Strong local field increase in perfect plasmonic absorbers

M. Albooyeh[1] **and C. R. Simovski**[1]

[1]Department of Radio Science and Engineering
Aalto University
P.O. Box 13000, FI-00076, Espoo, Finland
email: mohammad.albooyeh@aalto.fi

Abstract

The possibility of a huge local field enhancement in subwavelength volumes combined with a total power absorption of light within a metasurface/metafilm is studied here. The presence of a magnetic mode simultaneously with an electric mode is a key prerequisite for a planar grid in order to absorb all incident power when there is only one reflecting interface. This regime can be implemented in the optical range with the help of the so-called substrate-induced bianistropy. The local field enhancement results in such a perfect absorber due to the nanoantenna-like effect when the field in the gap between every nanoparticle and the substrate is similar to that in a gap between two elements of some plasmonic nanoantennas.

1. Introduction

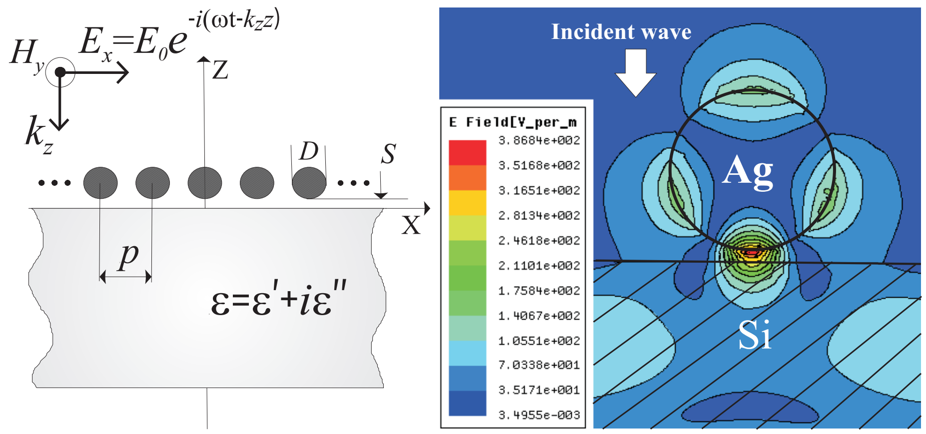
Local field enhancement of light in a strongly subwavelength volume has many important applications in many areas, such as nonlinear optics [1] , light-matter interactions [2], photochemistry [3], optical nanomanipulation [4], biosensing [5], etc. There is also a very important application where the cancelation of the reflected and refracted waves are necessary, as well. In the Surface Enhanced Raman Scattering (SERS) schemes field should be enhanced in a nano-volume. However, fields reflected from the surface and transmitted below it, which possess the source wave frequency are considered to be parasitic. Firstly, the Raman frequency shift is small that makes the detection of Raman signals very difficult on the background of of these parasitic signals. Secondly, parasitic signals may cause Raman scattering from undesirable regions located above or below the surface where the objects under study are located. Therefore, a SERS scheme is needed which would minimize both reflected and transmitted waves in combination with the huge local field enhancement. This novel structure comprises a planar grid of plasmonic nanospheres located over a semiconductor interface with a very small distance from the spheres to the semiconductor surface. We have used the concept of metasurfaces (e.g. [6, 7]) in order to homogenize these grids and explain the local field enhancement involving the known data about plasmonic nanoantennas.

2. Local field enhancement together with maximal power absorption

Let us consider a square array of plasmonic nano-spheres of diameter D located with the period p over a semiconductor substrate at a distance s from it, see Fig. 1(a). The grid is assumed to be optically dense ($p,\ D \ll \lambda$). The whole structure can be replaced by an infinitesimally thin sheet (metafilm) referred to the interface. The plane wave is impinging normally to the array plane.

In this structure, the electric field of the incident wave within the range of the plasmon resonance induces the plasmon oscillations in Ag nanoparticles so that the field experiences the huge enhancement within

ISBN 978-952-67611-2-1



(a) (b)

Fig. 1: (a) – Horizontally isotropic grid of plasmonic particles located over a semiconductor substrate. (b) – Color map of the local field at the wavelength of maximal absorption.

the hot spot. The plasmonic hot spot is shifted to the gap s due to two factors: the curvature of the nanoparticle and the presence of the Si substrate [7]. The local field weakly decreases across the gap s and the significant part of this hot spot is located inside the substrate. Since the local polarizations of Si and Ag are distanced, and the effective dipoles excited in Si and Ag are not in phase (at the frequency f_P of the collective plasmon resonance they have opposite phases) the structure is equivalent to a pair of electric and magnetic dipoles which can be both referred to the interface. The color map of the field amplitude (see Fig. 1(b)) at the plasma frequency (λ_P=361.9 nm) illustrates this statement. The local field enhancement is accompanied by a maximal power absorption $A \equiv 1 - |R|^2 - |T|^2$ that implies minimal reflectance and transmittance. Fig. 2 demonstrates that the maximal absorption occurs at the same frequency where local field is maximally enhanced at the center of the gap.

Let us prove that the effect of total power absorption is possible if one creates both electric and magnetic modes together. This is presented in our illustrative example. The generation of the magnetic mode becomes possible due to the presence of the substrate. The magnetic mode is induced by the incident electric field. This effect is called substrate-induced bianisotropy [7]. Using the theory of [7] one can relate both reflected and transmitted fields with tangential electric and electro-magnetic susceptibilities α_{xx}^{ee} and α_{xy}^{em} introduced as follows:

$$\mathcal{P}_x = \alpha_{xx}^{ee} < E_x > + \alpha_{xy}^{em} < H_y >, \quad \mathcal{M}_y = -\alpha_{xy}^{em} < E_x > . \tag{1}$$

Here $< E >$ and $< H >$ are defined as averaged values of electric and magnetic fields taken on two sides of the effective sheet, $\mathcal{P}_x$ and $\mathcal{M}_y$ are electric and magnetic surface polarizations, respectively. Using boundary conditions for such metafilms [7], we obtain reflection and transmission coefficients from (1) as:

$$R = \frac{(1+Y)^2 - n(1-Y)^2 - 2X}{(1+Y)^2 + n(1-Y)^2 + 2X}, \tag{2}$$

$$T = \frac{2(1-Y)(1+Y)}{(1+Y)^2 + n(1-Y)^2 + 2X}. \tag{3}$$

Here n is the complex refractive index of the substrate and $X = -\frac{i}{2}\frac{k_0}{\varepsilon_0}\alpha_{xx}^{ee}$ and $Y = -\frac{i}{2}\frac{k_0}{\sqrt{\varepsilon_0\mu_0}}\alpha_{xy}^{em}$. The only possible solution for (2) and (3) leading to the total absorption $A = 1$ is $Y = 1$ and $X = 2$ i.e. in terms of surface susceptibilities:

$$\alpha_{xx}^{ee} = 4i\frac{\varepsilon_0}{k_0}, \quad \alpha_{xy}^{em} = 2i\frac{\sqrt{\varepsilon_0\mu_0}}{k_0}. \tag{4}$$

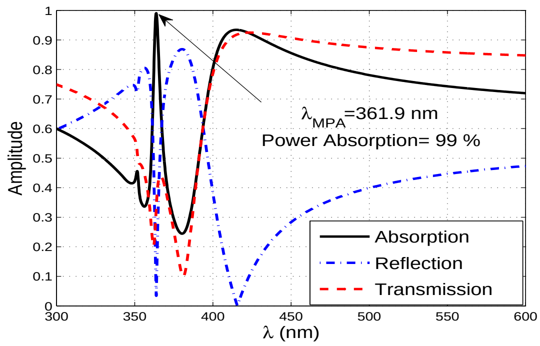


Fig. 2: (Color online) Coefficients of reflection (amplitude), transmission (amplitude), and absorption (power) of the normally incident plane wave in the proposed plasmonic structure.

Imaginary electric susceptibility in (4) is achievable at the resonance and corresponds to the maximum of electric losses. Imaginary magneto-electric susceptibility, on the contrary, corresponds to the absence of magneto-electric losses [8]. Conditions (4) mean that a metafilm with lossy electric susceptibility accompanied by a lossless electro-magnetic susceptibility absorbs all incident power i.e. operates as a perfect plasmonic absorber. This condition is an idealization: one can hardly create a metafilm with lossless electro-magnetic (and magneto-electric) response. In practice, one can, however, very closely approach to the target conditions (4) as we proved with our aforementioned illustrative example.

3. Conclusion

In this paper we demonstrated a huge local field enhancement due the the substrate-induced bianisotropy effect. We showed that this effect leads to generating a electro-magnetic mode in a metasurface. We proved that this magnetic mode in addition to the already present electric mode is a crucial factor in every metasurface in order to absorb all incident power. We achieved practically a 99 percent power absorption together with a local electric field intensity in the order of (2-3).10^3. This enhancement resulted from a localized plasmon resonance which in turn is caused by the effect of the substrate performing as an image surface for nano-particle's array. The combination of these two effects would be promising in SERS and perhaps some other applications.

References

[1] S. Kim, J. Jin, Y. J. Kim, I. Y. Park, Y. Kim and S. W. Kim, High-harmonic generation by resonant plasmon field enhancement, *Nature (London),* vol. 453, p. 757, 2008.
[2] T. H. Taminiau, F. D. Stefani, F. B. Segerink and N. F. Van Hulst, Optical antennas direct single-molecule emission, *Nat. Photon.,* vol. 2, p.234, 2008.
[3] K. Watanabe, D. Menzel, N. Nilius and H. J. Freund , Photochemistry on metal nanoparticles, *Chem. Rev.,* vol. 106, p. 4301, 2006.
[4] D. G. Grier, A revolution in optical manipulation, *Nature (London),* vol. 424, p. 810, 2003.
[5] B. Rothenhausler andW. Knoll, Surface-plasmon microscopy, *Nature (London),* vol. 332, p. 615, 1988.
[6] E.F. Kuester, M.A. Mohamed, M. Piket-May, and C.L. Holloway, Averaged transition conditions for electromagnetic fields at a metafilm, *IEEE Trans. Antennas Propag.,* vol. 51, p. 2641, 2003.
[7] M. Albooyeh, D. Morits, and C. Simovski, Electromagnetic characterization of substrated metasurfaces, *Metamaterials,* vol. 5, p. 178, 2011.
[8] A. Serdyukov, I. Semchenko, S. Tretyakov, and A. Sihvola, *Electromagnetics of Bi-anisotropic Materials: Theory and Applications*, Gordon and Breach Science: Amsterdam, The Netherlands, 2001.