Dynamic Beam Steering from a Subwavelength Slit by Selective Excitation of Guided Modes

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Dynamic control of the direction of radiation of the light emanating from a subwavelength slit carved out of a thin metal film is experimentally demonstrated. This is achieved by selective excitation of the individual guided modes in the slit by setting the phase of three coherent laser beams. By changing the voltage across a piezoelement, we obtain unprecedented directional steering, without relying on any mechanical alignment of optical elements. The angular range over which this maximum can be swept is determined by the intensity setting of one of the incident beams. Through simulations, we show that this method can also be applied to steer the radiation from a square hole in two independent directions. Our method can be applied to create a directional nanoemitter which can selectively address one or more detectors, or as an optical switch in photonic circuits.

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The analysis of light transmission by small apertures has a venerable history [1–4]. The study of these nanosystems has been a subject of renewed interest since Ebbesen *et al.* [5] demonstrated experimentally that arrays of cylindrical cavities cut in metal plates allow a transmission that is much larger than is predicted from standard aperture theory. This so-called extraordinary optical transmission has been attributed to the coupling of light with surface plasmon polaritons [5–7] and to Fabry-Pérot cavitylike resonant modes [8,9]. Different optical phenomena, like beaming [10] and wave guiding [11], have been predicted and observed in these systems.

An important aspect of light transmission by nanoapertures is the *directionality* of the radiated field. A highly directional transmission has been achieved, for example, by using a single subwavelength slit surrounded by surface corrugations or grooves [12,13] and by varying the refractive index of neighboring subwavelength slits [14]. However, such schemes typically depend on a *static* built-in asymmetry in the setup to obtain radiation in a specific direction. Achieving *dynamic* beam steering would open up the possibility of fabricating phased-array nanoemitters with a strong and flexible directionality. In this Letter, we report a novel method to realize precisely this. We experimentally demonstrate beam steering in one direction from a slit. Furthermore, we show through simulations the possibility of beam steering in two directions from a square hole.

In a recent publication [15], a setup was demonstrated for selective excitation of two nonevanescent transverse magnetic (TM) modes in a subwavelength slit. This allowed for active manipulation of surface plasmons in the two launching directions perpendicular to the slit. Here, we report that by controlling the linear combination of the two modes (by varying their relative phase and amplitude), it is possible, for the first time, to dynamically steer the direction in which the slit radiates. This opens up the possibility of light switching on the nanoscale.

The principle of an active and dynamic control setup involves three coherent laser beams that impinge on a narrow slit etched in a metal film, as sketched in Fig. 1. The slit width is chosen such that only two nonevanescent TM modes (one symmetric, the other antisymmetric) are supported. The normally incident beam B excites only the

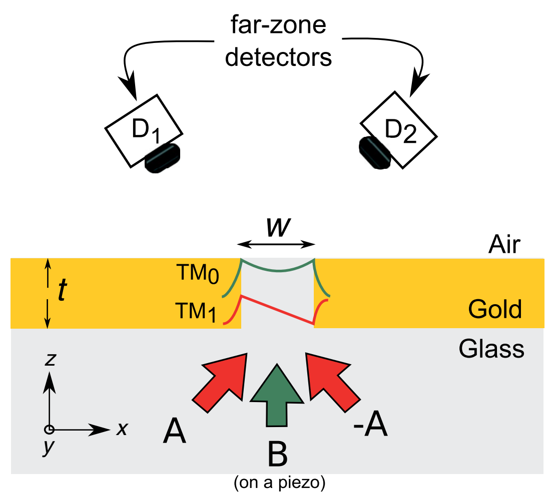

FIG. 1 (color online). A narrow slit in a gold film supports only two TM modes at $\lambda = 632.8$ nm, a symmetric TM_0 mode (green curve), and an antisymmetric TM_1 mode (red curve). Three coherent beams A, $-A$ (with opposite angle of incidence compared to A and π-phase shifted), and B are incident on the slit from the glass substrate. By varying the voltage across the piezoelement, the angle of maximum radiation can be varied dynamically. This can be used, for example, to selectively address detector D_1 or D_2.

symmetric TM_0 mode. The two obliquely incident beams A and $-A$ make equal angles with B. Beams A and $-A$ are set to the same amplitude, but they are out of phase. Although the two oblique beams individually excite both the symmetric and the antisymmetric modes, their superposition results in the cancellation of the symmetric mode and hence excites only the antisymmetric TM_1 mode. The path of beam B contains a mirror that is mounted on a piezoelement, which is used to vary the relative phase δ of the two guided modes.

As an approximate model for the beam-steering device, we consider a two-dimensional, perfectly conducting waveguide. In that case, we have for the y component of the magnetic field of the two modes in the exit plane ($z = t$) of the slit the expressions [16]

$$H_y(x) = C_0 \exp(i\delta), \quad |x| < w/2 \quad (TM_0),$$
$$H_y(x) = C_1 \sin(\pi x/w), \quad |x| < w/2 \quad (TM_1). \tag{1}$$

Here, the modal amplitudes C_0 and C_1 are both constants, and w denotes the slit width. Also, $H_y(x) = 0$ if $|x| > w/2$, for both modes. The intensity in the far zone at an angle θ with the normal of the metal film equals [17]

$$I(\theta) \propto \cos^2(\theta)|\tilde{H}_y(k\sin(\theta))|^2, \tag{2}$$

where $k = \omega/c$, with c being the speed of light, denotes the wave number associated with frequency ω, and the tilde indicates the Fourier transform with respect to x. Hence, when both modes are excited, we have

$$\tilde{H}_y(u) = \frac{C_0 \exp(i\delta)}{\pi u}\sin(uw/2) - i\frac{C_1}{\pi u}\cos(uw/2)\frac{u^2}{(\pi/w)^2 - u^2}, \tag{3}$$

with u the conjugate variable of x. Using Eqs. (2) and (3), we can calculate the radiation pattern of the slit as a function of the piezocontrolled phase δ. The direction in which the maximum intensity occurs is determined by the ratio of the modal amplitudes C_1/C_0 and *not* by the angle of incidence of the two beams A and $-A$. This is illustrated in Fig. 2. When $C_1/C_0 = 1.0$, the intensity can be targeted towards either $\theta \approx -16°$ (curve a) or $\theta \approx 16°$ (curve b) when the phase difference is $\delta = -\pi/2$ or $\pi/2$, respectively. Also, it is possible to distribute the intensity more equally by setting $\delta = 0$ (curve c). If the amplitude ratio $C_1/C_0 = 2.4$, the angular sweep of the radiation pattern is increased to $-27° < \theta < 27°$. In that case, however, minor side lobes of the radiation pattern appear.

In the experiment, we use a slit of width $w = 500$ nm in a gold film of thickness $t = 170$ nm, evaporated on a glass plate. The output of a 16 mW He-Ne laser operating at $\lambda = 632.8$ nm and with a coherence length of about 10 cm is divided into three beams. Each beam is passed through a linear polarizer to ensure that the three incident fields are all TM polarized. The combination of wavelength and slit

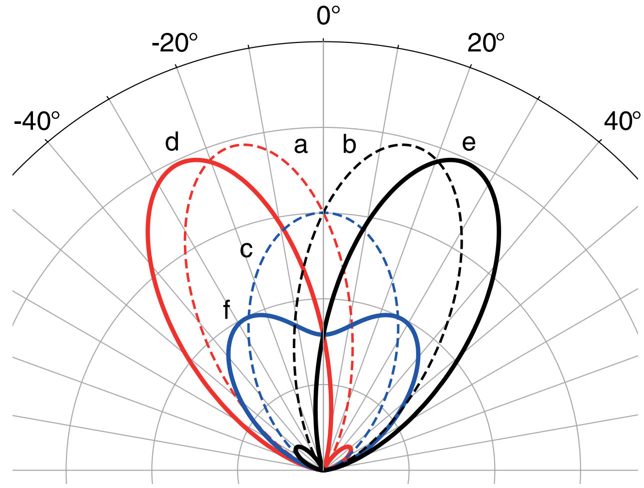

FIG. 2 (color online). Simulation of the radiation patterns for two different ratios of the modal amplitudes $C_1/C_0 = 1.0$ (dashed curves a, b, and c) and $C_1/C_0 = 2.4$ (solid curves d, e, and f). For the red, black, and blue curves, the phase difference $\delta = -\pi/2$, $\pi/2$, and 0, respectively. Zero degrees indicates the z direction, normal to the metal film.

width ensures that only the first two TM modes in the slit are nonevanescent. To achieve coherent mode excitation, the path difference between the arms is minimized by use of delay lines in arms A and B. The use of a laser with a significantly longer coherence length would make the delay lines superfluous. By mounting the last mirror in arm $-A$ on a micrometer linear translator, connected to a dc voltage source, the phase difference of the two oblique arms is set to π. The angle of incidence of the two oblique beams is $\pm 21°$. A smaller angle would have provided easier alignment but was not possible due to crowding of the optical elements. The last mirror in arm B is mounted on a piezoelement and connected to a dc voltage source with a range 0–300 V. This voltage determines the phase difference δ. In a separate interference experiment with the same laser, the piezovoltage scale was calibrated in terms of phase, yielding that a 120 V ramp corresponds to a π-phase shift in δ. A CCD camera, positioned at a distance of 3 mm from the sample, captures the radiation pattern with an angular field of view ranging from $-40°$ to $+40°$. The intensity of beam B, controlled by a gray filter, is set such that near the angles $+10°$ and $-10°$, the radiation patterns of the two individual modes have the same intensity (corresponding to $C_1/C_0 \approx 0.6$). Therefore, maximal constructive and destructive interference will take place in these two directions.

By increasing the voltage across the piezoelement, a dynamic beam steering is observed. In Fig. 3, the two maximally steered radiation patterns are shown. Their intensities peak at $\theta \approx -11°$ and $\theta \approx +9°$, respectively. There is also some contribution of the three directly transmitted beams at $-21°$, $0°$, and $21°$. This instrumental

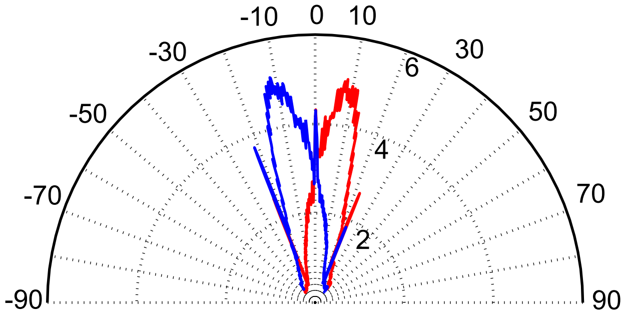

FIG. 3 (color online). Measurement of two maximally steered radiation patterns. For two different voltage settings, the peak intensity occurs at $\theta \approx -11°$ (blue curve) or at $\theta \approx +9°$ (red curve). The narrow peaks at $-21°$, $0°$, and $21°$ are due to direct transmission of the three incident beams.

artifact of the present geometry can be easily mitigated in future applications by using a thicker and hence more opaque gold film or by tighter focusing. If the voltage is set exactly in between the two values of the previous figure, a radiation pattern that is symmetric around the forward direction $\theta = 0°$ is produced, as is shown in Fig. 4. Note that our experimental results are in very good qualitative agreement with the simulations shown in Fig. 2.

Our technique of selective mode excitation can also be applied to obtain beam steering from a hole instead of a slit, as we will now demonstrate. This involves also transverse electric (TE) modes. Consider a square hole with sides $\lambda < a < \lambda\sqrt{5}/2$ in a perfect conductor. If the incident fields are all x polarized, only three modes can be excited, namely, TE_{01}, TE_{02}, and a combined TE_{11}-TM_{11} field, the latter such that $E_y = 0$ (see Sec. 8.4 of Ref. [18]). The x component of the electric field vector of the mn mode is (apart from an inconsequential prefactor)

$$E_{x,mn}(x, y) = \frac{n\pi}{a} \cos\left(\frac{m\pi x}{a}\right) \sin\left(\frac{n\pi y}{a}\right) \exp[i(k_z z - \omega t)]. \quad (4)$$

The symmetry properties of these three guided modes with respect to the center of the hole are summarized in Table I.

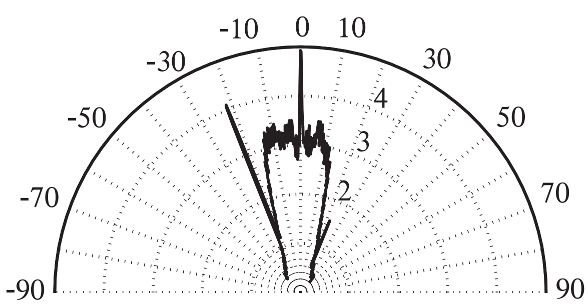

FIG. 4. Measurement of the radiation pattern for a voltage in between those of Fig. 3. The maximum intensity occurs near $\theta \approx 0°$.

From these symmetries, it is seen that we can selectively excite the TE_{01} mode with a normally incident beam B. The combined TE-TM_{11} mode can be excited with the help of two oblique beams A and $-A$ in the zx plane (as in Fig. 1). The beams A, $-A$, and B allow the radiation to be steered in the x direction. The TE_{02} mode can be excited with an additional pair of oblique beams C and $-C$ in the zy plane. The presence of these two beams adds the possibility of steering in the y direction. Note that in this three-mode configuration, the radiation pattern can be steered simultaneously in the horizontal and vertical directions.

The radiated electric field due to each mn mode is calculated using the far-field diffraction formula [see Eq. (10.109) of Ref. [18]]

$$\mathbf{E}_{mn}(\mathbf{r}) = \frac{ie^{ikr}}{2\pi r} \mathbf{k} \times \int \mathbf{n} \times \mathbf{E}_{mn}(\mathbf{r}') e^{i\mathbf{k}\cdot\mathbf{r}'} dx' dy', \quad (5)$$

where $\mathbf{k} = k\mathbf{r}/|\mathbf{r}|$, and the integral extends over the aperture. Since the normal $\mathbf{n}$ is along the z direction and $E_y = 0$ for all considered modes, it follows from Eq. (5) that only the x component is needed to obtain the far-zone field. If we denote the only nonzero component of the integral in Eq. (5) as $\tilde{E}_{mn}(k_x, k_y)$, we find (apart from overall prefactors) that

$$\tilde{E}_{01}(k_x, k_y) = \frac{2\sin(k_x a/2)}{k_x} \frac{2\pi/a}{\pi^2/a^2 - k_y^2} \cos(k_y a/2), \quad (6)$$

$$\tilde{E}_{02}(k_x, k_y) = \frac{2\sin(k_x a/2)}{k_x} \frac{4\pi/a}{4\pi^2/a^2 - k_y^2} \sin(k_y a/2), \quad (7)$$

$$\tilde{E}_{11}(k_x, k_y) = \frac{2k_x}{\pi^2/a^2 - k_x^2} \cos(k_x a/2) \frac{2\pi/a}{\pi^2/a^2 - k_y^2} \times \cos(k_y a/2). \quad (8)$$

The radiated intensity is given by sum of the three modal contributions, i.e.,

$$I(k_x, k_y) \propto (k^2 - k_y^2)|C_{01}\tilde{E}_{01} + C_{02}e^{i\delta_{02}}\tilde{E}_{02} + C_{11}e^{i\delta_{11}}\tilde{E}_{11}|^2, \quad (9)$$

where C_{mn} denotes the amplitude of the mn mode, and δ_{02} and δ_{11} indicate the phases of the TE_{02} and TE-TM_{11} modes with respect to the TE_{01} mode.

TABLE I. Symmetry properties of guided modes in a square hole.

Mode	x direction	y direction
TE_{01}	Symmetric	Symmetric
TE_{02}	Symmetric	Antisymmetric
TE-TM_{11}	Antisymmetric	Symmetric

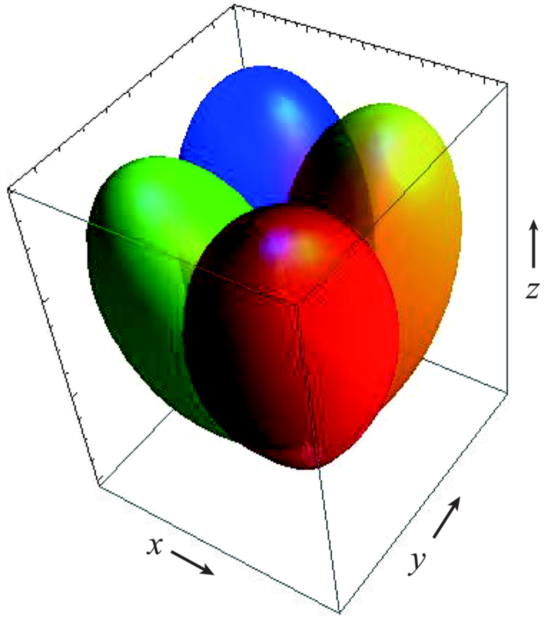

FIG. 5 (color online). Polar plot of three-dimensional radiation patterns showing the four extreme directions into which the radiation from a small square aperture can be steered. In all four cases, the intensity peaks at an angle of 18° with the forward direction. In this example, $C_{01} = 1$, $C_{02} = 0.6$, $C_{11} = 0.7$, and $a = 1.01\lambda$. The phase $\delta_{02} = 0$ (yellow and blue patterns) or π (red and green patterns), whereas $\delta_{11} = 0$ (yellow and red patterns) or π (blue and green patterns).

The four radiation patterns that are maximally steered in both the x and y directions are shown in Fig. 5. The yellow pattern, which is deflected in the positive x and y directions, is obtained by setting $\delta_{11} = \delta_{02} = 0$. It makes an angle $\theta = 18°$ with the forward direction. By gradually increasing δ_{02} to π, the radiation is steered along the y direction until it reaches its extreme position (red pattern). If we then increase δ_{11} to π, the pattern is steered along the x axis until its maximum position (green pattern). Decreasing δ_{02} back to 0 will eventually produce the blue pattern. By simultaneously varying δ_{11} and δ_{02}, the radiation can be moved in between these four extreme angles in a continuous manner.

In conclusion, we have demonstrated dynamic control of the radiation from a narrow slit in a metal film, by only manipulating the phase properties of beams incident onto the slit, and without any mechanical adjustment of optical elements. This is accomplished by the selective excitation of the individual guided modes in the slit. A voltage-controlled phase induces beam steering in one direction. The angular steering range is controlled by choosing the beam amplitudes. A simple wave-guiding model provides physical understanding and excellent qualitative agreement with the experimental results. Furthermore, this model shows that the same technique can also be applied to dynamically steer the radiation emanating from a small square hole in two directions. Unlike previously reported static configurations, our dynamic setup can be used as an optical switch in photonic circuitry.

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[1] Lord Rayleigh, Philos. Mag. **43**, 259 (1897).
[2] H. A. Bethe, Phys. Rev. **66**, 163 (1944).
[3] C. J. Bouwkamp, Rep. Prog. Phys. **17**, 35 (1954).
[4] M. Born and E. Wolf, *Principles of Optics* (Cambridge University Press, Cambridge, England, 1999), 7th ed., Sec. 11.8.3.
[5] T. W. Ebbesen, H. J. Lezec, H. F. Ghaemi, T. Thio, and P. A. Wolff, Nature (London) **391**, 667 (1998).
[6] J. A. Porto, F. J. García-Vidal, and J. B. Pendry, Phys. Rev. Lett. **83**, 2845 (1999).
[7] L. Martín-Moreno, F. J. García-Vidal, H. J. Lezec, K. M. Pellerin, T. Thio, J. B. Pendry, and T. W. Ebbesen, Phys. Rev. Lett. **86**, 1114 (2001).
[8] S. Astilean, P. Lalanne, and M. Palamaru, Opt. Commun. **175**, 265 (2000).
[9] Y. Takakura, Phys. Rev. Lett. **86**, 5601 (2001).
[10] H. J. Lezec, A. Degiron, E. Devaux, R. A. Linke, L. Martín-Moreno, F. J. García-Vidal, and T. W. Ebbesen, Science **297**, 820 (2002).
[11] H. F. Schouten, T. D. Visser, D. Lenstra, and H. Blok, Phys. Rev. E **67**, 036608 (2003).
[12] F. J. García-Vidal, L. Martín-Moreno, H. J. Lezec, and T. W. Ebbesen, Appl. Phys. Lett. **83**, 4500 (2003).
[13] C. Wang, C. Du, and X. Luo, Phys. Rev. B **74**, 245403 (2006).
[14] M. A. Vincenti, A. D'Orazio, M. Buncick, N. Akozbek, M. J. Bloemer, and M. Scalora, J. Opt. Soc. Am. B **26**, 301 (2009).
[15] S. B. Raghunathan, C. H. Gan, T. van Dijk, B. Ea Kim, H. F. Schouten, W. Ubachs, P. Lalanne, and T. D. Visser, Opt. Express **20**, 15 326 (2012).
[16] G. L. Pollack and D. R. Stump, *Electromagnetism* (Addison-Wesley, San Francisco, 2002), Sec. 14.1.
[17] H. F. Schouten, T. D. Visser, G. Gbur, D. Lenstra, and H. Blok, Phys. Rev. Lett. **93**, 173901 (2004).
[18] J. D. Jackson, *Classical Electrodynamics* (Wiley, New York, 1999), 3rd ed.