PROCEEDINGS OF THE YEREVAN STATE UNIVERSITY

Physical and Mathematical Sciences 2012, № 3, p. 56–59

Physics

PECULIARITIES OF SURFACE LOCALIZED PLASMONS IN THE METAMATERIALS

A. Yu. VARDANYAN*

Chair of Ultra High Frequencies Radiophysics and Telecommunications YSU, Armenia

The possibility of localized surface plasmons formation in spherical structure based on metamaterials, with both the positive and negative dielectric constants, are considered. In contrast to ordinary localized surface plasmons, where the field decreases according to the power law with increasing distance from metallic nanoparticles, in case of strongly localized surface plasmons the field decreases according to the exponential law. Owing to that good preconditions are created for formation of structures with controllable parameters, where the wave energy is concentrated within nanometric ranges as is the case in atoms.

Keywords: localized plasmon, metamaterials, field enhancement.

Introduction. The localized surface plasmons (LSP) are non-propagating excitations of conduction electrons in electromagnetic field coupled metallic nanostructures. These modes are seen to naturally occur due to the scattering of a small sub-wavelength conductive nanoparticle in an oscillating electromagnetic field. Due to the roughness of particle surface an effective restoring force is exerted on driven electrons giving rise to a resonance that amplifies the field both inside and in the near-field zone outside the particle. This resonance is called a localized surface plasmon or a localized surface plasmon resonance. Another consequence of surface roughness is that in contrast to the propagating surface plasmon polaritons the plasmon resonances may be excited under direct illumination. For gold and silver nanoparticles the resonance gets into the visible part of electromagnetic radiation spectrum, in consequence of which are bright colors exhibited by particles both in the transmitted and reflected light due to the resonantly enhanced absorption and scattering. This effect that was known during many centuries and used in many applications, e.g., for staining of glass in leaded panels and ornamental cups. Strong local fields generated by LSP at the interface between media could be tuned up spatially and spectrally by controlling the morphology and composition of metal nanostructure. In their turn, the extended local fields may be used for notable increase of molecular optical cross-section (as in the surface-enhanced Raman scattering), determination of the response of LSP to changes in the index of interface refraction (as a basis of LSP biosensors) and propagation and channeling of information in novel nanophotonic devices. A good understanding of

* E-mail: vardanyan.artashes@gmail.com

processes with elementary plasmon resonances have been achieved due to the application of advanced analytical methods used for electrodynamical simulation. However, many of the most promising applications in this field are based on complicated coherent interactions between elementary plasmons or between plasmons and other kinds of excitations. Metallic metamaterials give an example of this case, in which the hybridization between plasmons can induce a magnetic response, as a result of which the refractive index may turn negative [1–8].

However, with a distance from the nanoparticle the fields of localized plasmons decrease relatively slow. In case of metal sphere we have for the electric field $E \sim r^{-3}$, where r the is distance from the center of the sphere. It is possible to achieve high concentrations of the fields under conditions of exponential decrease of field as in the case when using metamaterials.

In the past few years new developments in structured electromagnetic materials gave rise to negative refractive index materials, which have both negative dielectric permittivity and negative magnetic permeability in definite frequency ranges. The idea of a negative refractive index opens up new conceptual frontiers in photonics. One much-debated example is the concept of perfect lens that enables the imaging with sub-wavelength image resolution. The metamaterials constructed from artificial metallic nanostructures exhibit such unusual electromagnetic properties as the extraordinary transmission of light through subwavelength hole arrays [9, 10], negative refraction [11, 12], local field enhancement [13, 14] and sub-wavelength concentration of light beyond the near-field [15, 16].

Results and Discussions.

A possibility of localized plasmons formation in a spherical structure based on metamaterials is considered. It is supposed that the sphere of R radius with negative dielectric permittivity $(\varepsilon_1 < 0)$ and positive magnetic permeability $(\mu_1 > 0)$ is in an environment having positive dielectric permittivity $(\varepsilon_1 > 0)$ and negative magnetic permeability $(\mu_1 < 0)$ (Fig. 1).

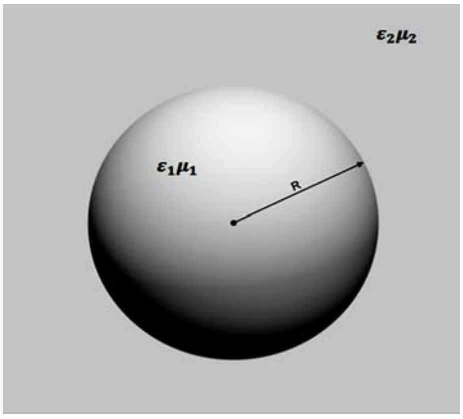

Fig. 1. The sphere with radius R and with dielectric and magnetic constants $\varepsilon_1 < 0$ and $\mu_1 > 0$ in the material with $\varepsilon_1 > 0$ and $\mu_1 < 0$.

First, in case of $r < R$, $\varepsilon_1 < 0$ and $\mu_1 > 0$ we have from the wave equations the following expressions for $\vec{E}$ and $\vec{H}$ field components:

$$E_r = \frac{2A}{r^2}\left(\operatorname{ch} k_1 r - \frac{\operatorname{sh} k_1 r}{k_1 r}\right)\frac{(-i)}{\sqrt{|\varepsilon_1|}}\cos\theta e^{i\omega t}, \quad (1)$$

$$E_\theta = \frac{Ak_1}{r}\left(\operatorname{sh} k_1 r - \frac{\operatorname{ch} k_1 r}{k_1 r} + \frac{\operatorname{sh} k_1 r}{(k_1 r)^2}\right)(-\sin\theta)\frac{(-i)}{\sqrt{|\varepsilon_1|}}e^{i\omega t}, \quad (2)$$

$$H_\varphi = \frac{Ak_1}{r}\left(\operatorname{ch} k_1 r - \frac{\operatorname{sh} k_1 r}{k_1 r}\right)(-\sin\theta)\frac{(-i)}{\sqrt{\mu_1}}e^{i\omega t}, \quad (3)$$

$$H_\theta = E_\varphi = H_r = 0, \tag{4}$$

where A is constant and $k_1 = \dfrac{\omega}{c}\sqrt{|\varepsilon_1|\mu_1}$.

Second, in the case for $r > R$, $\varepsilon_2 > 0$ and $\mu_2 < 0$ we have the following expressions for $\vec{E}$ and $\vec{H}$ fields components:

$$E_r = \frac{2B}{r^2}\left(1 + \frac{1}{k_2 r}\right)e^{-k_2 r}\cos\theta \frac{1}{\sqrt{\varepsilon_2}}e^{i\omega t}\,, \tag{5}$$

$$E_\theta = \frac{Bk_2}{r}\left(1 + \frac{1}{k_2 r} + \frac{1}{(k_2 r)^2}\right)e^{-k_2 r}\sin\theta \frac{1}{\sqrt{\varepsilon_2}}e^{i\omega t}\,, \tag{6}$$

$$H_\varphi = \frac{Bk_2}{r}\left(1 + \frac{1}{k_2 r}\right)e^{-k_2 r}(-\sin\theta)\frac{(-i)}{\sqrt{|\mu_2|}}e^{i\omega t}\,, \tag{7}$$

$$E_\varphi = H_r = H_\theta = 0\,, \tag{8}$$

where B is constant and $k_2 = \dfrac{\omega}{c}\sqrt{\varepsilon_2|\mu_2|}$. A and B constants are determined from the boundary conditions. On the surface of sphere for $r = R$ we have

$$\begin{cases}(E_\theta)_1 = (E_\theta)_2, \\ (H_\varphi)_1 = (H_\varphi)_2.\end{cases} \tag{9}$$

Thus, we get following expression

$$\frac{(k_1 r)^2 \operatorname{sh} k_1 r - k_1 r \operatorname{ch} k_1 r + \operatorname{sh} k_1 r}{k_1 r \operatorname{ch} k_1 r - \operatorname{sh} k_1 r} = \frac{k_1}{k_2}\cdot\frac{(k_2 r)^2 + k_2 r + 1}{k_2 r + 1}\sqrt{\frac{|\varepsilon_1||\mu_2|}{\varepsilon_2\mu_1}}\,. \tag{10}$$

Within the framework of the quasistatic approximation for $k_1 r \ll 1$ and $k_2 r \ll 1$ the dispersion Eq. (10) is significantly simplifying $\sqrt{\dfrac{|\varepsilon_1||\mu_2|}{\varepsilon_2\mu_1}} = 2$.

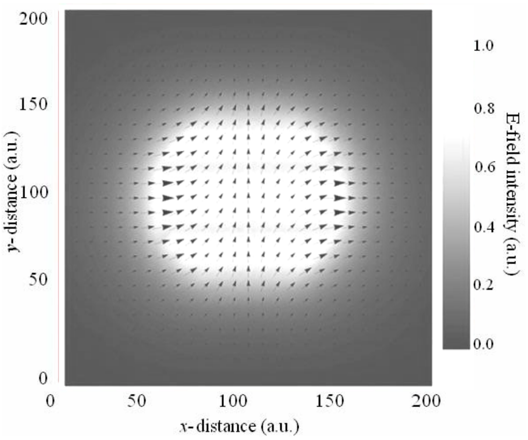

Fig. 2. The electrical field distribution inside and outside of the sphere.

In the Fig. 2 the characteristic distribution of the electric field of the LSP in the structure is shown schematically.

Conclusion. Thus, in metamaterials, where the dielectric constants can be both positive and negative, a basically novel type of LSP can be formed. In contrast to ordinary LSP, where a power-law decrease of the field occurs as the distance from metallic nanoparticle is increased, here we deal strongly localized plasmons, where the field deacreases exponentially as the distance from metallic nanoparticle increases. This feature creates good preconditions for formation of structures with controllable parameters, where the wave energy is concentrated in nanoscale ranges like the concentration of energy in atoms.

Received 11.06.2012

REFERENCES

1. **Valentine J., Zhang S., Zentgraf T., Ulin-Avila E., Genov D.A., Bartal G., Zhang X.** Three-Dimensional Optical Metamaterial with a Negative Refractive Index. // Nature, 2008, v. 455, p. 376–379.
2. **Cai W.S., Chettiar U.K., Kildishev A.V., Shalaev V.M.** Optical Cloaking with Metamaterials. // Nat. Photonics, 2007, v. 1, p. 224–227.
3. **Maier S.A., Kik P.G., Atwater H.A., Meltzer S., Harel E., Koel B.E., Requicha A.A.G.** Local Detection of Electromagnetic Energy Transport below the Difraction Limit in Metal Nanoparticle Plasmon Waveguides. // Nat. Mater., 2003, v. 2, p. 229–232.
4. **Lal S., Link S., Halas N.J.** Nanooptics from Sensing to Waveguiding. // Nat. Photonics, 2007, v. 1, p. 641–648.
5. **Larsson E.M., Alegret J., Käll M., Sutherland D.S.** Sensing Characteristics of NIR Localized Surface Plasmon Resonances in Gold Nanorings for Application as Ultrasensitive Biosensors. // Nano Lett., 2007, v. 7, p. 1256–1263.
6. **Soukoulis C.M., Linden S., Wegner M.** Negative Refractive Index at Optical Wavelengths. // Science, 2007, v. 315, p. 47–49.
7. **Pakizeh T., Abrishamian M.S., Granpayeh N., Dmitriev A., Käll M.** Magnetic Field Enhancement in Gold Nanosandwiches. // Opt. Express, 2006, v. 14, p. 8240–8246.
8. **Pakizeh T., Dmitriev A., Abrishamian M.S., Granpayeh N., Käll M**. Structural Asymmetry and Induced Optical Magnetism in Plasmonic Nanosandwiches. // J. Opt. Soc. Am. B, 2008, v. 25, p. 659–667.
9. **Ebbesen T.W., Lezec H.J., Ghaemi H.F., Thio T. and Wolff P.A.** Extraordinary Optical Transmission Through Sub-Wavelength Hole Arrays. // Nature, 1998, v. 391, p. 667–669.
10. **Papasimakis N., Fedotov V.A., Schwanecke A.S., Zheludev N.I. and Garcia de Abajo F.J.** Enhanced Microwave Transmission Through Quasicrystal Hole Arrays. // Appl. Phys. Lett., 2007, v. 91, p. 081503.
11. **Shalaev V.M., Cai W., Chettiar U.K., Yuan H.-K., Sarychev A.K., Drachev V.P. and Kildishev A.V.** Negative Index of Refraction in Optical Metamaterials. // Opt. Lett., 2005, v. 30, p. 3356–3358 .
12. **Dolling G., Enkrich C., Wegener M., Soukoulis C.M., Linden S.** Observation of Simultaneous Negative Phase and Group Velocity of Light. // Science, 2006, v. 312, p. 892.
13. **Hryciw A.C., Jun Y.C. and Brongersma M.L.** Plasmon-Enhanced Emission from Optically-Doped MOS Light Sources. // Opt. Express, 2009, v. 17, p. 185.
14. **Félidj N., Aubard J., Levi G., Krenn J.R., Hohenau A., Schider G., Leitner A. and Aussenegg F.R.** Optimized Surface-Enhanced Raman Scattering on Gold Nanoparticle Arrays. // Appl. Phys. Lett., 2003, v. 82, p. 3095.
15. **Huang F.M., Zheludev N.I., Chen Y. and Garcia de Abajo F.J.** Focusing of Light by a Nanohole Array. // Appl. Phys. Lett., 2007, v. 90, p. 091119–21.
16. **Huang F. M., Chen Y., Garcia de Abajo F.J. and Zheludev N.I.** Optical Super-Resolution Through Super-Oscillations. // J. Opt. A: Pure Appl. Opt., 2007, v. 9, p. S285.