Imaging slit-coupled surface plasmon polaritons using conventional optical microscopy

R. Mehfuz, F. A. Chowdhury, and K. J. Chau*

School of Engineering, The University of British Columbia, Kelowna, British Columbia, Canada

*keneth.chau@ubc.ca

Abstract: We develop a technique that now enables surface plasmon polaritons (SPPs) coupled by nano-patterned slits in a metal film to be detected using conventional optical microscopy with standard objective lenses. The crux of this method is an ultra-thin polymer layer on the metal surface, whose thickness can be varied over a nanoscale range to enable controllable tuning of the SPP momentum. At an optimal layer thickness for which the SPP momentum matches the momentum of light emerging from the slit, the SPP coupling efficiency is enhanced about six times relative to that without the layer. The enhanced efficiency results in distinctive and bright plasmonic signatures near the slit visible by naked eye under an optical microscope. We demonstrate how this capability can be used for parallel measurement through a simple experiment in which the SPP propagation distance is extracted from a single microscope image of an illuminated array of nano-patterned slits on a metal surface. We also use optical microscopy to image the focal region of a plasmonic lens and obtain results consistent with a previously-reported results using near-field optical microscopy. Measurement of SPPs near a nano-slit using conventional and widely-available optical microscopy is an important step towards making nano-plasmonic device technology highly accessible and easy-to-use.

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Contributing factors to its widespread use in commercial plasmonic chips [12]. The Kretschmann configuration boasts simplicity of operation and low-cost of implementation, detected by viewing the top surface of the metal film under an optical microscope [10, 11].

A beam of polarized light incident at a critical angle onto the metal film achieves momentum matching with SPPs on the other side or adjacent to an oil-immersion objective lens [7, 8]. A coupling mechanism works by boosting the momentum of light so that it matches the SPP momentum and is commonly implemented by placing discrete optical elements near a metal surface. The popular Kretschmann configuration consists a thin metal film, which is either deposited onto one face of a prism [5, 6] or adjacent to an oil-immersion objective lens [7, 8]. A beam of polarized light incident at a critical angle onto the metal film achieves momentum matching with SPPs on the other side of the film, which can be measured by a characteristic drop in the reflected light intensity or via dispersion engineering,” Opt. Express 18, 18206–18216 (2010).

Light that is bound to propagate along the surface of a metal is known as a surface plasmon polariton (SPP). Plasmonic chips, miniaturized devices that exploit SPPs for functional use, are an emerging optical technology of growing importance for bio-chemical sensing [1, 9], medical diagnostics [3], and environmental monitoring [4]. Three basic components are common to plasmonic chips: a source of free-space light, a mechanism to couple incoming free-space light into SPPs, and a detection scheme to measure SPP signatures. The coupling mechanism works by boosting the momentum of light so that it matches the SPP momentum and is commonly implemented by placing discrete optical elements near a metal surface. The popular Kretschmann configuration consists a thin metal film, which is either deposited onto one face of a prism [5, 6] or adjacent to an oil-immersion objective lens [7, 8]. A beam of polarized light incident at a critical angle onto the metal film achieves momentum matching with SPPs on the other side of the film, which can be measured by a characteristic drop in the reflected light intensity or detected by viewing the top surface of the metal film under an optical microscope [10, 11]. The Kretschmann configuration boasts simplicity of operation and low-cost of implementation, contributing factors to its widespread use in commercial plasmonic chips [12].

An alternative method to realize a plasmonic chip is to pattern a metal surface with nano-
scale surface defects, such as holes, slits, or grooves [13–16]. Scattering from a defect provides a boost to the momentum of incident light, enabling a small portion of the scattered light to couple into SPPs localized near the defect site. Coupling using nano-patterned surfaces enables extreme miniaturization not possible using discrete optical elements and opens up the possibility for plasmonic lab-on-a-chip applications. Specialized techniques, such as leakage radiation microscopy [17–20] and near-field optical microscopy [21,22], have been developed in the past decade to measure SPPs localized near defect sites. Leakage radiation microscopy works by providing a pathway for SPPs to radiate from a metal surface, which is commonly achieved by surrounding one side of a thin metal film with a dielectric of higher refractive index than on the other side. SPPs radiated in a characteristic emission cone away from the metal surface are then captured by an oil-immersion optical microscope and identified by distinctive features in the Fourier plane of the microscope image. Near-field optical microscopy, on the other hand, uses a nano-scale tip to locally sample the SPP fields and generates a SPP image by rastering the tip over a region near the defect site. Both methods, although well-accepted, have yet to achieve widespread use due in part to their operational complexity and, for the case of near-field optical microscopy, high cost.

In this work, we develop a method to directly image SPPs near a slit in a metal film by simple transmission optical microscopy using a standard objective lens. We use a common plasmonic chip configuration consisting of a single slit in an optically-opaque metal film, flanked by two parallel grooves on the top surface of the metal film. The slit is illuminated from below using polarized visible-light, and the top of the slit is viewed under an optical microscope. The key component of our implementation is an ultra-thin polymer layer on the metal film coating the slit and grooves. Variation of the thickness of the polymer layer enables controllable adjustment of the SPP momentum [23], a concept that has been theoretically discussed in Ref. [9] and experimentally applied to enable selective SPP coupling via the Kretschmann configuration in Refs. [7,8], but has yet to be applied to facilitate slit-coupling to SPPs. We show here that when the SPP momentum matches the momentum of light transmitted through the slit, the resulting SPP coupling efficiency is about six times that without the layer. Due to momentum matching conferred by the polymer layer, signatures of SPPs near the slit are directly visible by inspection under an optical microscope and appear as distinct, tell-tale bright spots at the groove locations adjacent to the slit. Direct visualization of SPPs near slits enables parallel SPP measurement by imaging arrays of nano-patterned features. We show how this can be useful by extracting the SPP propagation length from a single microscope image of an array of slit and grooves in which the spacing between the slit and grooves is variable. It is also shown that a focussed SPP beam emitted from a curved array of sub-wavelength holes, previously characterized using more-complex near-field optical microscopy, can now be imaged using optical microscopy. We believe that the simplification of slit-coupled SPP detection is an important initial step towards making nano-plasmonic technology highly accessible, commercially viable, and easy-to-use.

We first propose a coupling mechanism and design the detection scheme of our plasmonic chip. The coupling structure consists of a slit in a metal film having a width $w$. The slit is filled with a dielectric of refractive index $n$ and the metal surface adjacent to the slit is coated with a planar layer of thickness $d$ consisting of the same dielectric. We conceptually divide the coupling structure into two regions — the near-field region at the slit exit and the dielectric-coated region above the metal surface — and then match the momentum of light in the two regions. In general, the momentum of light in the near-field of a slit is indeterminate. Diffraction of light at the slit exit yields a near-field light distribution describable by a distribution of wavevector values oriented along a continuum of directions. For initial design considerations, however, we make the simplifying assumption that a large fraction of light at the slit exit possesses wavevector values near $nk_0$, with a component oriented along the metal surface.
Fig. 1. (a) \( \text{Re}[k_{\text{SPP}}] \) corresponding to SPP modes propagating along a silver metal surface coated with a dielectric layer of refractive index \( n = 1.5 \) and surrounded by air, for various layer thickness values, along with the \( nk_0 \) line. Complex \( k_{\text{SPP}} \) values are calculated by solving the dispersion relation of a semi-infinite three-layer silver-glass-air waveguide, where the permittivity of silver \( \varepsilon_m \) is fitted to experimental data [27]. The circles highlight, for a given dielectric layer thickness, the frequency at which the momentum matching condition \( \text{Re}[k_{\text{SPP}}] = nk_0 \) is satisfied. It should be noted that the momentum matching condition is an approximation and provides only a first-order procedure to estimate the optimal dielectric layer thickness. (b) Schematic of the experimental set-up. Polarized light from a He-Ne laser (\( \lambda_0 = 632.8 \text{ nm} \)) illuminates the sample and the far-field transmission image is captured by an optical microscope (Zeiss Axio Imager) using a 100× objective lens with a numerical aperture of 0.90 in air ambient and recorded using a Si CCD camera.

that is amenable to SPP coupling. This assumption is supported by our previous work [23], in which we used finite-difference time-domain (FDTD) electromagnetic simulations to predict the SPP coupling efficiency of a dielectric-filled and dielectric-coated slit illuminated by an electromagnetic plane wave and showed that maximal SPP coupling efficiency occurred when the SPP wavevector \( k_{\text{SPP}} \) was tuned so that is was equivalent to \( nk_0 \), where \( k_0 = 2\pi/\lambda_0 \) is the wavevector of free-space light and \( \lambda_0 \) is the wavelength. Physically, the portion of light at the slit exit with wavevector \( nk_0 \) could be associated with evanescently diffracted components confined within the dielectric region (thus modifying the free-space wavevector by the factor of \( n \)). However, this assumption should be used only as a first-order approximation, as the wavevector...
distribution of light at the slit exit is inherently intricate and dependent on the dielectric layer thickness, slit width, and even the thickness of the metal film, particular if the film thickness is comparable to or less than the skin depth. Light leaving the slit region can propagate along the dielectric-coated metal surface in the form of an SPP, which has a wavevector $k_{\text{SPP}}$ dependent on the thickness $d$. For a given frequency, $\text{Re}[k_{\text{SPP}}]$ increases as the dielectric layer thickness increases [23]. The limits $d = 0$ and $d >> \lambda_0$ correspond to lower and upper bounds, respectively, of the SPP dispersion curve. By adjusting the layer thickness over a range comparable to $\lambda_0$, portions of the SPP dispersion curve can be moved to either side of the dielectric light line. Calculated $\text{Re}[k_{\text{SPP}}]$ curves are highlighted in Fig. 1(a) for the representative and idealized case of a silver surface having a frequency-dependent relative permittivity $\varepsilon_m$, which is coated with a non-dispersive dielectric layer of refractive index $n = 1.5$ and thickness ranging from approximately 50nm to 150nm. Variations in $\text{Re}[k_{\text{SPP}}]$ about the $nk_0$ line suggest that, at a given operation frequency $\omega$, a dielectric layer thickness in the range of 10s to 100s of nanometers can be selected so that the momentum-matching condition $\text{Re}[k_{\text{SPP}}] = nk_0$ is satisfied and, we hypothesize, efficient SPP coupling is achieved. SPPs coupled by the slit are detected by placing grooves in the metal surface spaced a distance $s$ from the slit. SPPs incident onto the grooves are scattered from the metal surface into the far field, which can then be captured and detected by conventional optical methods. The detection of radiated SPPs from isolated grooves is fundamentally different than the detection methodology used in leakage radiation microscopy, which allows SPPs to freely radiate from the metal surface at any location.

We implement our plasmonic chip by sequentially evaporating a 5-nm-thick chromium adhesion layer and then a 300-nm-thick, optically-opaque silver layer onto a glass substrate. Using a FEI Dual Beam Strata-235 focused ion beam tool, we mill a series of slits having a fixed length of 3 $\mu$m and widths ranging between $100 \text{nm} \leq w \leq 300 \text{nm}$, where the lower bound is set by the milling resolution of the focused ion beam tool and the upper bound is set by the restriction that the dielectric-filled slit sustain only the lowest order mode (which was confirmed by performing FDTD simulations of plane-wave, normal incidence illumination of the slit having...
a variable width and then visually corroborating that the simulated field structure in the slit was consistent with that of the lowest order mode. Each slit is flanked by two parallel grooves placed 1 µm on both sides from the edges of the slit. The grooves have a depth of ≃ 100 nm, a width of ≃ 200 nm, and a length of 2 µm. We create 6 identical sets of slits and grooves, each on its own separate glass substrate. Five of the substrates are spin-coated with a layer of PMMA \((n = 1.49)\), with layer thicknesses varying from 60 nm to 140 nm in increments of 20 nm. The remaining substrate is left uncoated and serves as an experimental control. The optical response of a chip is characterized by illuminating the bottom of the chip with polarized laser light at a wavelength \(\lambda_0 = 632.8 \text{ nm} \) and viewing the top of the structure under an optical microscope (Zeiss Axio Imager) with a 100× objective lens, as shown in Fig. 1(b). At the chosen visible wavelength, the experimental range of dielectric layer thickness values is expected to yield a range of SPP momentum values that spans the momentum of light in the dielectric. We examine the structure under illumination with light that is either x-polarized (electric field perpendicular to the slit axis) or y-polarized (electric field along the slit axis). It has been established that a slit illuminated with y-polarized light produces negligible SPP coupling, whereas a slit illuminated with x-polarized light produces a SPP beam emanating from the slit perpendicular to the slit axis [15, 22]. The experiment is designed so that SPPs scattered by the grooves produce a bright spot in the resulting microscope image at the groove location. Due to placement of the grooves on the transmission side of the optically-opaque metal film, the grooves should be visible only when they are illuminated by SPPs propagating along the metal surface and are otherwise invisible.

One of the immediate challenges of measuring SPPs coupled from a slit using transmission-mode optical microscopy is the isolation of weak SPP signatures from light diffracted through the slit. In the absence of the polymer layer, the microscope image of the slit region [Fig. 2(a)] under x-polarized illumination is dominated by a diffraction pattern from the slit consisting of a bright main lobe centered on the slit with subsidiary lobes spanning several microns to the side of the slit. Any light scattered from the groove locations is disguised by the side lobes of the diffraction pattern, precluding unambiguous identification of SPPs by direct observation. The overwhelming diffraction from the slit can be mitigated by adding a polymer layer, which is predicted to better match the momentum of SPPs with the momentum of light and enhance SPP coupling efficiency. With the addition of a 80-nm-thick polymer layer, the microscope image of the slit region [Fig. 2(b)] now reveals distinctive SPP signatures as bright spots at the groove locations. The bright spots have an intensity comparable to that of the main lobe of the diffraction pattern from the slit, indicating that a significant portion of the light in the slit couples into SPPs. The momentum matching conferred by the polymer layer is highly sensitive to the layer thickness. As the polymer layer thickness increases to 120 nm, the intensity of the bright spots at the groove locations reduces and it again is difficult to distinguish the diffraction pattern from SPP signatures at the groove locations [Fig. 2(c)]. Comparative microscope images under y-polarized illumination show similar diffraction patterns, albeit without any SPP signatures at the groove location, regardless of the presence of the polymer layer or its thickness.

We next quantitatively determine the SPP coupling efficiency. A comparative experiment is designed consisting of two identical slits of width \(w = 150 \text{ nm}\) and length 3 µm, aligned and off-set along the direction of the slit axis so that the transmission through the slits are independent. Grooves are created on both sides of slit 1 [top slit in Fig. 3(a)], spaced \(s = 1 \mu m\) from the center of the slit, while the metal surface adjacent to slit 2 [bottom slit in Fig. 3(a)] is left pristine. Figure 3(b) shows a microscope image of the slits under x-polarized illumination. By comparing the images of the slits, image artifacts due to diffraction from the slit and SPP scattering from the grooves can be separated. For example, subtraction of the region of the microscope image encompassing the slit without the grooves (R2) from the region encompassing
the slit and the grooves (R1), yields a resulting image in which the diffraction from the slit is suppressed and SPP signatures from the grooves are isolated. Under y-polarized illumination, the same subtraction procedure yields an image without any observable SPP signatures [Fig. 3(c)].

![Image](image_url)

Fig. 3. Experiment to distinguish diffraction from a slit and SPP scattering from adjacent grooves. (a) SEM image of a representative sample consisting of two identical slits of width \( w = 150\,\text{nm} \), one of which is flanked by grooves. The sample is coated with a PMMA layer of thickness \( d = 80\,\text{nm} \). Optical microscope image of the sample under (b) x-polarized illumination and (c) y-polarized illumination. We apply a subtraction procedure to images (b) and (c) in which the region R2 is subtracted from R1. The resulting subtracted image derived from (b) show bright spots at the groove location indicative of SPP scattering. These bright spots are absent in the subtracted image derived from (c), suggesting the absence of SPPs.

We use the brightness of different portions of the microscope image of the slit and grooves to measure the SPP coupling efficiency. The brightness of the slit is proportional to the amount of light that diffracts and radiates from the slit exit. The brightness of the grooves is proportional to the amount of light that has converted into SPPs at the slit exit and radiates upon striking the grooves. We define the quantities \( I_{g,L} \) and \( I_{g,R} \) as the integrated intensity over a region encompassing the left and right grooves, respectively, the quantities \( I_{ng,L} \) and \( I_{ng,R} \) as the integrated intensity over a region spaced \( s = 1\,\mu\text{m} \) to the left and right of slit 2, respectively, and the quantity \( I_s \) as the integrated intensity over a region encompassing exit side of slit 2. The SPP coupling efficiency is now defined as

\[
\eta = \frac{I_{g,L} + I_{g,R} - I_{ng,L} - I_{ng,R}}{I_s + I_{g,L} + I_{g,R} - I_{ng,L} - I_{ng,R}} \times 100\%
\]

where the numerator describes the intensity contributions to the image due to SPP scattering from the grooves and the denominator describes the intensity contributions to the image due to both SPP scattering from the grooves and diffraction from the slit. Physically, the efficiency as defined in Eq. (1) describes, to a good approximation, the fraction of light at the slit exit that couples into SPPs. For the representative case depicted in Fig. 3 where \( w = 150\,\text{nm} \) and \( d = 80\,\text{nm} \), an efficiency of \( \eta = 52 \pm 6\% \) is measured, considerably higher than the efficiency value (20%) previously reported for nano-slits [26], which do not use the dielectric coating technique described here.

Performing similar coupling efficiency measurements as a function of the polymer layer thickness yields the efficiency curve shown in Fig. 4(a). The coupling efficiency has a sharp peak at a layer thickness of 80 nm, nearly six times higher than the efficiency without the layer. The measurements are compared with numerical two-dimensional FDTD simulations of x-polarized illumination (at \( \lambda_0 = 632.8\,\text{nm} \)) of a slit in a metal film for discrete \( d \) values ranging
from 0 to 200nm. We extract $\eta$ from the simulations by directly measuring the SPP intensity at the metal surface and light intensity radiated from the slit. Similar to the experimentally-measured efficiency, the FDTD-calculated efficiency peaks at a layer thickness of 80nm. Two observations suggest that the enhanced coupling is due to momentum matching. First, the experimental and simulated efficiency plots both peak at a $d$ value that agrees, within a factor of 2, to the $d$ value predicted to satisfy $\text{Re}[k_{SPP}] \approx n k_0$ using the simplistic design procedure described in Fig. 1(a), which assumed a momentum of light in the slit describable by $n k_0$. Second, the experimental and simulated efficiency plots both drop-off for $d$ values slightly off the optimal value. The drop-off in the simulated $\eta$ for $d > 80$nm is not as sharp as that observed in the experiments. We attribute this discrepancy to surface roughness present in the experiment but absent in the simulations. Due to the tighter confinement of SPPs near the surface for increasing $d$ [which can be inferred from the dispersion diagrams in Fig. 1(a)], losses due to surface roughness should be more pronounced for thicker polymer layers and is evident in the efficiency plots. Over the range from 150nm $\leq w \leq$ 300nm, we observe good agreement between the experimentally-measured and FDTD-calculated SPP coupling efficiencies as a function of the slit width [Fig. 4(b)]. Over this slit width range (which corresponds to a normalized range of $0.24 \leq w/\lambda_0 \leq 0.47$), similar reductions in the SPP coupling efficiency as a function of slit width were theoretically predicted in Ref. [16] using a semi-analytical model of geometrical diffraction from a slit in an infinitely thick Au medium followed by SPP launching on an adjacent flat Au surface. It should be noted that the error in the experimentally-measured SPP coupling efficiency for the thinnest slit width $w = 100$nm is larger due to weak transmission through the slit.

Parallel measurement of SPP signatures near a slit can now be performed using optical microscopy. We demonstrate this capability by creating a linear array of 8 identical slits [shown in Fig. 5(a)] of width $w = 150$nm and length $3 \mu$m, again aligned and off-set along the direction of the slit axis so that the transmission through the slits are non-interfering. Pairs of grooves are then milled next to the slits, where the slit groove spacing, $s$, varies from 1 $\mu$m to 8 $\mu$m in 1 $\mu$m increments. A 80-nm-thick polymer layer is then applied to the device. The entire array encompasses an area of approximately $20 \mu m \times 50 \mu m$, well within the field of view of laboratory-grade microscopes using a 100× objective lens. The array is illuminated by x-polarized light and a microscope image of the entire array is captured [Fig. 5(b)]. In addition to the expected diffraction pattern emerging from the slits, the array image contains bright spots at the groove locations, which diminish as $s$ increases but are still visible for the largest ($s = 8 \mu m$) slit-groove separations. Analysis of the image yields line plots, shown in Fig. 5(c), of the intensity distribution along the $x$ direction, from which SPP signatures can be clearly identified as intensity spikes amidst a background diffraction pattern. An exponential fit to the intensity of the SPP signature as a function of slit-groove separation [Fig. 5(d)] yields an intensity decay constant of $9.35 \mu$m, which is in good agreement with the expected intensity decay constant $\alpha = 1/(2 \text{Im}[k_{SPP}]) = 9.26 \mu$m extracted from the imaginary part of the SPP wavevector for $d = 80$nm, $n = 1.5$, and $\lambda_0 = 632.8$nm. This agreement reinforces that the groove brightness arises from groove illumination by SPP modes, rather than by higher-order guided modes in the polymer layer (which are expected to be cutoff at $\lambda_0 = 632.8$nm for $d = 80$nm).

Massively-parallel SPP measurements can potentially be performed by imaging large two-dimensional arrays, composed of hundreds or thousands of slit-groove structures, under a conventional microscope. The maximum number of slit-groove structures that can be accommodated using this technique is dependent on the field-of-view of the microscope, the length of the slits, and the minimum separation distance between slits, which must be greater than the SPP decay constant to ensure minimal cross-talk. For example, a microscope with a 100 $\mu$m field-of-view could image approximately 250 slits, assuming a slit length of 2 $\mu$m and a separation.
Fig. 4. (a) SPP coupling efficiency, $\eta$, as a function of the PMMA layer thickness, for a fixed slit width of $w = 150$ nm. $\eta$ is measured using two methods. In the first method, labeled “expt-1”, $\eta$ is calculated by using $I_{ng,L}$ and $I_{ng,R}$ derived from the image of the slit and grooves under y-polarized illumination and then using Eq. (1) (red circles). In the second method, labeled “expt-2”, $\eta$ is calculated by using $I_{ng,L}$ and $I_{ng,R}$ derived from the image of the slit with no grooves under x-polarized illumination and then using Eq. (1) (magenta diamond). We calculate $\eta$ from two-dimensional FDTD simulations modeling x-polarized plane-wave illumination of a coated slit for various $d$ values (blue squares).

We also calculate, for the optimal case of $d = 80$ nm, the SPP coupling efficiency when a 20-nm-deep dimple is present in the dielectric layer above the slit (cyan square), which emulates possible non-planarity of the polymer layer due to conforming to the slit walls. (b) shows the SPP coupling efficiency measured using the method “expt-1” (red circles) and calculated using FDTD simulation (blue squares) as a function of the slit width. The error bars in (a) and (b) correspond to the variance of five independent measurements.

distance between slits of 20 $\mu$m, chosen to accommodate a SPP decay constant of 10 $\mu$m.

We next use optical microscopy to revisit the SPP lensing experiment described in Ref. [14], in which a focussed SPP beam emitted from a curved array of subwavelength holes is measured using near-field scanning optical microscopy. Assuming that the momentum of light in a dielectric-filled sub-wavelength hole is the same as in a dielectric-filled sub-wavelength slit (that is, describable by $n k_0$), the aforementioned principles of momentum matching should also apply here. We fabricate three identical, off-set semi-circular lens arrays consisting of 17 holes, each with a diameter of $200$ nm $< \lambda_0$, arranged into a semi-circle of radius 5 $\mu$m. To enhance
Fig. 5. Parallel SPP measurement from a nano-patterned array illuminated by x-polarized visible light and viewed under an optical microscope. (a) SEM image of an array of identical \( w = 150 \text{nm} \) slits where the groove spacing from the slits is varied from \( s = 1 \mu \text{m} \) to \( s = 8 \mu \text{m} \) in 1 \( \mu \text{m} \) increments. The array is coated with a PMMA layer of thickness \( d = 80 \text{nm} \). (b) shows the corresponding microscope image of the array. (c) depicts profiles of the image intensity along horizontal lines intersecting the slit and grooves for various slit-groove separation values. (c) The integrated SPP intensity normalized to the integrated intensity of the slit as a function of the slit-groove separation (red circles), where the blue line corresponds to an exponential fit.
SPP coupling from the holes to SPPs, the entire array is coated with an 80-nm-thick polymer layer. As shown in Fig. 6(a), we create different groove patterns next to the arrays to probe different aspects of the SPP beam. The groove pattern next to the top lens probes the confinement of the SPP beam within the cone defined by the arc angle of the array; the groove pattern next to the middle lens measures the SPP distribution at the focal plane; the groove pattern next to the bottom lens is expected to disrupt any SPP lensing effects. The image of the top and middle lens arrays under x-polarized illumination reveals a single sharp, bright spot at the groove located at the focus [Fig. 6(b)]. The absence of SPP signatures at any of the other grooves means that the SPP beam from the lens array is confined within the cone and focussed onto a single point in the focal plane, consistent with the results from Ref. [14]. As expected, SPP focusing is absent from the image of the bottom lens array. Under y-polarized illumination, the three lens arrays produce similar diffraction patterns, with no pronounced groove signatures to indicate SPP focusing [Fig. 6(c)].

An added benefit of incorporating a thin polymer layer on a plasmonic chip is passivation of the metal surface, which is especially important for reactive metals like silver. We have observed that the SPP coupling efficiencies of the coated plasmonic chips have remained stable for at least several months and show no visible signs of tarnishing or deterioration.

In conclusion, we have developed a simple method to image SPPs coupled from slits and scattered by grooves using optical microscopy with conventional objective lenses. This method of detection is possible due to an ultra-thin polymer layer on the metal surface, whose thickness can be varied, with precision on the order of 10 nm, to controllable tune the SPP momentum. When a thickness is selected which yields momentum matching, the SPP coupling efficiency is enhanced by nearly six times relative to that without the layer. The high coupling efficiency results in SPP signatures that are visible under inspection by an optical microscope and appear as distinctive bright spots located at the groove locations. This method can be used to perform parallel SPP measurement, which we have demonstrated using a linear array of slits and grooves,
and can be extended for massively-parallel SPP measurement using larger two-dimensional arrays accommodating the entire microscope field-of-view. A SPP lensing experiment previously performed using near-field optical microscopy has also been re-visited here using optical microscopy. We believe that the development of a simple method to detect SPPs near slits using standard optical microscopy represents an important step towards reducing the technological requirements and operational complexity of nano-scale plasmonic devices.

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