Layered Au-Si hyperbolic metamaterial for near infrared

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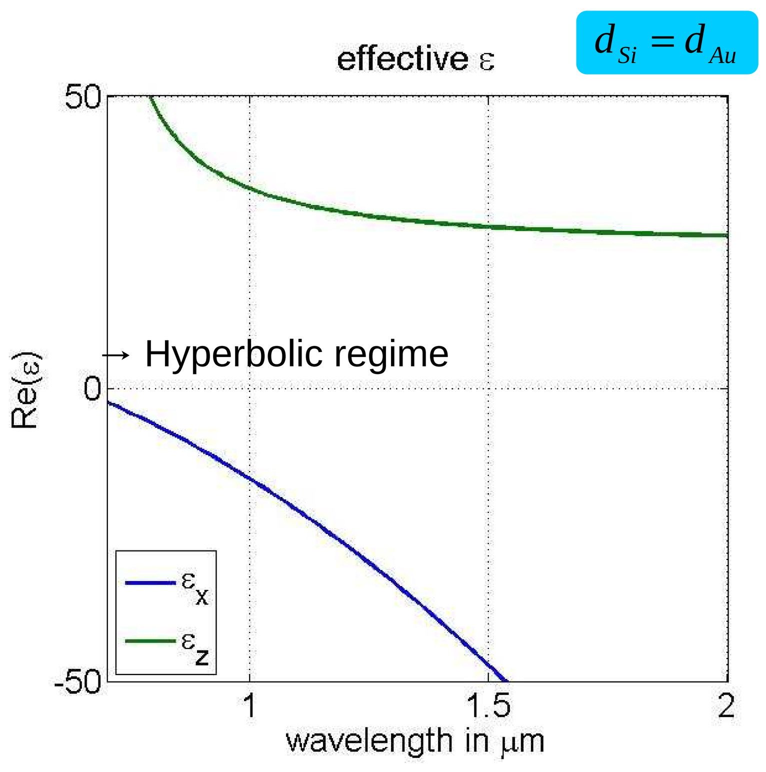
Introduction

Artificial, structured materials with a hyperbolic equifrequency contour for one of their two principle polarizations – so called hyperbolic metamaterials (HMMs) [1] – promise interesting applications including enhanced spontaneous emission [2] and enhanced heat transfer [3]. In thermophotovoltaics heat transfer beyond the limits of a black body can increase efficiency and total generated power. But HMMs for the near infrared (NIR) range tend to be challenging. Although metals are assumed to be a bad choice for NIR metamaterials we show that they can even outperform alternative plasmonic materials [4].

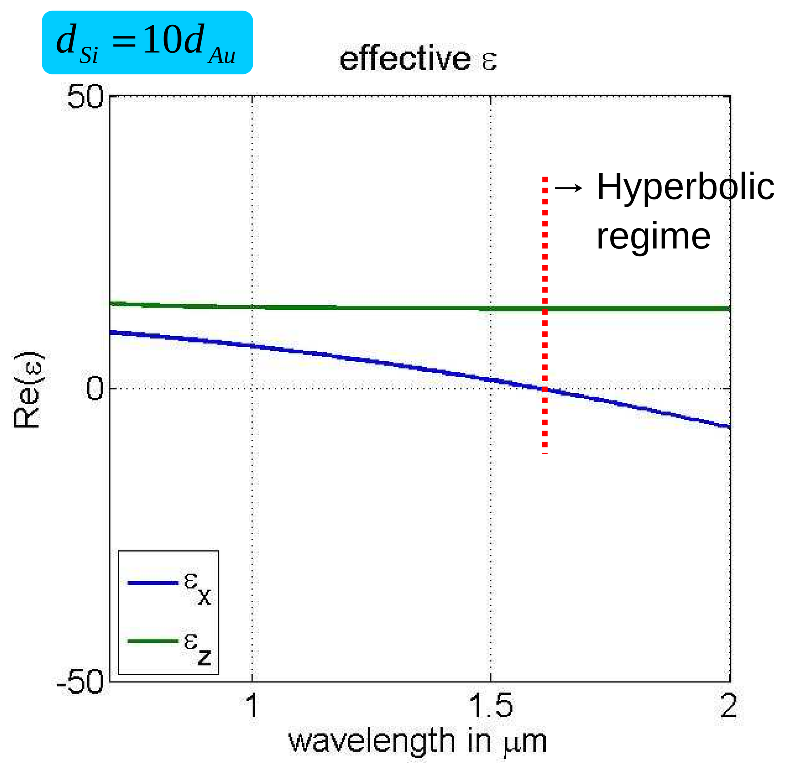
NIR hyperbolic metamaterial containing a metal

Idea of using gold and silicon for HMM

- Silicon is chosen because it has a high refractive index of 3.5 which compensates for the large negative permittivity of the metal.
- Gold is chosen because it is stable in thin films and has low losses compared to other metals.
- By making the silicon layers much thicker than the gold layers losses are reduced (Si is practically lossless) and the transition to hyperbolic regime is shifted to NIR.

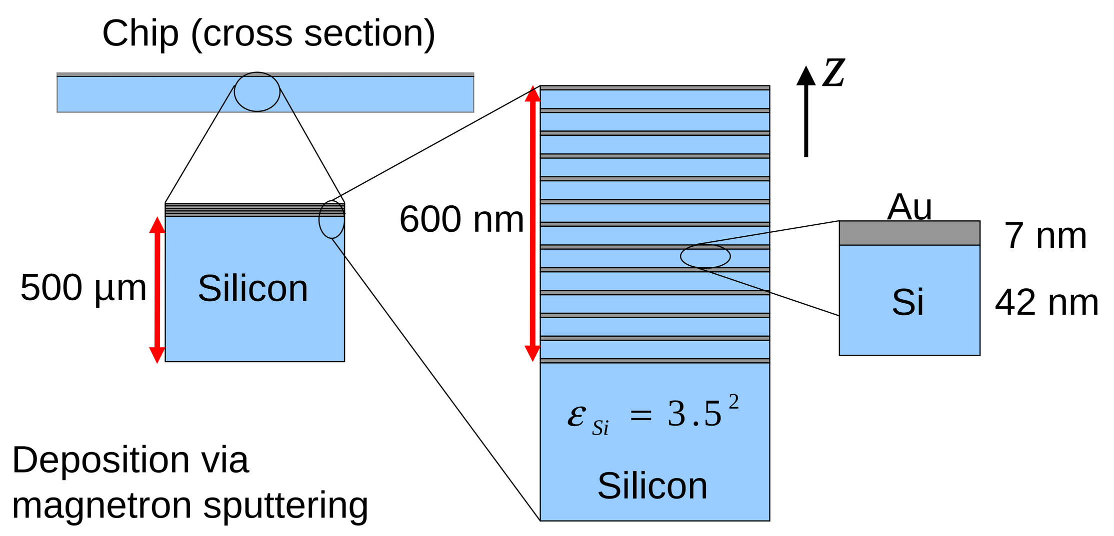


Top: *Real part of effective permittivities of Au-Si HMM for equal layer thicknesses.*



Top: *Real part of effective permittivities of Au-Si HMM for Si layers 10 times thicker than Au layers. The hyperbolic transition is shifted to longer wavelengths*

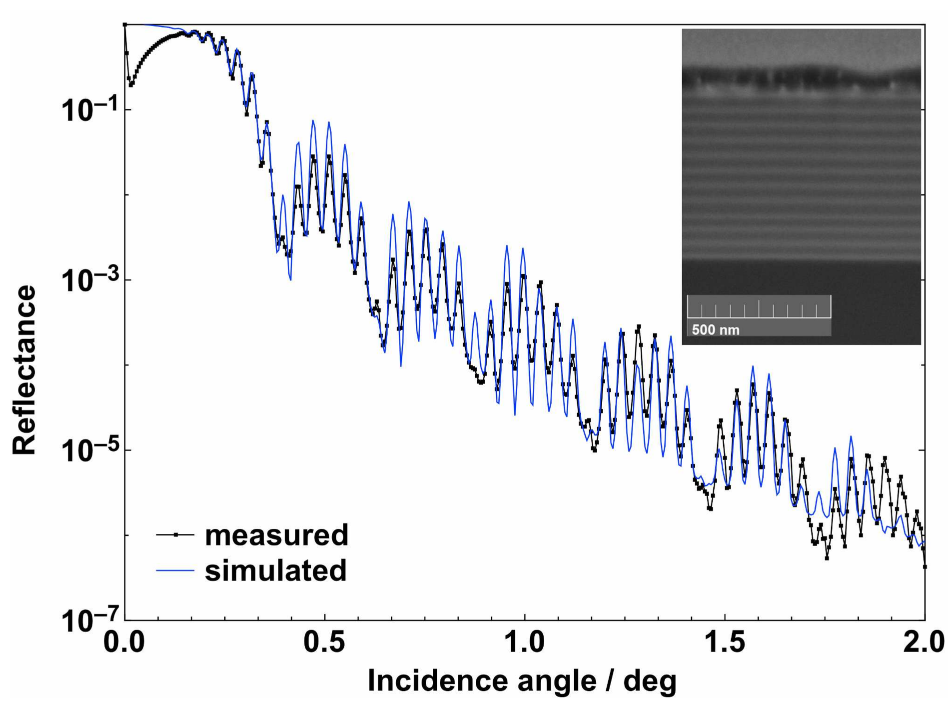
Fabrication and measurements



Effective permittivities:

$$\varepsilon_{x,y} = \frac{\varepsilon_{Au} d_{Au} + \varepsilon_{Si} d_{Si}}{d_{Au} + d_{Si}}$$

$$\varepsilon_z = \frac{d_{Au} + d_{Si}}{\frac{d_{Au}}{\varepsilon_{Au}} + \frac{d_{Si}}{\varepsilon_{Si}}}$$



Left: *XRR measurement together with a simulation. Both coincide well. The clearly visible periodicity is an indicator for a layered periodic structure.*
Inset: SEM picture of the multilayer stack located on double polished silicon substrate.

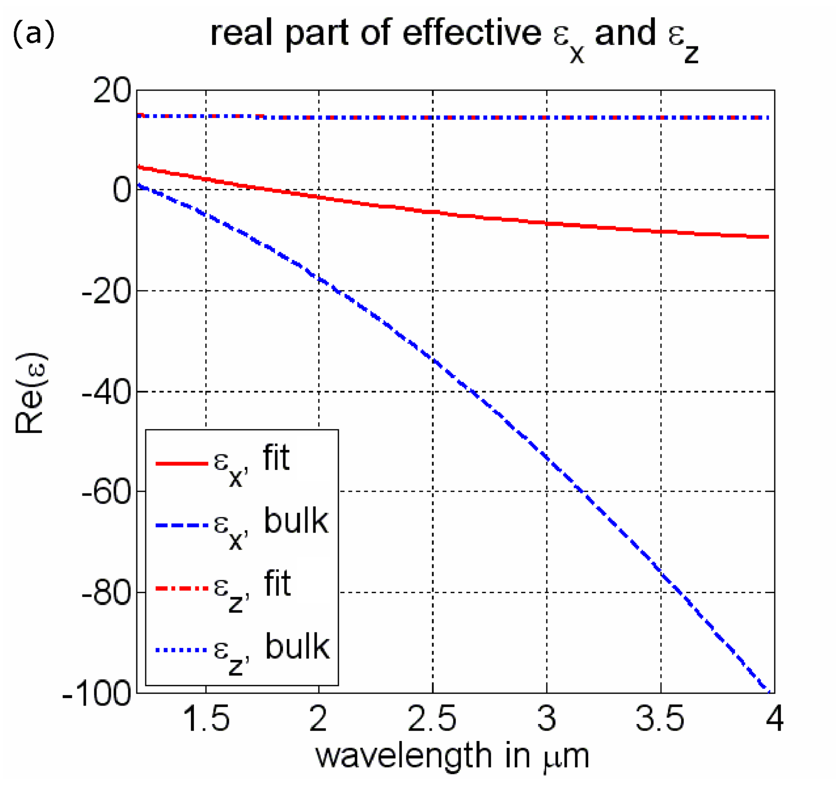
Simulation and fitting

Normal transmission and angle dependent reflection (15°, 20°, …, 60°, s- and p-polarized) were measured with a FTIR. A transfer-matrix method was used for simulation. Since thin film gold has properties different from bulk [5] we fitted the Drude model parameters of gold to reproduce the measurements. Collision frequency is significantly increased while the other parameters are close to bulk values.

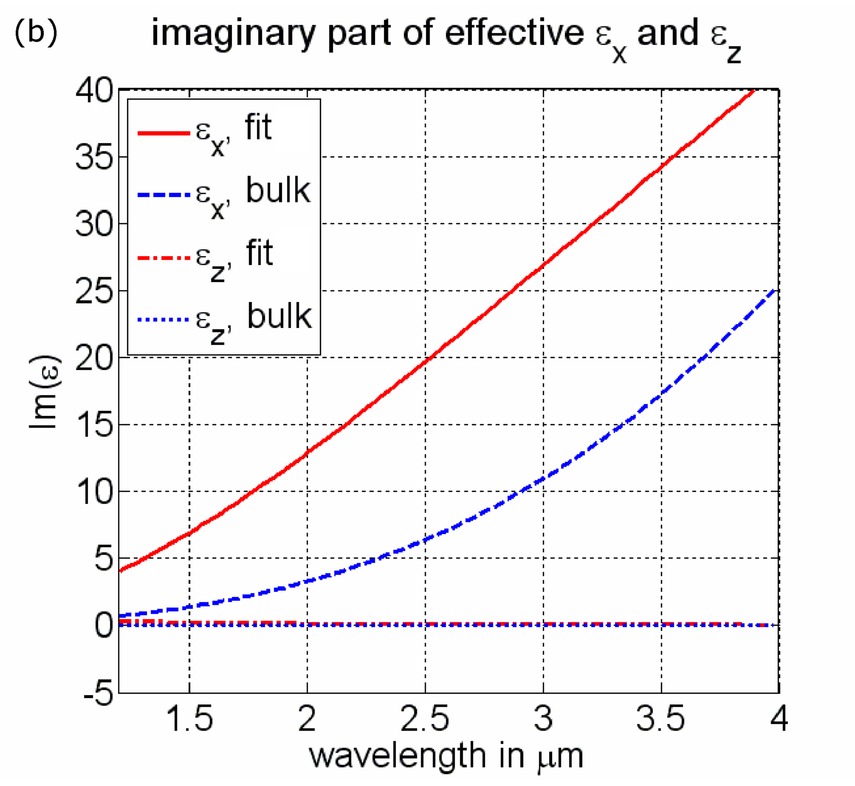
$$\varepsilon_{r,Au} = \varepsilon_\infty - \frac{(2\pi f_p)^2}{\omega(\omega - i\omega_{col})}$$

Bulk:
ε_∞ = 8.2, f_p = 2152 THz, ω_{col} = 106 THz

Fit:
ε_∞ = 6.9, f_p = 2005 THz, ω_{col} = 932 THz



Top: *Real part of effective permittivities of Au-Si HMM with the fitted gold properties and as it would be with bulk gold. The increase in collision frequency further shifts the transition to longer wavelengths.*

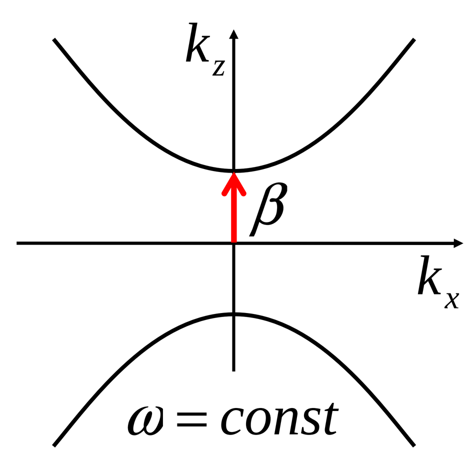


Top: *Imaginary part of effective permittivities of Au-Si HMM with the fitted gold properties and as it would be with bulk gold.*

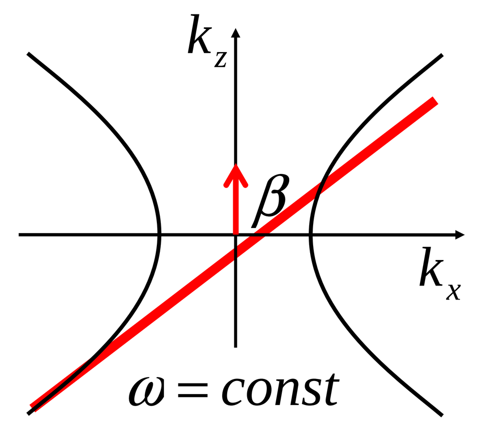
Figure-of-merit

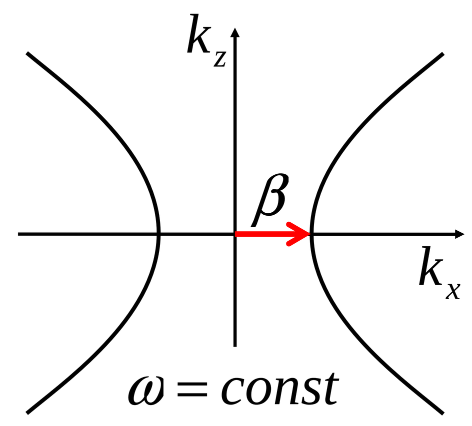
Often used FOM for HMMs designed for negative refraction [6]:

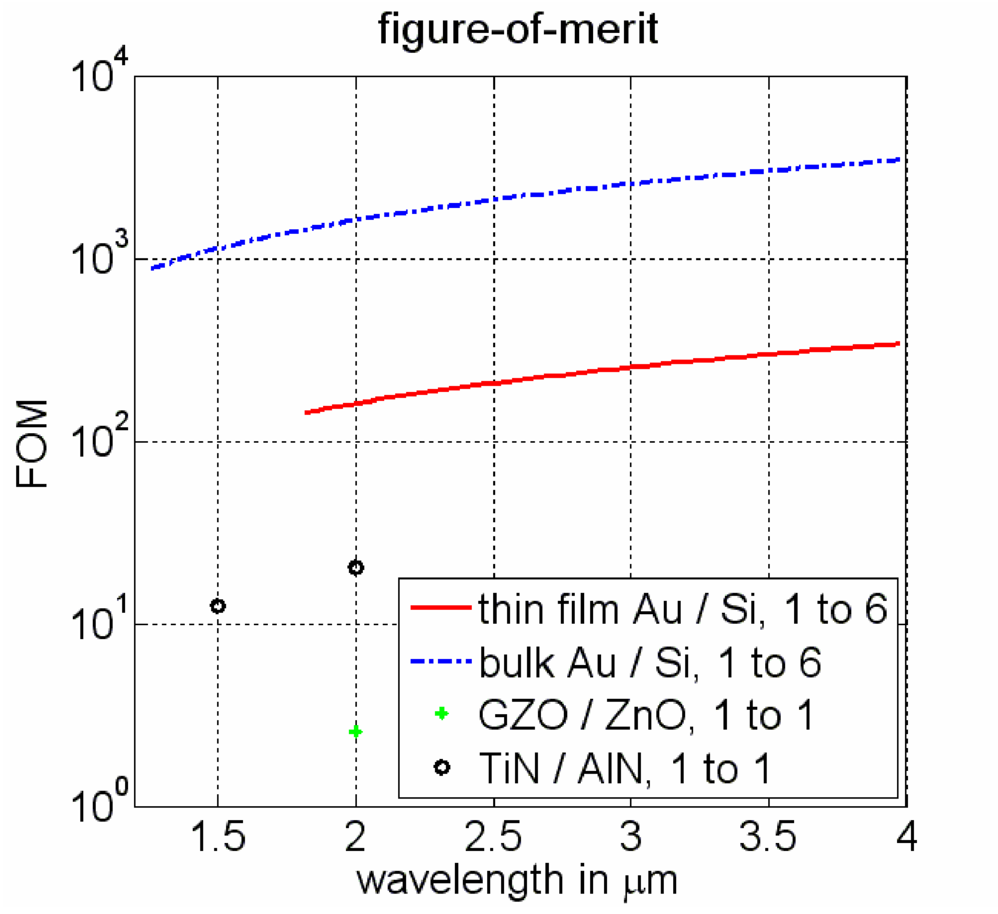
$$FOM = \frac{\Re(\beta)}{\Im(\beta)}$$



For HMMs with hyperboloids of one sheet (rotated hyperbola) the same FOM makes no sense. But it can be easily adjusted by rotating β.







Left: *Figure-of-merit of Au-Si HMM with the fitted gold properties and as it would be with bulk gold. Also shown are HMMs with alternative plasmonic materials for NIR. Dielectric and plasmonic layer thicknesses are equal for those.*

Conclusion and Outlook

We fabricated and characterized a layered gold-silicon HMM with transition to hyperbolic regime in NIR. Despite a competitive figure-of-merit one of our findings is the extremely increased collision frequency of thin layer gold [5]. This effect is very strong and cannot be neglected for HMMs containing metals.
Further studies should concentrate on systems which are thermally stable even at very high temperatures. As shown metals are a reasonable choice but other plasmonic materials [4] should also be investigated.

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