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LETTER TO THE EDITOR

Enhanced optical near-field transmission through subwavelength holes randomly distributed in a thin gold film

Mufei Xiao[1] **and Nikifor Rakov**

Centro de Ciencias de la Materia Condensada, Universidad Nacional Autónoma de México, Apartado Postal 2681, CP 22800 Ensenada, Baja California, Mexico

E-mail: mufei@ccmc.unam.mx

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Abstract
Randomly distributed small holes of various subwavelength sizes were fabricated in a thin gold film. We study the optical near-field transmission of the film. In the wavelength spectrum from 350 to 650 nm, a number of strongly enhanced transmission peaks were observed. These transmission peaks can only be observed in the near field. We attribute the new phenomenon to the surface plasmon coupling inside the holes and between the surfaces on the two sides of the thin film.

In several recent papers [1–4], extraordinarily high transmission was reported for arrays of subwavelength cylindrical holes in metallic films. In these experiments, periodic transmission peaks were observed for wavelengths longer than the size of the holes [1–4]. Since similar effects could not be observed for nonmetal films [1], the high transmission seems to be caused by the interaction between light and the surface plasmon [5]. Furthermore, the position of the peaks appeared to be determined by the periodicity of the hole arrays, and the spectra depended strongly on the incident angle of the light [1], which suggests that the surface plasmon is excited by the grating structures on the surface [6]. In other words, the excitation of the surface plasmon by the grating on the surface is responsible for the extraordinary enhancement of the transmission through the subwavelength holes. This enhancement is huge (up to a factor of 2), considering the theoretic prediction ($\sim(r/\lambda)^4$; r—radius of the hole) based on the well-known Bethe theory [7].

Shortly after the publication of [1, 2], theoretical results based on numerical calculations in one-dimensional [8] and two-dimensional [9] models were reported to support the experiments. In this regard, it is worth mentioning a number of relevant theoretical works [10–13] that also

[1] Address for correspondence: CCMC-UNAM, PO Box 439036, San Ysidro, CA 92143, USA.

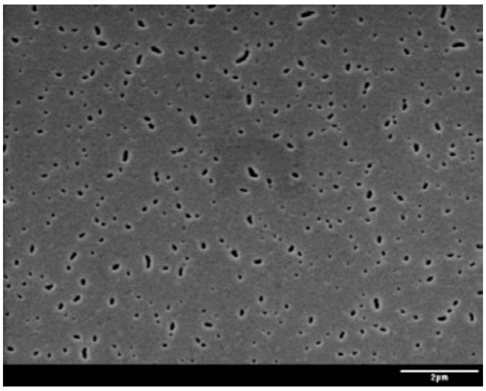

Figure 1. A SEM image of the film studied in the present work.

suggest the importance of the coupling between the surface plasmon and grating structures on a metal surface.

In the present letter, we report on optical near-field transmission of a large number of small holes of various subwavelength sizes randomly distributed in a thin gold film of thickness 55 nm.

In [1–4], the samples contained only a few small holes that have a unique size and shape and are distributed with a unique distance between the holes, so the film acts as a grating. Our samples are different. The main differences are as follows. Macroscopically, the small holes are uniformly distributed everywhere over the whole sample area. Microscopically, the distances between the small holes are random and the size as well as the shape of the holes varies too. In other words, there are not the uniform objects and unique periodicity required for the system to be considered as a grating structure. We used a simple method to produce the sample. An example of the sample preparation is described as follows. We prepared a thin gold film of thickness 55 nm by the usual vapour deposition process. We then applied a DC voltage to the film. The film was monitored under an atomic force microscope (AFM, Quesant QScope-250). After some time, the film started to show microscopic holes. We stopped the process when we saw the image that we wanted to study. We have performed scanning electron microscopy (SEM) and energy dispersive spectroscopy (EDS) on the film. In figure 1 a SEM image of the prepared film is presented. The SEM study shows that there are everywhere in the film (an area about 3 mm $\times$ 3 mm) randomly distributed small holes of various shapes and of different sizes (mostly $<$250 nm), and the distances between the holes vary from 200 up to 800 nm. When performing the SEM we also checked the film with EDS at different points on the film surface. The EDS study shows that at a hole area the dominant material is glass (the substrate), which confirms that the objects are holes passing through the film.

We illuminated the sample film with an incoherent white light source. The light was coupled to an optical fibre (900 mm long, 1.0 mm diameter) which was in vertically contact with the glass substrate (170 μm thick). The transmission was received by another optical fibre with the end well polished and tightly glued to the surface of the gold film. The collected signals were analysed by an optical spectrometer. In figure 2(a) two spectra are presented. The lower spectrum was obtained for a film without holes. This spectrum appears flat at the noise level. The upper curve in figure 2(a) is a spectrum observed for the film with holes (see figure 1). Spectra in figure 2(a) shows that the transmission is dramatically enhanced for the film with holes, and there are several enhanced peaks in the spectrum. In the spectrum the first

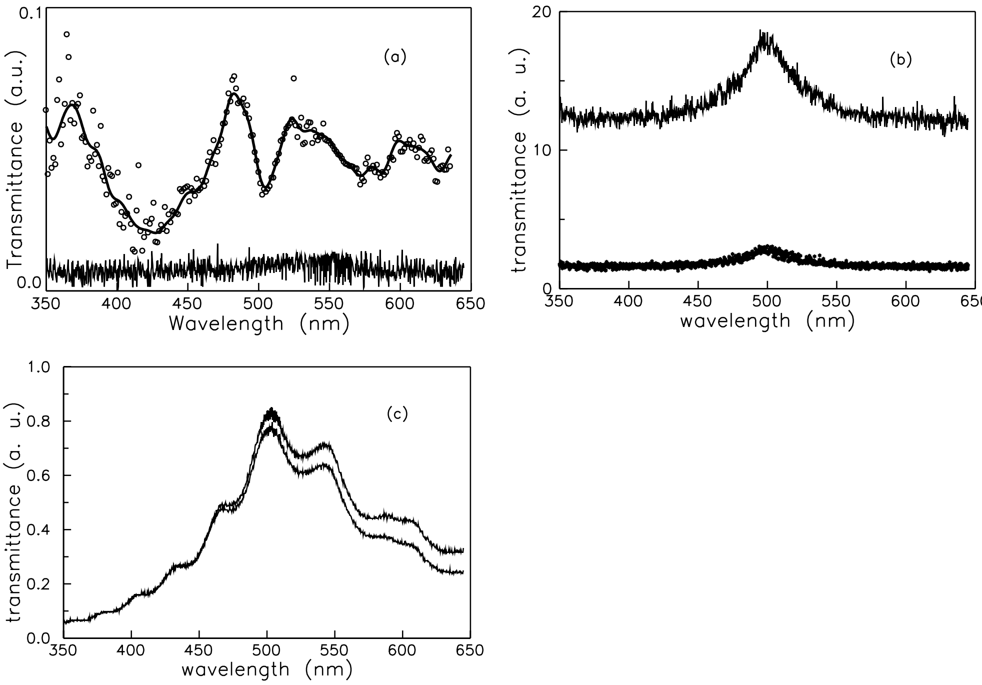

Figure 2. Optical transmission as a function of the wavelength for film with (lower curve) and without (upper curve) holes. (1) Near field; (2) intermediate field; (3) far field.

peak corresponds to the plasmon in the conduction band of gold. After the plasmon peak, the spectrum shows a few enhanced peaks at longer wavelengths. These peaks are nearly periodic, with distances between the minima of 55, 65 and 55 nm, which are roughly the same as the film thickness.

We have also found that the periodic transmission peaks could only be observed when the fibre end was in tight touch with the surface of the gold film. To confirm this, we modified the experiment set-up by reversing the illuminating and receiving fibres so that the transmission is received about 170 μm (the thickness of the substrate) away from the gold film. Two spectra for films with and without holes are presented in figure 2(b). The transmission is in general enhanced for film containing holes. However, in both spectra there is no plasmon peak at all, which means that the surface plasmon does not present far away from the metal surface. The only enhanced peak, in both spectra, is at about 500 nm, which is a known phenomenon for a gold surface [14]. The peak at 500 nm is not for a surface wave but a photoemission from the d-band electrons [14]. Furthermore, we have measured the far-field transmission as follows. We pulled the fibre about 3 mm away from the sample and used a collimator to collect the far-field transmission. We obtained two far-field transmission spectra for the films with and without holes. The spectra are presented in figure 2(c). As we expected, both spectra contain only the photoemission peak with a periodic feature that stems from the multi-reflections between the films. It is important to note that there is almost no enhancement for the film with holes.

The above three measurements in near, intermediate and far fields reveal that subwavelength holes in gold film can enhance the transmission, and the enhanced transmission can only be observed in near field. In the following we shall discuss a mechanism that could be responsible for the enhanced near-field transmission.

Firstly, the notion that a small hole allows only little light to pass through is not correct, at least for near-field transmission. Bethe theory [7] was constructed with the simplest model, where the film is considered infinitely thin. Recently, with the development of near-field optics, model calculations beyond Bethe theory have been reported [15–17]. In [17], the thickness of the film is considered. Numerical results in [17] showed that it is possible for the transmission of a subwavelength hole of a certain size to become as high as 1.8. Further increase of the hole size will result in a decrease of the transmission. The calculation in [17] is too simple to include the surface plasmon mechanism; we may however qualitatively conclude that the transmission predicted by Bethe theory would be too simple and that it is possible for the transmission to be resonantly enhanced. The above discussion is also supported by various experiments in scanning near-field optical microscopy (SNOM). It is widely known in SNOM that the subwavelength aperture in the thin metal cover formed on top of a fibre tip does allow very high near-field transmission and that the transmission may be resonant.

Secondly, it is true that the collective interactions of objects in a grating structure may excite and resonantly localize surface plasmons. However, surface plasmons can also be generated by any kind microscopic object in the surface, such as discontinuities (edges) and small particles. And the interactions between randomly distributed microscopic objects may be enhanced due to the configurational resonances and thus cause localization of light in near-field regions [18–20].

Thirdly, it is also interesting to note that in the case of near-field detection, the substrate, the metal film and the fibre probe form a symmetrical glass–metal–glass sandwich structure, whereas in the far-field case, the structure is asymmetric with a big air gap between the metal surface and the fibre probe. In the case of symmetric structure, multiple or at certain frequencies resonant multiple reflections may occur, which explains the unique periodic resonant reflection spectra in the near field. On the other hand, the excited surface plasmon polariton is a field highly localized on the surface and the scattering of the surface plasmon field into the far field is insignificant in comparison with the photoemission, which does not require holes in the film. This further explains the fact that the far-field transmission spectrum contains mainly the photoemission peak (with some minor presence of periodic resonances).

Finally, based on the above reasoning, we put forward our conjecture regarding the mechanism behind the enhanced near-field transmission that we observed in our experiments as follows. A subwavelength hole in a thin metallic film allows a considerable amount of light to pass through, and the transmission can be enhanced for holes that have certain size and shape. Surface plasmons may be excited at the entrances of the holes on the two sides of the film. The interactions between the two side plasmons may resonantly localize light inside the holes, which is the reason for the observed spectrum having periodic peaks, and its periodicity corresponds to the thickness of the film. The transmission may be further enhanced because of the interactions between the holes. If the holes form a grating structure, the enhancement of the transmission may be strong and can be observed in the far-field region. However, for randomly distributed holes, the interactions are mostly of the near field (the evanescent field); thus the enhanced transmission can only be observed in the near-field region. We believe that the present work could initiate a new way to establish two-dimensional photonic devices and to study the surface plasmon optics in metallic thin films.

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References

[1] Ebbesen T W, Lezec H J, Ghaemi H F, Thio T and Wolff P A 1998 *Nature* **391** 667
[2] Ghaemi H F, Thio T, Grupp D E, Ebbesen T W and Lezec H J 1998 *Phys. Rev.* B **58** 6779
[3] Kim T J, Thio T, Ebbesen T W, Grupp D E and Lezec H J 1999 *Opt. Lett.* **24** 256
[4] Thio T, Lezec H J and Ebbesen T W 2000 *Physica* **279** 90
[5] Raether H 1988 *Surface Plasmons* (Berlin: Springer)
[6] Ritchie R S, Arakawa E T, Cowan J J and Hamm R N 1968 *Phys. Rev. Lett.* **21** 1530
[7] Bethe H A 1944 *Phys. Rev.* **66** 163
[8] Schröter U and Heitmann D 1998 *Phys. Rev.* B **58** 15419
[9] Salomon L, Grillot F, Zayats A and de Fornel F 2001 *Phys. Rev. Lett.* **86** 1110
[10] Barnes W L, Preist T W, Kitson S C and Sambles J R 1996 *Phys. Rev.* B **54** 6227
[11] García-Vidal F J and Pendry J B 1996 *Phys. Rev. Lett.* **77** 1163
[12] Sobnack M B, Tan W C, Wanstall N P, Preist T W and Sambles J R 1998 *Phys. Rev. Lett.* **80** 5667
[13] Tan W C, Preist T W, Sambles J R and Wanstall N P 1999 *Phys. Rev.* B **59** 12661
[14] Khriachtchev L, Heikkilä L and Kuusela T 2001 *Appl. Phys. Lett.* **78** 1994
[15] Roberts A 1987 *J. Opt. Soc. Am.* **4** 1970
[16] Alvarez L and Xiao M 2000 *J. Vac. Sci. Technol.* B **18** 82
[17] Alvarez L and Xiao M 2000 *J. Microsc.* **202** 351
[18] Xiao M, Zayats A and Siqueiros J 1997 *Phys. Rev.* B **55** 1824
[19] Xiao M 1999 *J. Opt. Soc. Am.* A **14** 2977
[20] Xiao M and Bozhevolnyi S 2001 *J. Phys.: Condens. Matter* **13** 3001