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Plasmonic Airy beam manipulation in linear optical potentials

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We demonstrate, both theoretically and numerically, the efficient manipulation of plasmonic Airy beams in linear optical potentials produced by a wedged metal-dielectric-metal structure. By varying the angle between the metallic plates, we can accelerate, compensate or reverse the self-deflection of the plasmonic Airy beams without compromising the self-healing properties. We also show that in the linear potentials the Airy plasmons of different wavelengths could be routed into different directions, creating new opportunities for optical steering and manipulation. © 2011 Optical Society of America

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The study of Airy beams has attracted surging attention because of their recent experimental demonstrations in optics [1, 2]. In comparison with other non-diffracting waves, Airy beams have unique features including an asymmetric field profile and self-deflection [1–3]. Those features have been employed for various applications, including optical trapping [4], plasma guiding [5], and light bullet generation [6,7]. Meanwhile, Airy beams have been recently introduced theoretically into the field of plasmonics [8]. Being combined with the virtue of surface plasmon polaritons, the plasmonic Airy beams could be a promising candidate for subwavelength beam manipulation and on-chip signal processing, in the emerging fields of nanophotonics and plasmonics.

The manipulation of Airy beams has been demonstrated in both linear and nonlinear regimes [9–12]. However, the schemes are reliant on the Airy beam generation processes, and thus are dependent on the amplitude (nonlinear) or phase (linear) of the incident light. The drawbacks prevent those manipulation methods to be widely used. The development of more robust and flexible Airy beam manipulation mechanisms and techniques are important and urgent but still unavailable.

In this letter, we suggest and demonstrate theoretically the plasmonic Airy beam manipulation by means of linear potentials created by a wedged metal-dielectric-metal structure [Fig. 1(a)], where one of the metal plates is tilted. We show both analytically and by direct FDTD numerical simulations with different tilting angles, that the plasmonic Airy beam deflection could be enhanced, compensated or even reversed, while still maintaining the self-healing properties. Based on the wavelength dependent features of the linear potentials, we also show that different frequency plasmonic Airy beams could be routed into different directions.

The control of Airy beams by linear potentials was firstly discussed by Berry and Balazs more than thirty years ago [3], but it has not attracted much attention since. In fact, the *linear potential* is the only potential that could be used to change the propagation direction of Airy beams, while preserving its non-diffracting properties [13]. To achieve a linear optical potential in the transverse direction, we utilize a linear modulation of the thickness of the dielectric layer along the x-axis, as shown in Fig. 1(a).

In an unmodulated metal-dielectric-metal structure, the effective refractive index of the symmetric mode (with respect to the magnetic field distribution) could be expressed as [14, 15] $n_{\mathrm{eff}}(h) = \alpha/h + \beta$, where h is the width of the dielectric layer. Correspondingly, in the wedged structure shown in Fig. 1(a) (the tilting angle is θ and the gap width in the middle is h_0), we obtain a linear effective index distribution (linear optical potential) under the approximation of $|\theta x| \ll h_0$:

$$n(x) = n_0 - \alpha\theta x/h_0^2, \tag{1}$$

where $n_0 = n_{\mathrm{eff}}(h_0)$. Using the effective index method, we can express the vertical electric field as [14, 15] $E_y(x, y, z) = A(x, y)\psi(x, z)\exp(in_0kz)$, where $A(x, y)$ is the plasmon eigenmode field, $\psi(x, z)$ is the envelope function and k is the wavenumber in vacuum. When $|\theta\Delta x| \ll h_0$, $A(x, y)$ and $\psi(x, z)$ can be decoupled [14]. While the expression for $A(x, y)$ can be found in Ref. [14], the equation for $\psi(x, z)$ under paraxial approximation is:

$$i\frac{\partial\psi}{\partial\xi} + fs\psi + \frac{1}{2}\frac{\partial^2\psi}{\partial s^2} = 0, \tag{2}$$

where $s = x/x_0$ (x_0 is the characteristic width of the first Airy beam lobe), $\xi = z/(n_0kx_0^2)$, and $f = -\alpha\theta k^2 n_0 x_0^3/h_0^2$ is effective optical force. Eq. (2) is exactly the Shrödinger equation for a particle in a linear potential (fs). This problem has a known solution [16, 17]:

$$\begin{split}\psi(s,\xi) = \sqrt{\tfrac{1}{2\pi i\xi}}\exp[i(fs\xi - \tfrac{f^2\xi^3}{6})]\int_{-\infty}^{+\infty}\psi(\chi,0)\\ \exp(\tfrac{i}{2\xi}[(s - \tfrac{f\xi^2}{2}) - \chi]^2)d\chi,\end{split} \tag{3}$$

where $\psi(\chi, 0)$ is the initial beam distribution. For an initial truncated Airy distribution $\psi(s, 0) = Ai(s)\exp(as)$ ($a > 0$ is the apodization parameter truncating the negative s part of the Airy beam distribution, and thus the

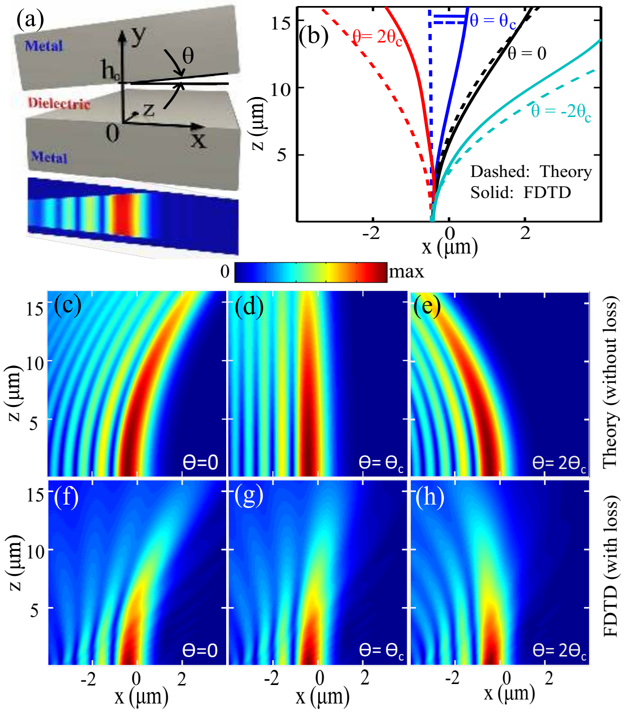

Fig. 1. (Color online) (a) Wedged metal-dielectric-metal structure with a tilting angle θ. The transverse field distribution is shown schematically below. (b) Positions of the main-lobe center of the plasmonic Airy beam for four tilting angles. Both theoretical (no losses, dashed lines) and numerical (with losses, solid lines) results are shown. Field distributions of the plasmonic Airy beam in the plane $y = 0$ are shown in (c-e) (theory, $|\psi(x,z)|$) and (f-h) (numerical, $|E|$). The parameters are: $\lambda = 632.8\,\text{nm}$, $h_0 = 60\,\text{nm}$, $a = 0.1$, and $x_0 = 500\,\text{nm}$. The corresponding critical angle is $\theta_c = 0.175°$.

deflection of Airy beam in free space is towards the positive x direction), we obtain the solution [1,17]:

$$\psi(s,\xi) = Ai[s - \tfrac{1}{4}(1+2f)\xi^2 + ia\xi] \exp[a(s - \tfrac{f\xi^2}{2} - \tfrac{\xi^2}{2})] \exp[i(-\tfrac{f^2\xi^3}{6} + fs\xi - \tfrac{f\xi^3}{4} - \tfrac{\xi^3}{12} + \tfrac{a^2\xi}{2} + \tfrac{s\xi}{2})]. \tag{4}$$

From Eq. (4) it follows that there exists a critical tilting angle $\theta_c = h_0^2/(2\alpha k^2 n_0 x_0^3)$ [satisfying the condition $f(\theta = \theta_c) = -1/2$] for which the Airy function becomes a stationary solution. Furthermore, Eq. (4) shows that when $a \ll 1$ the deflection of the plasmonic Airy beam could be accelerated ($\theta < 0$), compensated ($\theta = \theta_c$) or even reversed ($\theta > \theta_c$). We note that $\psi(x,z)$ is also the envelope function of E_z and therefore of $|E|$, considering the fact that $E_x \ll E_y, E_z$.

Next, we compare our theoretical results of Eq. (4) for $|\psi(x,z)|$ with numerical results ($|E|$) based on finite-difference time-domain (FDTD) technique (Lumerical) in Figs. 1(b-h). In the simulations, we make the mesh size to 0.5 nm in the region close to the metal dielectric interface and choose PML (perfectly matched layer) boundary conditions. Parameters used here are $\lambda = 632.8\,\text{nm}$, $h_0 = 60\,\text{nm}$, $a = 0.1$, $x_0 = 500\,\text{nm}$. The dielectric is air ($\varepsilon_\text{d} = 1$) and the metal is silver. We use the Drude model for silver, $\varepsilon_\text{m} = 1 - \omega_p^2/(\omega^2 + i\omega\omega_c)$, where $\omega_p = 1.37 \times 10^{16}\,\text{rad/s}$ and $\omega_c = 7.25 \times 10^{13}\,\text{rad/s}$. Fig. 1(b) shows the positions of the the main-lobe center of the Airy plasmons for four values of the tilting angle ($\theta_c = 0.175°$). For three cases, the field distribution in the plane $y = 0$ is shown in Figs. 1(c-h). We observe that the deflection of plasmonic Airy beams could be indeed accelerated [$\theta < 0$, Fig. 1(b)], compensated [$\theta = \theta_c$, Figs. 1(b,d,g)] or even reversed [$\theta = \theta_c$, Figs. 1(b,e,h)]. In general, there is a good qualitative agreement between our analytical theory and the numerical results showing that this analysis can be used to predict the behavior of plasmonic Airy beams. As θ increases, however, larger discrepancies between the theoretical and numerical results are observed [Fig. 1(b)]. This is because larger tilting angles render both the linear potential and paraxial wave approximations less accurate.

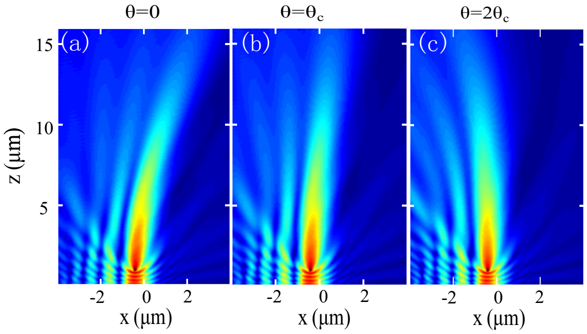

Fig. 2. (Color online) Numerical results for the field distribution ($|E|$) of plasmonic Airy beams in linear optical potentials with perturbations for three tilting angles. An ellipsoid particle ($\epsilon = 2.25$) with $(R_x, R_y, R_z) = (0.1, 0.025, 0.1)\,\mu\text{m}$ is centered at $(x, y, z) = (-0.4, 0.025, 1)\,\mu\text{m}$. Other parameters are the same as in Fig. 1.

One of the most important properties of Airy beams is their self-healing capabilities. This has been demonstrated both experimentally and theoretically for free-space Airy beams [4,18], which are of a great significance for particle guidance. Here we demonstrate that introducing linear potentials for the manipulation of Airy beams does not compromise their self-healing properties. As shown in Eq. (3), the evolution of Airy beams in linear potentials obeys the Fresnel transform [16]. This means that we can understand the effects of perturbations on Airy beams by applying Babinet's principle [18,19]: $U_{pa}(x,z) = U_a(x,z) - U_p(x,z)$. This indicates that the diffraction pattern of the Airy beam with perturbations U_{pa} could be obtained directly through the diffraction patterns of the unperturbed plasmonic Airy beam U_a [as shown in Fig. 1(c-h)] and those of the perturbations U_p. If the perturbation is of small size and thus rapidly diffracting [4, 19], we have $U_p(x,z) \approx 0$ and $U_{pa}(x,z) \approx U_a(x,z)$. This means that in linear potentials the plasmonic Airy beam still possess self-healing capabilities as the free propagating Airy beams

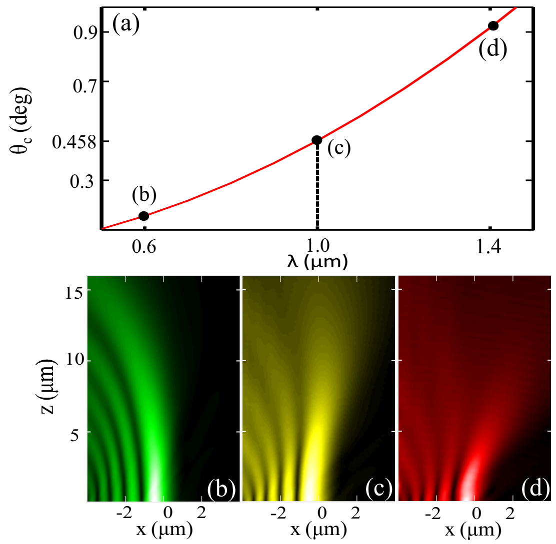

Fig. 3. (Color online) (a) Critical angle vs. wavelength in the range of $0.5-1.5\,\mu$m. (b-d) Numerical results for the field distributions ($|E|$) of three plasmonic Airy beams of wavelengths $0.6\,\mu$m, $1\,\mu$m and $1.4\,\mu$m presented in false colors. Parameters used are the same as in Fig. 1, with $\theta = 0.458°$, which is the critical angle at $\lambda = 1\,\mu$m (point c).

do. In Figs. 2(a-c) we show our numerical results for the diffraction patterns of the plasmonic Airy beams in the wedged metal-dielectric-metal structure where we place an ellipsoid particle ($\epsilon = 2.25$) at the position $(x, y, z) = (-0.4, 0.025, 1)\,\mu$m with $(R_x, R_y, R_z) = (0.1, 0.025, 0.1)\,\mu$m. Other parameters are the same as in Fig. 1. Importantly, we observe the self-healing properties in all three cases.

Finally, we study how the linear potential affects the propagation of plasmonic Airy beams of different wavelengths. As the critical angle θ_c depends on the wavelength, plasmonic Airy beams generated at different wavelengths will be steered into different directions. Fig. 3(a) shows the critical angles for the wavelength range of $0.5-1.5\,\mu$m at $h_0 = 60\,$nm. Shorter wavelength corresponds to smaller critical angle, and this means that the deflection of shorter wavelength plasmonic Airy beam is easier to control. For $\theta = 0.458°$ we obtain a critical linear potential that could compensate the deflection of the plasmonic Airy beam and force it to propagate straight. This is shown in Fig. 3(c) for $\lambda = 1\,\mu$m beam. When the corresponding critical angle is smaller, the deflection direction is reversed, as is shown in Fig. 3(b) for $\lambda = 0.6\,\mu$m. The action of the linear potential on longer wavelength plasmonic Airy beams is weaker, and then the deflection direction is only slightly modified, being still towards the positive x direction [see Fig. 3(d)]. As plasmonic Airy beams of different colors could be directed into different directions, the mechanism shown here could find possible applications in routing of signals on a photonic chip into different processing channels.

In conclusion, we have studied the propagation of Airy plasmon beams in linear optical potentials created by a transversely wedged metal-dielectric-metal structure. By employing an analytical model and direct numerical simulations, we have demonstrated that by changing the angle between the metallic plates, the deflection of the Airy plasmon could be enhanced, compensated, or even reversed without compromising their self-healing properties. We have also shown that the linear potential could be used to switch multi-color plasmonic Airy beams into different directions. It is worth mentioning that the mechanism shown here is not restricted to the field of plasmonics, and it could be extended to other problems of nanophotonics and graded-index structures, thus opening a door to various applications, such as optical transportation, subwavelength beam manipulation, light bullets control, and on-chip signal processing.

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