NIR multilayer hyperbolic metamaterial

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Abstract

Hyperbolic metamaterials based on a 1D multilayer system with metal-dielectric combination are typically considered at the visible spectrum. The transition to the hyperbolic region at NIR is difficult to obtain due to a large negative dielectric constant of metals at these wavelengths. A possibility of compensating the large negative epsilon of metal with large positive epsilon of silicon at NIR is investigated. It is shown that a combination of silicon and gold in multilayers with a thickness ratio of 9 to 1 can shift the transition to the hyperbolic region to approximately 1.5µm. Transmission and reflection measurements at such medium confirm the hyperbolic transition at NIR.

Hyperbolic or indefinite media with anisotropic permittivity of different signs are interesting due to their large density of states [1], [2] and subwavelength imaging properties [3], [4]. Usually, a layered system consists of metal layers combined with oxides or polymers in proportion close to a 1/1 ratio. Following the effective medium equations [5] such materials usually are described as uniaxial anisotropic media. Polarisation parallel to the axis (orthogonal to the layers) typically probes a positive epsilon $\varepsilon_{\parallel}$, polarisation orthogonal to the axis (parallel to the layers) probes a negative epsilon $\varepsilon_{\perp}$. Then the equation for effective parameters looks as following [5]:

$$\varepsilon_{\perp} = \frac{a\varepsilon_a + b\varepsilon_b}{a+b} \qquad \frac{1}{\varepsilon_{\parallel}} = \frac{1}{a+b}\left(\frac{a}{\varepsilon_a} + \frac{b}{\varepsilon_b}\right). \tag{1}$$

Where ε_a and ε_b are the permittivities of the constituting materials and a and b are the thicknesses of corresponding layers. If ε_a belongs to the metallic layer, then at some wavelength this permittivity assumes large negative values and makes the effective parameter also negative. Thus with approximately equal layer thicknesses and low refractive index of dielectric material the transition to hyperbolic region is obtained already for visible light [6], [7]. Such metamaterials will have a very large negative real and positive imaginary permittivity at 1.5µm what will limit the density of states and imaging properties at this wavelength. To shift the transition to negative permittivity to 1.5µm a high index dielectric material should be used in the multilayer with large thickness ratio of dielectric to metal. We present in this paper simulations and experiment of a Si-Au metamaterial with a thickness ratio of 9 to 1.

The effective medium approach presented in equation (1) is used to calculate the expected effective permittivities. Silicon refractive index was assumed to be 3.5 neglecting dispersion and absorption. Thus the model is applicable only below the silicon band gap. For the dispersion of gold the Drude model was fitted to the experimental results of Ref. [8] at NIR (0.7-2µm). The obtained parameters are: infinite frequencies equal to 10, a plasma frequency of 2246 THz and a collision frequency of 112 THz. The ratio *a/b* was taken 1/9. As can be seen in Fig. 1a the transition to negative permittivity

ISBN 978-952-67611-2-1

occurs at approximately 1.5µm. Due to the small fraction of metal in the metamaterial the expected loss is still low as can be seen in Fig 1b.

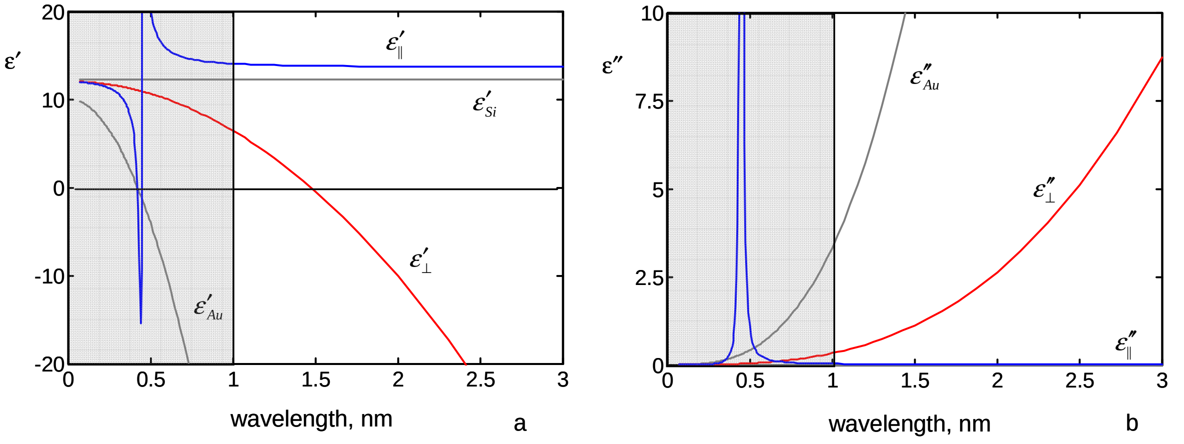

Fig. 1: Real ε' and imaginary ε'' effective permittivity of Au-Si multilayer with 1/9 thickness ratio. The shaded region shows the absorption band of silicon where the model is not applicable as the silicon absorption and dispersion was neglected here.

The transmission through the multilayer structure was also simulated using the transient solver of finite integration software of CST Microwave Studio [9]. As can be seen in Fig. 2a, a Fabry-Perot oscillation should be observed close to the hyperbolic transition wavelength. Significant, but still tolerable absorption is predicted.

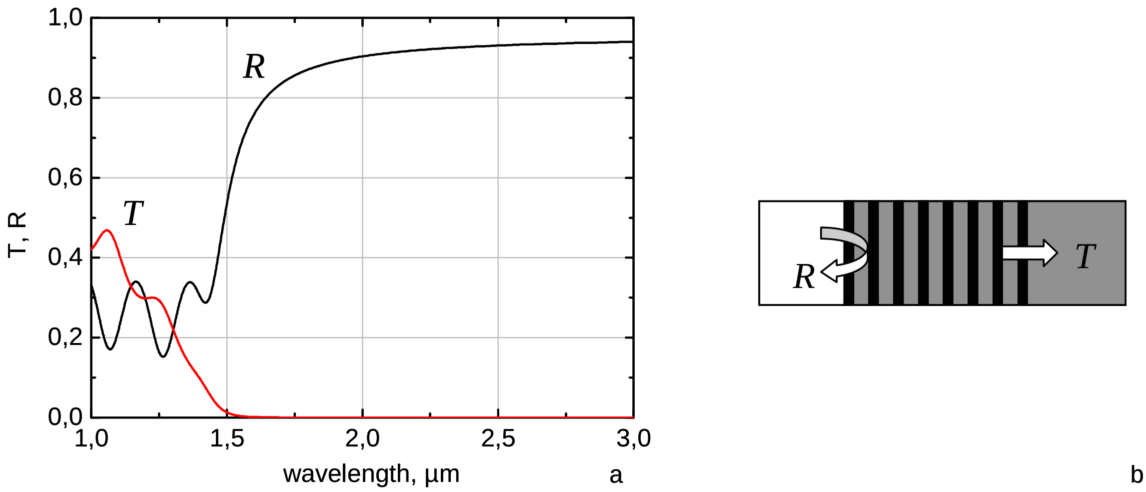

Fig. 2: Simulation of a) transmission and reflection, and b) absorption from metamaterial slab of 12 Au-Si double layers with 5 and 45 nm each and additional 5 nm Au layer on top. Silicon is used as the substrate.

The Au/Si multilayer system was coated on super polished silicon wafer using the magnetron sputtering technique applied for X-ray mirror manufacturing [10]. 12 double layers of 5 nm thick Au and 45 nm Si with an additional top layer of 5 nm Au were deposited. After coating the film thickness and roughness were investigated by means of X-ray reflectometry. The obtained reflectivity curves were fitted with theoretical models. The obtained thicknesses of gold 5.3 nm and silicon 44.3 nm correspond closely to the designed values. A film roughness of approximately 0.5 nm was assumed to fit the theoretical curve.

As expected for the metamaterial at approximately 1.5µm optical reflection from these samples starts to increase above the reflection observed from a polished pure silicon surface which is approximately 0.375 at 1µm and 0.3 at 1.5µm as measured on pure silicon sample. The Fabry-Perot oscillations are not observed, what can be explained by significant absorption, much higher than is theoretically predicted with simulations in Fig. 2 based on the bulk metal absorption. The transmission through the metamaterial is very small but comparable to the values obtained in other experiments on such metamaterials. It is still larger than the transmission through a similar metamaterial for visible light [7]. To obtain similar curves in the simulation the imaginary permittivity of gold at 1.5µm should be increased about 5 times compared to the bulk metal permittivity. The additional loss may be attributed to the roughness and polycrystalline of the gold films.

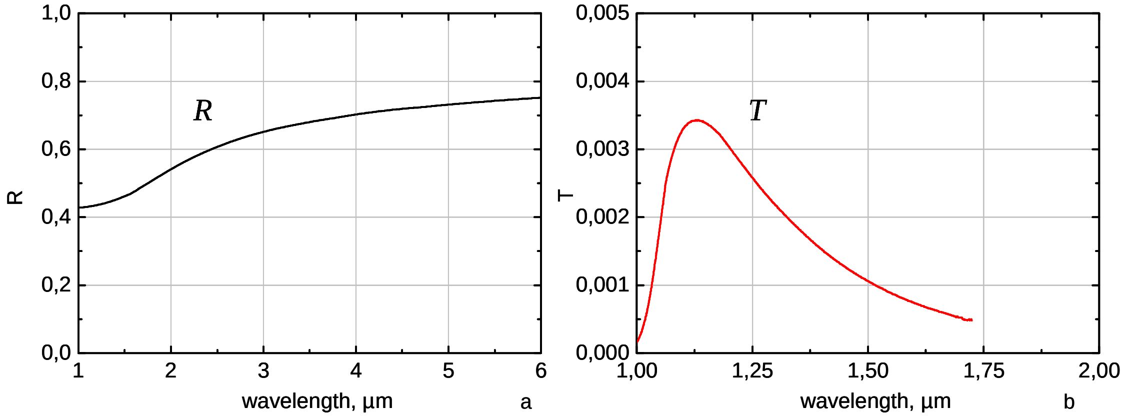

Fig. 3: FTIR measurements on metamaterial sample. a) Reflection at 13% incidence. b) Transmission at normal incidence.

First metamaterial with a hyperbolic transition at 1.5 µm wavelength is demonstrated. Similar to other reported multilayer metamaterials a significant loss is observed, higher that would be predicted from bulk properties of the metal. Thus, an additional loss mechanism should exist within the deposited film. Further investigations will be conducted to identify the origin of the loss and to reduce it.

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