Total light absorption in a wide range of incidence by nanostructured metals without plasmons

Nicolas Bonod* **and Evgeny Popov**

Institut Fresnel, CNRS UMR 6133, Aix-Marseille Université, Domaine Universitaire de Saint Jérôme, 13397 Marseille, France

**Corresponding author: nicolas.bonod@fresnel.fr*

Received July 31, 2008; accepted August 26, 2008;
posted September 16, 2008 (Doc. ID 99662); published October 14, 2008

Metals structured by nanocavities have recently been demonstrated to efficiently absorb light in a wide range of angles of incidence. It has been assumed that nanovoid plasmons are at the origin of the strong absorption. It is shown that it is possible to totally absorb incident light without plasmons. To avoid their excitation, a diffraction grating consisting of cylindrical cavities in a metallic substrate is illuminated in transverse electric polarization. It is found that cylindrical cavities can sustain cavity resonances with a high enhancement of the light intensity, provoking a total absorption of light in a wide range of incidence.

OCIS codes: 050.1950, 240.6680, 260.3910, 050.5745.

Structuring of metals at nanometer scales can lead to strong modifications of their optical properties [1,2]. If a metallic plane can reflect more than 98% of the incident light, nanostructured metals can strongly absorb light. Wood observed more than one century ago anomalies in the reflection of light by metallic gratings [3]. It is nowadays well-known that such anomalies are due to the collective oscillation of free electrons, called surface plasmons [4–7]. Excitation of surface plasmons induces a strong enhancement of the electric field at the surface of metals [8]. This field enhancement attracts the attention of a wide scientific community interested in the light–matter interaction [1,8]. In this context, absorption of light is a very interesting topic with great applications in solar cells, in the surface enhanced Raman spectroscopy (SERS), as well as in nonlinear optics. Recently, an efficient optical device has been reported that consists of a two-dimensional array of nanocavities in a gold substrate [9,10]. It must be stressed that the manufacturing of this device does not require a lithographic technique since it is obtained by the coating of gold over an ensemble of latex spheres, positioned over a plane surface. This structure permits a full absorption of unpolarized light in a wide range of incidence. It is assumed that such absorption occurs due to the excitation of void plasmons in the nanocavities. But an electric field map shows that light intensity does not occur at the metallic surface [9], and is maximum inside the cavity as happens in the case of cavity resonances [11,12]. In deep metallic gratings illuminated in TM polarization (electric field vector perpendicular to the grooves), surface plasmons are coupled with a transverse-electric-magnetic (TEM) mode that can propagate inside the grooves [13–18], a coupling that can also lead to total absorption of light. An interesting question that remains open is whether cavity resonances alone would be able to provide a total light absorption.

Nanocavities in a gold substrate can be considered as crossed gratings. Such gratings can couple incident light to surface plasmons simultaneously for both fundamental polarizations [19,20]. To avoid the excitation of surface plasmons, a noncrossed diffraction grating consisting of cylindrical cavities in a metallic (Al or Au) substrate is considered. This grating has to be illuminated in transverse electric (TE) polarization. Figure 1 is a schematic of the device under study. It can be manufactured by depositing a metallic coating upon an ensemble of latex or silica cylinders put in contact, the period d of the system is fixed only by the diameter of the cylinders. It has to be stressed that with cylinders in place of spheres, the contact is infinite in the z direction so that the grating is split in two pieces. To avoid that, grooves have to be filled with a solid material, in our case, silica. After applying a suitable metal coating over the cylinders, it is polished together with the top part of the cylinders in order to obtain the structure presented in Fig. 1 with the height of the cavities denoted as h. The light absorption is optimized in normal incidence with respect to the two parameters, d and h, with the

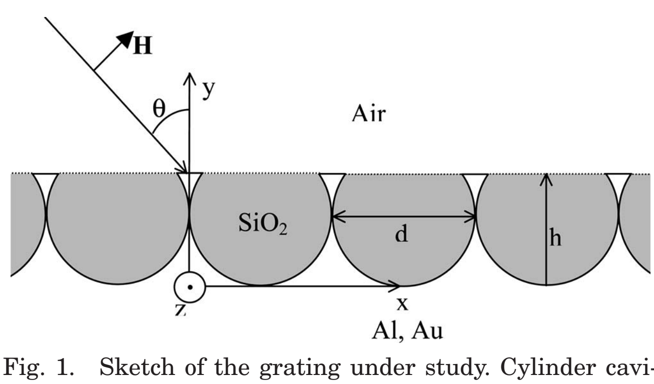

Fig. 1. Sketch of the grating under study. Cylinder cavities are invariant with respect to the z axis. Grooves are filled with silica ($n=1.45$), metals are Au (optical index $n=0.197+i3.0901$) and Al ($n=1.374+i7.62$). The grating period is d and is equal to the diameter of the cylinders' cross section, h denotes the distance between the bottom of the cavities and the top of the grating. Superstrate is air ($n=1$). The plane of incidence is Oxy, angle of incidence is θ, and the incident wavelength is $\lambda=632.8$ nm. The grating is illuminated in TE polarization.

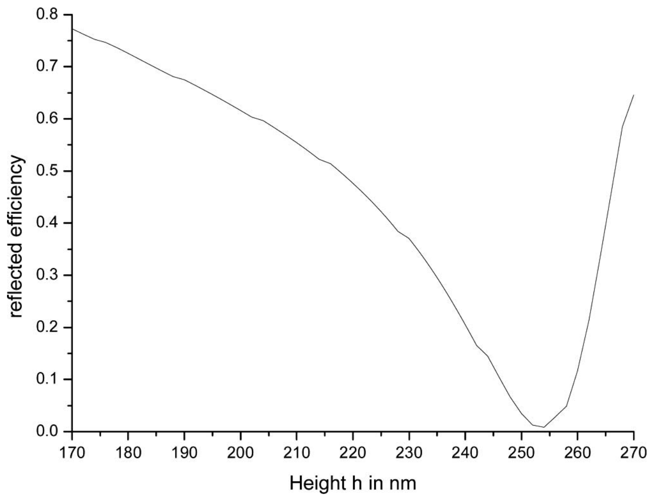

Fig. 2. Reflected efficiency as a function of h (see Fig. 1) with optimum period $d=270$ mn. Metal is aluminum.

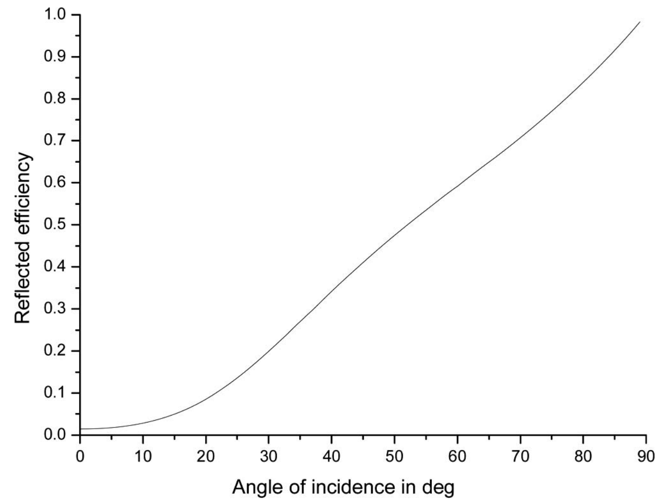

Fig. 4. Reflected efficiency as a function of the angle of incidence θ, with $d=270$ nm, $h=255$ nm. Metal is aluminum.

use of the differential method [21,22]. This method develops the electromagnetic fields in Fourier series, which permits the reduction of Maxwell equations onto a set of first-order differential equations. Its integration from the substrate to the superstrate permits one to calculate the electric field in both homogeneous media, and a second integration with the known field components in the superstrate determines the electromagnetic field components inside the modulated area (see, for example, Figs. 3 and 5). The convergence of the results have been thoroughly studied with respect to the number of Fourier components. For this study, 65 Fourier components have been used, and the convergence is ensured for the ensemble of the presented results. In the case of aluminum, numerical optimization shows that with values of the two parameters $d=270$ nm and $h=255$ nm, the reflected efficiency falls to 1.5%. Figure 2 shows the calculated reflected efficiencies as a function of h with the optimized period $d=270$ nm. It can be deduced that the open cavities, i.e., small h, do not lead to strong absorption. In fact, the cavities have to be closed enough to sustain cavity resonances. However, since the skin depth of aluminum illuminated at $\lambda=632.8$ nm is quite small, it is necessary to have an opening of the cavity to couple incident light into the cavity resonance. As a consequence, a trade-off has to be found, and values close to $h\sim 0.94d$ result in an almost total light absorption. The reconstruction of the electric field map in Fig. 3 with optimized absorption ($d=270$ nm and $h=255$ nm) shows the existence of a strong enhancement of the electric field in the center of the cavities. Owing to the cylindrical symmetry of the cavities, such resonances are expected to be rather insensitive to angles of incidence [12]. This study is carried out in Fig. 4 where the reflected efficiency is calculated as a function of the angle of incidence with the optimized parameters obtained in normal incidence. It is shown that the absorption of light is higher than 90% over a range of angles of incidence $[-20°;+20°]$.

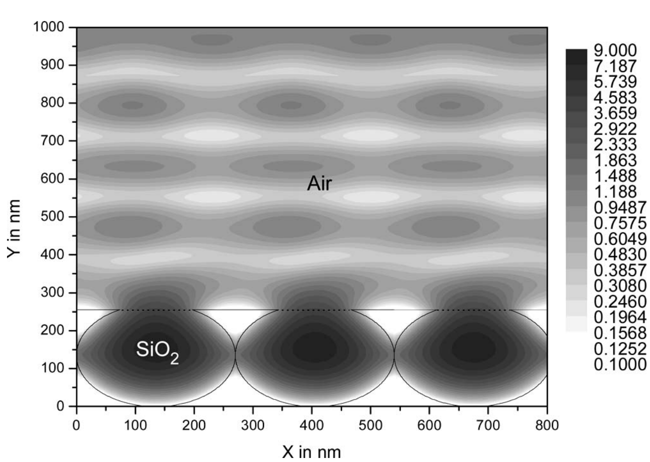

Fig. 3. Map of the field intensity ($|E|^2$) when the grating is illuminated in normal incidence. $d=270$ nm, $h=255$ nm, absorption of 98.5%. Metal is aluminum.

To go further in the study, aluminum is replaced by gold. In that case, maximum light absorption (>99%) occurs with a much smaller period ($d=215$ nm) and, more surprisingly, with an entirely closed cavity ($h=d$), and with a gold layer of 13 nm thick coating the dielectric cylinders (Fig. 5). Thus the configuration with gold as cavity walls differs significantly from the first case studied (with aluminum as the wall material), and this difference can be explained by the fact that in the studied spectral region, the skin depth of gold (≈16 nm) is much larger than with aluminum (≈7 nm). As a consequence, the cavity can be entirely closed and the coupling with the incident wave occurs via a tunneling effect through the thin gold layer. The dependence of the reflected efficiency with respect to the angle of incidence is displayed in Fig. 6. Absorption is higher than 99% in a range of angle of incidence equal to $[-9°;9°]$.

It has been shown that total light absorption by buried metal cavities can occur without the aid of surface plasmons. This absorption happens in TM polarization and the role of cavity resonances in the light absorption has to be taken into account in photonic device studies. The light absorption phenom-

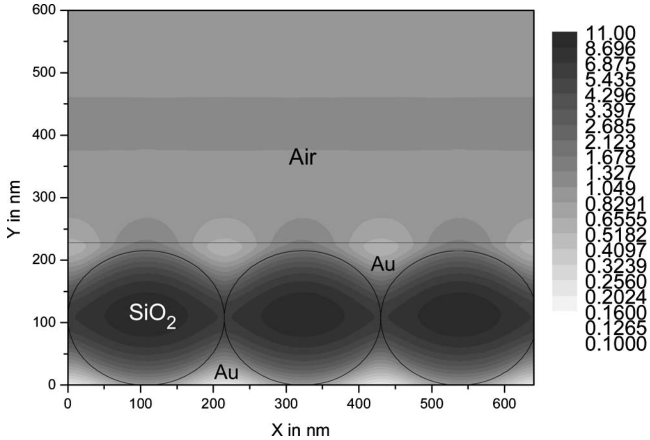

Fig. 5. Map of the field intensity ($|E|^2$) when the grating is illuminated in normal incidence with $d=h=215$ nm, gold as the coating layer with a thickness of 13 nm. Absorption reaches 99.9%.

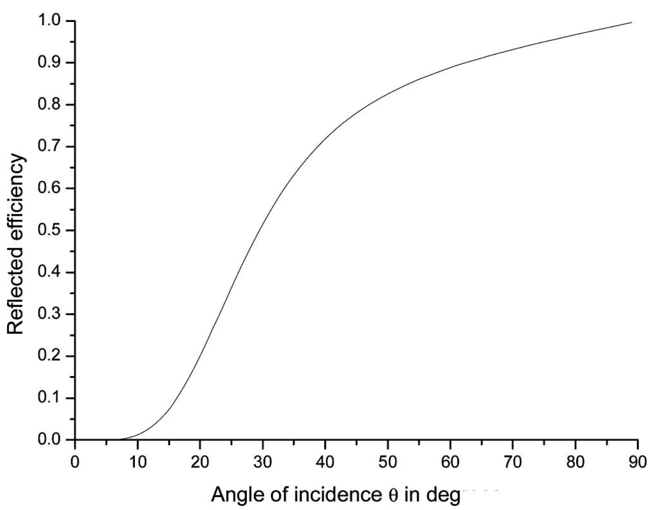

Fig. 6. Reflected efficiency as a function of the angle of incidence θ. Same parameters as in Fig. 5.

enon reported here depends weakly on the angle of incidence; in addition, the range of incidence giving strong absorption can be widened by optimizing the absorption in the oblique incidence.

References

1. W. A. Murray and W. L. Barnes, Adv. Mater. (Weinheim, Ger.) **19**, 3771 (2007).
2. J. B. Pendry, L. Martin-Moreno, and F. J. Garcia-Vidal, Science **305**, 847 (2004).
3. R. W. Wood, Philos. Mag. **4**, 396 (1902).
4. A. Hessel and A. A. Oliner, Appl. Opt. **4**, 1275 (1965).
5. D. Maystre, in *Electromagnetic Surface Modes*, A. D. Boardman, ed. (Wiley, 1982), Chap. 17.
6. M. C. Hutley and D. Maystre, Opt. Commun. **19**, 431 (1976).
7. J. Le Perchec, P. Quémerais, A. Barbara, and T. López-Rios, Phys. Rev. Lett. **100**, 066408 (2008).
8. W. L. Barnes, A. Dereux, and T. W. Ebbesen, Nature **424**, 824 (2003).
9. T. V. Teperik, V. V. Popov, and F. J. García De Abajo, Phys. Rev. B **71**, 085408 (2005).
10. T. V. Teperik, F. J. García De Abajo, A. G. Borisov, M. Abdelsalam, P. N. Bartlett, Y. Sugawara, and J. J. Baumberg, Nat. Photonics **2**, 299 (2008).
11. E. Popov, L. Tsonev, and D. Maystre, Appl. Opt. **33**, 5214 (1994).
12. E. Popov, S. Enoch, G. Tayeb, B. Gralak, and N. Bonod, Appl. Opt. **43**, 999 (2004).
13. A. Wirgin and T. López-Rios, Opt. Commun. **48**, 416 (1984).
14. E. Popov, L. Tsonev, and D. Maystre, J. Mod. Opt. **37**, 379 (1990).
15. T. López-Rios, D. Mendoza, F. J. Garcia-Vidal, J. Sánchez-Dehesa, and B. Pannetier, Phys. Rev. Lett. **81**, 665 (1998).
16. F. J. Garcia-Vidal, J. Sánchez-Dehesa, A. Dechelette, E. Bustarret, T. López-Rios, T. Fournier, and B. Pannetier, J. Lightwave Technol. **17**, 2191 (1999).
17. R. Hooper and J. R. Sambles, J. Opt. Soc. Am. A **20**, 836 (2003).
18. E. Popov, N. Bonod, and S. Enoch, Opt. Express **15**, 4224 (2007).
19. F. C. Garcia d'Abajo, Rev. Mod. Phys. **79**, 1267 (2007).
20. E. Popov, D. Maystre, R. C. McPhedran, M. Nevière, M. C. Huthley, and G. H. Derrick, Opt. Express **16**, 6146 (2008).
21. M. Nevière and E. Popov, *Light Propagation in Periodic Media: Diffraction Theory and Design* (Marcel Dekker, 2003).
22. E. Popov and M. Nevière, J. Opt. Soc. Am. A **18**, 2886 (2001).