PLASMONICS

Surface plasmons at work?

Further analysis of controversial data questioning the role of surface plasmons in extraordinary optical transmission reasserts the conventional view, and suggests there is still much to be done to understand the details of this phenomenon.

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When Ebbesen *et al.* first reported in a now famous paper[1] that a thin metal film perforated with an array of subwavelength-sized holes can transmit much more light than expected — a phenomenon known as extraordinary optical transmission (EOT) — they immediately suggested the involvement of surface plasmons. Surface plasmons are electromagnetic surface waves that propagate at the interface between a metal and a dielectric by the collective motion of electrons[2]. Unlike most guided modes, the electric fields associated with surface plasmon modes are evanescent, and decay exponentially with distance from the interface. But once excited by an optical field at a hole in a metal film they can travel several micrometres (equivalent to dozens of optical wavelengths) along the film's surface before eventually being absorbed. However, they can turn back into a freely propagating optical wave when they are scattered at another hole or groove. This interplay between light waves and surface plasmons apparently enables EOT. More importantly, the realization that surface plasmons can give rise to exotic and potentially useful phenomena has given birth to an entire new field, known as 'plasmonics'.

Recently however, the explanation of enhanced optical transmission through nano-holes in terms of plasmons has been challenged in a report by Gay and co-workers[3], one of whom was also an author of the original Ebbesen paper[1]. The authors of this report suggest that the principle agents of EOT are not surface plasmons, but 'composite diffracted evanescent waves' (CDEW). To support this Gay *et al.* showed that the transmission of light through two different nanoscopic structures in a thin silver film — one consisting of a narrow slit next to a thin groove, and the other of a small hole next to a thin groove — varies with slit–groove/hole–groove separation in a way that is more accurately described by the CDEW model than the surface plasmon model. But on page 551 of this issue[4], Lalanne and Hugonin present subsequent analysis of these data that suggests the issue is far from clear cut, and that the discrepancies of the results with the surface plasmon picture could simply be the result of a layer of contamination on the silver film.

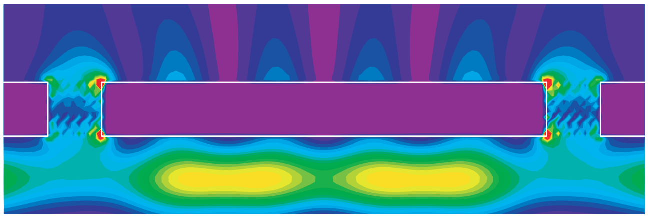

Figure 1 Standing wave pattern between two parallel slits in a gold film caused by interfering surface plasmons, excited by an optical field incident from below. Reprinted with permission from ref. 5. Copyright (2005) by the American Physical Society.

In drawing conclusions from any experiment, it is important to recognize that surface plasmons are not the only things that contribute to the total field — scattered waves, evanescent waves and 'normal' guided modes can make significant contributions also. Moreover, when the sample consists of a multilayered medium with closely spaced apertures, the precise role of plasmons is difficult to isolate. To complicate the matter even further, it has been shown in Young's double-slit experiment that surface plasmons can both suppress and enhance optical transmission, depending on the slit separation[5]. This was attributed to the modulating action of plasmons travelling between the slits that interfere with the light that is directly transmitted by the slits (see Fig. 1). In addition, EOT systems are most often modelled as an array of slits and grooves, rather than an array of holes and bumps, despite the fact that it is known that the precise shape of holes is of great influence on the transmission[6]. In light of these sorts of issues, it has become increasingly clear that our understanding of what happens when light travels through nano-apertures is incomplete. It would seem reasonable therefore, to question the precise role of surface plasmons in EOT.

Although there is still much we do not know in this field, the CDEW model seems to throw out the baby with the bathwater. For starters, it is not based on Maxwell's equations but on an approximate scalar wave model. This means that plasmons, which only occur for a specific polarization of the field, cannot be described by it. Moreover, it relies on the so-called

Kirchhoff assumption that the field at the entrance of a hole is, just like the incident laser field, a plane wave. The use of this assumption is common, and in many instances justified. But it is well-known that it breaks down when the hole size is comparable to the wavelength of the field — precisely the situation that exists in the case of EOT. Finally, the model assumes an opaque metal film, an idealization that seems rather questionable for the films with a subwavelength thickness that are typically used in experiments.

It is therefore not surprising that this new model is now itself called into question. Lalanne and Hugonin[4] use two different models to re-analyse the experimental data collected by Gay and colleagues[3]. One is a simple phenomenological model that assumes the presence of plasmons[7], the other is a rigorous calculation based on Maxwell's equations, which automatically incorporates plasmons. The structures that Gay *et al.* study consist of a narrow slit in a metal film with a nearby groove. The power radiated by this setup is strongly dependent on the separation between the slit and the groove. Both the plasmon model and the rigorous calculation reproduce the oscillatory behaviour observed in the experiment. Lalanne and Hugonin then look at what the three different approaches predict for a variety of groove widths and for different wavelengths. They found that over a wide range of values the phenomenological model and the rigorous calculation are in good agreement, whereas the CDEW model predicts strongly deviating field patterns. As Maxwell's equations generally provide the last word in such fundamental matters, this result clearly vindicates the role of surface plasmons in EOT.

Although this exchange of studies has led to a deeper understanding of plasmon physics, it should be emphasized that this principally applies to the response of two-dimensional structures. The more general lesson then is that we should be just as aware of what we don't know as what we do, and that a rigorous framework for understanding the behaviour in three dimensions of an array of arbitrarily shaped subwavelength holes, still remains on the horizon.

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