Investigation of the Influence of Optical Pumping on Optical Properties of Bismuth Thin Film

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***Abstract*—Nowadays active research is held in the field of the development of electromagnetic metamaterials (MMs). MMs have much more advantages comparing with the 'ordinary' materials because MMs mostly are composite media consisted of these. Still there are some serious restrictions on design of such a composite media as fabrication and properties of 'ordinary' materials from which they made. In this work bismuth has properties of hyperbolic medium in terahertz and far-infrared, what makes it good addition to existent materials. Moreover, the tunability of optical properties of bismuth at optical pumping opens numerous opportunities for realization in terahertz photonics, sensors, imaging and telecommunication systems.**

***Index Terms*—Optical pumping, terahertz metamaterials**

I. Introduction

HYPERBOLIC media are the most exotic class of electromagnetic metamaterials. They have hyperbolic dispersion which is caused by one of the components of effective permittivity or permeability tensor has opposite sign than other diagonal components. These anisotropic materials have some unique features like amplification of spontaneous emission, negative refractive index and superlens effect [1]–[3].

$$\hat{\varepsilon} = \begin{pmatrix} \varepsilon_\perp & 0 & 0 \\ 0 & \varepsilon_\perp & 0 \\ 0 & 0 & \varepsilon_\parallel \end{pmatrix}, \hat{\mu} = \begin{pmatrix} \mu_\perp & 0 & 0 \\ 0 & \mu_\perp & 0 \\ 0 & 0 & \mu_\parallel \end{pmatrix}, \quad (1)$$

where ∥ and ⊥ indices corresponding to components parallel and perpendicular to the anisotropy axis. In this work the research is focused on electrical hyperbolic structures with $\mu_\perp=\mu_\parallel>0$ and $\varepsilon_\parallel<0$, $\varepsilon_\perp>0$ or $\varepsilon_\parallel>0$ и $\varepsilon_\perp<0$. Their unique properties are derived from isofrequency surfaces of extraordinary waves, which assigned with

$$\frac{k_x^2+k_y^2}{\varepsilon_\parallel} + \frac{k_z^2}{\varepsilon_\perp} = \left(\frac{\omega}{c}\right)^2, \quad (2)$$

where k_x, k_y, k_z – *x*,*y*,*z*-components of wavevector accordingly and *c* is the speed of light. Z is the anisotropy axis of the crystal.

At first hyperbolic properties of the bismuth were theoretically predicted in 2012 [4]. In this work the optical properties of bismuth thin film with mica/polyimide substrate with thickness of bismuth of 40,70, 105, 150, 200 nm were investigated using fourier and terahertz time-domain spectroscopy.

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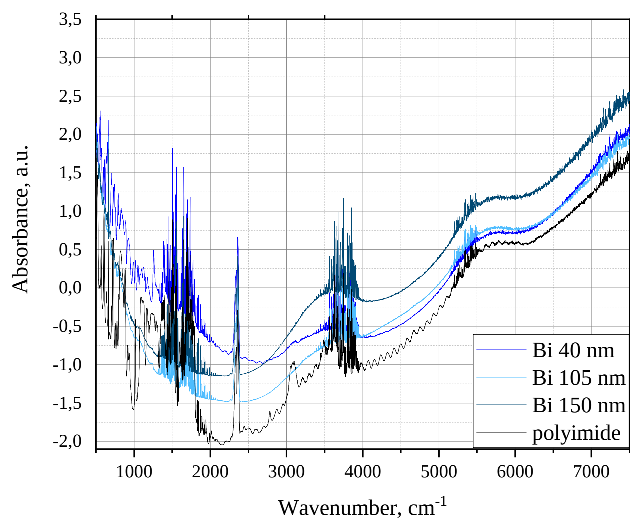
II. Investigation of the Properties of Thin-Film Bismuth by Fourier Spectroscopy

Firstly, spectral characteristics for thin-film bismuth were obtained with different angles of incidence. Transmission and absorbance spectra of samples showed that mica has narrow absorption band of 3640-3650 cm^{-1} and a wide one of 610-880 cm^{-1}; polyimide has narrow absorption band of 3070-3090 cm^{-}
Fig. 1. Absorbance spectra of bismuth thin film samples of different thicknesses on polyimide substrate



III. Investigation of the Properties of Thin-Film Bismuth by Terahertz Time-Domain Spectroscopy

The waveforms of investigated samples obtained by terahertz time-domain spectroscopy method shows negative delay of the sample signal from the reference signal. Samples with small thicknesses (40-120 nm) have weak tunability of perpendicular component of the effective permittivity tensor when exposed to 980 nm pumping. With the optical pumping the properties of ENZ-material for the sample of 70 nm thickness are exposed in 0,47-0,53 THz range which also means transition from elliptic to hyperbolic medium.

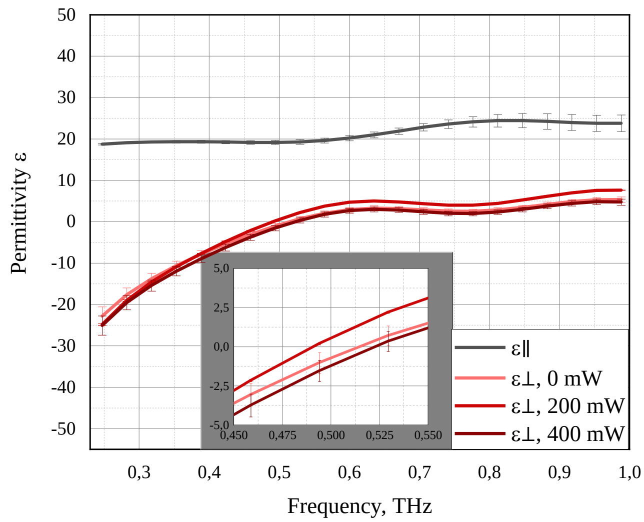


Fig. 2. Dispersion of the components of the real part of effective permittivity tensor for bismuth thin film (70 nm) on the mica substrate exposed to optical pumping of different magnitudes of power

Measurements of samples with bigger thicknesses (150-200 nm) show that tunability effect becomes sufficiently stronger.

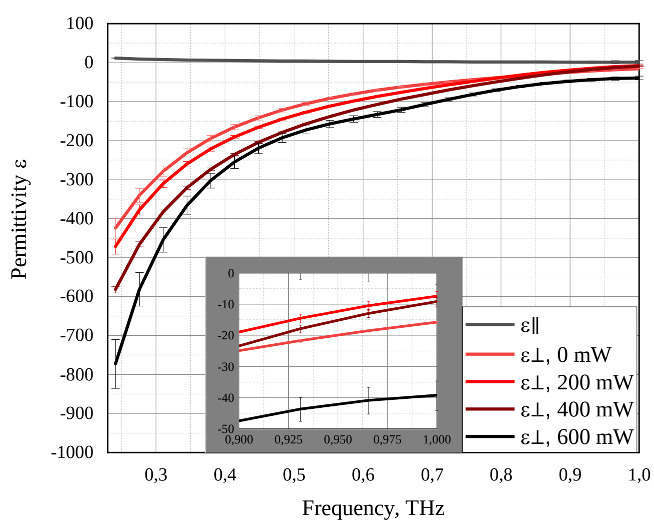


Fig. 3. Dispersion of the components of the real part of effective permittivity tensor for bismuth thin film (150 nm) on the mica substrate exposed to optical pumping of different magnitudes of power

IV. Conclusions

Results of Fourier spectroscopy showed that heat oscillations of bismuth's crystal grid are very strong and 'extinguish' absorbance bands in IR. The waveforms of investigated samples obtained by terahertz time-domain spectroscopy method show negative delay of the sample signal from the reference signal. With the optical pumping the properties of ENZ-material for the sample of 70 nm thickness are exposed in 0,47-0,53 THz range which also means transition from elliptic to hyperbolic medium.

V. Future Plans

With such a extraordinary material as bismuth it is possible to design broadband phase compensator for terahertz frequency range. I plan to continue work on that during my PhD studies after my master's thesis.

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