Surface-Plasmon Holographic Beam Shaping

Ido Dolev, Itai Epstein, and Ady Arie*
Department of Physical Electronics, Fleischman Faculty of Engineering, Tel-Aviv University, Tel-Aviv 69978, Israel
(Received 17 April 2012; published 16 November 2012)

Surface plasmon polaritons and free-space beams are often coupled through periodic gratings. Here we show that by employing holographic-based techniques for modulating the grating, one can systematically control the amplitude and phase of the free-space beam. Alternatively, arbitrarily shaped surface plasmon can be generated. By using gratings with different periods for the input and output coupling, we obtain a planar beam transformer, whose resonance angles are related through a generalized form of the Bragg law. Specifically, we demonstrate the coupling of surface plasmon polaritons into focused free-space beams, as well as into accelerating Airy beams and vortex beams.

DOI: 10.1103/PhysRevLett.109.203903 PACS numbers: 42.25.Fx, 42.40.Jv, 71.45.Gm, 73.20.Mf

Surface plasmon polaritons (SPPs) are surface electromagnetic waves that propagate at the interface between the metal and the dielectric, and are coupled to collective oscillation of the electron in the metal. SPPs play a key role in many applications due to their relatively long propagation distance and strong confinement to the surface [1]. For example, SPPs are used for chemical and biochemical sensors [2], solar cells [3], lasing spaser [4], surface-enhanced nonlinear mixers [5] cancer cell treatment [6], etc.

The dispersion curve of SPPs lies to the right of the light line of the dielectric, and therefore special excitation techniques are needed [1]. A widely used method is based on grating coupling: A metal grating with a period Λ on top of the metal layer provides an additional wave vector, so that an incoming electromagnetic wave at an angle θ will satisfy the condition of momentum conservation:

$$k_{\mathrm{dielectric}}\sin(\theta) + m\frac{2\pi}{\Lambda} = \pm\mathrm{Re}(k_{\mathrm{SP}}), \qquad (1)$$

where $k_{\mathrm{dielectric}}$ and k_{SP} are the dielectric and SPP wave numbers, respectively, and $m = \pm 1, \pm 2, \ldots, \pm N$.

In some cases, coupling between a plasmonic wave and special free-space beams, such as vortex beams [7,8] or accelerating Airy beams [9,10] or coupling light into a specific plasmonic wave, e.g., an Airy-plasmon wave [11–13] or a vortex-plasmon wave [14] is needed. Several methods have been demonstrated in the past for coupling between free-space light beams and plasmonic beams: Lezec *et al.* [15] have shown that light can be emitted at low divergence and controlled direction from a small metallic grating. This method was utilized by Yu *et al.* [16,17] for realizing semiconductor lasers with small divergence. Two-dimensional nanoantenna arrays [18] were recently shown to reflect and refract light at chosen angles that depend on discontinuities in the phase response of the nanoantenna array. By modulating the phase response in a spiral fashion, this method was utilized to couple an SPP into a free-space vortex beam.

In this Letter we consider a novel method for coupling SPPs to free-space beams of arbitrary shapes. The method provides a systematic algorithm for controlling the amplitude and phase of the desired free space beam. This method can be further generalized in the future to the case in which a free-space beam is coupled to an arbitrary shaped SPP. In addition, generalization of one of the most fundamental laws of diffraction, the Bragg law, is revealed when the SPP couples between two different gratings.

Let us consider the case of out-coupling a regular SPP into a free-space beam with a desired shape. The proposed method is based on concepts that were previously developed in the field of holography—the grating spatial frequency can be considered as a carrier frequency on which amplitude and phase are encoded. Specifically, for a binary modulated grating, the coupler function is given by [19]

$$h(x, y) = \frac{h_0}{2}\left\{1 + \mathrm{sgn}\left[\cos\left[\frac{2\pi}{\Lambda}x - \phi(x, y)\right] - \cos[\pi q(x, y)]\right]\right\}, \qquad (2)$$

where h_0 is the grating's ridge height and $\sin[\pi q(x, y)] = A(x, y)$, $A(x, y)$ and $\varphi(x, y)$ are the amplitude and the phase, respectively, of the Fourier transform of the desired wave front in the first diffraction order. $A(x, y)$ is normalized to the range 0–1, and $\varphi(x, y)$ is in the range 0–2π. In this case, the desired beam $FT\{A(x, y)\exp[i\phi(x, y)]\}$ is obtained at the first far-field diffraction order. We will refer to this coupler as a computer generated hologram (CGH) coupler, in analogy to Ref. [20]. We note that SPPs were used previously for writing holograms optically, either in emulsion films [21] or recently on a photoresistant layer [22], but in those cases, the grating was optically written in the light-sensitive dielectric layer and relied on interference of the SPP reference wave and a signal wave that was scattered from a real object. In our work, the grating is made in the metal using standard electronic lithography and the required pattern is computed; hence, we can reconstruct abstract arbitrary shapes without the need of a real object.

In addition, we do not need a light-sensitive dielectric, which makes the fabrication process much easier.

We coupled a free-space beam into the SPP with a periodic grating. The SPP then propagates a short distance and is out-coupled through the CGH coupler. According to Eq. (1), assuming the input and CGH couplers have periods Λ_{in}, Λ_{out}, respectively, the input and output waves obey the relation

$$k_0 \sin(\theta_{in}) \pm m_{in} 2\pi/\Lambda_{in} = \pm \mathrm{Re}(k_{SP}) \quad (3.1)$$

$$k_0 \sin(\theta_{out}) \pm m_{out} 2\pi/\Lambda_{out} = \pm \mathrm{Re}(k_{SP}) \quad (3.2)$$

Equations (3.1) and (3.2) can now be combined to a single equation that describes the relation between the incident and the refracted angles:

$$\sin\theta_{out} + \sin\theta_{in} = 2\pi/k_0(m_{out}/\Lambda_{out} - m_{in}/\Lambda_{in}), \quad (4)$$

which is a generalized form of the well-known Bragg diffraction condition for periodic gratings

$$\sin\theta_{out} + \sin\theta_{in} = 2\pi/k_0 m/\Lambda. \quad (5)$$

θ_{in} and θ_{out} are determined by the periods of the input and output grating, according to Eq. (1). In this case light will diffract to new diffraction angles which are different than the diffraction angles that arise from Bragg diffraction condition [Eq. (5)] of each periodic grating. We note that Eq. (4) is valid only when SPP is excited, hence, only TM mode that fulfills the SPP resonance conditions will give rise to the new diffraction order.

We demonstrated experimentally the concept of a binary CGH as an SPP output coupler, starting with 1D modulation at the axis that is perpendicular to the SPP propagation direction. The following patterns were fabricated (see Supplemental Material [23] for the fabrication process): (i) sample #1: 1D quadratic phase modulation: $t_1(x, y) = h_0/2(1 + \mathrm{sgn}\{\cos[2\pi f_{carrier} x + k_0 \cdot y^2/(2f)]\})$, where $f = 10$ cm. This design acts as a 1D lens and provides focusing in the y axis, with a focal length of 10 cm. (ii) sample #2: 1D cubic phase modulation, $t_2(x, y) = h_0/2(1 + \mathrm{sgn}\{\cos(2\pi \cdot f_{carrier} x + 75y^3/500^3)\})$. Since the Fourier transform of a function with a cubic phase is an Airy function [9], this design provides 1D Airy beam at the far field. In the last few years several methods were proposed in order to generate and control Airy beams [9,10,24,25]. Airy SPP were also predicted [11] and recently observed [12,13]. Yet, this is the first time, to our knowledge, that SPP is decoupled into an Airy beam in free space. (iii) sample #3: A reference sample with a periodic decoupling grating, $t_3(x, y) = h_0/2\{1 + \mathrm{sgn}[\cos(2\pi f_{carrier} x)]\}$ providing an output-coupled free-space wave without any modulation.

The size of each grating was $500 \times 500\ \mu\mathrm{m}^2$ and the period, $1/f_{carrier}$, was 0.98 μm.

Figure 1 presents an illustration of the samples and the diffraction orders (which are equal for all the samples since the carrier frequencies are equal in all three samples). Using rigorous coupled-wave analysis [26] the calculated incoming and outgoing angles for efficient coupling and decoupling of SPP, between air and silver at wavelength of 1047.5 nm, from and to free space are −54 degree and 2.3 degree, respectively. We note that from Eq. (5), when illuminating with angle of −54 degree the coupling grating has only zero-order diffraction (at 54 degree) and the decoupling grating has zero and −1 diffraction orders at 54 degree and −15.1 degree, respectively. The diffraction at 2.3 degree cannot be obtained separately from any one of the two gratings; however, it is obtained from the generalized Bragg law in Eq. (4). We also note that the SPP is propagating backwards with respect to the illumination direction.

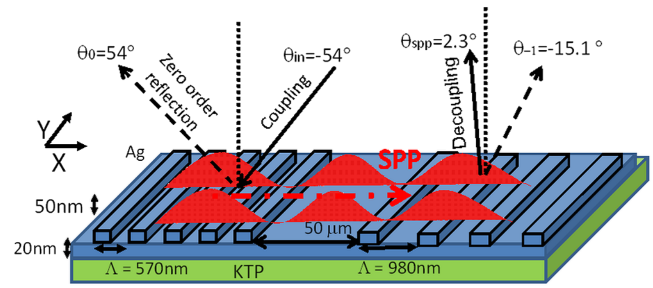

FIG. 1 (color online). Illustration of the sample layout, consisting of SPP coupling and decoupling gratings. Beam shaping is achieved by modulating the decoupling grating.

We verified that the gratings diffraction angles were consistent with the theoretical values (see Supplemental Material at Ref. [23] for the experimental setup, tuning, and efficiency). As expected from theory, we noticed the new plasmonic resonance diffraction order to the angle of 2.3 degree. As we noted before, the new diffraction order satisfies the generalized Bragg law [Eq. (4)] only for SPP resonance and does not exist in any of the periodic gratings separately. To verify that this is SPP resonance, we have changed the input light to TE polarization, and as a result, the new diffraction order disappeared together with the reflection dip.

We then used the $2f$ system ($f = 50$ mm) to optically Fourier transform the diffracted light. The cross section of the captured images from samples #2 and sample #3, are presented in Figs. 2(a) and 2(b), respectively. Figures 2(c) and 2(d) present a section of the designed gratings of these samples. The 1D Airy beam is clearly observed in the cubic modulation. We note that the decay rate is not symmetric in the propagation and transverse coordinates, even for the sample with the periodic output coupler. In the propagation direction the SPP is decoupled into free space; hence, it decays over a distance of several tens of microns, whereas in the orthogonal direction it limited by the coupler dimension and the illumination area. We will address this issue later on. This result shows the first 1D CGH of SPP and a new method to generate free-space Airy beams from SPPs.

Next we measured sample #1 with the quadratic phase modulation. We recorded the diffracted light in different positions with the $4f$ imaging system ($f_1 = 10$ mm,

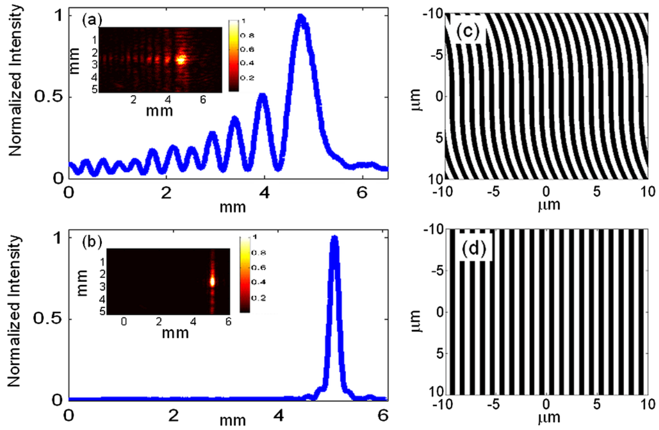

FIG. 2 (color online). Airy beam generation with CGH of SPP. Cross section of the beam from the cubically modulated grating (a) and the unmodulated grating (b). Insets show the full frame images (scale maximum is normalized to 1). (c) and (d) drawings of a segment from the decoupling cubically modulated and the unmodulated gratings, respectively.

$f_2 = 75$ mm). In sample #3 (the sample with periodic, nonmodulated output coupler) the beam expanded while propagating (not shown) while in sample #1 the beam converged in the modulation axis and expanded in the other axis. The cross section of the beam in the modulation axis is presented in Fig. 3(a) and top view of that image in Fig. 3(b). The full frame of the beam at $z = 0$ cm, $z = 10$ cm (at focus), and $z = 20$ cm are presented in Figs. 3(c)–3(e). The SPP decoupling grating acts in this case as 1D lens with focal length of 10 cm. This can be very useful for many applications in which the decoupled light is measured far from the sample or whenever it should be coupled into an optical fiber or a into any other small aperture device.

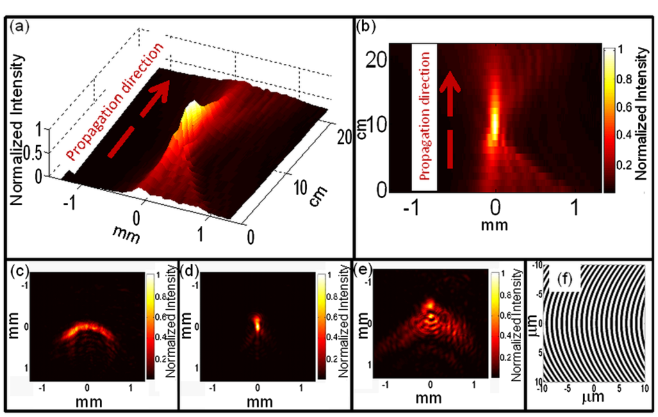

FIG. 3 (color online). 1D lens generated by output coupling of the SPP wave through a grating with quadratic phase. (a) Cross section of the free-space beam and (b) top view of the free-space beam. The full frame of the beam at $z = 0$ cm, $z = 10$ cm (at focus), and $z = 20$ cm (c), (d) and (e), respectively (scale maximum is normalized to 1). (f) Drawing of a segment from the decoupling grating.

Now let us consider different case where the phase modulation is in the propagation direction of the SPP, i.e., $t(x, y) = h_0/2(1 + \mathrm{sgn}\{\cos[2\pi f_{\mathrm{carrier}} \cdot x + \varphi(x)]\})$, where $\varphi(x)$ is an arbitrary function of x only. Phase modulation in the propagation direction is not trivial since the SPP is decaying rapidly due to the decoupling into free-space; hence, in the propagation direction, the field is not uniform (whereas in the transverse direction it is nearly uniform, since the grating size is smaller than the illumination area). This nonuniformity must be taken into account in order to generate the desired amplitude and phase profile. For this purpose we performed numerical simulations using a commercial finite element solver (COMSOL), to estimate the distance in which the SPP is decoupled from the grating and to quantify the out- coupling wave phase profile. The simulations contained the same parameters as in the experiment with a few exceptions (due to computation limitation): The SPP was launched as a boundary condition, the decoupling grating total length was 100 μm and the simulation was done in a 2D model with 1D grating modulation, i.e., $t(x) = h_0/2(1 + \mathrm{sgn}\{\cos[2\pi f_{\mathrm{carrier}} x + \varphi(x)]\})$. In Fig. 4(a) we present the cross section of the field intensity vs the propagation distance of the SPP. From the simulation we measured $\sim$30 μm distance, at the decoupling grating, in which the field intensity drops to half of its initial value. This is much smaller than the propagation length of the SPP in a planar interface (without a grating) between silver and air ($\sim$ 800 μm), meaning that the main decay mechanism of the field is induced by the grating. This explains the relatively low efficiency of the experiment and implies for several methods to improve efficiency such as: reducing the beam size, grating thickness optimization (to reduce absorption) or considering different SPP device in which the SPP propagate in smooth planar interface separated from the coupling gratings (e.g., between the metal and the substrate). Figures 4(d) and 4(e) present the phase profile of the outgoing wave for quadratic [$\varphi(x) \sim x^2$]

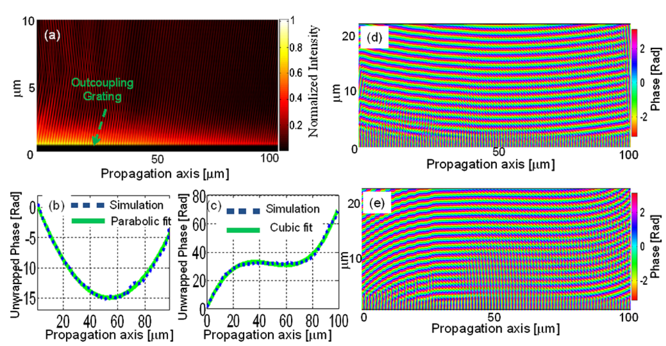

FIG. 4 (color online). Simulations of the decoupling SPP. (a) The out-coupled SPP intensity. The out-coupled unwrapped phase cross section vs propagating distance for (b) quadratically modulated and (c) cubically modulated gratings 20 μm above the gratings, respectively, and their full phase profile (d) and (e), respectively.

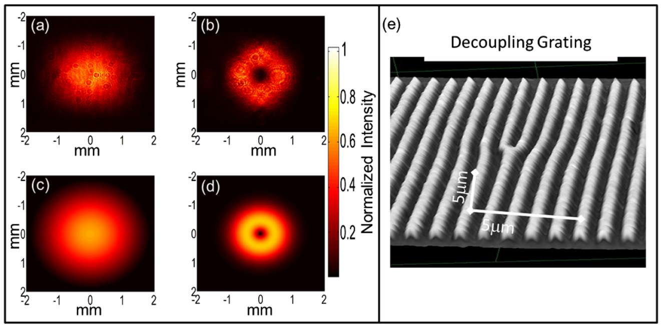

FIG. 5 (color online). Generation of a free-space vortex beam from an SPP. Measured beam intensity (a) without modulation of the decoupling grating and (b) with fork-shape modulation with a topological charge of $m = 1$. (c), (d) Corresponding theoretical shapes. (e) Image of the decoupling grating generating a free-space vortex beam, taken with a confocal microscope (x100, NA 0.95).

and cubic $[\varphi(x) \sim x^3]$ grating modulation, respectively. The unwrapped phase front [Figs. 4(b) and 4(c)] from the simulations clearly shows the quadratic and cubic curves for cases (a) and (b), meaning that the SPP was coupled out to free space with the desired phase front.

We demonstrated experimentally the usefulness of our method in the most general case of 2D modulation (both in the transverse and propagation directions, i.e., $t(x, y) = h_0/2(1 + \mathrm{sgn}\{\cos[2\pi f_{\mathrm{carrier}} x + \varphi(x, y)]\})$. According to the simulation, we fabricated 2D samples with decoupling area of $\sim 30 \times 30\ \mu\mathrm{m}^2$ (Figure 5(e)) with lateral shift of 30 μm. Two samples were fabricated—a reference sample without modulation and a sample with a fork shape which induces phase singularity and generates vortex beam in the far field [7,27]. We used a simplified version of Eq. (2) [27], in which the modulation was of the form $t(x,y) = h_0/2(1+\mathrm{sgn}\{\cos[2\pi f_{\mathrm{carrier}} x + m\theta(x,y)]\})$, where $\theta(x, y) = \tan^{-1}(x/y)$ and $m = 1$ is the topological charge of the generated beam. We then optically Fourier transform the out-coupled beam. Figure 5 presents the images from the nonmodulated reference coupler [Fig. 5(a)] and from the 2D fork-shaped coupler [Fig. 5(b)] and the theoretical shapes that were obtained by optically Fourier transform the corresponding theoretical phase profiles [Figs. 5(c) and 5(d)]. The vortex beam with a dark core is clearly seen in Fig. 5(b). Hence, the 2D CGH of SPP was realized.

So far we have discussed the case in which a nonmodulated SPP reference wave diffracts through the metal-based hologram into a special free-space beam; however, the same method can be also used in the future to shape the plasmonic wave [11,12,14]. Here, the modulated grating will serve as an input coupler, and will convert an input beam into a spatially modulated SPP. In this case, the free-space beam acts as the reference wave, whereas the SPP signal wave is diffracted from the hologram. To reach the desired pattern, the SPP should propagate to the far field, e.g., by passing through a plasmonic lens [28] and propagating to its focal plane. We also note that due to the reciprocity of Maxwell's equations, the out-coupled waves that we experimentally demonstrated here can be sent into the grating and will be efficiently coupled to SPP waves. For example, this would provide efficient coupling of accelerating Airy beam into SPP waves [11–13], and, in general, under the assumptions of the paraxial approximation, any free-space beam and any SPP with arbitrary shape can be coupled by using the CGH method.

We have shown that the resonance diffraction orders of two nearby periodic grating obey a generalized Bragg law of diffraction; however, a single quasiperiodic grating can produce the same phenomenon if its reciprocal lattice contains two different values [29]. Moreover, for the case of two separated periodic gratings, the new diffraction order that depends on both periods is extremely sensitive to the coupling of the SPP between the two gratings. We can therefore envision sensors that utilize this effect. The efficiency of the device can be further improved by the use of more complicated grating structures such as blazed gratings or by replacing the coupling grating with a waveguide SPP or a prism.

To conclude, we demonstrated experimentally beam engineering from SPP waves. An accelerating Airy beam, a focused beam, and a vortex beam with phase singularity were formed using this technique. The CGH of SPP gives new degrees of freedom for the design of beams coupled out of or in to SPP waves, and, in addition, the method can be expanded to shape SPP beams. Theoretical study and experimental verification of SPP resonance diffraction orders enabled us to generalize the well-known Bragg law of diffraction to the case where two periodic couplers are employed. The new CGH SPP technique can be very useful for the design of a new type of diffractive elements and for improving existing sensors based on SPP resonance and more.

We thank Y. Lilach for the e-beam writing. This work was supported by the Israel Science Foundation, Grant No. 960/05.

*Corresponding author.
ady@post.tau.ac.il

[1] S. A. Maier, *Plasmonics: Fundamentals and Applications* (Springer, Berlin, 2007).
[2] J. Homola, S. S. Yee, and G. Gauglitz, Sens. Actuators B Chem. **54**, 3 (1999).
[3] V. E. Ferry, L. A. Sweatlock, D. Pacifici, and H. A. Atwater, Nano Lett. **8**, 4391 (2008).
[4] N. I. Zheludev, S. L. Prosvirnin, N. Papasimakis, and V. A. Fedotov, Nature Photon. **2**, 351 (2008).
[5] S. Palomba and L. Novotny, Phys. Rev. Lett. **101**, 056802 (2008).
[6] C. Loo, A. Lowery, N. Halas, J. West, and R. Drezek, Nano Lett. **5**, 709 (2005).
[7] L. Allen, M. W. Beijersbergen, R. J. C. Spreeuw, and J. P. Woerdman, Phys. Rev. A **45**, 8185 (1992).

[8] P. S. Tan, X.-C. Yuan, J. Lin, Q. Wang, T. Mei, R. E. Burge, and G. G. Mu, Appl. Phys. Lett. **92**, 111108 (2008).
[9] G. A. Siviloglou, J. Broky, A. Dogariu, and D. N. Christodoulides, Phys. Rev. Lett. **99**, 213901 (2007).
[10] G. A. Siviloglou and D. N. Christodoulides, Opt. Lett. **32**, 979 (2007).
[11] A. Salandrino and D. N. Christodoulides, Opt. Lett. **35**, 2082 (2010).
[12] A. Minovich, A. E. Klein, N. Janunts, T. Pertsch, D. N. Neshev, and Y. S. Kivshar, Phys. Rev. Lett. **107**, 116802 (2011).
[13] P. Zhang, S. Wang, Y. Liu, X. Yin, C. Lu, Z. Chen, and X. Zhang, Opt. Lett. **36**, 3191 (2011).
[14] H. Kim, J. Park, S. W. Cho, S. Y. Lee, M. Kang, and B. Lee, Nano Lett. **10**, 529 (2010).
[15] H. J. Lezec, A. Degiron, E. Devaux, R. A. Linke, L. Martin-Moreno, F. J. Garcia-Vidal and T. W. Ebbesen, Science **297**, 820 (2002).
[16] N. Yu, J. Fan, Q. J. Wang, C. Pflügl, L. Diehl, T. Edamura, M. Yamanishi, H. Kan, and F. Capasso, Nature Photon. **2**, 564 (2008).
[17] N. Yu, R. Blanchard, J. Fan, F. Capasso, T. Edamura, M. Yamanishi, and H. Kan, Appl. Phys. Lett. **93**, 181101 (2008).
[18] N. Yu, P. Genevet, M. A. Kats, F. Aieta, J. P. Tetienne, F. Capasso, and Z. Gaburro, Science **334**, 333 (2011).
[19] W. H. Lee, Appl. Opt. **18**, 3661 (1979).
[20] B. R. Brown and A. W. Lohmann, Appl. Opt. **5**, 967 (1966).
[21] J. J. Cowan, Opt. Commun. **12**, 373 (1974).
[22] M. Ozaki, J. Kato, and S. Kawata, Science **332**, 218 (2011).
[23] See Supplemental Material at http://link.aps.org/supplemental/10.1103/PhysRevLett.109.203903 for samples fabrication and experimental setup, tuning and efficiency.
[24] T. Ellenbogen, N. Voloch-Bloch, A. Ganany-Padowicz, and A. Arie, Nature Photon. **3**, 395 (2009).
[25] I. Dolev, T. Ellenbogen, and A. Arie, Opt. Lett. **35**, 1581 (2010).
[26] M. G. Moharam, E. B. Grann, and D. A. Pommet, J. Opt. Soc. Am. A **12**, 1068 (1995).
[27] M. S. Soskin, V. N. Gorshkov, M. V. Vasnetsov, J. T. Malos, and N. R. Heckenberg, Phys. Rev. A **56**, 4064 (1997).
[28] Z. Liu, J. M. Steele, W. Srituravanich, Y. Pikus, C. Sun, and X. Zhang, Nano Lett. **5**, 1726 (2005).
[29] I. Dolev, M. Volodarsky, G. Porat, and A. Arie, Opt. Lett. **36**, 1584 (2011).