"Negative" nanophotonics: controlling diffraction limit and group velocity in anisotropy-based NIMs

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Abstract:

In contrast to conventional NIMs, based either on magnetism or on periodicity, anisotropy-based NIMs described here are non-magnetic and rely on the effective-medium response of meta-materials in waveguide geometries. Being highly-tolerable to fabrication defects, anisotropic systems provide versatile control over the magnitude and sign of effective refractive index and open new ways to efficiently couple the radiation from micro-scale optical fibers to nm-sized waveguides followed by sub-diffraction light manipulation inside nm-thick waveguiding structures. Specific applications include photonic funnels, capable of transferring over 25% of radiation from conventional telecom fibers to spots smaller than 1/30-th of a wavelength, and NIM-based lenses with far-field resolution of the order of 1/10-th of a wavelength. Also, the group velocity in anisotropy-based waveguides can be efficiently controlled from ultra-fast to ultra-slow values with (weak) material gain

Brief intro:

Diffraction limit: *impossibility to compress a series of propagating waves with the same frequency to areas much smaller than internal wavelength.*

- prevents high-resolution imaging
- prevents construction of highly-confined waveguides
- prevents coupling between micro- and nano-scales

Conventional NIMs:

- Magnetism-based NIMs
  - may be used for near-field superlens
  - operate in proximity of a resonance
  - severely limited by resonant absorption (may be partially compensated by material gain)

- Photonic crystal-based NIMs
  - can be realized in all-dielectric materials
  - low loss
  - require periodicity (intolerable to fabrication defects)
  - typically do not support broad spectrum of surface waves and therefore are not applicable for super-imaging

Anisotropy-based planar NIMs

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Idea:

- Use waveguide geometry **and** material anisotropy to achieve negative refraction

TM waveguide modes: $\nu = 1 - \dfrac{k^2}{\epsilon_{\|}\kappa^2}$

Waveguide: $k_{prop}^2 = \boxed{\epsilon_\perp \nu}\dfrac{\omega^2}{c^2}$

Free space: $k_x^2 + k_y^2 + k_z^2 = \boxed{\epsilon\mu}\dfrac{\omega^2}{c^2}$

$$\boxed{n = \pm\sqrt{\epsilon_\perp \nu}}$$

Transparent {ε,ν} combinations

$\epsilon>0$ $\nu>0$	= "conventional" waveguide
$\epsilon<0$ $\nu<0$	= NIM waveguide

Key Advantages:

- non-magnetic and non-periodic alternative to conventional NIM designs
- low-loss
- provide |n|>>1, therefore
  - reducing the effective wavelength
  - increasing far-field resolution
- possibility of **far-field superlens**

Photonic funnels

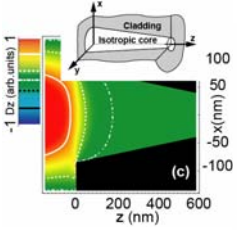
A.A. Govyadinov, V.A. Podolskiy – PRB 73, 155108 (2006)
– arXiv:physics/0605036 (J.Mod.Opt, 2006)

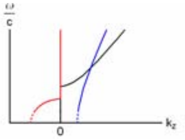
Idea:

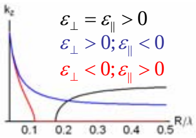
- Use waveguides with anisotropic core to compress the light beyond free-space diffraction limit

Key Advantages:

- Volume modes, identical to the ones in telecom fibers
- Low loss light transmission (~25% of light transmitted to ~λ/30 spots)
- Versatile phase manipulation: both n>0 and n<0 configurations available







$\epsilon_\perp = \epsilon_{\|} > 0$
$\epsilon_\perp > 0; \epsilon_{\|} < 0$
$\epsilon_\perp < 0; \epsilon_{\|} > 0$

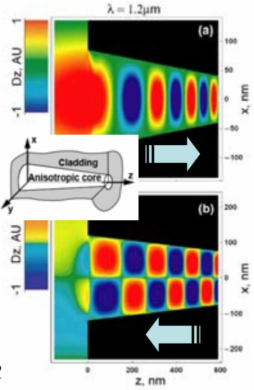
$$k_{prop}^2 = \epsilon_\perp \nu \frac{\omega^2}{c^2}$$

$$\nu = 1 - \frac{m^2\lambda_0^2}{\epsilon_{\|} R^2}$$

$$n = \pm\sqrt{\epsilon_\perp \nu} \propto 1/R$$

Core material:
15-nm layers of Si and Ag

Energy transmission: ~25%



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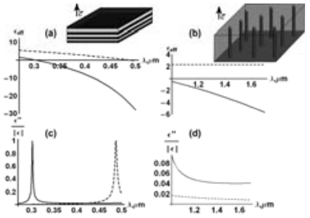
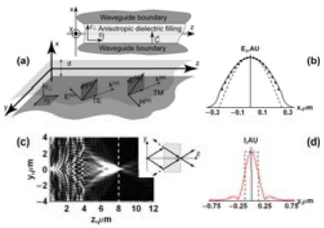
Anisotropic plasmonic meta-materials



By appropriate choice of constituents, anisotropic meta-materials can be realized at UV to THz frequencies;
Natural low-loss materials are available at far-IR, and THz

Telecom far-field superlens

Far field resolution: 300 nm=λ/6:



Group velocity manipulation at the nano-scale

A.A. Govyadinov, V.A. Podolskiy – arXiv:physics/0604065 (2006)

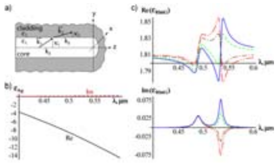
Idea:

- Use waveguide geometry **and** material gain to manipulate **group velocity** of modes in nm-thick waveguides

Key Advantages:

- Slow ($0<v_g<<c$) and ultra-fast ($v_g<0$) light in the same waveguide
- Both waveguide geometry **and** external pumping can be used to control v_g
- Low pumping levels required
- All-optical analog of a field transistor
- Works for surface (plasmonic) modes, **and** for volume modes in anisotropy-based waveguides

Example: Ag-Rh6G nano-composites



Plasmonic nanorod

NIM photonic funnel