Airy plasmon: a nondiffracting surface wave

Alessandro Salandrino* and Demetrios N. Christodoulides

CREOL/College of Optics and Photonics, University of Central Florida, Orlando, Florida 32816, USA
**Corresponding author: asalan@creol.ucf.edu*

Received March 1, 2010; accepted May 17, 2010;
posted June 2, 2010 (Doc. ID 124913); published June 11, 2010

We introduce a new class of nondiffracting surface plasmonic wave: the Airy plasmon. The propagation properties of such a field configuration are unique among the family of surface waves and could lead to interesting applications in plasmonic energy routing. The self-bending and self-healing behavior of these solutions is discussed. Schemes for experimental realization and potential applications are proposed. © 2010 Optical Society of America

OCIS codes: 240.6680, 050.1940.

In recent years, advances in nanotechnology have led to an increased interest in surface plasmons as a means to manipulate light at the nanoscale. The part of optics that deals with surface plasmons has grown into a discipline of its own, commonly referred to as plasmonics. Several peculiar properties of surface plasmons have been experimentally demonstrated and successfully exploited in waveguides [1], plasmonic nanoantennas [2], and plasmonic collimators [3], to cite a few.

Although a great deal of attention has been devoted to surface plasmon guidance, propagation, and diffraction, to the best of our knowledge no diffraction-free field configurations have so far been suggested for these plasmon waves. In this Letter, inspired by recent developments in diffraction-free beams, we present the only possible class of surface plasmons compatible with paraxial diffraction-free, surface-bound propagation, and exhibiting a unique self-bending behavior.

Diffraction-free beams are associated with field configurations (exhibiting a definite peak in amplitude) for which the transverse intensity profiles at any two locations along the propagation direction remain invariant. In free space, several families of diffraction-free beams have been identified in the literature, such as Bessel beams [4], Mathieu beams [5], and, more recently, Airy beams [6].

In general, however, the surface-wave nature of plasmons does not allow a straightforward extension of these ideas to a metal/dielectric interface. In this case, the exponential decay of the transverse field distribution is fixed, and, hence, the plasmon propagation properties are exclusively dictated by its one-dimensional (1D) angular spectrum. Along these very lines, one may ask whether a 1D projection of the conical angular spectrum of a two-dimensional (2D) diffraction-free solution could yield a surface wave of similar characteristics. In this regard, the answer is negative, since a "conical" superposition in 1D leads to a sinusoidal interference pattern, which is by no means a localized beam.

Lately, nondiffracting Airy beams have been suggested and observed in optics [6,7]. As first indicated by Berry and Balazs [8], the Airy wave packet happens to be unique: it represents the only nonspreading solution to the 1D potential-free quantum Schrödinger equation. Given the isomorphism between the quantum mechanical Schrödinger equation and the paraxial wave equation, the Airy beam indeed represents the only nondiffracting 1D beam profile [9,10]. But perhaps the most intriguing feature of this solution is its very ability to freely self-bend, even in the absence of any external potential [7]. This aspect has thus far been exploited in several physical settings, such as in microparticle manipulation [11], plasma filamentation in air [12], nonlinear Airy beam generation [13], and optical Airy bullets [14], to mention a few.

The problem of surface plasmon propagation at the planar interface $y=0$ between a dielectric medium of permittivity ε_d placed over a metallic substrate of permittivity ε_m is polarization dependent and, therefore, is strictly vectorial. It is, however, possible to select a Cartesian component of the field to be used as a scalar potential, from which all the other field components may be deduced. Without loss of generality, the problem may be effectively formulated in terms of the component of the electric field normal to the boundary, which obeys the scalar Helmholtz equation:

$$\nabla^2 E_{dy} + k_0^2 \varepsilon_d E_{dy} = 0. \quad (1)$$

For a surface plasmon, the field exponentially decays away from the interface, leading to a functional dependence of the form $E_y(x,y,z)=A(x,z)\exp(ik_z z)\exp(-\alpha_d y)$, where the parameters k_z and α_d are related through the dispersion relations $\alpha_d^2 = k_z^2 - k_0^2\varepsilon_d$ and $k_z = k_0\sqrt{\varepsilon_d\varepsilon_m/(\varepsilon_d+\varepsilon_m)}$. Assuming that the transverse beam profile is slowly varying with respect to the propagation coordinate z, it is straightforward to show that the problem reduces to the 1D free-particle Schrödinger equation:

$$\frac{\partial^2 A}{\partial x^2} + 2ik_z\frac{\partial A}{\partial z} = 0. \quad (2)$$

In this case, one can directly show that the complex amplitude of the normal component of the electric field associated with a finite energy plasmon-Airy beam solution is described by

$$A(x,z) = Ai\left[\frac{x}{x_0} - \left(\frac{z}{2k_z x_0^2}\right)^2 + i\frac{az}{k_z x_0^2}\right] \times \exp\left[i\left(\frac{x+a^2x_0}{2x_0}\frac{z}{k_z x_0^2} - \frac{1}{12}\left(\frac{z}{k_z x_0^2}\right)^3\right)\right] \times \exp\left[a\frac{x}{x_0} - \frac{a}{2}\left(\frac{z}{k_z x_0^2}\right)^2\right]. \quad (3)$$

The parameter a in Eq. (3) is a measure of the strength of the exponential apodization of the field profile. Of importance is the angular spectrum of this solution, which is given by

$$\tilde{A}(k_x,z) = x_0 \exp\left(\frac{a^3}{3}\right)\exp(-ia^2x_0k_x)\exp(-ax_0^2k_x^2) \times \exp\left(\frac{ix_0^3k_x^3}{3}\right)\exp\left(-i\frac{k_x^2z}{2k_z^2}\right). \quad (4)$$

In Eq. (4), the Gaussian spectrum arises from the exponential apodization of the beam [in Eq. (3)], while the cubic phase term is associated with the Fourier transform of the Airy wave itself. Given the Gaussian spectrum of this Airy plasmon, the paraxial treatment will hold provided that

$$\sqrt{\ln 2/(ax_0^2)} \ll k_0\sqrt{\frac{\varepsilon_d\varepsilon_m}{(\varepsilon_d+\varepsilon_m)}}. \quad (5)$$

In this case, the k-spectrum of the remaining electric field components can be written in terms of the angular spectrum $\tilde{E}_y(k_x)$, e.g.,

$$\tilde{E}_z = -\frac{i\alpha_d}{k_0^2\varepsilon_d+\alpha_d^2}k_z\tilde{E}_y \approx -\frac{i\alpha_d}{\sqrt{k_0^2\varepsilon_d+\alpha_d^2}}\tilde{E}_y, \quad (6a)$$

$$\tilde{E}_x = \frac{\alpha_d}{k_0^2\varepsilon_d+\alpha_d^2}(-ik_x)\tilde{E}_y. \quad (6b)$$

Based on Eqs. (6), the electric field associated with the Airy plasmon in the dielectric region can be finally written as

$$\mathbf{E}_d = \frac{1}{\varepsilon_d}\left[\left(\hat{\mathbf{y}} - \frac{i\alpha_d}{\sqrt{k_0^2\varepsilon_d+\alpha_d^2}}\hat{\mathbf{z}}\right)A(x,z) + \hat{\mathbf{x}}\frac{\alpha_d}{k_0^2\varepsilon_d+\alpha_d^2}\frac{\partial A(x,z)}{\partial x}\right] \times \exp\left(i\sqrt{k_0^2\varepsilon_d+\alpha_d^2}z\right)\exp(-\alpha_d y). \quad (7)$$

The corresponding electromagnetic fields in the metal region can be readily obtained from Eqs. (7) using the substitutions $\varepsilon_d \to \varepsilon_m$ and $\alpha_d \to \alpha_d(\varepsilon_m/\varepsilon_d)$. Plots of the intensity distribution of an Airy plasmon on the interface plane and on transverse cuts are presented in Fig. 1. The diffraction-free character of this Airy plasmon wave is evident. In addition, the self-bending features of this solution are clearly depicted in this same figure.

The parabolic self-deflection experienced by the Airy plasmon during propagation can be estimated from Eq. (3). Taking the quantity $2x_0$ as a measure of the width of the main lobe, one can define a characteristic propagation length $Z_c = 2\sqrt{2}k_zx_0^2$ for which the beam is approximately displaced by one full width (of the main lobe). This characteristic parameter can be used to estimate an upper limit of propagation losses that can be tolerated in an experimental setup aimed to observe Airy plasmons. Given the losses of the system, this behavior can only be detected provided that the $1/e$ power decay is comparable to Z_c. This particular choice leads to the condition $\max[\mathrm{Im}(k_z)] = 1/[4\sqrt{2}\mathrm{Re}(k_z)x_0^2]$. Based on this criterion, Fig. 2 depicts the $\{\lambda, x_0\}$ region where such

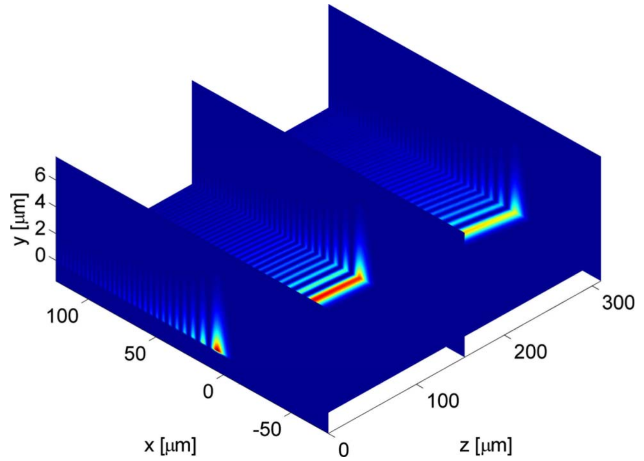

Fig. 1. (Color online) Intensity distribution on the interface plane and on three transverse cuts along propagation.

Airy plasmons are practically allowed to propagate along a silver–air interface.

As previously indicated, apart from its characteristic self-bending, Airy plasmons remain essentially diffraction free during propagation. This important feature can be more easily appreciated by directly comparing this solution with a Gaussian plasmon wave whose width is comparable to that of the Airy main lobe. In the numerical example shown in Fig. 3, we considered an Airy and a Gaussian plasmon wave propagating at an interface between silver and air at a wavelength of 1.55 μm. As it becomes apparent from the simulations, both plasmons experience attenuation due to the loss in the metal, but, while the Gaussian undergoes significant spreading, the Airy plasmon propagates almost undiffracted. Furthermore, as theoretically and experimentally shown in [15] for the 2D counterpart, the Airy plasmon shares one of the most attractive properties typical of nondiffracting waves: an inherent resilience against perturbations and a self-healing behavior. This concept translated into the plasmonic realm leads to a field configuration that is relatively unaffected by surface roughness and fabrication defects of the metallic layer. Based on these properties,

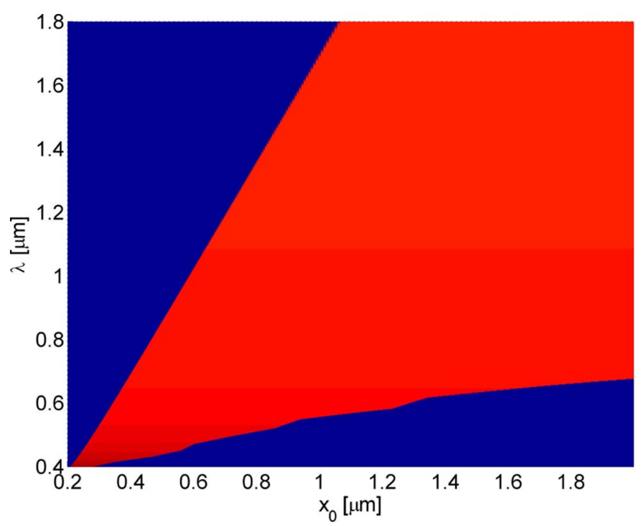

Fig. 2. (Color online) Central shaded area represents the region in the parameter space (x_0, λ) over which the criterion $\max[\mathrm{Im}(k_z)] = 1/[4\sqrt{2}\mathrm{Re}(k_z)x_0^2]$ is met for a silver–air interface.

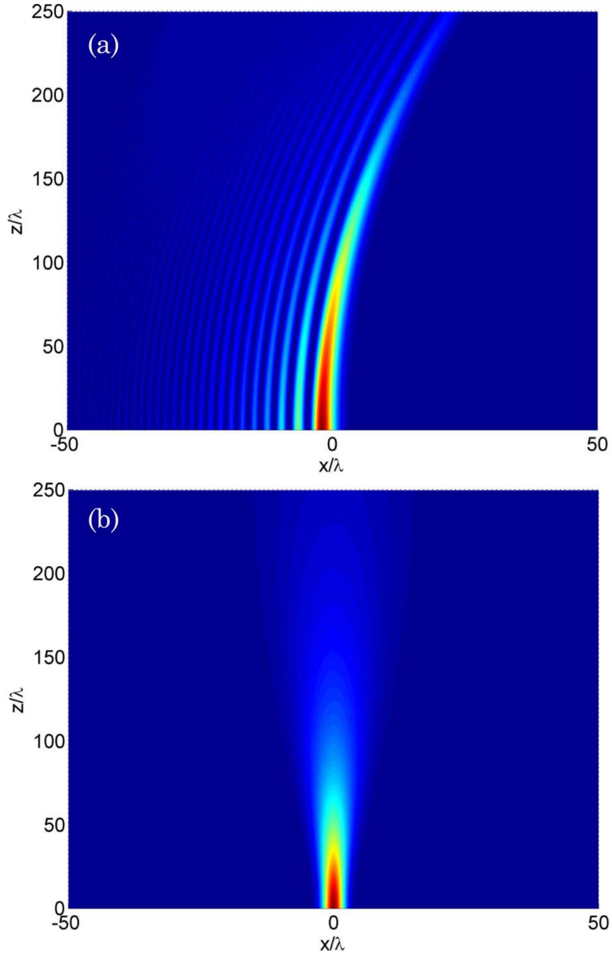

Fig. 3. (Color online) Comparison between the propagation of (a) an Airy plasmon and (b) a Gaussian plasmon at a silver–air interface.

the Airy plasmon could find applications as an effective means to route energy over a metallic interface between plasmonic devices.

It is important to note that the aforementioned interesting features of an Airy plasmon can be displayed only provided that a sufficiently long range of propagation is possible. In this respect, while the idea of a subwavelength Airy beam appears extremely attractive in principle, the high losses of strongly confined surface plasmons would most likely prevent the practical realization of such a concept. At this stage, perhaps only weakly guided plasmons hold promise as far as the experimental implementation of the Airy plasmon is concerned.

The commonly used schemes for the excitation of surface plasmons over a metallic block, such as the Otto configuration [16] or the grating coupling, are not without challenges in this specific case, in which a carefully imprinted transverse profile is necessary. From a practical standpoint, thin metallic films deposited over dielectric substrates could represent a more viable route toward the excitation and the observation of Airy plasmons. Power could be effectively coupled into the surface plasmon by using the substrate as a waveguide, provided that the thickness of the dielectric is chosen so as to support just the first TM mode properly phase matched to the mode of the metallic film. By using this scheme, an Airy beam could be generated in free space, as is done in [6], and then focused down into the input facet of the substrate with a cylindrical lens, exciting only the TM mode coupled to the surface plasmon.

In conclusion, a novel class of surface plasmons capable of propagating almost diffraction free was introduced. Our analysis indicates that this class of solutions can freely self-bend during propagation—a unique property among all other surface waves. Such field configurations may find interesting applications in energy routing over plasmonic boards. The associated electromagnetic field distribution was analyzed and suitable coupling schemes were discussed.

References

1. R. Charbonneau, N. Lahoud, G. Mattiussi, and P. Berini, Opt. Express **13**, 977 (2005).
2. P. Muhlschlegel, H. J. Eisler, O. J. F. Martin, B. Hecht, and D. W. Pohl, Science **308**, 1607 (2005).
3. N. Yu, J. Fan, Q. J. Wang, C. Pflügl, L. Diehl, T. Edamura, M. Yamanishi, H. Kan, and F. Capasso, Nat. Photon. **2**, 564 (2008).
4. J. Durnin, J. J. Miceli, Jr., and J. H. Eberly, Phys. Rev. Lett. **58**, 1499 (1987).
5. J. C. Gutiérrez-Vega, M. D. Iturbe-Castillo, and S. Chávez-Cerda, Opt. Lett. **25**, 1493 (2000).
6. G. A. Siviloglou, J. Broky, A. Dogariu, and D. N. Christodoulides, Phys. Rev. Lett. **99**, 213901 (2007).
7. G. A. Siviloglou and D. N. Christodoulides, Opt. Lett. **32**, 979 (2007).
8. M. V. Berry and N. L. Balazs, Am. J. Phys. **47**, 264 (1979).
9. I. M. Besieris and A. M. Shaarawi, Opt. Lett. **32**, 2447 (2007).
10. M. A. Bandres, Opt. Lett. **34**, 3791 (2009).
11. J. Baumgartl, M. Mazilu, and K. Dholakia, Nat. Photon. **2**, 675 (2008).
12. P. Polynkin, M. Koleskik, J. V. Moloney, G. A. Siviloglou, and D. N. Christodoulides, Science **324**, 229 (2009).
13. T. Ellenbogen, N. Voloch-Bloch, A. Ganany-Padowicz, and A. Arie, Nat. Photon. **3**, 395 (2009).
14. A. Chong, W. H. Renninger, D. N. Christodoulides, and F. W. Wise, Nat. Photon. **4**, 103 (2010).
15. J. Broky, G. A. Siviloglou, A. Dogariu, and D. N. Christodoulides, Opt. Express **16**, 12880 (2008).
16. A. Otto, Z. Phys. **216**, 398 (1968).