infty)\frac{\omega_L^2 - \omega^2 + i\gamma\omega}{\omega_T^2 - \omega^2 + i\gamma\omega}$$

Typically, ω_T and ω_L are in 1-30 THz range → surface phonons, long lifetime!



Proven Properties of Photonic Materials

•Smaller damping of IR phonons (reduced by cooling)

$$\varepsilon = \varepsilon(\infty)\frac{\omega_L^2 - \omega^2 + i\gamma\omega}{\omega_T^2 - \omega^2 + i\gamma\omega}$$

For SiC $\gamma/\omega_L = 0.005 << 1$

For ZnSe $\gamma/\omega_L = 0.001 << 1$

•Higher sensitivity to surface quality and laser frequency is explored in surface science! (Hillenbrand et. al., Nature 2002)

•Desirable ε = -1 regime is not accessible in mid-IR using metal films

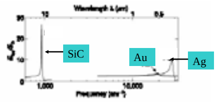
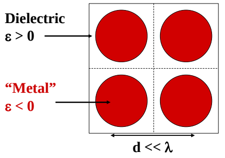


Figure 1 Calculated field enhancement due to Fröhlich resonance at the surface of a 10-nm-diameter sphere. The infrared lattice vibration (phonon) of a polar dielectric (SiC) induces a considerably stronger near-field amplitude than the green/blue electronic excitation (plasmon) of a noble metal (Au, Ag).

Sub-wavelength Plasmonic Crystal



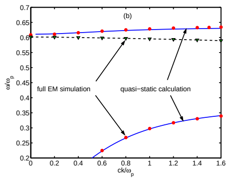
Transverse magnetic (TM) waves in 2-D:

$$-\nabla\left(\frac{1}{\varepsilon}\nabla H_z\right) = \frac{\omega^2}{c^2} H_z$$

•"Left-handed" propagation bands with non-vanishing magnetic dipole

•Sub-wavelength resolution in those bands

Wave Propagation in a Sub-wavelength Plasmonic Crystal (SPC)

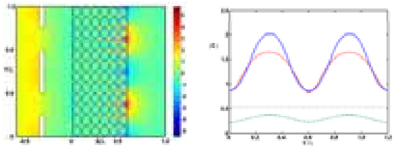


•Dots: "regular" (non-magnetic) propagation band described by $\mu_{eff} = 1$ and $\varepsilon_{qs}(\omega) > 0$

•Diamonds: "left-handed" propagation band with $\mu_{eff} < 0$ and $\varepsilon_{eff}(\omega) < 0$

Note: quasi-static theory predicts a bandgap (cutoff) in the region of the "left-handed" propagation band: **$\varepsilon_{qs} < 0$**

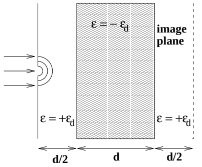
Sub-wavelength Imaging with SPC



Magnetic field behind plane wave illuminated double-slit: D = λ/5, separation 2D

Blue → $\omega/\omega_p = 0.6$, X = -0.2λ
Red → $\omega/\omega_p = 0.6$, X = 0.8λ no damping
Black → same as red, but with damping
Dotted → $\omega/\omega_p = 0.606$ (outside of the left-handed band)

Poor man's super-lens: ε < 0, μ = 1



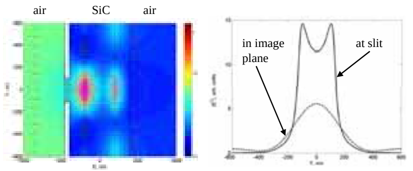
What determines the accuracy of image reconstruction in the image plane?

1. **Retardation (finite lens thickness) → Important for μ = 1 even if ε = -ε$_d$**
2. **Losses → ε = -ε$_d$ + i σ**

$$T = \frac{4(\chi_v/\varepsilon_v)(\chi_p/\varepsilon_p)\exp(-\chi_v d)}{(\chi_p/\varepsilon_p + \chi_v/\varepsilon_v)^2 \exp(\chi_p d) - (\chi_p/\varepsilon_p - \chi_v/\varepsilon_v)^2 \exp(-\chi_p d)}$$

Ideally, want T = 1, but issues (1) and (2) interfere…

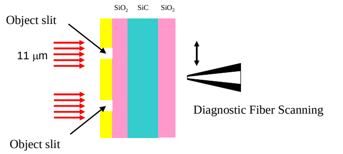
Image Formation by SiO$_2$/SiC/SiO$_2$ Superlens



Object: periodic array of slits.
Slit Width: 200 nm
Array Period: 1.2 μm
Reflection: 7.8 %

Image FWHM: 350 nm → individual slits clearly resolved

Possible Methods to Verify the Image Formation



Diagnostic Fiber Scanning

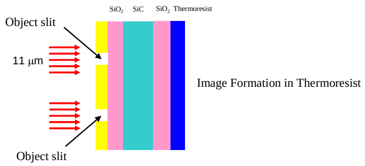
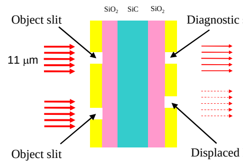


Image Formation in Thermoresist



45 % (simulations)

Transmitted Power Measurements

9 % (simulations)

Conclusions

Two approaches to making an IR sub-wavelength "superlens" are explored using materials with negative permittivity ε:

•Engineering 2-D sub-wavelength plasmonic crystals (SPC). Reveal double-negative propagation bands when cylinders are almost touching. SPC slabs can be used for sub-wavelength imaging → simulations show λ/5 resolution.

•A superlens consisting of thin SiO$_2$/SiC/SiO$_2$ layers was designed and shown to exhibit 350 nm resolution due to surface wave exhitation. This near-field effect can be probed in far field by measuring the transmission through 2 sets of slits, using NSOM, or imprinting the image on thermoresist.