Active Two-Dimensional Steering of Radiation from a Nanoaperture

Laura S. Dreissen,† Hugo F. Schouten,† Wim Ubachs,‡,† Shreyas B. Raghunathan,§ and Taco D. Visser*,†,‡,§

†Department of Physics and Astronomy, LaserLaB, Vrije Universiteit, De Boelelaan 1081, 1081 HV Amsterdam, The Netherlands
‡Advanced Research Center for Nanolithography, Science Park 110, 1098 XG Amsterdam, The Netherlands
§ASML, De Run 6501, 5504 DR Veldhoven, The Netherlands
*Department of Physics and Astronomy, University of Rochester, Rochester, New York 14627, United States

ABSTRACT: We experimentally demonstrate control over the direction of radiation of a beam that passes through a square nanoaperture in a metal film. The ratio of the aperture size and the wavelength is such that only three guided modes can be excited, namely $TE_{01}$, $TE_{02}$, and a hybrid $TE_{11}/TM_{11}$ mode, the latter being such that $Ey = 0$. The $x$-component of the electric field of the $mn$-mode is given by the expression

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

where $\lambda$ denotes the free-space wavelength. If the incident field of frequency $\omega$ is $x$-polarized, only three modes can be excited, namely $TE_{01}$, $TE_{02}$, and a hybrid $TE_{11}/TM_{11}$ mode, the latter being such that $E_y = 0$. The $x$-component of the electric field of the $mn$-mode is given by the expression

$$(1) \lambda < a < \frac{\sqrt{5} \lambda}{2}$$

Several methods have been proposed to dynamically control the total transmission, in order to achieve all-optical switching. However, all these approaches lead to a static asymmetry of the radiated field. What has not been achieved so far is the possibility to dynamically steer the transmitted field in two orthogonal directions.

Here we report an experiment in which such steering is clearly demonstrated. Central to our approach is the selective excitation of guided modes in a wavelength-sized aperture in a metal film. We previously used a similar technique to control the direction in which surface plasmon polaritons are launched, and to obtain one-dimensional beam steering from a narrow slit. A nontrivial extension to two-dimensional steering has now been realized by using a square aperture illuminated by light with a wavelength such that only three guided modes can be excited. Using a spatial light modulator the phase of each of the three modes is controlled. The transmitted field, which is a coherent superposition of these modes, can thus be altered, leading to a change in the directionality of the emanating field.

The radiation from an aperture can be understood by analyzing the guided (i.e., nonevanescent) modes that it can sustain. Consider a square hole with sides $a$ in a perfect conductor such that

$$(2) \lambda < a < \frac{\sqrt{5} \lambda}{2}$$

$\frac{m \pi x}{a}$$ and $\frac{n \pi y}{a}$ are points in space, $t$ is a moment in time, $A_{mn}$ denotes the effective longitudinal wavenumber of the mode. In eq 2, the origin of the coordinates is taken at the bottom left corner of the aperture. The spatial symmetry properties of each mode with respect to the center of the aperture are listed in Table 1. It is seen that every mode displays a unique combination of symmetries in the $x$- and $y$-direction. As will be shown shortly, by considering modes with

Table 1. Symmetries of $E_x$ of Guided Modes

| mode          | $x$-direction | $y$-direction |
|---------------|---------------|---------------|
| $TE_{01}$     | even          | even          |
| $TE_{02}$     | even          | odd           |
| $TE_{11}/TM_{11}$ | odd           | even          |

Received: August 15, 2018
Revised: October 5, 2018
Published: October 29, 2018

© 2018 American Chemical Society
specific spatial symmetries in two dimensions, rather than one (as in 18 and 19), we can achieve active radiation steering in both the x- and y-direction. For our method it is essential that the aperture is square-shaped with sides given by eq 1. Only then does a degenerate, hybrid TE11/TM11 mode exist, and only then does the aperture allow exactly three guided modes with the right spatial symmetries. It is unclear if the same goal of selective excitation of non-evanescent modes with a prescribed symmetry could be achieved with a circular aperture.

The radiated electric field due to each mode can be calculated using the far-field diffraction formula

$$E_m(x,y) = \frac{ik}{2\pi r} \int_{-a/2}^{a/2} \int_{-a/2}^{a/2} E_m(r)e^{-ikr}dr'dy'$$

where

$$E_m(k_x, k_y) = \int_{-a/2}^{a/2} \int_{-a/2}^{a/2} \left[ \frac{m(a' + a/2)}{a} \right] \left[ \frac{n(a' + a/2)}{a} \right] e^{-i(k_x x + k_y y')} dx' dy'$$

$k$ is the free-space wavenumber, $k = kr/|r|$, $n = (0,0,1)$, and $T$ denotes the transpose. Also, a change of variables was applied to shift the origin of the coordinate system to the center of the aperture, and the time dependence has been suppressed for brevity. Carrying out the integration in eq 5 gives, apart from constant phase factors, that

$$E_{01}(k_x, k_y) = \frac{2}{\pi} A_{01} e^{-i\delta_1}$$

$$E_{02}(k_x, k_y) = \frac{2}{\pi} A_{02} e^{-i\delta_2}$$

$$E_{11}(k_x, k_y) = \frac{2}{\pi} A_{11} e^{-i\delta_3}$$

The radiated intensity $I = \mathbf{S} \cdot \mathbf{r}$ with $\mathbf{S}$ the Poynting vector, is given by the sum of the three modal contributions, that is

$$I(k_x, k_y) \propto (k^2 - k_z^2)A_{01}\bar{E}_{01} + A_{11}\bar{E}_{11} + A_{02}\bar{E}_{02}^2$$

where $\delta_1$ and $\delta_2$ indicate the phase of the TE11/TM11 and TE02 modes with respect to the TE01 mode at the exit plane of the aperture. By changing the phase $\delta_1$ we can steer the radiated intensity along the x-direction, whereas changing $\delta_2$ steers the radiation in the y-direction. This principle is illustrated in Figure 1 for the case of just two modes. The left-hand panel

Figure 1. Principle of radiation steering. (a) The far zone field amplitude along the y-direction due to the TE01 mode (blue) and the TE02 mode (orange). (b) Polar plot of the radiated intensity for three values of the relative phase: $\delta_2 = 0$ (blue), $\delta_2 = \pi/2$ (orange), and $\delta_2 = \pi$ (green). (a,b) The amplitude ratio is set to 0.6. (c) The ratio is increased to 2.0.

Figure 2. Schematic of the setup (a) with an electron microscope image of the gold sample (inset). The optical elements indicated with L1–L5 are lenses, LP are linear polarizers, ND are neutral density filters, and SPM refers to a plate with five holes (see text). (b) Layout of the opaque plate with five holes. The fields passing through these holes are labeled A, $-A$, B, C, and $-C$, respectively. (c) Calibration curve of the phase change imparted by the SLM as a function of the applied gray level/voltage setting.
to be very stable with the radiation pattern undergoing no change over a period of hours. This is a significant improvement of the stability obtained in 19. The efficiency of the setup, that is, the ratio of the power that is transmitted by the aperture and the power of the focused field, is largely determined by the Fresnel number of L5, the last lens.

Simulated and observed intensities captured with a charge-coupled device (CCD) camera are shown in Figure 4. The left-hand column shows the measured intensity patterns for maximum steering angles $-9.5^\circ$ and $9.5^\circ$ in two orthogonal directions. The right-hand column shows a simulation, based on eq 9, for four different settings of $\delta_1$ and $\delta_2$. The amplitudes were chosen to obtain a reasonable qualitative agreement between the simulations and the measurements. A less than perfect agreement is to be expected, because the simulated results are for the idealized case of a perfectly conducting metal film. This assumption leads to narrower modes and hence a broader radiation pattern. Also, the precise value of the mode amplitudes is not known. Furthermore, the uncertainty in the angles of observation is approximately $1^\circ$.

We note that for the particular SLM that was available, a change in the phase setting also produced a change in the amplitude and state of polarization. Therefore, variable neutral density filters were used to ensure that the mode amplitudes remained approximately equal after $\delta_1$ and $\delta_2$ had been varied. The use of a more advanced SLM device22,23 would make this amplitude adjustment and correction for polarization changes unnecessary.

In our earlier work, 19 we obtained one-dimensional steering from a nanoslit. The current setup is much simpler, involves only one optical path and is significantly more stable. A piezo element is no longer required, and the use of a thicker film has solved the issue of direct transmission leaking through the sample. And, of course, dynamic two-dimensional steering is now obtained.

We emphasize that our experiment provides a proof of principle of active, two-dimensional beam steering. The effect that we observe is a linear optical phenomenon, meaning that a high power laser, as was used in our setup, is not necessary. The phenomenon of beam steering is scalable to the low power levels that may be produced and handled “on-chip” in semiconductor devices. In our experiment, a laser with a very long coherence length ($2$ MHz optical bandwidth) was used. However, because our setup essentially uses a single optical
A shorter coherence length would also suffice. The 403 nm wavelength was chosen to obtain the full $2\pi$ phase range of the specific SLM that was used. Our technique can be applied at different wavelengths, provided that the inequalities (1) that relate the aperture size $a$ to the wavelength $\lambda$, are satisfied and the SLM provides a full $2\pi$ phase range. For example, for the choice of a telecom wavelength $\lambda = 1500$ nm, the required value of the aperture size would be $1500$ nm $\leq a \leq 1677$ nm. It is worth noting that the maximum steering angle can be tuned by changing the relative amplitudes of the modes, although larger steering angles are accompanied by a broadening of the radiation pattern and the onset of side lobes as was shown in Figure 1.

In conclusion, we have demonstrated dynamic control of the direction of radiation that emanates from a narrow square aperture in a metal film. This was accomplished by selective excitation of the three guided modes that such an aperture allows. Our method uses only an SLM and does not involve any mechanical adjustment of optical elements. A simple waveguiding model provides physical understanding and, even though it assumes perfect conductivity, gives good qualitative agreement with the experimental results. Unlike previously reported static configurations,15–17 our dynamic setup can be used as an optical switch in photonic circuitry in which light is sent to different ports, or in optical biosensors in which samples need to be scanned.

**AUTHOR INFORMATION**

**Corresponding Author**

*E-mail: t.d.visser@vu.nl.*

**ORCID**

Taco D. Visser: 0000-0002-6269-1068

**Notes**

The authors declare no competing financial interest.

**ACKNOWLEDGMENTS**

The authors wish to thank Andries Lof of AMOLF NanoCenter Amsterdam for fabrication of the sample. T.D.V. acknowledges support from the Air Force Office of Scientific Research under award number FA9550-16-1-0119.

**REFERENCES**

(1) Bethe, H. A. *Phys. Rev.* 1944, 66, 163–182.
(2) Bouwkamp, C. J. *Rep. Prog. Phys.* 1954, 17, 35–100.
(3) Ebbesen, T. W.; Lezec, H. J.; Ghaemi, H. F.; Thio, T.; Wolff, P. A. *Nature* 1998, 391, 667–669.
(4) Ghaemi, H. F.; Thio, T.; Grupp, D. E.; Ebbesen, T. W.; Lezec, H. J. *Phys. Rev. B: Condens. Matter Mater. Phys.* 1998, 58, 6779–6782.
(5) Schouten, H. F.; Visser, T. D.; Gbur, G.; Lenstra, D.; Blok, H. *Opt. Express* 2003, 11, 371–380.
(6) Schouten, H. F.; Visser, T. D.; Gbur, G.; Lenstra, D.; et al. *Phys. Rev. Lett.* 2004, 93, 173901.
(7) Dégiron, A.; Lezec, H. J.; Yamamoto, N.; Ebbesen, T. W. *Opt. Commun.* 2004, 239, 61–66.
(8) García-Vidal, F. J.; Moreno, E.; Porto, J. A.; Martín-Moreno, L. *Phys. Rev. Lett.* 2005, 95, 105901.
(9) Liu, H.; Lalanne, P. *Nature* 2008, 452, 728–731.
(10) García-Vidal, F. J.; Martín-Moreno, L.; Ebbesen, T. W.; Kuipers, L. *Rev. Mod. Phys.* 2010, 82, 729–787.
(11) Genet, C.; Ebbesen, T. W. *Nature* 2007, 445, 39–46.
(12) Kim, T. J.; Thio, T.; Ebbesen, T. W.; Grupp, D. E.; Lezec, H. J. *Opt. Lett.* 1999, 24, 256–258.
(13) Pacifici, D.; Lezec, H. J.; Atwater, H. A. *Nat. Photonics* 2007, 1, 402–406.
(14) Daniel, S.; Saastamoinen, K.; Saastamoinen, T.; Rahomaki, J.; Friberg, A. T.; Visser, T. D. *Opt. Express* 2015, 23, 22512–22519.
(15) García-Vidal, F. J.; Martín-Moreno, L.; Lezec, H. J.; Ebbesen, T. W. *Appl. Phys. Lett.* 2003, 83, 4500–4502.
(16) Wang, C.; Du, C.; Luo, X. *Phys. Rev. B: Condens. Matter Mater. Phys.* 2006, 74, 245403.
(17) Vincenti, M. A.; D’Orazio, A.; Buncick, M.; Akobzek, N.; Bloemer, M. J.; Scalora, M. *J. Opt. Soc. Am. B* 2009, 26, 301–307.
(18) Raghunathan, S. B.; Gan, C. H.; van Dijk, T.; Ea Kim, B.; Schouten, H. F.; Ubachs, W.; Lalanne, P.; Visser, T. D. *Opt. Express* 2012, 20, 15326–15335.
(19) Raghunathan, S. B.; Schouten, H. F.; Ubachs, W.; Kim, B.; Gan, C. H.; Visser, T. D. *Phys. Rev. Lett.* 2013, 111, 153901.
(20) Jackson, J. D. *Classical Electrodynamics*, 3rd ed.: Wiley: New York, 1999; Section 8.4 and Chapter 10.
(21) Gu, Z.; Vieitez, M. O.; van Duijn, E. J.; Ubachs, W. *Rev. Sci. Instrum.* 2012, 83, 053112.
(22) Chen, H.; Hao, J.; Zhang, B.; Xu, J.; Ding, J.; Wang, H. *Opt. Lett.* 2011, 36, 3179–3181.
(23) Moreno, I.; Davis, J. A.; Hernandez, T. M.; Cottrell, D. M.; Sand, D. *Opt. Express* 2012, 20, 364–376.