QTuI2.pdf

Nonlocality in Multilayered Metal-Dielectric Optical Metamaterials

Alexey A. Orlov[1], **Pavel M. Voroshilov**[1], **Pavel A. Belov**[1,2], **Yuri S. Kivshar**[1,3]

[1]*St. Petersburg State University of Information Technologies, Mechanics and Optics, Kronverksky pr. 49, 197101, St. Petersburg, Russia;*
[2]*Queen Mary University of London, Mile End Road, London, E1 4NS, UK*
[3]*Nonlinear Physics Centre, The Australian National University, Canberra ACT 0200, Australia*
alexey.orlov@phoi.ifmo.ru

Abstract: We have accomplished rigorous dispersion analysis and showed clearly impact of nonlocality on properties of multilayered metal-dielectric metamaterial. The main discovered effect is an appearance of additional extraordinary waves in the metamaterial which leads to the splitting of the TM-polarized beam at the air-MDN interface.

OCIS codes: 160.3918, 260.1440, 260.2065, 260.2030, 310.4165, 310.6628, 350.4238.

Optical metamaterials formed by periodic layered metal-dielectric nanostructures (MDNs) provide great possibilities for near-field manipulations. This property is employed in numerous applications including subwavelength imaging [1–3], nanolithography [4], optical nanocircuitry [5], and even invisibility cloaks [6].

The effective medium model (EMM) is a conventional approach to description of MDNs. EMM describes the metamaterial under consideration as an uniaxial anisotropic medium with permittivity tensor of the form:

$$\varepsilon_{\text{eff}} = \begin{pmatrix} \varepsilon_\perp & 0 & 0 \\ 0 & \varepsilon_\parallel & 0 \\ 0 & 0 & \varepsilon_\parallel \end{pmatrix}, \quad \begin{aligned} \varepsilon_\parallel &= \frac{\varepsilon_1 d_1 + \varepsilon_2 d_2}{d_1 + d_2}, \\ \varepsilon_\perp &= \left(\frac{\varepsilon_1^{-1} d_1 + \varepsilon_2^{-1} d_2}{d_1 + d_2} \right)^{-1}, \end{aligned} \tag{1}$$

where $\varepsilon_1, \varepsilon_2$ and d_1, d_2 are dielectric permittivities and thicknesses of the layers, respectively.

The principal elements of the permittivity tensor can have nearly arbitrary values. For example, if $\varepsilon_\parallel$ and $\varepsilon_\perp$ have different signs then the MDN is a typical realization of indefinite medium [7]. Such medium features negative refraction effect since its isofrequency contours have hyperbolic form.

In this work we considered three MDNs formed by layers of metal and dielectric with various thickness ratios (3:2, 1:1, and 2:3), but fixed total period. Configurations and parameters of the structures are illustrated schematically in the insets of Fig. 1. The dispersion diagrams $\omega(k_y)$ for the three MDNs under consideration shown in Fig. 1 were

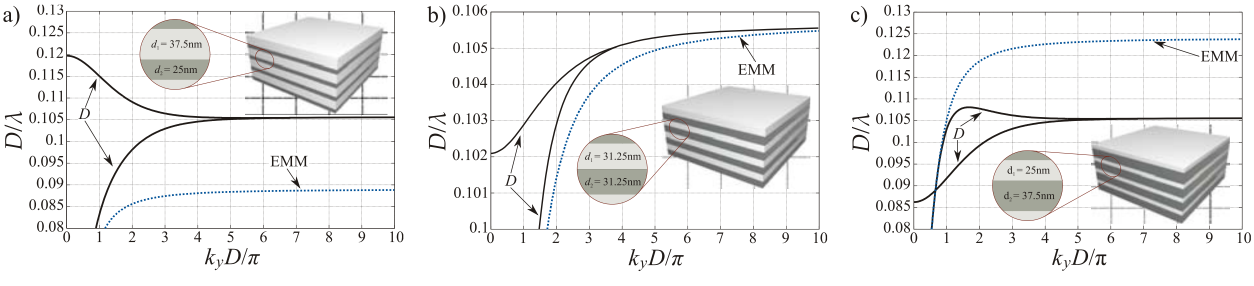

Fig. 1. The dispersion diagrams and geometry of the MDNs composed of alternating HfO_2 and Ag layers. The permittivity of HfO_2 is assumed to be equal to $\varepsilon_1 = 4.6$. The permittivity of silver is given by Drude model: $\varepsilon_2 = 1 - \omega_p^2/\omega^2 = 1 - \lambda^2/\lambda_p^2$, where $\lambda_p = 2\pi c/\omega_p$=250 nm. The ratio of layers thicknesses is varied as follows: a) $d_1 = 1.5 d_2$, b) $d_1 = d_2$, and c) $d_2 = 1.5 d_1$.

computed using two approaches: the effective medium model (approximate approach) and the well-known classical dispersion relation for 1D photonic crystals (exact description).

Different ratios of layers thicknesses were chosen in order to demonstrate different behaviors of dispersion curves. In all cases the dispersion curves consists of two branches with joint surface plasmon polariton (SPP) resonance as asymptote if $k_y \to \infty$ for actual MDN and of one branch with $\varepsilon_\perp = \infty$ resonance for effective medium model. The presence of two branches of dispersion curve (in contrary to just one brunch predicted by effective medium model) is a consequence of strong spatial dispersion in the structure.

In the first case (Fig. 1.a), the SPP resonance appears above the frequency where epsilon very large behavior is expected and the dispersion diagram features forward and backward wave branches with different frequency bands. In the second case (Fig. 1.b), the frequencies are chosen to be equal and both branches correspond to forward waves, but the waves exist at the same frequency band in contrary to the previous case. In the third case (Fig. 1.c), the branches cross each other at certain point and one of the branches has a maximum leading to existence of backward and forward waves simultaneously at the same range of frequencies. The effective medium model in all cases predicts only one forward propagating wave at all frequencies. The presence of two propagating waves is a consequence of nonlocality and strong spatial dispersion which are caused by SPPs at the interfaces of the layers.

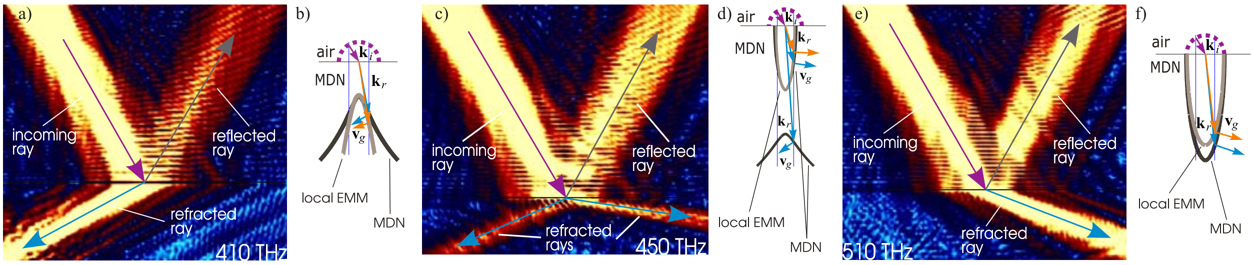

Fig. 2. Results of ray refraction simulations with corresponding refraction diagrams based on isofrequency contours both for local effective medium model and actual MDN.

Next, we have performed numerical experiments of ray refraction at the air-MDN interface at different frequencies (see Fig. 2). At 410 THz only one negatively refracted ray is observed (see Fig. 2.a,b) and effective medium model is applicable in such a situation. Appearance of an ellipse at the isofrequency contour at 450 THz shown in Fig. 2.d as compared to Fig. 2.b leads to birefringence phenomena in the MDN. The negatively refracted ray is still there while in addition to it a positively refracted ray corresponding to the ellipse appears. In this case the local effective medium model is not able to predict the presence of the two rays and describes only one of them. At the higher frequency (510 THz) only one positively refracted ray is observed and this fact is well described by effective medium model.

In conclusion, we compared dispersion characteristics of actual periodic structure with ones predicted by effective medium model and revealed significant differences between them. In particular, two dispersion branches of extraordinary waves are observed instead of one predicted by effective medium model. Our numerical simulations revealed the splitting of the TM-polarized wave at the interface between air and metal-dielectric-nanostructure into two refracted waves inside of the structure instead of one extraordinary wave predicted by effective medium model. All obtained results demonstrate presence of strong spatial dispersion in the structure and provide a proof that the metal-dielectric nanostructure is actually a nonlocal material. These conclusions are in a good agreement with results of precedent works where the guiding modes of metal-dielectric multilayered structures [8] and the surface waves at interfaces of metal-dielectric nanostructures [9] were investigated.

References

1. S. A. Ramakrishna and J. B. Pendry, Phys. Rev. B **67**, 201101 (2003).
2. P. Belov and Y. Hao, Phys. Rev. B **73**, 113110 (2006).
3. Z. Liu, H. Lee, Y. Xiong, C. Sun, and X. Zhang, Science **315**, 1686 (2007).
4. Xiong, Y., Liu, Z., and Zhang, X., Appl. Phys. Lett. **93**, 111116 (2008).
5. N. Engheta, Science **317**, 16981702 (2007).
6. W. Cai, U. K. Chettiar, A. V. Kildishev, and V. M. Shalaev, Opt. Express **16**, 5444 (2008).
7. D. Smith and D. Schurig, Phys. Rev. Lett. **90**, 077405 (2003).
8. J. Elser, V. A. Podolksiy, I. Salakhutdinov, and I. Avrutsky, Appl. Phys. Lett. **90**, 191109 (2007).
9. S. M. Vukovic, I. V. Shadrivov, and Y. S. Kivshar, Appl. Phys. Lett. **95**, 041902 (2009).