Super–light metainterfaced plasmon–polaritons

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Abstract: The present work brings a simple design of and revealing the superluminal properties of plasmon–polaritons at the interface of hyperbolic metamaterial Ag/TiO_2 and external dielectric medium SiO_2. Effective medium theory (EMT) services as a framework of the simulation carried out and provides an insight into spectral dynamics of plasmon–polariton's velocities in the tested energy range of 0.5 ÷ 8 eV. The simulation predicts that the group velocity of the quasi–particles considered can exceed velocity of light in vacuum up to 2.8 times and change own sign from positive to negative depending on metamaterial parameters. At this the phase velocity of the plasmon–polaritons traveling along the interface exceeds the value of light velocity in vacuum up to 4 times. Subluminal features of the model assist to the superluminal ones as well and incorporate an unique property observed as light stop. Transmission lines, digital electromagnetic devices, memory and transformation units may utilize the findings revealed.

Key–Words: plasmon–polariton, hyperbolic metamaterial, effective medium theory, dielectric permittivity tensor, group velocity, phase velocity.

1 Introduction

The first analytical description of as well as prediction looking as discussion regarding the finding of unusual materials possessing a negative refraction index within the transparency range of electromagnetic scale results from paper by Veselago [1]. In years, now one knows the trick is that the Earth does not born the materials envisaged by itself. Instead one can construct such materials by the use of different appropriate components. Therefore one calls the constructions fabricated to interact unusually with electromagnetic waves as artificial materials, electromagnetic materials, or metamaterials of different types or classes.

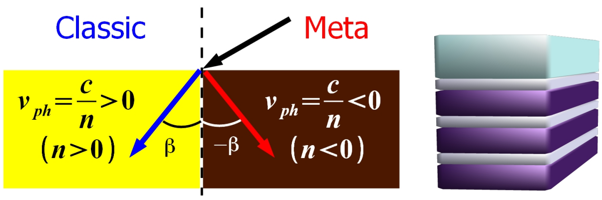

Fig. 1 Electromagnetically transparent boxes: comparison of classic box vs metabox

Fig. 1 shows difference between transparent classic material (yellow box on the left) and metamaterial (brown box at the centre). Light beam propagates normally with positive refractive angle in the case of classic box (right hand material) and undergoes propagation in opposite side relatively to incident direction in the case of metabox (left hand material). Fig. 1 shows schematically metabox as black box and provides its decryption in the form of sandwich covered with an external dielectric on the right. The proper metamaterial consists periodic layers of TiO_2 and metallic Ag. Such simple covered metabox is the material object of the present investigation.

Artificially fabricated electromagnetic materials, like the shown on Fig. 1, form a new basis for scientific investigations and practical applications [1]. Sea of such possible materials includes so–called hyperbolic metamaterials (HM) [2]. Their name results from mathematical form of hyperbolic dispersion law they posses contrary to elliptic law observed in ordinary (right hand) dielectrics.

An internal interface envisaged and locked between the metabox and the covered external dielectric localizes exotic collective electromagnetic states which can walk through the interface. When density of free carriers of charge is enough high the so–called plasmon–polaritons appear as a response on an input electromagnetic perturbation. In general, plasmon–polariton is a conglomerate of electrons excited by electromagnetic wave. An “ocean” of free electrons belongs to the metal and interacts with electromagnetic field that can exist within the dielectric layer. As a result, an exotic oscillations of electronic gas appears at the interface between the dielectric and metabox. These oscillations keep both light and carriers of charge and provides the subject of the current work.

Velocity of propagation through and/or along an interface is the main working characteristic of any wave–particle including the electromagnetic excitations envisaged. A key feasibility of such propagation is the possibility to posses different velocities. In general, the velocities are different for both signal phase and signal energy. The recent study showed that both phase and group velocities of the wave that passes through the metamaterial can posses both negative and positive sign [3]. Besides, the interface excitations can exhibit superluminal behaviour. However quantitative map of the phenomenon waits to be revealed and is the aim of the present study. Obviously, the features mentioned are of fresh practical interest for the design of different electromagnetic devices, including antennas, digital transmission lines, etc.

2 Effective medium approach

Metabox and an external dielectric SiO_2 construct metasandwich. Metabox consists alternative layers of metal Ag and rutile TiO_2. Metal is guest, and rutile is host. Dielectric constants are different for both metal (ϵ_g) and dielectric (ϵ_h). To avoid difficulties owing to nonuniform distribution of dielectric function one uses Maxwell–Garnett model of a composite medium [3, 4].

In line with the Maxwell–Garnett approach nonuniform sandwich transforms virtually into the uniform metabox (hyperbolic metamaterial) with an effective dielectric function ϵ . The use of the Lorentz field results in the next relationship between the introduced dielectric functions:

$$\frac{\epsilon-\epsilon_h}{\epsilon+2\epsilon_h}=\delta\frac{\epsilon_g-\epsilon_h}{\epsilon_g+2\epsilon_h}\quad ,(1)$$

where δ is the fraction of a guest mediun relatively a host one. For the metamaterial in the form of sandwich, an effective dielectric function is a tensor of the second order. The taking into account the tensor symmetry the matrix of its components transforms into the next representation:

$$\begin{pmatrix}\epsilon_{11} & \epsilon_{12} & \epsilon_{13}\\ \epsilon_{21} & \epsilon_{22} & \epsilon_{23}\\ \epsilon_{31} & \epsilon_{32} & \epsilon_{33}\end{pmatrix}\to\begin{pmatrix}\epsilon_{xx} & 0 & 0\\ 0 & \epsilon_{xx} & 0\\ 0 & 0 & \epsilon_{zz}\end{pmatrix}\quad .(2)$$

The diagonal elements of the matrix keeps relations to the dielectric functions of the guest and the host:

$$\begin{array}{rcl}\epsilon_{xx} & = & \delta\epsilon_g+(1-\delta)\epsilon_h\\ 1/\epsilon_{zz} & = & \delta/\epsilon_g+(1-\delta)/\epsilon_h\end{array}\quad ,(3)$$

where ϵ_{xx} and ϵ_{zz} denote the transverse and longitudinal components [3].

Taking into account the above–mentioned, one gets the tensor component corresponding to the direction of propagation of the envisaged plasmon–polaritons travelling along the x–axis in the form:

$$\epsilon_x=\epsilon_{out}\epsilon_{zz}(\epsilon_{out}-\epsilon_{xx})/(\epsilon_{out}^2-\epsilon_{xx}\epsilon_{zz})\quad (4)$$

where ϵ_{out} is the dielectric permittivity of the external medium, such as SiO_2 according to Fig. 1. This function controls the dispersion law and provides a quantitative map of the velocities sought at taking into account conductivity of guest (metal).

3 Phase and group velocities map

Refractive index of an external medium and δ serviced as variable input parameters. Fig. 2 shows spectral dynamics of the calculated ratios of phase velocities for the plasmon–polaritons guided by the plane of interface covered dielectric—metabox.

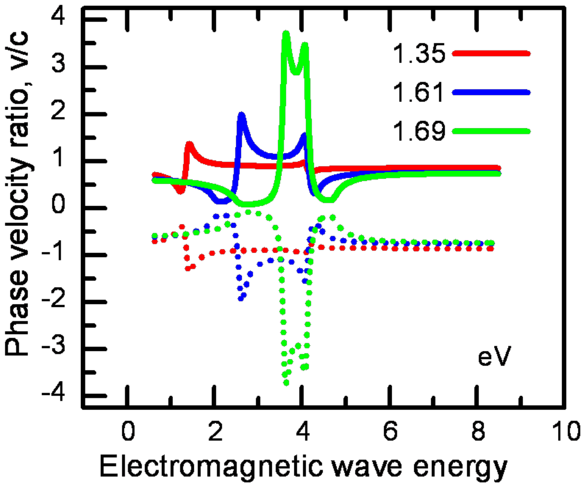

Fig. 2 Phase velocities of plasmon–polaritons excited in the interface plane presented as ratios to the light velocity in vacuum. Solid and dashed curves correspond to positive and negative directions of x–axis.

One can see that superluminal feature, satisfying to condition $v_{ph}/c>1$, can imagine in a wide spectral range. Its specific location depends on both refractive index of an external dielectric and ratio of guest/host layers thicknesses. The higher refractive index, the higher phase velocity. Its maximum absolute value registered exceeds value of light velocity in vacuum up to 4 times. Besides, the higher refractive index, the more blue shift of the peak phase velocity on the electromagnetic scale. One more finding is that the phase velocity scaling increases as well and can exceed one order of magnitude following by the mentioned blue shift.

Simulation also shows that superluminal features coexists with extra subluminal ones. Fig. 2 underlines subluminal capabilities of the plasmon–polaritons alongside with their counterparts. The minimum value of phase velocity registered can be more than 12 times less in comparison with the light velocity in vacuum. This effect looks like trapping and suggests memory design.

To be sure that the observed features have rights to be natural one should mention the relationship between the phase and group velocities. If we suppose that the dispersion laws for the dielectric and magnetic functions are the same then, taking into account data [1, 3] one can write the relationship envisaged in the following form:

$$1/\Re(v_g)+1/\Re(v_{ph})=\zeta\Re(n)/c \quad , (5)$$

where ζ takes value of 2 in the framework of the accepted assumption. In other words, the simplest control prevents overflow of any of two velocities in the point of view both the value and sign.

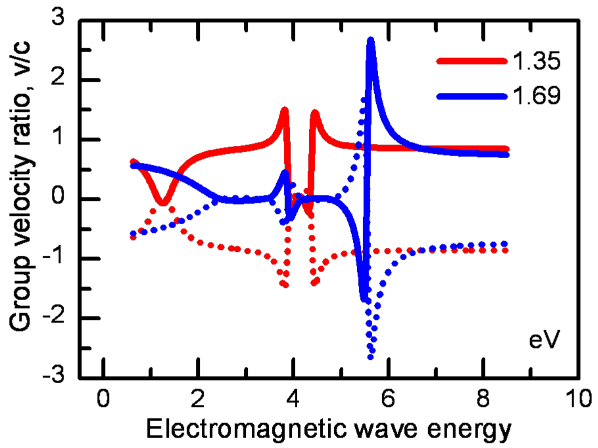

Fig. 3 Ratios of group velocities of the plasmon–polaritons to the light velocity in vacuum. Solid and dashed curves correspond to positive and negative directions of x–axis in the interface plane.

To check real correlation between spectral dynamics of phase and group velocities of the plasmon–polaritons one simulated the last in the same spectral range. Fig. 3 visualizes capabilities of the metamaterial studied in the energy velocity point of view. Correlation between curves of Fig. 2 and Fig. 3 is evident. Group velocity exhibits both super and subluminal properties and can exceed the light velocity more than 2 times: the more refractive index, the more velocities ratio alongside with the blue shift of peaks. The fraction δ also takes effect. Besides, its minimal value controls an applicability of the approach used for the given spectral range

Remarkable difference is that group velocity changes own sign. This feature exhibits the threshold behaviour. For the composite structure investigated, Fig. 3 shows example of a clear sign changing when index refraction reaches value of 1.69. The negative value of the group velocity does not correspond to the backward propagation of the coupled wave along negative direction of x–axis. Its negative value can correspond to the coupled wave pulse reshaping.

4 Conclusion

Simulation worked out in the framework of the effective medium theory shows that a simple design of a composite metal–dielectric structure turns up bidirectional plasmon–polaritons supposing the validity of the simulation. Both superluminal and subluminal features can come to light in a wide both spectral range and absolute values. Unusual spectral dynamics of the metainterfaced plasmon–polaritons' velocities forecasts light stop as well being used for novel electromagnetic devices.

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