The physics of the perfect lens

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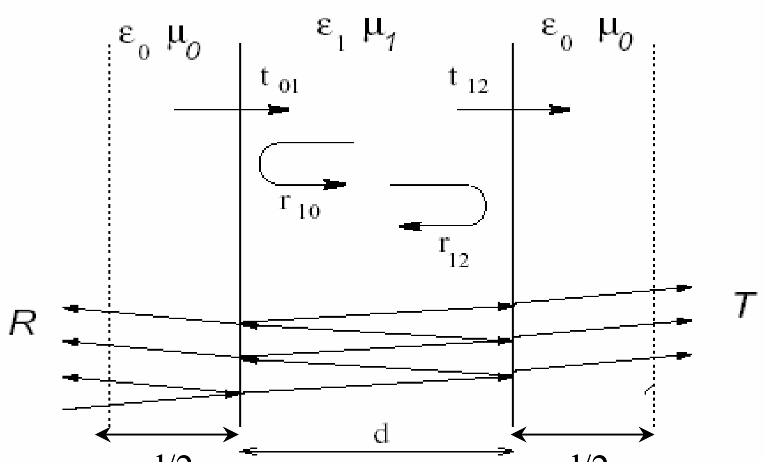
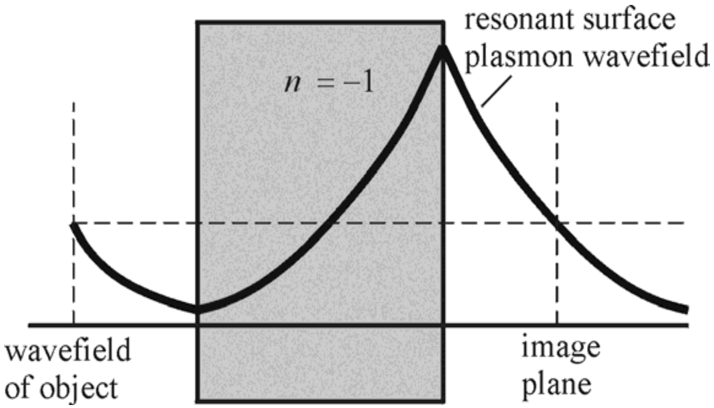
Pendry's proposal for a perfect lens

Consider Veselago's slab of negative refractive material with ε < 0, μ < 0.





$$T = t_{21}t_{32}e^{ik_z^{(2)}d} + t_{21}r_{32}r_{12}t_{32}e^{3ik_z^{(2)}d}\cdots = \frac{t_{21}t_{32}e^{ik_z^{(2)}d}}{1 - r_{32}r_{12}e^{2ik_z^{(2)}d}}$$

$$R = r_{21} + t_{21}r_{32}t_{12}e^{2ik_z^{(2)}d} + t_{21}r_{32}r_{12}t_{12}e^{4ik_z^{(2)}d} + \cdots = \frac{r_{21} + r_{32}e^{2ik_z^{(2)}d}}{1 - r_{32}r_{12}e^{2ik_z^{(2)}d}}$$

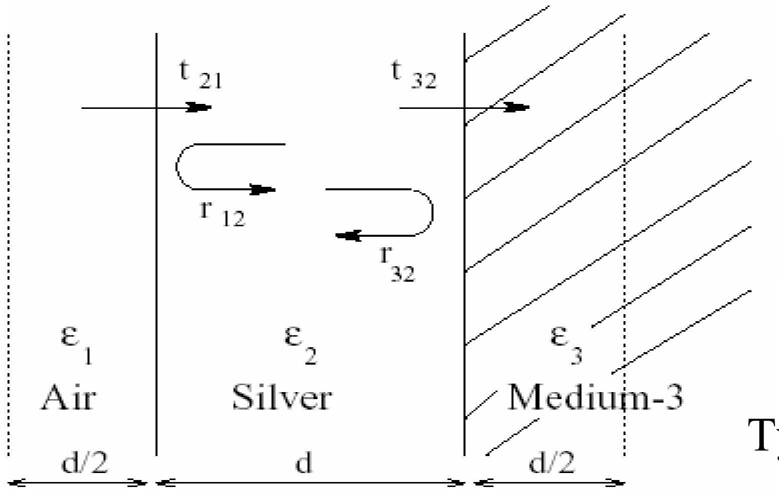
$$\lim_{\substack{\epsilon \to -1 \\ \mu \to -1}} T = \exp[-ik_z^{(2)}d] \qquad \lim_{\substack{\epsilon \to -1 \\ \mu \to -1}} R = 0$$

Phase Reversal for the propagating waves (Real k_z)

Amplification for the Evanescent modes (Imaginary k_z)

J.B. Pendry, Phys. Rev. Lett. 85, 3966 (2000)

The Near-Perfect Lens: An Asymmetric Slab



The Transmission coefficient is

$$T_P(k_x) = \exp[-ik_z^{(2)}d]\left[\frac{2\epsilon_3 k_z^{(1)}}{\epsilon_3 k_z^{(1)} + \epsilon_1 k_z^{(3)}}\right]$$

Typically d = 40nm.

Amplification of evanescence when,

$$\varepsilon_2 = -\varepsilon_1 \quad \& \quad \mu_2 = -\mu_1$$

OR

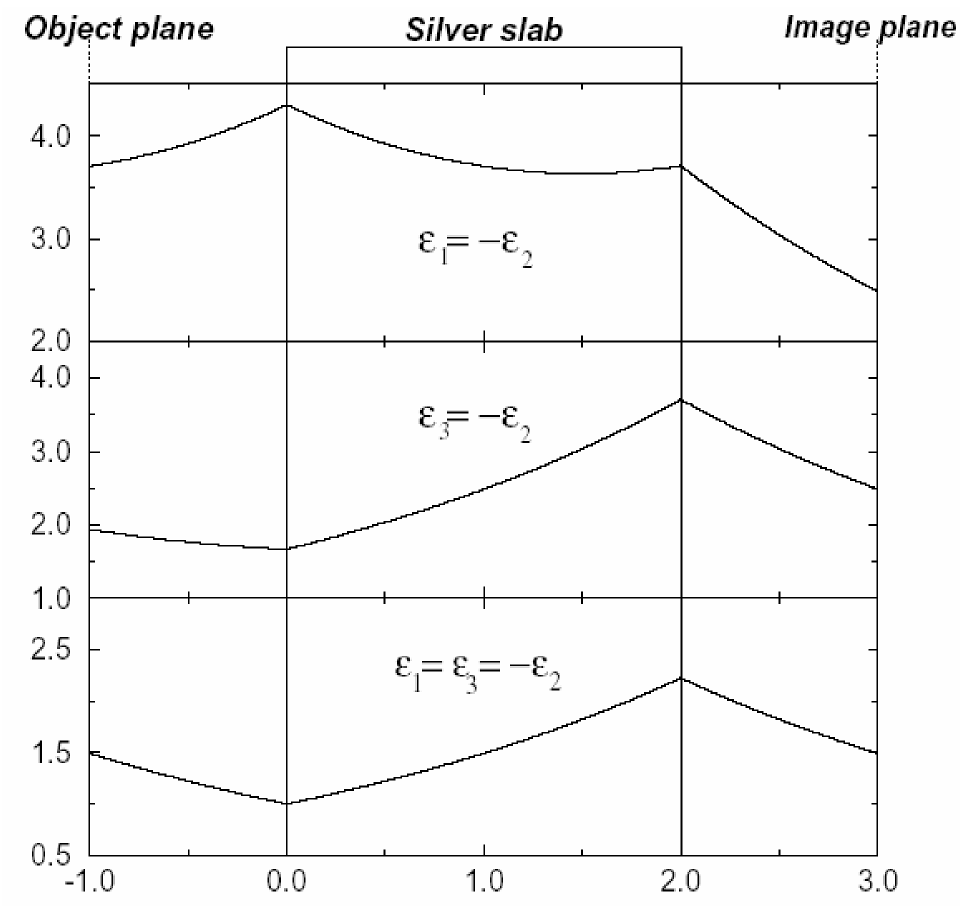
$$\varepsilon_2 = -\varepsilon_3 \quad \& \quad \mu_2 = -\mu_3$$

i.e. Perfect lens conditions at ANY ONE SURFACE should be achieved.

- Image intensity is changed
- Aberration due to non-unique image plane for all k_x
- Non-zero reflectivity

Surface states and amplification of evanescence

$\varepsilon_- = -\varepsilon_+$ is exactly the condition for the existence of surface plasmon states at an interface
When this condition is satisfied at the latter interface only the growing solution is present



$\varepsilon_2 = -\varepsilon_1$,- Large reflectivity

The unfavourable configuration

$\varepsilon_2 = -\varepsilon_3$ – Small Reflectivity

The favourable configuration

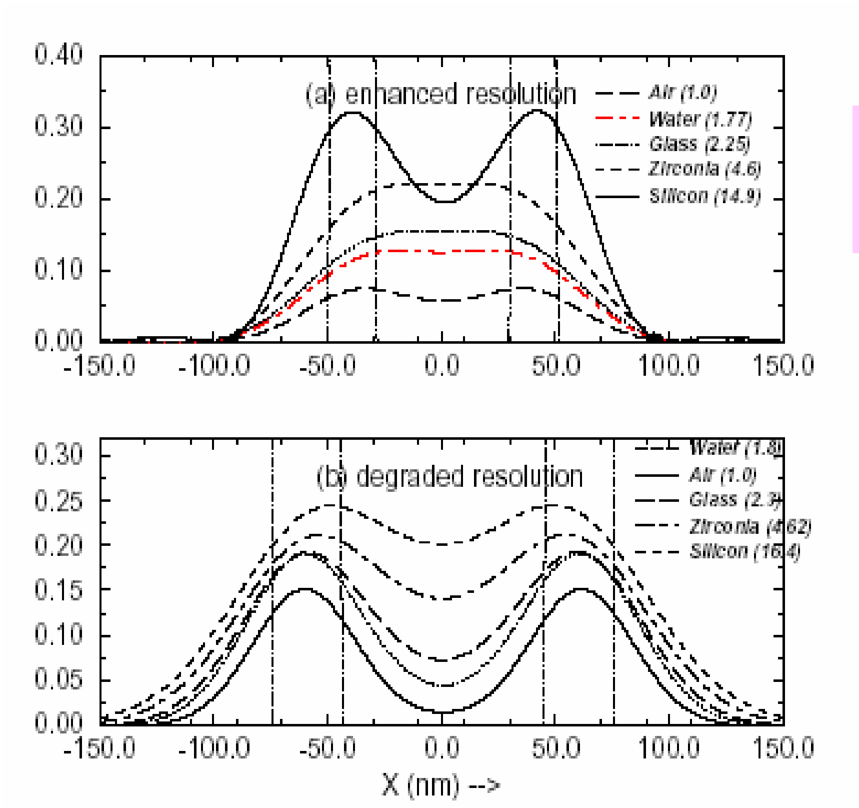
Symmetric configuration – the multiple reflections cancel out giving R = 0.

A practicable lens - the silver slab.

Consider the extreme near-field limit $k_x \rightarrow \infty$, all relevant lengthscales << λ,

Electric fields depend only on ε $\Rightarrow$ negative ε is a superlens for P-Polarization

Magnetic fields depend only on μ $\Rightarrow$ negative μ is a superlens for S-Polarization



Absorption makes the lens less than perfect.

In (a), large $\varepsilon_3 \Rightarrow$ better image resolution, with the limit on the resolution given by

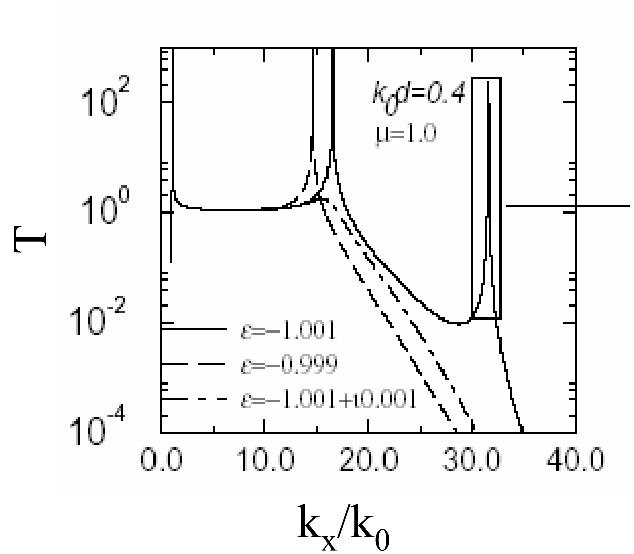
$$\text{res} = \frac{\lambda_0}{\lambda_{\min}} \simeq \frac{1}{4\pi d} \ln |\epsilon_2''/2\epsilon_3| \lambda_0$$

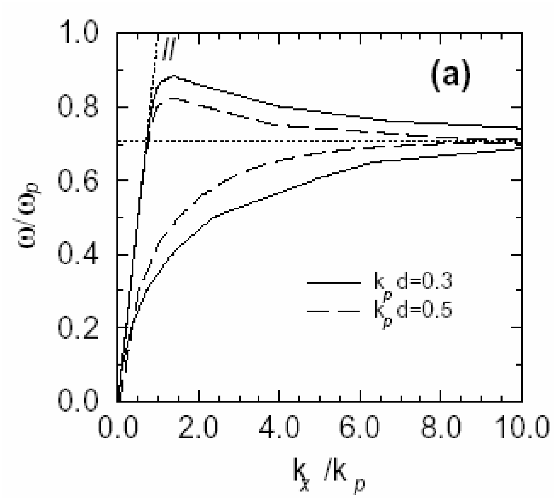
where $\epsilon_2 = \epsilon_2' + i\epsilon_2''$.

Effects of retardation and positive μ

No surface states are excited only exactly for $\varepsilon_{-} = -\varepsilon_{+}$ and $\mu_{-} = -\mu_{+}$.

Any deviations from these conditions always excites coupled slab plasmon polaritons



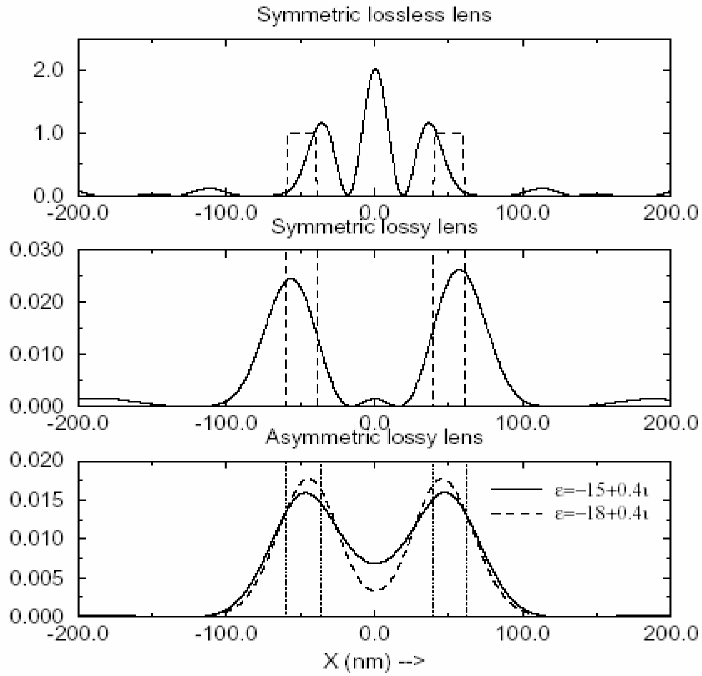


$\omega_p > \omega_{mp}$

The transmission resonances lead to disproportionate representation of some wave vectors. $\Rightarrow$ **IMAGE SWAMPED BY NOISE**

Absorption softens the divergences.

Effects of retardation for the silver lens



For a lossless lens, the image is destroyed by the SPP resonances

Absorption softens the effects of the resonances and is actually vital for the imaging

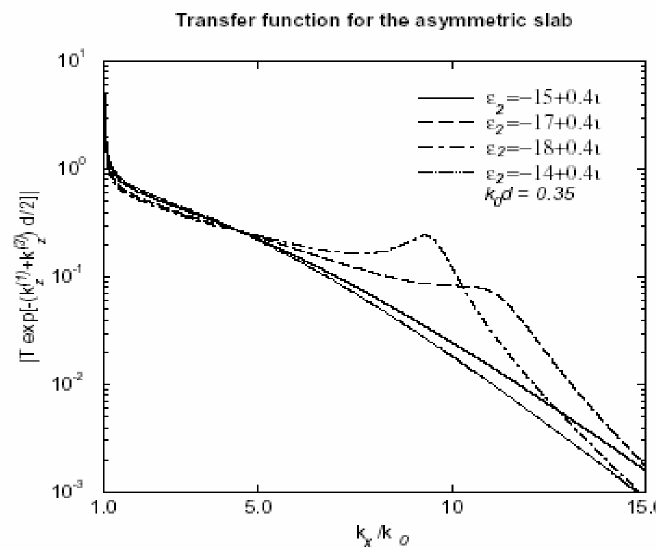
Asymmetric lens is less affected by the resonances – there is only one surface mode.

Can compensate for the deviation in **μ** by deviating from the ideal in **ε**

The slab polariton resonance causes an increase in T_p near the resonance

Gain more at smaller k_x but lose some at much higher k_x

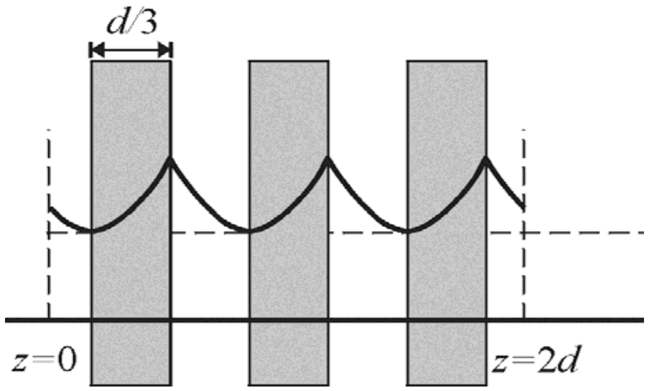
Results in better image resolution.

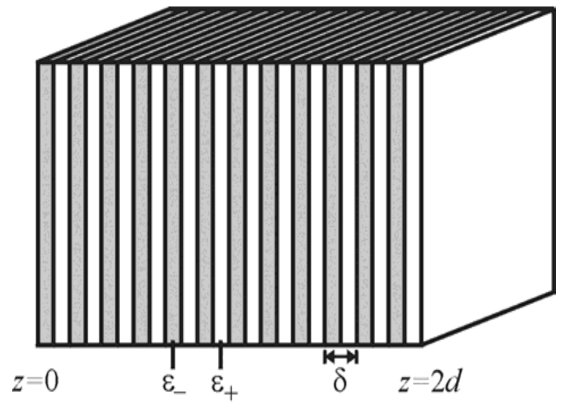


The image transfer function

The layered perfect lens: A near-field fibre optic bundle

The single slab can perfectly well be cut up into slices , distributed between source and image, and yet act as a perfect lens.





The lens acts through a series of surface plasmon resonances.
Using very thin slices is useful because:

1. The resolution capability is less affected by absorption in the lens
2. For a silver slab, the deleterious effects of retardation are smaller.

$$\Delta \simeq \frac{2\pi}{k_{\max}} = 2\pi\varepsilon''_{-} d.$$

The layered lens behaves effectively as a highly anisotropic medium.

$1/\varepsilon_z = \frac{1}{2}(1/\varepsilon_+ + 1/\varepsilon_-)$ and $\varepsilon_x = \frac{1}{2}(\varepsilon_+ + \varepsilon_-)$; $\Rightarrow$ $\varepsilon_z \to \infty$ and $\varepsilon_x \to 0$ as $\varepsilon_- \to -\varepsilon_+$

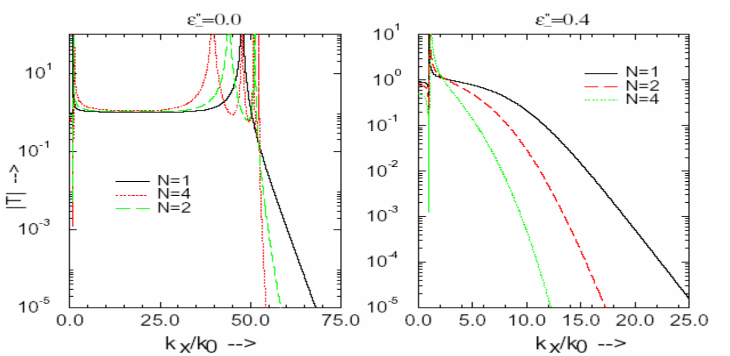
$$\frac{k_x^2 + k_y^2}{\varepsilon_z} + \frac{k_z^2}{\varepsilon_x} = \frac{\omega^2}{c^2}$$

and radiation propagates without change of phase or amplitude

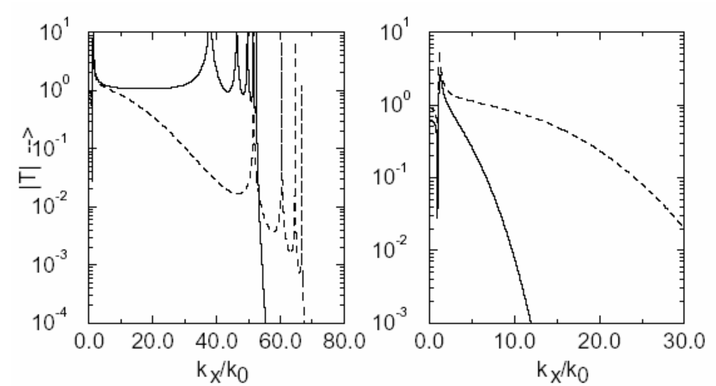
The layered silver lens

The frequencies of the slab plasmon polaritons split more for a thinner slab.

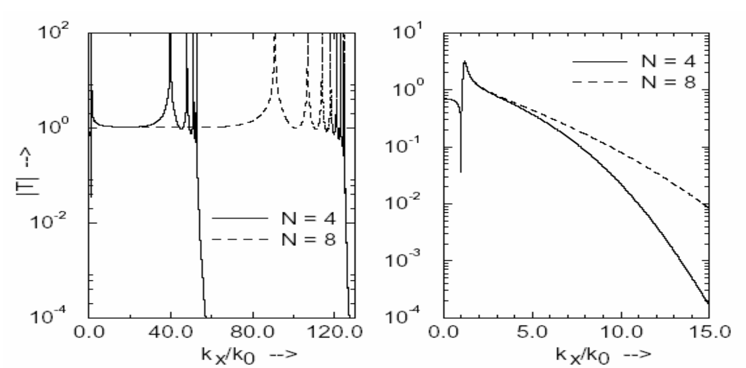
The effects of retardation and damping set in at a much larger k_x



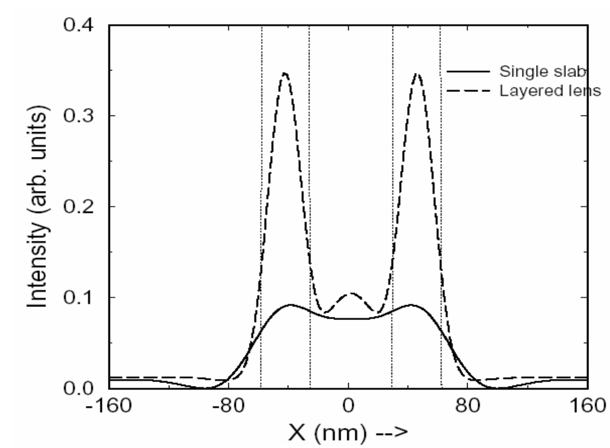
Transmission for increasing number of layers with the layer thickness kept constant



Transmission for ε_= -1+i0.4 and ε_= -12+i0.4



Transmission for increasing number of layers with the total stack thickness kept constant



Images produced by the single slab and a layered stack of silver.

Optical amplification to remove absorption

The eventual limit on resolution is set by absorption in the lens material.

Negative media are intrinsically lossy and dispersive.

Absorption can be compensated for by using optical amplification.

The Perfect lens conditions: $\varepsilon_- = -\varepsilon_+$

For absorptive negative media, $\varepsilon_- = \varepsilon_-' + i\,\varepsilon_-''$ with $\varepsilon_-'' \geq 0$.

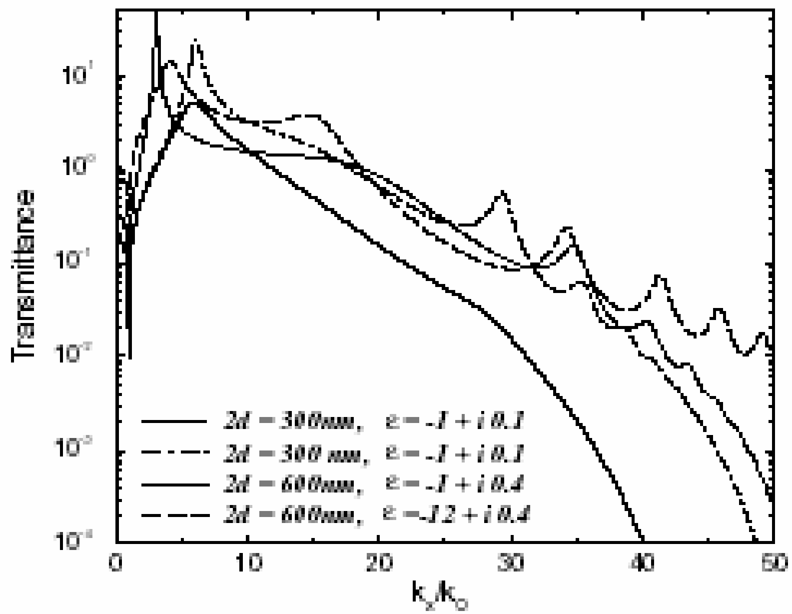
$\varepsilon_+'' = -\varepsilon_-'' \leq 0$ $\quad\Rightarrow\quad$ **The positive medium should be optically amplifying**

The transmission becomes almost independent of the total length of the stack

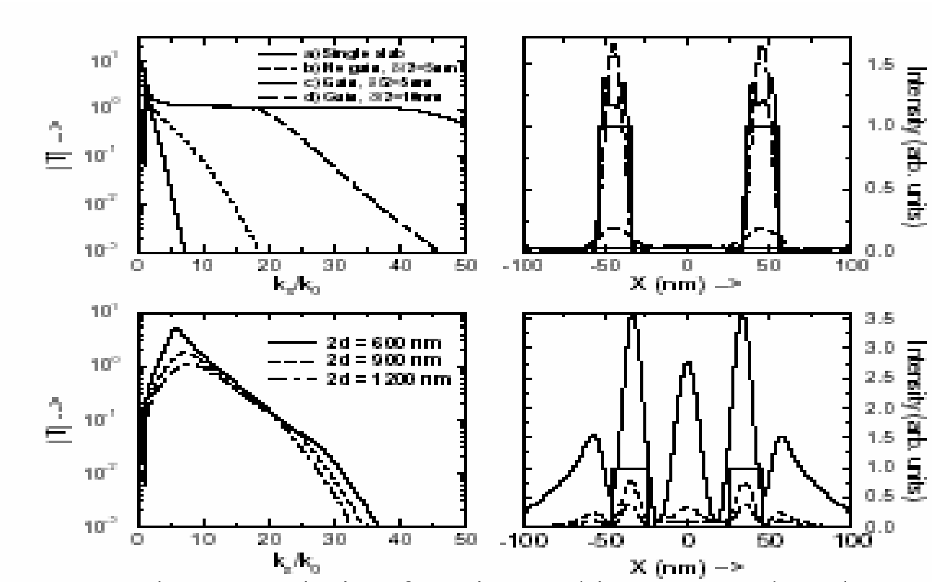
The amplification almost completely cancels out the deleterious effects of absorption.

Appreciable transmission even at large k_x results.

Transmission function to the right suggests a resolution of about $\lambda/25$ for a stack of a few λ thick.



Optical amplification and the perfect lens



The transmission function and images produced.

For smaller total stack thickness it works very well. But there is some overcompensation for larger stack thickness for sub-wavelength wave-vectors in the range $k_0 < k_x < 10\ k_0$.

The over-compensation at smaller k_x can be controlled by structuring the metal in the transverse plane and creating plasmonic bandstructures.

Since the image information at large k_x is transferred across, knowledge of the transmission function of the stack can enable recovery of the image.

Possible problems: Optical gain saturation and instabilities of laser oscillations.

Both problems will be minimised for very thin layers.