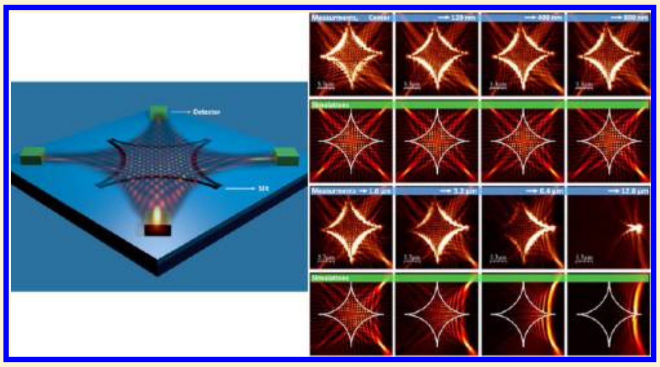
NANO LETTERS
Letter
pubs.acs.org/NanoLett

Pin Cushion Plasmonic Device for Polarization Beam Splitting, Focusing, and Beam Position Estimation

Gilad M. Lerman and Uriel Levy*

Department of Applied Physics, The Benin School of Engineering and Computer Science, The Center for Nanoscience and Nanotechnology, The Hebrew University of Jerusalem, Jerusalem, 91904, Israel

S *Supporting Information*



ABSTRACT: Great hopes rest on surface plasmon polaritons' (SPPs) potential to bring new functionalities and applications into various branches of optics. In this paper, we demonstrate a pin cushion structure capable of coupling light from free space into SPPs, split them based on the polarization content of the illuminating beam of light, and focus them into small spots. We also show that for a circularly or randomly polarized light, four focal spots will be generated at the center of each quarter circle comprising the pin cushion device. Furthermore, following the relation between the relative intensity of the obtained four focal spots and the relative position of the illuminating beam with respect to the structure, we propose and demonstrate the potential use of our structure as a miniaturized plasmonic version of the well-known four quadrant detector. Additional potential applications may vary from multichannel microscopy and multioptical traps to real time beam tracking systems.

KEYWORDS: *Surface plasmons, polarization, plasmonic circuiting, quadrant detector, plasmonic lens*

The field of plasmonics has become a widespread research topic with myriad applications, for example, in physics, engineering, chemistry, biology, medicine, material science, and environmental science.[1−5] Further development of plasmonic applications relies on the emergence of advanced passive and active plasmonic devices that can control the propagation of plasmonic fields. In particular, directional beaming, splitting, and focusing of plasmonic signals are prerequisites for plasmonic circuiting and plasmonic sensing applications. To date, such capabilities were demonstrated by several groups,[6−15] and future work is expected to yield even better devices. A common feature for many of these demonstrations is their dependency in the polarization state of the excitation source. The property of polarization sensitivity is inherent to plasmonic devices, owing to the fact that only a transverse magnetic (TM) polarized field can excite surface plasmons polaritons (SPP) waves. Indeed, the importance of polarization in plasmonic devices was addressed by several researchers, for example, in the context of transmission through nanoscale holes, amplification of SPPs, polarization dependency in plasmonic-enhanced fluorescence, plasmonic-enhanced recording and plasmonic lenses.[16−25]

In this paper, we demonstrate the integration of several functionalities in a single device. Our device is capable of splitting and focusing SPPs into different locations depending on the polarization of the excitation source. Having such a device in hands, one can control the propagation direction and focal position of the SPPs simply by modulating the polarization of the illuminating source. Therefore, our plasmonic device may play a role in plasmonic circuiting where there is a need to control the flow of SPPs and focus them into specific locations, for example, in order to couple them into a plasmonic waveguides or focus them into several spots for multichannel microscopy applications. Following the capability of polarization dependent splitting and focusing of SPPs, we propose and demonstrate the possible use of this plasmonic structure as a plasmonic quadrant detector. Owing to its small foot print, such a miniaturized four quadrant detector is expected to show features such as low dark current and fast operation speed, both of which are important in real time accurate tracking of optical beams.

The operation of our device can be understood by first referring to the work of Yin et al.[26] in which the focusing and guiding of SPPs were demonstrated by the use of a plasmonic structure made of set of nanometric holes milled into a thin metallic layer and arranged in a quarter circle shape. Upon the impinging of light on the structure SPPs are generated and, depending on the polarization of the incident light, constructively interfere to form a focal spot at the center of the quarter circle. An extended version of this structure is that of the plasmonic lens (PL).[21,27] The basic PL consists of a subwavelength slit that is milled into a metal surface in the

Received: December 1, 2012
Revised: February 14, 2013
Published: February 18, 2013

shape of a closed circle. When illuminated, the subwavelength slit converts the incident light into SPPs propagating toward the center of the circle to form a sharp hot spot. Following these demonstrations, we designed and fabricated a pin cushion structure consisting of four, quarter-circle-shaped, subwavelength slits milled into a thin metallic film with their centers facing outward of the geometrical center of the device. These structures can generate SPPs and focus them toward a predesigned position depending on the polarization of the incident light. Figure 1 shows a scanning electrons microscope

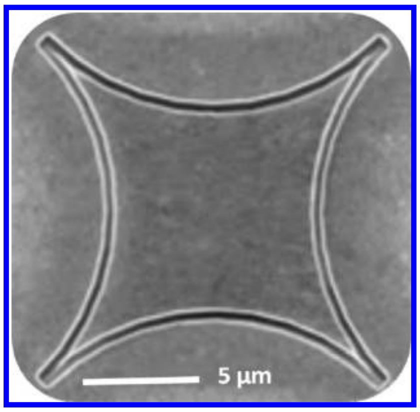


Figure 1. An SEM micrograph of a pin cushion structure with circles radius of 10 μm and slit width of 250 nm.

(SEM) micrograph of the fabricated device. As can be seen, it is composed of four identical nanometric slits milled into a silver layer having a quarter circle shapes and arrange in a way to form a pin cushion structure. The radius of each slit is 10 μm and its width is 250 nm. When light is impinging on the slits SPPs are generated on the surface. These SPPs can interfere constructively at the center of each of the quarter circle slits. Clearly, the coupling strength of light into SPPs depends on the polarization of light with respect to the direction of the slit. Only TM polarized light (i.e., magnetic field parallel to the slit and electric field perpendicular to the slit) will contribute to the excitation of SPPs.

In order to calculate the field distribution resulted from the pin cushion structure we used the Green function approach[28] so that

$$U(x, y) \alpha \iint E_{\text{inc}}(x', y') G(|r - r'|) \mathrm{d}x' \, \mathrm{d}y' \tag{1}$$

Where U is the z-component of the electric field, E_{inc} is the normal component of the electric field with regard to the slit incident on the pin cushion slits, G is the green function of the problem, $|r - r'|$ is the distance between the observation point and the sources located on the slit, and the integration is performed over the pin cushion slits boundary. The SPPs propagate on the metallic surface and thus the two-dimensional green function needs to be used, that is, the zeroth order Hankel function of the first kind[29,30] $H_0^{(1)} = J_0(k|r - r'|) + iN_0(k|r - r'|)$ where k is the plasmonic wave vector and J_0 and N_0 are the zeroth order Bessel functions of the first and the second kind, respectively. Assuming a constant electric field impinging on the slit, SPPs will be generated according to the projection of the polarization direction along the normal to the slit so each point along the slits is a point source for the diffraction pattern with polarization based amplitude. We calculated the electric field distribution generated by the pin cushion structure for the vacuum wavelength of λ_0 = 1064 nm. At this wavelength, the wave vector of a plasmonic mode running on the interface between silver and air is nearly equal to the vacuum wavenumber with negligible loss over the propagation distances that are considered here.

Figure 2a,b shows the calculated intensity of the z-polarized (out of plane) electric field component $|E_z|^2$ for the case of illuminating a pin cushion structure with circles radius of 10 μm by a linearly polarized field at the wavelength of 1064 nm. Because SPPs are generated only from sections where the incident polarization is TM with regard to the slits it can be seen that two focal spots are formed along a line parallel to the incident polarization direction (shown by the white arrow). If the polarization direction is rotated by 90°, the two focal spots will appear at the centers of the other two circles and the whole field pattern will be rotated by 90°, as can be seen in Figure 2b. This effect makes the pin cushion structure a very attractive plasmonic device as it can be used as a plasmonic polarized beam splitter, splitting the SPPs into perpendicular directions, depending on the polarization content of the incident light, and in addition it focuses the SPPs into small spots, for example, for the purpose of launching plasmonic signals into small plasmonic waveguides, enhancing light matter interactions, or for detection by a small plasmonic detector. Figure 2c,d shows the near-field scanning optical microscope (NSOM) measurements on the surface of a pin cushion device corresponding to the simulation results shown in Figure 2a,b, respectively. The two focal spots along the polarization direction and the nice agreement to the simulation results are easily noticed. The high intensity apparent in the measurements near the slits of the pin cushion structures is probably due to the localization of energy in the slits and the direct radiation of the light from the slit into free space. This effect was not taken into account in the simulations.

As discussed and demonstrated, the locations of the focal spots generated by the pin cushion device are determined by the geometry of the slits and the direction of polarization of the incident beam of light. One can use this feature for additional applications other than splitting and focusing of SPPs. Specifically, the pin cushion device may become an attractive choice as a plasmonic four quadrant detector. When illuminated with either circularly polarized or unpolarized light, four focal hot spots are obtained, each located at the center of the corresponding quarter circle of the pin cushion structure. Yet, the intensity of each focal spot may vary, depending on the position of the incident beam with respect to the structure. If the incident Gaussian beam is located at the center of the pin cushion structure, the intensity of the four focal spots is expected to be identical. Nevertheless, if the Gaussian beam is shifted from the center of the structure the intensity at each focal spot will increase or decrease depending on the new position of the incident beam. Measuring the intensity at each of the four focal spots by on-chip detectors located at the center of the four quarter circles provides useful information on the position of the beam and may enable to use the pin cushion structure as a plasmonic quadrant detector capable of measuring the relative position of the illuminating beam with respect to the center of the structure. A schematic of the proposed plasmonic quadrant detector is shown in Figure 3.

An appealing approach for the realization of such a device would be the integration of the pin cushion device with a set of four plasmonic enhanced Schottky detectors.[31−33] These hot electron based devices can detect the propagating plasmons via

dx.doi.org/10.1021/nl304431y | Nano Lett. 2013, 13, 1100−1105

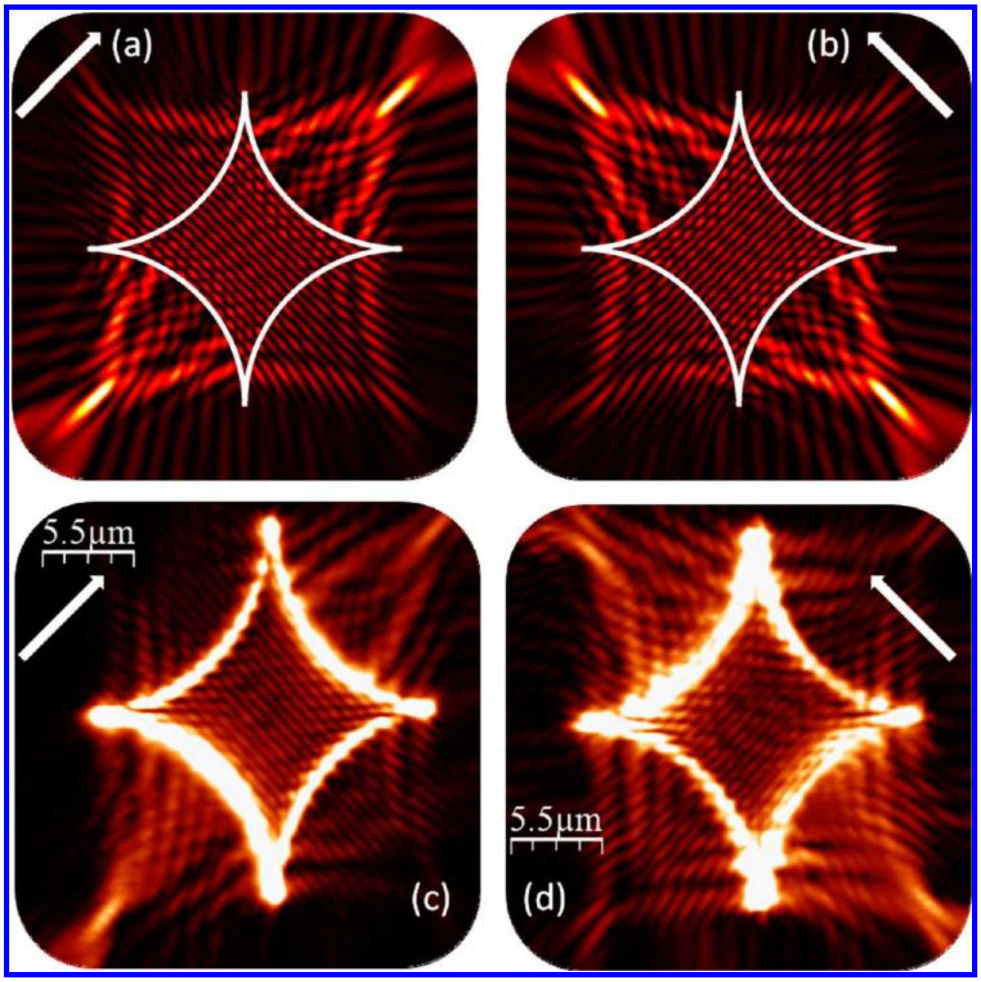


Figure 2. A pin cushion structure with circles radius of 10 μm and slit width of 250 nm illuminated with linearly polarized 1064 nm light. (a,b) Computer simulation results showing the out-of-plane field distribution intensity; (c,d) experimental NSOM measurements, respectively. The white arrows represent the polarization direction of the illuminating light.

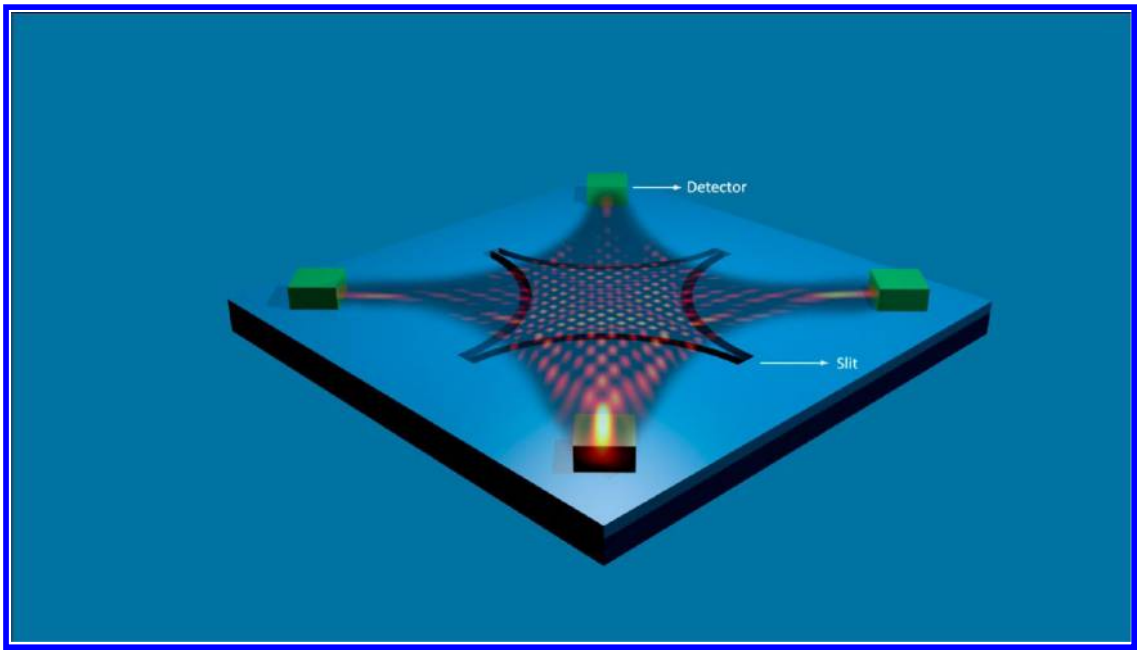


Figure 3. Schematic of proposed plasmonic quadrant detector capable of measuring the relative position of the illumination beam with respect to the center of the structure.

dx.doi.org/10.1021/nl304431y | *Nano Lett.* 2013, 13, 1100−1105

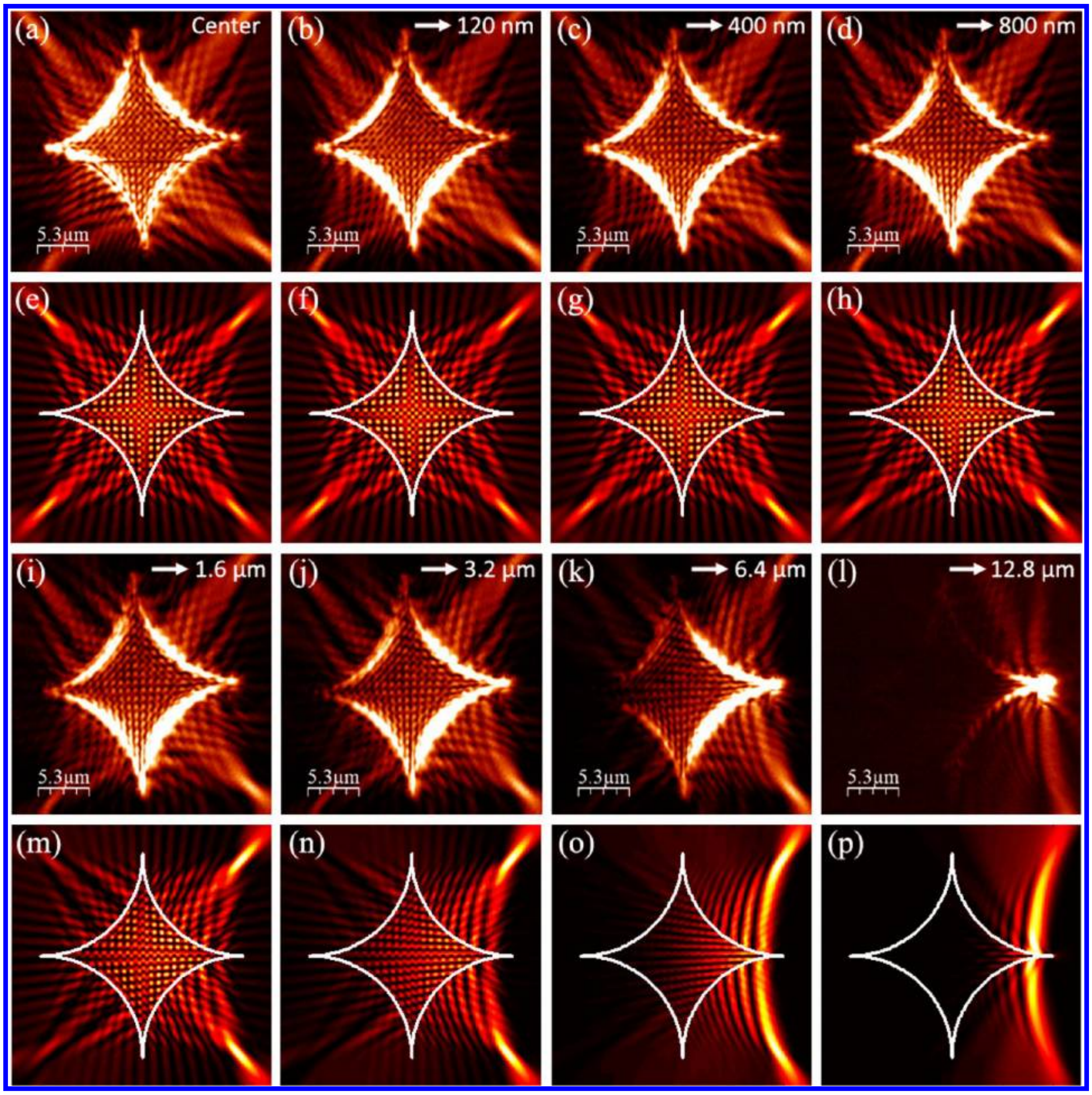


Figure 4. (a−d) and (i−l) NSOM measurements for several values of relative shifts between the device and the illuminating beam. The shift values are noted in the figure. (e−h) and (m−p) The corresponding computer simulations showing the expected intensity pattern of the out of plane electric field component.

the mechanism of internal photoemission. In particular, such detectors are promising for the operation at near IR wavelengths, beyond the operation range of conventional silicon photo detectors. In designing such an integrated device one should seek to optimize the optical energy arriving at the detectors. This can be done by using grating couplers consisting of several grating ridges rather than a single slit for each quadrant. Such plasmonic grating couplers can provide coupling efficiency of few tens of percents. It was shown that even a single slit, if properly designed, can couple ~40% of the incident light to SPP mode.[34] Moreover, the propagation length of the SPP mode should be kept short, such that ohmic loss will not play a major role in attenuating the SPP signals.

While the integration of nanodetectors into the structure is beyond the scope of this work, the feasibility of the proposed concept is demonstrated by illuminating the pin cushion structure with a circularly polarized Gaussian beam, scanning its position with regard to the structure and performing NSOM scans for several representing cases of relative shift between the center of the illuminating beam and the center of the device. From these scans, we were able to extract the intensity at each of the four focal spots for each of these representing cases. Figure 4a−d,i−l shows the obtained NSOM measurements for several positions of the illuminating beam with regards to the center of the device. Figure 4e−h,m−p shows the corresponding computer simulations. As can be seen the intensity pattern varies significantly when the center of the illuminating beam is shifted from the center. These variations are the basis for the operation of the pin cushion device as a four quadrant detector.

In order to extract the exact location of the illuminating beam with regards to the center of the devices, we used a known procedure[35] and adapted it to our needs (see Supporting

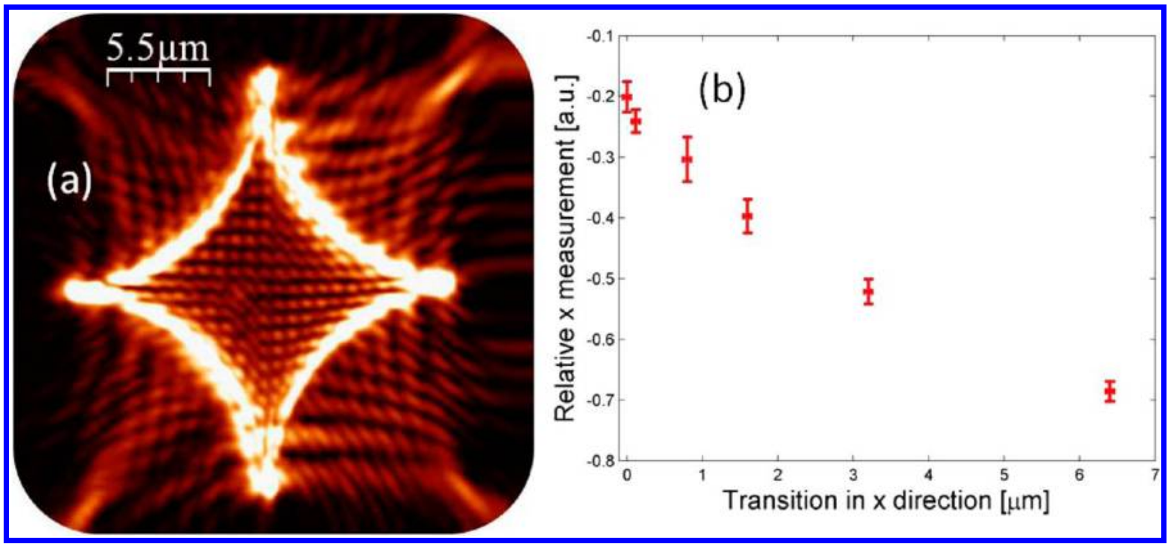


Figure 5. (a) An NSOM scan of the SPPs intensity generated when the device is illuminated by a circularly polarized Gaussian beam positioned as close as possible to the center of the pin cushion structure. (b) The relative x-position of the illumination Gaussian beam as a function of the actual beam shift. The shift values were calculated from the measured NSOM scans as explained in the Supporting Information. The horizontal error bars correspond to the accuracy limit of the translation stage and the vertical error bars were estimated by performing the calculation over different regions around the four focal points.

Information for more details). The result of this procedure is shown in Figure 5b, alongside with the measured NSOM scan for the case where the beam was aligned with the center of the device (Figure 5a). As expected, it can be seen that a focal spot is generated at the center of each quarter circle. Additionally, the intensity pattern within the pin cushion device consists of a 2D grid rather than lines as observed for the case of linear polarization illumination (Figure 2). While the intensity of each of the focal spots was expected to be equal, one can clearly observe variations in intensities between the various spots. This is probably the result of alignment inaccuracies (i.e., the sample is probably not perfectly aligned with the center of the beam), nonuniform illumination, and imperfections in sample fabrication. Using the standard method of quadrant detectors for calculating the position of the beam,[31] we calculated the relative position of the beam and verified that indeed we can obtain a relative measurement of the beam's position (see Supporting Information). This is shown in Figure 5b presenting the measured relative x-position of the illumination Gaussian beam (as calculated from the four values of intensities in the vicinity of the four focal spots) as a function of the actual beam shift. As can be seen, the relative measured position varies monotonically with the change in actual beam position. This result indicates the feasibility of using the structure as a four quadrant detector. Owing to the small foot print and the small size of each focal spots, the integrated detectors can be reduced to the micrometer size scale, providing significant advantages such as low dark current and high speed.

To summarize, we have proposed, fabricated, and demonstrated a pin cushion-shaped plasmonic device capable of splitting SPPs based on the polarization of the illuminating beam of light, direct them to different directions, and focus them into a small focal spot. Using computer simulations and near-field experimental characterization, it was shown that this structure split orthogonally polarized light into orthogonal directions. Furthermore, by illuminating the device with circularly polarized light, four focal spots are obtained at the centers of each of the quarter circles composing the pin cushion device. The relative intensity of the four focal spots varies as a function of the relative shift between the illuminating beam of light and the center of the structure. This property is used to demonstrate the potential use of our device as a plasmonic quadrant detector.

Methods. *Sample Preparation.* The pin cushion plasmonic structure was fabricated by depositing 200 nm thick Ag layer on top of a glass surface followed by a focused ion beam (FIB) milling to define a 250 nm wide transparent slits in the metal. The pin cushion shape is defined by the cross points of four circles with radius R whose centers are located at a distance of $\sqrt{2}$R from the center of the device. Each quarter circle slit has a radius of 10 μm.

NSOM Measurements. Linearly polarized 1064 nm light emerging from an Nd:YAG laser was focused by a 4× objective lens onto the sample, which was situated on a translation stage of an inverted microscope. The sample was raster scanned by an NSOM system (Nanonics Ltd.) using a metal-coated tapered fiber probe with a circular aperture of 250 nm diameter. For the quadrant detector measurements, the light was circularly polarized by a quarter wave plate and the sample position was controlled by a translation stage with 100 nm resolution (Prior scientific) and was raster scanned at several selected values of relative shift between the sample and the illuminating beam.

■ ASSOCIATED CONTENT

Ⓢ Supporting Information

Additional information and figures. This material is available free of charge via the Internet at http://pubs.acs.org.

■ AUTHOR INFORMATION

Corresponding Author

*E-mail: ulevy@cc.huji.ac.il.

Notes

The authors declare no competing financial interest.

■ ACKNOWLEDGMENTS

The authors acknowledge financial support from the AFOSR.

■ REFERENCES

(1) Maier, S. A. *Plasmonics: fundamentals and applications*; Springer: New York, 2007; p xxiv, 223.
(2) Vivekchand, S. R. C.; Engel, C. J.; Lubin, S. M.; Blaber, M. G.; Zhou, W.; Suh, J. Y.; Schatz, G. C.; Odom, T. W. *Nano Lett.* **2012**, *12* (8), 4324−4328.
(3) Anker, J. N.; Hall, W. P.; Lyandres, O.; Shah, N. C.; Zhao, J.; Van Duyne, R. P. *Nat. Mater.* **2008**, *7* (6), 442−453.
(4) Fei, Z.; Rodin, A. S.; Andreev, G. O.; Bao, W.; McLeod, A. S.; Wagner, M.; Zhang, L. M.; Zhao, Z.; Thiemens, M.; Dominguez, G.; Fogler, M. M.; Neto, A. H. C.; Lau, C. N.; Keilmann, F.; Basov, D. N. *Nature* **2012**, *487* (7405), 82−85.
(5) Zhou, W.; Lee, J.; Nanda, J.; Pantelides, S. T.; Pennycook, S. J.; Idrobo, J. C. *Nat. Nanotechnol.* **2012**, *7* (3), 161−165.
(6) Liu, Z. W.; Steele, J. M.; Lee, H.; Zhang, X. *Appl. Phys. Lett.* **2006**, *88*, 171108.
(7) Lezec, H. J.; Degiron, A.; Devaux, E.; Linke, R. A.; Martin-Moreno, L.; Garcia-Vidal, F. J.; Ebbesen, T. W. *Science* **2002**, *297* (5582), 820−822.
(8) Liu, J. S. Q.; Pala, R. A.; Afshinmanesh, F.; Cai, W. S.; Brongersma, M. L. *Nat. Commun.* **2011**, *2*, 525.
(9) Choi, S. B.; Park, D. J.; Jeong, Y. K.; Yun, Y. C.; Jeong, M. S.; Byeon, C. C.; Kang, J. H.; Park, Q. H.; Kim, D. S. *Appl. Phys. Lett.* **2009**, *94*, 063115.
(10) Caglayan, H.; Ozbay, E. *Opt. Express* **2008**, *16* (23), 19091−19096.
(11) Xu, T.; Zhao, Y. H.; Gan, D. C.; Wang, C. T.; Du, C. L.; Luo, X. G. *Appl. Phys. Lett.* **2008**, *92*, 101501.
(12) Wang, Y.; Wang, L. L.; Li, J. Q.; Zhai, X.; Wang, L.; Xiang, D.; Wan, Q.; Meng, B. *Opt. Commun.* **2010**, *283* (9), 1777−1779.
(13) Evlyukhin, A. B.; Bozhevolnyi, S. I.; Stepanov, A. L.; Kiyan, R.; Reinhardt, C.; Passinger, S.; Chichkov, B. N. *Opt. Express* **2007**, *15* (25), 16667−16680.
(14) Lee, B.; Kim, S.; Kim, H.; Lim, Y. *Progr. Quantum Electron.* **2010**, *34* (2), 47−87.
(15) Gjonaj, B.; Aulbach, J.; Johnson, P. M.; Mosk, A. P.; Kuipers, L.; Lagendijk, A. *Nat. Photonics* **2011**, *5* (6), 360−363.
(16) Degiron, A.; Lezec, H. J.; Yamamoto, N.; Ebbesen, T. W. *Opt. Commun.* **2004**, *239* (1−3), 61−66.
(17) Garcia-Vidal, F. J.; Moreno, E.; Porto, J. A.; Martin-Moreno, L. *Phys. Rev. Lett.* **2005**, *95*, 103901.
(18) Ming, T.; Zhao, L.; Yang, Z.; Chen, H. J.; Sun, L. D.; Wang, J. F.; Yan, C. H. *Nano Lett.* **2009**, *9* (11), 3896−3903.
(19) Berini, P.; De Leon, I. *Nat. Photonics* **2012**, *6* (1), 16−24.
(20) Zijlstra, P.; Chon, J. W. M.; Gu, M. *Nature* **2009**, *459* (7245), 410−413.
(21) Lerman, G. M.; Yanai, A.; Levy, U. *Nano Lett.* **2009**, *9* (5), 2139−2143.
(22) Lerman, G. M.; Yanai, A.; Ben-Yosef, N.; Levy, U. *Opt. Express* **2010**, *18* (10), 10871−10877.
(23) Shitrit, N.; Nechayev, S.; Kleiner, V.; Hasman, E. *Nano Lett.* **2012**, *12* (3), 1620−1623.
(24) Wang, X. L.; Wang, P.; Chen, J. X.; Lu, Y. H.; Ming, H.; Zhan, Q. W. *Appl. Phys. Lett.* **2011**, *98*, 023701.
(25) Chen, W. B.; Zhan, Q. W. *Opt. Lett.* **2009**, *34* (6), 722−724.
(26) Yin, L. L.; Vlasko-Vlasov, V. K.; Pearson, J.; Hiller, J. M.; Hua, J.; Welp, U.; Brown, D. E.; Kimball, C. W. *Nano Lett.* **2005**, *5* (7), 1399−1402.
(27) Liu, Z. W.; Steele, J. M.; Srituravanich, W.; Pikus, Y.; Sun, C.; X, Z. *Nano Lett.* **2005**, *5* (9), 1726−1729.
(28) Born, M.; Wolf, E. *Principles of optics: electromagnetic theory of propagation, interference and diffraction of light*, 7th expanded ed.; Cambridge University Press: Cambridge, 1999; p xxxiii, 952.
(29) Morse, P. M.; Feshbach, H. *Methods of theoretical physics*; McGraw-Hill: Boston, MA, 1999; p v..
(30) Chang, S. H.; Gray, S. K.; Schatz, G. C. *Opt. Express* **2005**, *13* (8), 3150−3165.
(31) Knight, M. W.; Sobhani, H.; Nordlander, P.; Halas, N. J. *Science* **2011**, *332* (6030), 702−704.
(32) Akbari, A.; Tait, R. N.; Berini, P. *Opt. Express* **2010**, *18* (8), 8505−8514.
(33) Goykhman, I.; Desiatov, B.; Khurgin, J.; Shappir, J.; Levy, U. *Nano Lett.* **2011**, *11* (6), 2219−2224.
(34) Lalanne, P.; Hugonin, J. P.; Rodier, J. C. *Phys. Rev. Lett.* **2005**, *95* (263902), 1−4.
(35) Manojlovic, L. M. *Appl. Opt.* **2011**, *50* (20), 3461−3469.