Ultra-broadband and efficient surface plasmon polariton launching through metallic nanoslits of subwavelength period

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Ultra-broadband, efficient and unidirectional surface plasmon polariton (SPP) launching is of great concern in plasmonic devices and circuits. To address this challenge, a novel method adopting deep-subwavelength slits of subwavelength period \(\lambda_{SPP}/4 \sim \lambda_{SPP}/3\) in a thick metal film and under backside illumination is proposed. A new band pattern featuring broadband and wide angular characteristics, which is due to the coupling of the zeroth-order SPP resonance at the superstrate–metal interface and the first-order SPP resonance at the metal–substrate interface, is observed for the first time in the dispersion diagram. Unidirectional SPP launching efficiency of \(\sim 50\%\), ultra-broad bandwidth of up to 780 nm, covering the entire optical fiber communication bands, and relatively wide angular range of \(7^\circ\) are achieved. This remarkable efficient, ultra-broadband and wide angular performance is demonstrated by carefully designed experiments in the near infrared regime, showing good agreement with numerical results.
In order to achieve high unidirectional efficiency and simultaneously ultra-broadband width of more than 415 nm so as to cover the entire optical fiber communication bands (O, E, S, C, L, and U bands), in this work, we propose a novel SPP launching method using periodic deep-subwavelength slits of subwavelength period ($\lambda_{\text{SPP}}/4 \sim \lambda_{\text{SPP}}/3$), where $\lambda_{\text{SPP}}$ is the SPP wavelength. The slits are milled in an optically thick metal film and obliquely illuminated from the back side, prohibiting the incident light from becoming significant source of noise and reducing the system’s size. Interestingly, for the first time we find a new band pattern featuring broadband and wide angular characteristics, which is due to the coupling of the zeroth-order SPP resonance at the superstrate–metal interface and the first-order SPP resonance at the metal–substrate interface. The corresponding unidirectional SPP launching efficiency is found to be $\sim 50\%$ over an ultra-broadband range (up to 780 nm) and relatively large angular range ($\sim 7^\circ$). This remarkable performance makes the proposed SPP launching approach distinct from conventional periodic or aperiodic metallic gratings, of which periods or neighboring distances are usually comparable with or larger than the SPP wavelengths, featuring spectrally and angularly sensitive SPP launching efficiencies. It is experimentally demonstrated in the near-infrared regime.

**Results**

The configuration in Fig. 1(a) illustrates $N$ periodic slits of deep-subwavelength width $w$ and subwavelength period $p$ in an optically-thick metal film of thickness $h$. The slits are back-side illuminated by a transverse-magnetic polarized light of oblique incidence angle $\theta$. This structure is distinct from the Kretschmann–Raether configuration because of the slit array and the optically thick metal film. It also differs from conventional metallic gratings because $p$ is much smaller than the SPP wavelength.

We first calculate the band structure of the corresponding one-dimensional (1D) plasmonic crystal, i.e. the fully-periodic ($N = \infty$) grating. To cover entire optical fiber communication bands (1260 nm $\sim$ 1675 nm), we set $p = 440$ nm, which is about $\lambda_{\text{SPP}}/4 \sim \lambda_{\text{SPP}}/3$, $w = 100$ nm, and $h = 300$ nm (optically thick enough). Fig. 1(b) shows the $\omega$–$k_{//}$ dispersion diagram, where $\omega$ is the angular frequency, $k_{//} = k_0 n_{\text{sub}} \sin \theta$ is the in-plane wavevector of the incident light from the substrate. The color scale represents the absorption intensity. As have been pointed out in refs. 27 and 28, there are narrow bright bands that generally follow two sets of curves: the folded dispersion relations of SPPs on flat metallic surfaces (black lines) and the Rayleigh anomaly (RA) wavelengths (red lines) at the Au–substrate interface (solid lines) and the superstrate–Au interface (dashed lines). The dispersion relations of SPPs are determined by the Bragg coupling condition,

$$k_0 \Re(n_{\text{SPP, sub}}) p = k_0 n_{\text{sub}} \sin \theta = 2m_1 \pi,$$

where $n_{\text{SPP, sub}} = \sqrt{\varepsilon_0 \varepsilon_{\text{sub}} / (\varepsilon_0 + \varepsilon_{\text{sub}})}$ is the effective index of SPP on flat metallic surface with $n_{\text{sub}}$ being the relative permittivity of the substrate (sub) or superstrate (sup), and $m_1$ is the diffraction order. The RA wavelengths are defined by the passing-off of a diffraction order ($m_2$),

$$k_0 \varepsilon_{\text{sub}} / \varepsilon_{\text{sup}} p = k_0 n_{\text{sub}} \sin \theta = 2m_2 \pi.$$  

We should note that these narrow bands are observed for wavelengths comparable to the periods and the SPP and RA curves almost merge at small energies, for which $k_{\text{SPP}} \approx k_0$. These properties agrees well with previous studies on conventional metallic gratings of which periods are comparable with or larger than the SPP wavelengths. These narrow bands explain why the SPP launching efficiencies of conventional metallic gratings are spectrally and angularly sensitive.

Interestingly, for the first time we observe a new bright band featuring large spectral and angular ranges. It locates between the 0th-order SPP resonance wavelength at the superstrate–Au interface, SPP$_{0,\text{sup}}$, and the first-order SPP resonance wavelength at the Au–substrate interface, SPP$_{1,\text{sub}}$. Its spectral and angular characteristic and location make it distinct from the above-mentioned narrow bands locates between the SPP and RA curves, as well as the slit Fabry-Perot (F–P) resonance curve determined by $2 k_0 \Re(n_{\text{eff}}) h + \arg(r_{\text{stop}}) + \arg(r_{\text{stop}}) = 2 \pi m_3$, where $n_{\text{eff}}$ is the effective index of the slit mode, $r_{\text{stop}}$ and $r_{\text{stop}}$ are the reflectance coefficients of the slit mode at the top and bottom openings, respectively, the function “$\arg$” refer to the argument of a complex number, and $m_3$ is an integer.

To further understand the physical origin of the new band, we theoretically calculate the SPP launching efficiency for $N$ periodic

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**Figure 1** | (a) Schematic of the proposed SPP launching configuration. (b) Absorption diagram of the plasmonic crystal. (c) The spectral and angular dependence of $n_{\text{eff}}$ for $N = 25$ with the white contour indicating half the optimal efficiency. (d)–(f) Near-field $|H_y|$ under various wavelengths and incidence angles as indicated by the diamonds in (c). The incident plane indicated by a dashed line locates at 100 nm below the quartz-metal interface. The dashed and solid arrows show incident direction and specular reflection direction, respectively. The calculations were performed with $h = 300$ nm, $w = 100$ nm, and $p = 440$ nm.
metallic slits, $\eta_z^\pm$, which is defined as the ratio of the power of the launched forward- ($^+$) or backward-propagating ($^-\,$) SPPs to that of the incident light over the whole grating length, $(N-1)p + w$. Fig. 1(c) shows the spectral and angular dependence of $\eta_z^\pm$ of $N = 25$. It reveals that $\eta_z^\pm$ reaches as large as 50% and holds more than 25% over extremely wide spectral range and relatively large angular ranges. An ultra-broad spectral full width at half maximum (FWHM) of up to 780 nm (from 1210 nm to 1990 nm) at $\theta = 44^\circ$ and an angular FWHM of $\theta^\circ$ at $\lambda = 1550$ nm are achieved. The ultra-broad bandwidth covers the entire optical fiber communication bands, making the proposed SPP launching approach very promising in WDM plasmonic circuits. We note that $\eta_z^-$ is extremely small over the corresponding spectral and angular ranges, corresponding to large extinction ratio, which is defined as $E_R \equiv \eta_z^+ / \eta_z^-$ and more than 20 (see Fig. S1 in Supplementary Information). We also note that the spectral FWHM ranges of $\eta_z^+$ have been indicated by the location of the new band of the dispersion diagram in Fig. 1(b).

Given that the slit period of $\lambda_{\text{SPP}}/4 \sim \lambda_{\text{SPP}}/3$, if and only if $m_1 = 0$, Eq. (1) can be satisfied. In other words, only the 0th-order SPP resonance exists for the transmitted diffraction. Each slit acts as a channel that converts the back-side incident light into SPPs propagating along the superstrate-metal interface (referred to as top-SPPs). SPPs propagating along the metal-air interface (referred to as bottom-SPPs) are also generated by the slits. Meanwhile, the launched top- and bottom-SPPs couple with each other through the slits and also re-radiate to the substrate because of Rayleigh-like scattering by the slit array. These re-radiated emissions interfere with the reflected diffraction field by the subwavelength metallic ridges, resulting in energy redistribution between the reflected field and launched top-SPPs in the transmitted field. In the dispersion diagram, the coupling of top-SPPs and bottom-SPPs will result in a band between their corresponding dispersion curves. In other words, the new band that locates between $\text{SPP}_{\text{top}}$ and $\text{SPP}_{\text{bot}}$ in Fig. 1(b) should originate from the coupling of top-SPPs at the 0th-order resonance and bottom-SPPs at the first-order resonance. On the other hand, the interference between SPP re-radiations and the metallic ridges’ reflected diffraction is vividly visualized by the near field distributions under various incident wavelengths and angles, as illustrated in Figs. 1(d)–1(f). The incident plane locates at 100 nm below the quartz-metal interface so as to manifest the reflected field. It is clearly shown that forward-propagating SPPs are launched efficiently while backward-propagating SPPs are very weak over the entire optical fiber communication bands and at various incident angles.

Since the new band locates between $\text{SPP}_{\text{top}}$ and $\text{SPP}_{\text{bot}}$, it is possible to tune its location and accordingly the ultra-broad bandwidth of $\eta_z^+$ to the desired spectral range by varying $\text{SPP}_{\text{top}}$ and $\text{SPP}_{\text{bot}}$ which are determined by structural parameters, such as $p$, $N_{\text{up}}$, and $N_{\text{bot}}$. By decreasing the geometrical parameters ($p$, $w$, and $h$), the location of the new band is shifted to higher frequency, and accordingly the bandwidth of $\eta_z^+$ is blue-shifted. Fig. 2 shows the results for $h = 200$ nm, $w = 30$ nm, and $p = 290$ nm. Comparing Figs. 1(c) and 2(a), we observe that the spectral bandwidth has been blue-shifted from 1210 nm to 1990 nm to 890 nm to 1270 nm at $\theta = 44^\circ$ by reducing the slit period from $p = 440$ nm into $p = 290$ nm. It is worth to note that the slit period holds to be about $\lambda_{\text{SPP}}/4 \sim \lambda_{\text{SPP}}/3$. The blue-shift by decreasing geometrical size is in accordance with the scaling law. Moreover, the angular FWHM is about $\theta^\circ$ at $\lambda = 1000$ nm.

Note that the idea of the proposed SPP launcher originates from the dispersion properties of an infinite periodic array of slits, while the use of the SPP launcher should adopt a finite number $N$ of slits so as to excite unidirectional SPPs on flat metallic surfaces. For conventional SPP launchers composed of periodic features with period comparable with $\lambda_{\text{SPP}}$, the SPP launching efficiencies depend on $N^3$. This property also holds for the proposed SPP launcher with some differences. As shown in Fig. 3(a), $\eta_z^+$ first increases to about 51% and then decreases slowly as $N$ increases. The decrease of $\eta_z^+$ is because the saturation of the launched SPPs due to scattering and propagation losses. Compared with conventional SPP launchers, which exhibit low $\eta_z^+$ and a rapid saturation of $\eta_z^+$ as $N$ increases, the proposed SPP launching configuration is of much higher efficiency and much slower saturation. Fig. 3(a) also shows that the extinction ratio is larger than 100 if $N > 6$, indicating that the proposed configuration launches highly unidirectional SPPs. Comparing Figs. 1(c), 3(b) and 3(c), we notice that although the angular FWHM of the proposed SPP launcher decreases and the optimal efficiency varies as $N$ increases, the ultra-broadband performance holds for various $N$. In other words, the efficient, unidirectional, ultra-broadband and relatively wide angular performance holds for the proposed SPP launchers of a very wide range of $N$. For the design of a SPP launcher of given $N$, the desired spectral ranges and the corresponding $p$, one may optimize $w$ and $h$ for the optimal efficiency using efficient theoretical models introduced in ref. 32.

To experimentally demonstrate the remarkable performance, we carefully designed samples composed of a launcher and a decoupler, as schematically shown in Fig. 4(a). Under back-side illumination of a TM-polarized light beam, forward-propagating top-SPPs are excited with a launching efficiency $\eta_{\text{top}}^+$, and then scattered into far field by the decoupler with a decoupling efficiency $\eta_d$. The decoupling efficiency $\eta_d$ is defined as the ratio of the re-radiated power $P_0$ from the decoupler within a cone with a $\pm 30^\circ$ extraction angle, which is determined by the numerical aperture (NA) of the collecting microscope objective (NA = 0.5 here), to the power of top-SPPs at the slits. In Fig. 4(a), $P_0$ is the incident power onto the launcher.

Taking into account of the tunable wavelength range of the laser source we used in the experiment (800 nm to 920 nm) and the...
fabrication yield, we designed the launcher of a sample, Launcher I, to be of the following parameters: \( w = 60 \text{ nm}, p = 240 \text{ nm}, \) and \( N = 15 \). The launcher of the other sample, Launcher II, has the following design parameters: \( w = 120 \text{ nm}, p = 480 \text{ nm}, \) and \( N = 8 \). Both launchers have the same slit length \( (L = 54 \text{ µm}) \). Furthermore, the decouplers share the same parameters as Launcher II, except for the slit length \( L/2 \), because of two considerations: the noise power could be eliminated and the SPP coupling efficiency could be accurately inferred, as will be elaborated later. The scanning electron microscopy (SEM) images are shown in Figs. 4(b) to 4(d) (and Figs. S2(a)–(b) in Supplementary Information). From the calibrated SEM images, the measured slit parameters are determined with the average values and the standard deviations, which are obtained from statistics of slit widths and distances at different positions: \( w = 55 \pm 15 \text{ nm} \) and \( p = 248 \pm 15 \text{ nm} \) for Launcher I, \( w = 105 \pm 6 \text{ nm} \) and \( p = 495 \pm 7 \text{ nm} \) for Launcher II, and \( w = 120 \pm 7 \text{ nm} \) and \( p = 499 \pm 7 \text{ nm} \) for the decouplers.

With the optical setup schematically illustrated in Fig. 4(e), we obtained the images of the decoupler and Launcher I with a charge coupled device (CCD), as shown by Figs. 4(f) and 4(g), respectively. We note that the far-field reflection by Launcher I is significantly suppressed compared with the specular reflection by the surrounding flat metal surface, as predicted by the near-field distributions shown in Figs. 1(d)–1(f), although different parameters were used. The CCD images were further processed (see Methods) to accurately obtain the total launching-decoupling efficiency expressed as:

\[
\eta^+ = \eta^+_c \eta_d \exp\left(-\frac{1}{l_{SPP}}\right),
\]

where \( l_{SPP} \) is the SPP propagation length. We measured \( l_{SPP} \) adopting a method improved from the one introduced in ref. 33. Fig. 5 shows the structure design, a fabricated sample, the optical characterization and the image post-processing (see Methods), and the measured results comparing with the theoretical values calculated using \( l_{SPP} = 1/(2k_0 \ln(n_{SPP})) \). The shorter-than-expected \( l_{SPP} \) in Fig. 5(d) is probably due to inelastic SPP scattering by the surface roughness inherently introduced during evaporated and increased by FIB patterning\(^3\). To infer \( \eta^+_c \) accurately from the measured \( \eta^+ \), we calculated \( \eta^+_c \) by \( \eta^+_c = 1.19 \eta^+_c \exp\left(-\frac{1}{l_{SPP}}\right) \), where \( l_{SPP} \) is the SPP propagation length.

We measured \( l_{SPP} \) and infer \( \eta^+_c \) and \( \eta_d \) from the measured \( \eta^+ \) as:

\[
\eta_d \approx \sqrt{1.17} \eta^+ \exp\left(-\frac{1}{l_{SPP}}\right),
\]

\[
\eta_c \approx \sqrt{1.17} \eta^+ \exp\left(-\frac{1}{l_{SPP}}\right).
\]

The linear relationship holds for the fabricated samples, but it is slightly modified into \( \eta_d \approx \sqrt{1.17} \eta^+ \exp\left(-\frac{1}{l_{SPP}}\right) \) and \( \eta_c \approx \sqrt{1.17} \eta^+ \exp\left(-\frac{1}{l_{SPP}}\right) \).

Figures 6(b) and 6(c) compare the experimental and the calculated \( \eta^+_c \) of the two launchers with respect to \( \lambda \) for \( \theta = 45^\circ \) and to \( \lambda = 830 \text{ nm} \), respectively. Although the measured efficiencies are smaller than the calculated results, especially for Launcher I, they agree well in general trends. In Fig. 6(b), a slight oscillation occurs for the experimental data of Launcher I because of the interference between top-SPPs and bottom-SPPs at the decoupler, which should not appear in practical applications. Limited by the wavelength range of the laser source we used, we have only demonstrated the front part of the broadband and meanwhile efficient performance (see Supplementary Information) in the near infrared regime. In Fig. 6(c), the angular FWHM of more than 8° has been demonstrated experimentally.

Discussion

The difference between measured and calculated efficiencies in Figs. 6(b) and 6(c) could originate from the fabrication imperfections. As we have pointed previously, the measured slit parameters determined from the calibrated SEM images indicate that the fabrication deviations of Launcher I are relatively large. This is due to the large size of the whole sample and the deep-subwavelength slit width. Aside from the size deviations, some metallic ridges of Launcher I separate from the substrate because of extremely small widths (see Fig. 5(d)). However, even with these fabrication imperfections, all the measured \( \eta^+_c \) (I) are larger than the measured slit duty factor (22.2%) across the laser wavelength range in the experiment for \( \theta = 45^\circ \), and the maximum value is up to 31.9%.

Up to now, the largest efficiency of ~52% has been reported from a carefully optimized aperiodic SPP launcher\(^1\), which is illuminated from the top and sensitive to both \( \lambda \) and \( \theta \). As pointed out in ref. 10, the incident light from the top is a significant source of noise, unless directed away from a region of interest, which then decreases the signal and increases the system’s size. This problem is eliminated using back-side illumination in optically thick metal films. Moreover, the neighboring distances of the aperiodic SPP launcher in ref. 18 is comparable to the SPP wavelength, whereas the period in our proposed method is of \( \lambda_{SPP}/4 \sim \lambda_{SPP}/3 \). As a result, the proposed SPP launching approach adopting back-side illumination and subwavelength period will also gain advantages in integration besides the attractive ultra-broadband and meanwhile efficient performance. Additionally, compared with aperiodic gratings\(^8,18,24,26\) of which the wavelengths are smaller than the calculated results, especially for Launcher I, they agree well in general trends. In Fig. 6(b), a slight oscillation occurs for the experimental data of Launcher I because of the interference between top-SPPs and bottom-SPPs at the decoupler, which should not appear in practical applications. Limited by the wavelength range of the laser source we used, we have only demonstrated the front part of the broadband and meanwhile efficient performance (see Supplementary Information) in the near infrared regime. In Fig. 6(c), the angular FWHM of more than 8° has been demonstrated experimentally.

**Figure 3** | (a) Dependence of \( \eta^+ \) and \( E_R \) on \( N \). (b)(c) Spectral and angular dependence of \( \eta^+_c \) for \( N = 5 \) (b) and \( N = 50 \) (c). The calculations were performed with \( \lambda = 1550 \text{ nm}, \theta = 44^\circ \), and other parameters \((h, w, p)\) are the same as Fig. 1(c).
Methods

Simulation. The band structure of the 1D plasmonic crystal, the SPP launching efficiency $\eta_+^c$ and decoupling efficiency $\eta_d$ are calculated using the rigorous coupled wave analysis/aperiodic Fourier modal method (RCWA/a-FMM)\textsuperscript{34,35}. The near fields are calculated using Lumerical FDTD Solutions. The wavelength-dependent complex permittivities of gold are interpolated from experimental data\textsuperscript{36}, the superstrate and the material filling the slits are assumed to be air ($n_{\text{sup}} = 1.0$), and the refractive index of the substrate $n_{\text{sub}} = 1.46$ is used throughout this work.

Fabrication. A 200 nm-thick gold film is sputtered onto a 2 cm $\times$ 2 cm quartz substrate. A focused ion beam (FIB) milling system is used to mill samples composed of a launcher and a decoupler with a separation distance $l$, and samples composed of a central slit and two surrounding grooves, all of which are 120 nm wide and separated with various pairs of asymmetric slit-groove distances (9, 12, 15, 21, 24, and 27 $\mu$m).

Characterization. The optical measurement is conducted using home-built experimental setups to obtain the CCD images. The light source is a continuous wave Ti:sapphire laser with a tunable wavelength range of 800 nm to 920 nm. The laser beam expanded by a telescope system and attenuated by a calibrated vari-ND filter illuminates a rectangle iris, which is imaged onto the launcher or the central slit from the substrate side using an imaging system composed of a lens $L_1$ and a microscope objective $O_1$ (50$\times$, NA = 0.5). To measure the SPP coupling efficiency, the sample is

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wavelength, we fit the decay of the re-radiation power with an exponential to extract the top-SPP propagation length, i.e., $\text{ln} \omega_{\text{p}} = (d_{\text{z}} - d_{\text{t}})/(\ln P_{\text{g2}} - \ln P_{\text{g1}})$.

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Author contributions
G.L. conceived the idea; J.Z. directed the project and designed the experiment; G.L. performed the simulation, fabrication and characterization. All authors analyzed the results, and contributed to the article.

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