Comment on "Enhanced transmission of light through a gold film due to excitation of standing surface-plasmon Bloch waves"

J. Weiner*

IRSAMC/LCAR, Université Paul Sabatier, 118 route de Narbonne, 31062 Toulouse, France
and IFSC/CePOF, Universidade de São Paulo, Avenida Trabalhador São-Calense, 400-CEP 13566-590, São Carlos São Paulo, Brazil

(Received 27 April 2007; revised manuscript received 29 June 2007; published 24 January 2008)

The purpose of this Comment is first to correct the claim of Smolyaninov and Hung [Phys. Rev. B **75**, 033411 (2007)] that the reported results "strongly contradict" the presence of diffracted evanescent waves in the vicinity of subwavelength structures and second to point out that periodic structures are unnecessary for the efficient production of the surface plasmon polariton guided mode either as traveling or standing waves. Guided surface waves originate from simple slit or groove edges illuminated under normal incidence, and one-dimensional surface cavities from these standing waves are easily realized.

DOI: 10.1103/PhysRevB.77.036401 PACS number(s): 78.66.Bz, 78.20.Ci, 78.67.−n

The authors of Ref. 1 report enhanced transmission of light through a thin gold film in a T-shaped structure acting as a Fabry-Pérot resonator. They interpret these results as showing that they "strongly contradict" the composite diffracted evanescent wave (CDEW) model[2] and cite an experimental study on subwavelength single slit-groove structures[3] as evidence supporting the CDEW model. This Comment points out that the situation is not quite that simple. Composite diffraction and bound surface plasmon polaritons (SPPs) are *not* mutually exclusive phenomena. The purpose of two experimental studies,[3,4] the first cited in Ref. 1, and a second, complementary set of measurements,[4] was to test two key predictions of the CDEW model: (1) surface wave amplitude behavior with distance from the originating structure and (2) the phase of the surface wave relative to the phase of the light wave incident on this structure. These studies showed that the surface wave amplitude indeed falls off rapidly within a "near-zone" of a few wavelengths distance from the originating groove edge, but that after the initial fall-off the surface wave continues to propagate with near-constant amplitude. The near-zone behavior clearly demonstrated the presence of evanescent diffracted modes. The "far-zone" behavior suggested population of the SPP guided wave mode, but the measured surface index of refraction $n_{\text{surf}} = 1.04 \pm 0.01$ did not correspond to the expected SPP index $n_{\text{SPP}} = 1.015$. The phase behavior measured in Ref. 4 did show a phase shift close to $\pi/2$ consistent with the CDEW model prediction. These tests, therefore, presented evidence consistent with diffraction in the near-zone but also confirmed the population of a long-lived surface wave, not predicted by CDEW. A follow-up study[5] showed that the "anomalous" surface index of refraction was due to this transient near-zone behavior. The surface wave originates as a composite, consisting of many surface modes *including* the bound SPP, but modes other than the SPP rapidly damp within a few optical cycles into dissipative phonon or radiative channels, consistent with a Drude model permittivity for real metals. This picture has been confirmed in yet another study of surface waves in slit-groove structures on gold films[6] and is contrary to the statement in Ref. 1 that only the SPP mode propagates and adjacent, unbound diffracted modes do not and cannot carry energy.

As stated earlier, the key point is that composite diffraction and bound SPPs are not mutually exclusive. The sharp edges of a subwavelength groove or slit diffract the normal-incident source waves into surface modes, all of which damp rapidly except for the bound SPP. This process demonstrates remarkable efficiency with about 40% of the initial surface wave amplitude evolving to the asymptotic SPP mode. A relevant point to emphasize here is that the oft-stated belief that grating or prism coupling is required to supply the missing momentum for efficient generation of the SPP mode is simply not true. The momentum spectrum associated with a grating structure of period a will be narrowly peaked at $2\pi/a$, while the momentum distribution of a subwavelength slit of width w will be broad, essentially its Fourier transform, $\simeq 2\pi/w$, and centered at $2\pi/\lambda_0$ with λ_0 the normal-incident wavelength. The use of a grating structure will produce Bloch modes on the surface and within the skin depth of the metal, but there is no reason to invoke structural periodicity as a *necessary* feature for the generation of SPPs and no need to distinguish "Bloch" surface waves from "regular" surface waves. The authors of Ref. 1 launch SPPs into a smooth one-dimensional (1D) surface cavity from an adjacent periodically structured region, but the studies on single slits and grooves previously cited show that similar results can be obtained by just using a subwavelength groove launcher. In fact the far-field fringes measured in Refs. 3–6 result from the interference between waves launched from a single slit-single groove structure. Figures 1 and 2, similar to those presented in Ref. 6, show finite-difference-time-domain (FDTD) simulations of the experiment in Ref. 3. A train of plane waves with $\lambda_0 = 852$ nm, incident from below, illuminates the slit-groove structure. The structure is a 400 nm layer of silver metal with a 100 nm wide slit milled through and a 100 nm wide groove milled to a depth of 100 nm. The slit and groove are separated by a center-to-center distance of 3.6 μm. Both the slit and the groove launch surface waves along the lower surface, and their counterpropagation forms a standing wave pattern. Figure 1 plots the amplitude of the electric field component E_z perpendicular to the surface plane as a function of z and y, the distance along the groove-slit reference plane. Figure 2 plots the magnetic field component H_x (the component parallel to

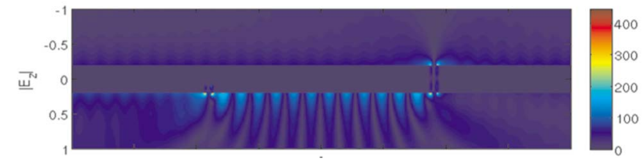

FIG. 1. (Color online) FDTD calculation of E_z amplitude as a function of z (perpendicular distance from the slit-groove reference plane) and y (transverse distance along the slit-groove reference plane). The center-to-center distance between the slit and groove is 3.6 μm. Slit and groove are both milled 100 nm wide; the groove depth is 100 nm, and the silver layer is 400 nm thick. The incident light has a free-space wavelength $\lambda_0 = 852$ nm. This plot is an unpublished result from Xie and Mansuripur, shown here with permission.

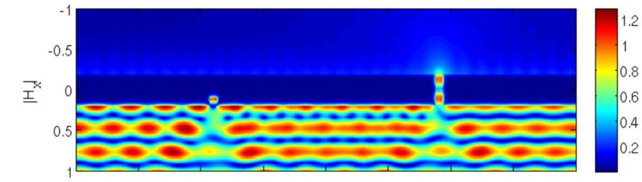

FIG. 2. (Color online) FDTD calculations of H_x amplitude as a function of z and y for the same structures as in Fig. 1. The H_x component of the magnetic field is aligned with the long axes of the slit and groove. This plot is an unpublished result from Xie and Mansuripur, shown here with permission.

the long axis of the slit and groove) as a function of the vertical and transverse dimensions of the structure. Concentration of E_z amplitude corresponds to surface charge concentration, and the standing wave pattern on the surface between the slit and groove is evident in Fig. 1. Another significant feature of Fig. 1 is the "hot spots" around the corners of the slit and groove on the lower surface as well as the appearance of hot-spot charge concentrations around the corners of the slit on the upper surface. These hot spots reveal the presence of localized oscillating charge that are the source of evanescent and propagating modes on the lower and upper surfaces of the structure.[7–9] Similar oscillating charge concentrations are responsible for the surface waves launched by the periodic structures in Ref. 1. Once launched there is no essential difference between the SPP standing waves shown here and the SPP standing waves reported in Ref. 1. The quality factor of the 1D surface cavity and the transmission from the incident (lower) side of the structure to the transmitted (upper) side can be optimized by a judicious choice of groove depth and metal layer thickness. This surface-cavity and slit-cavity coupling controls the efficiency of optical transmission through subwavelength metallic slit arrays.

*jweiner@irsamc.ups-tlse.fr

[1] I. I. Smolyaninov and Y.-J. Hung, Phys. Rev. B **75**, 033411 (2007).
[2] H. J. Lezec and T. Thio, Opt. Express **12**, 3629 (2004).
[3] G. Gay, O. Alloschery, B. Viaris de Lesegno, C. O'Dwyer, J. Weiner, and H. J. Lezec, Nat. Phys. **2**, 262 (2006).
[4] G. Gay, O. Alloschery, B. Viaris de Lesegno, J. Weiner, and H. J. Lezec, Phys. Rev. Lett. **96**, 213901 (2006).
[5] G. Gay, O. Alloschery, J. Weiner, H. J. Lezec, C. O'Dwyer, M. Sukharev, and T. Seideman, Phys. Rev. E **75**, 016612 (2007).
[6] F. Kalkum, G. Gay, O. Alloschery, J. Weiner, H. J. Lezec, Y. Xie, and M. Mansuripur, Opt. Express **15**, 2613 (2007).
[7] Y. Xie, A. R. Zakharian, J. V. Moloney, and M. Mansuripur, Opt. Express **13**, 4485 (2005).
[8] Y. Xie, A. R. Zakharian, J. V. Moloney, and M. Mansuripur, Opt. Express **14**, 6400 (2006).
[9] G. Lévêque, O. J. F. Martin, and J. Weiner, Phys. Rev. B **76**, 155418 (2007).