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Near-field characterization of bound plasmonic modes in metal strip waveguides

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Abstract: Propagation of bound plasmon-polariton modes along 30-nm-thin gold strips on a silica substrate at the free-space wavelength of 1500 nm is investigated both theoretically and experimentally when decreasing the strip width from 1500 nm down to the aspect-ratio limited width of 30 nm, which ensures deep subwavelength mode confinement. The main mode characteristics (effective mode index, propagation length, and mode profile) are determined from the experimental amplitude- and phase-resolved near-field images for various strip widths (from 30 to 1500 nm), and compared to numerical simulations. The mode supported by the narrowest strip is found to be laterally confined within \(\sim 100\) nm at the air side, indicating that the realistic limit for radiation nanofocusing in air using tapered metal strips is \(\sim \lambda/15\).

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1. Introduction

Surface plasmon polaritons (SPPs) are electromagnetic excitations, bound to and propagating along metal-dielectric interfaces [1]. SPPs have been intensively studied during the last decades due to their large number of potential applications, ranging from on-chip telecommunications and signal processing to biochemistry and sensing [2–4]. The excitation and propagation properties of SPPs on infinite thin metal film are well known. The SPPs can also propagate along the metal films of finite width, called metal strip waveguides. If such strip is completely embedded into a dielectric, then there are 2 types of modes with opposite symmetry that are supported: long-range SPP (LR-SPP) and short-range SPP (SR-SPP) modes [5,6]. If the dielectric environment around the metal strip is not uniform (for example, when strip is deposited on a glass substrate), then the LR-SPP mode becomes leaky due to the coupling to radiation modes inside the substrate, which results in substantial increase of propagation losses [7,8]. Therefore, the LR-SPP mode is not a bound mode in the case of a narrow metal strip placed on a dielectric substrate. The SR-SPP mode, on the other hand, does not become leaky in inhomogeneous dielectric surrounding and does not experience the cut-off when decreasing the strip width, a remarkable feature that allows nanofocusing [9–11] and propagation of strongly confined modes [12, 13]. Similar properties are present for a gap SPP mode, confined inside a dielectric between two strips, which allowed effective squeezing of the mode field into a subwavelength $14 \times 80 \text{ nm}^2$ area at $\lambda = 830 \text{ nm}$ [14]. However, in this case the field is mainly distributed in the dielectric between the metal strips, which might be a disadvantage compared to the nanofocusing with the strip waveguide, where the enhanced field in the air around the metal strip is readily accessible [10, 11]. Since the ultimate field enhancement achieved by nanofocusing strongly depends on the balance between squeezing the mode size and propagation loss by absorption [9, 10], the knowledge of evolution of mode characteristics for progressively narrow strip widths is crucial for optimum design of nanofocusing configurations.

In this paper, we present a detailed analysis of the SR-SPP mode properties (effective mode index, propagation length, mode profile, and mode width) when it is guided along gold strips of different widths deposited on a silica substrate at the telecom wavelength of 1500 nm. First we study waveguiding properties numerically with the finite element method implemented in COMSOL software. Then we experimentally investigate waveguiding for various strip widths (from 30 to 1500 nm) using amplitude- and phase-resolved scattering-type scanning near-field
optical microscope (SNOM). The recorded complex-valued near-field images are then fitted in MATLAB, allowing determining an effective mode index, propagation length, mode profile, and mode width for each strip width. Finally, we compare the numerical and experimental results.

2. Numerical investigation of dispersion properties

![Graph showing effective mode index and propagation length as a function of strip width](image)

Fig. 1. (a) Effective mode index and propagation length as a function of strip width for default parameters ($t = 30$ nm, $\varepsilon_{\text{gold}} = -108 + 10.4i$ [15], fundamental mode; solid line) and modified parameters: $t = 35$ nm (dashed), $\varepsilon_{\text{gold}} = -90 + 10.1i$ [16] (dotted), calculated at $\lambda_0 = 1500$ nm. For comparison the dispersion properties of the 1st order mode and SR-SPP (dash-dotted) mode of planar waveguide ($w = \infty$) are given. Top boundary of gray shaded area corresponds to the refractive index of silica ($n = 1.4446$). Inset shows an illustration of the studied gold strip waveguide of width $w$ and thickness $t$. (b-d) Electric-field amplitude profiles of the (b, c) fundamental and (d) 1st order modes for the strip width of: (b) 30 nm, (c) 1.5 $\mu$m, and (d) 3 $\mu$m, respectively. The green arrows schematically depict the direction of the transverse electric field. Dotted magenta lines represent the surface of the silica substrate and gold strip.

The investigated structure consists of a gold strip of width $w$ and thickness $t$, deposited on a silica substrate [inset in Fig. 1(a)]. In order to properly simulate the real fabricated structure, the edges of the strip were rounded with radius $r = 10$ nm. The designed gold thickness $t$ was 30 nm, and the default value for the permittivity of gold was taken from Jonson and Christy, $\varepsilon_{\text{gold}} = -108 + 10.4i$ at free-space wavelength $\lambda_0 = 1500$ nm [15]. Additionally to simulations of the fundamental mode with the default parameters [solid line in Fig. 1(a)] we conducted simulations with modified parameters: $t = 35$ nm [dashed line in Fig. 1(a)] and for gold permittivity $\varepsilon_{\text{gold}} = -90 + 10.1i$ [16], taken from Palik and Ghosh [dotted line in Fig. 1(a)]. The dispersion properties of the mode are presented in terms of the effective mode index $n_{\text{eff}}$ and propagation length $L_{\text{prop}}$:

$$n_{\text{eff}} = \text{Re} \left\{ \frac{\beta}{k_0} \right\}; \quad L_{\text{prop}} = \frac{1}{2 \text{Im} \{\beta\}}; \quad (1)$$

where $\beta$ is a propagation constant of the mode and $k_0 = 2\pi/\lambda_0$ is the free space wavevector. The electric field of the fundamental mode for the relatively large strip width [Fig. 1(b)] is predominantly located on the substrate side of the strip, similarly to the SR-SPP mode of the planar waveguide ($w = \infty$). With a decrease of the strip width or thickness the mode confinement increases, leading to the increase in the effective mode index and decrease in the propagation...
length. For a very narrow strip (called nanowire below), the mode profile [Fig. 1(c)] shows nearly uniform distribution of the electric field around the waveguide with “radial” polarization [12]. Additionally to the fundamental mode, higher-order modes are supported for the relatively wide strips [Fig. 1(d)]. However, at the certain strip width their effective mode index becomes less than the refractive index of silica (\(n = 1.4446\) at \(\lambda_0 = 1500\) nm), and they become leaky, which drastically decreases their propagation length and mode confinement.

3. Experimental investigation of dispersion properties

3.1. Experimental arrangement

The design of our nanofocusing structures is based on a 30-nm-thick and 1.5-\(\mu\)m-wide gold strip waveguide, excited with normal illumination via grating coupling [Fig. 2]. The sample was fabricated using a combination of electron-beam lithography and lift-off technique on a silica substrate. Approximately 5 \(\mu\)m away from the grating the strip was tapered down to the desired width of 30, 60, 100, 200, or 500 nm, using our optimized 2-section taper (its shape is optimized to provide the largest transmission [10]). Additionally there was a structure without tapering - a waveguide of 1.5 \(\mu\)m in width. Thus the length of the waveguides was \(\sim 10\) \(\mu\)m (from taper to taper), except for the 1.5-\(\mu\)m-wide waveguide, whose length was \(\sim 20\) \(\mu\)m (from grating to grating). For each designed structure there were 3 duplicates.

![Fig. 2. (a) Schematic layout of the background-free amplitude- and phase-resolved scattering-type SNOM. (b) SEM image of a typical investigated structure.](image)

The structures were experimentally investigated using a scattering-type SNOM, based on an atomic force microscope (AFM). We used our SNOM in the transmission mode [10, 17–20] with the sample illuminated normally from below [Fig 2(a)]. SNOM with a platinum-coated AFM Si probe was operating in a tapping mode at frequency \(\Omega \approx 250\) kHz, while the sample was moving during the scan. The lower parabolic mirror was moving synchronously with the sample in the \(xz\)-plane in order to maintain the excitation alignment during the scan. The signal, scattered by the probe, was detected and demodulated at the third harmonic (3\(\Omega\)) to filter the near-field contribution from the background. Additionally, our SNOM uses interferometric pseudoheterodyne detection [21], which allows imaging of both the amplitude and the phase of the near-field. Finally, it should be mentioned that because of the AFM probe shape, elongated along the out-of-plane \(y\)-axis, the measured optical signal corresponds mostly to the \(E_y\) component of the near-field [10, 17–20].
3.2. Near-field maps

The near-field phase maps demonstrate propagation of the mode along the strip, while amplitude maps indicate mode decay [Fig. 3]. One can directly see that the wider the strip, the longer the propagation length and the larger the mode wavelength (period of phase oscillations), meaning the smaller effective mode index. For strips of 100 nm width or wider one can notice a fringe pattern on amplitude maps, which can be explained by the back-reflection from either the output taper or grating. Finally, the near-field amplitude for narrow strips \((w = 30, 60, \text{ and } 100 \text{ nm})\) is distributed evenly over the strip width, while for wide strips \((w = 0.5 \text{ and } 1.5 \mu m)\) the amplitude profile exhibits bright spots near the strip edges, which agrees well with the numerical simulations of mode profiles [Figs. 1(b) and 1(c)].

![Fig. 3. SNOM images of (a) topography \(y\) and (b-g) near-field (amplitude \(|E|\) and phase \(\text{Arg}[E]\)) for waveguide width of: (a, b) 30, (c) 60, (d) 100, (e) 200, (f) 500, and (g) 1500 nm, respectively. The propagation direction is illustrated with red arrow in (a). Color bars are shown at the bottom.](image)

3.3. Fitting of near-field maps

The recorded near-field maps can be analyzed with Fourier transformation (FT) in order to determine the number of modes and effective mode index of each mode. However, the accuracy of FT is \(\Delta n_{\text{eff}} = \lambda_0/L\), which is quite low due to the short length \(L\) of the waveguide (for example, for \(L = 10 \mu m\) \(\Delta n_{\text{eff}} = 0.15\)). The propagation length of the mode can be found by fitting the amplitude profile with an exponential decay. However, this procedure works accurately only when one mode is present, without its reflection, which was not in our case. Therefore, in order to accurately determine the dispersion properties of the mode, we applied numerical fitting of the recorded near-field maps \(E_{\text{data}}\) with a superposition of direct and backward-reflected modes as following:

\[
E_{\text{data}}(x, z) = \sum_j A_j(x) [\exp(i\beta_j z) + r_j \exp(-i\beta_j z)] + E_{\text{residual}}(x, z),
\]

where \(A_j(x)\) is an amplitude of the direct \(j^{th}\) mode (for each line along \(z\)-axis), \(\beta_j\) is its complex-valued propagation constant, and \(r_j\) is its complex-valued reflection coefficient. In general, both \(\beta_j\) and \(r_j\) are global fitting parameters (for the whole near-field map), while \(A_j(x)\) is
a local fitting parameter - it is determined for each line along $z$-axis. The non-linear fitting was realized in MATLAB software, using \texttt{lsqnonlin} function and Levenberg-Marquardt algorithm. The fitting was set to minimize the average amplitude of the residuals $E_{\text{residual}}$. First, for each waveguide width we used fitting with one mode. However, the analysis of the residuals for wide strips ($w = 0.5$ and $1.5$ $\mu$m) indicated the presence of additional modes. Then the fitting with 2 modes for $w = 0.5$ $\mu$m revealed the presence of the leaky 1$^{\text{st}}$ order mode, additionally to the fundamental mode [Fig. 4]. Compared to the fundamental mode, the 1$^{\text{st}}$ order mode has a smaller effective mode index (even smaller than the refractive index of silica) and much shorter propagation length. It also has completely different near-field profile, with two lobes of opposite sign (phase difference $\sim \pi$) near the strip edges. The existence of the 1$^{\text{st}}$ order mode can be explained by the non-perfect excitation alignment, when the illumination spot is not centered along the waveguide symmetry axis, or by the not perfectly symmetric geometry due to fabrication tolerances. The fitting with 2 modes for $w = 1.5$ $\mu$m [Fig. 3(g)] revealed the presence of another leaky mode, with a short propagation length and effective mode index close to 1. The superposition of the fundamental and this leaky mode results in a beating pattern with a period of $\lambda_0/(1.46 - 1) \approx 3.3$ $\mu$m, visible in the amplitude map [Fig. 3(g)]. This mode can be identified as a LR-SPP strip mode, also noted as leaky quasi-TM surface plasmon mode in [8], where the electric field is predominantly located in the air above the strip.

Fig. 4. Results of fitting procedure for $w = 500$ nm. The near-fielded distribution was fitted with two modes (fundamental and leaky 1$^{\text{st}}$ order modes). The amplitude $|E|$ of reflected modes was 10 times enhanced for visibility.

3.4. Experimental results

The results of fitting procedure for all SNOM maps are shown in Fig. 5. Normalized SNOM profiles [Fig. 5(a)] of the fundamental mode show near Gaussian distribution of the amplitude for narrow strips ($w < 200$ nm), while for wider strips there is an enhancement near the strip edges, which agrees well with the numerical simulations of mode profiles [Figs. 1(b) and 1(c)]. The profiles of the 1$^{\text{st}}$ order mode demonstrate 2 lobes, which is also in agreement with the simulated mode profile [Fig. 1(d)]. Small asymmetry of mode profiles (the left peak of amplitude is slightly larger than the right one) can be explained by the transfer function of the SNOM: the detected signal represents mostly $E_y$ component of the near-field, but other components might also be scattered by the tip and detected, therefore their interference could lead to the above asymmetry.
The SNOM mode profiles were used to determine the mode width \( w_{\text{mode}} \) for each strip as full width at half maximum [Fig. 5(b)]. Thus the smallest measured mode width was \( \sim 100 \) nm for \( w = 30 \) nm, which is \( \sim \lambda_0/15 \). For wide strips, whose mode profiles have two peaks (\( w = 200, 500, \) and 1500 nm), the left and right maxima were used to set corresponding left and right bounds in order to determine the mode width [see example in Fig. 5(a)].

The same procedure was used to determine full width at half maximum for numerical simulations by taking a profile of \(|E(x,y)|\) distribution through the middle of the strip (at \( y = 15 \) nm above the silica substrate). It should be noted that for this determination \(|E|\) is used instead of its \( y\)-component \( |E_y|\) since on the side of the strip the \( |E_y|\) is negligible compared to the \( |E_x|\) [Figs. 1(b) and 1(c)], and, as follows from asymmetrical SNOM mode profiles [Fig. 5(a)], not only \( |E_y|\) component of the near-field is detected. Finally, the mode width can also be estimated from the effective mode index. According to [12], the electric field amplitude outside the nanowire of radius \( a \) in the air at the distance \( r \) from its axis is

\[
|E(r)| = \sqrt{|K_0(\gamma r)|^2 + \left| \frac{\beta}{\gamma} K_1(\gamma r) \right|^2}, \quad \gamma = \sqrt{\beta^2 - \varepsilon_{\text{air}} k_0^2},
\]

where \( K_m \) is the \( m\)-th-order modified Bessel function of the second kind and \( \varepsilon_{\text{air}} = 1 \) is the permittivity of air. Thus, distance \( d \) from the nanowire edge, where \( |E| \) drops to one half, can be found from the following equation:

\[
\sqrt{|K_0(\gamma (d + a))|^2 + \left| \frac{\beta}{\gamma} K_1(\gamma (d + a)) \right|^2} = 0.5 \sqrt{|K_0(\gamma a)|^2 + \left| \frac{\beta}{\gamma} K_1(\gamma a) \right|^2}
\]

According to the numerical simulation, the \(|E|\)-field distribution of the fundamental mode near the strip edges is similar for different strip widths [Figs. 1(b) and 1(c)], therefore one can assume the similar field decay, Eq. (3), from the strip sides along the \( x\)-axis. Thus the mode width can be estimated as

\[
w_{\text{mode}} = w + 2d.
\]
where $d(\beta)$ is determined from Eq. (4), using the mode propagation constant $\beta$ and $a = 15$ nm (half of the metal thickness). Interestingly, all different procedures of mode width evaluation demonstrated the same feature: the mode width differs from the strip width by a value, which does not strongly depend on the strip width. This value was $\sim 80$ nm for experiments, $\sim 50$ nm for simulations and $\sim 30$ nm for estimation from the propagation constant. The discrepancy between experimental and simulation results can be explained by the optical resolution limit of the SNOM, which is usually assumed to be approximately equal to the tip radius ($\sim 25$ nm).

Propagation constant $\beta$, extracted by fitting of SNOM maps, is presented in Fig. 6, expressed in terms of the effective mode index and propagation length, and compared with numerical simulations. The axes of the graph are chosen specifically to demonstrate the fundamental trade-off between the mode confinement (related to the effective mode index) and propagation length. Therefore the coincidence of two simulation curves for $t = 30$ (solid) and 35 nm (dashed) is not accidental: one cannot overcome this trade-off simply by reshaping the geometry of the waveguide. Overall experimental results agree well with the simulation. Because of the fabrication metal thickness $t$ was slightly larger than designed (30 nm) for wide strips and slightly smaller for narrow strips, which explains wider spread of experimental points along the simulation curve (experimental points for $w = 0.5$ and 1.5 $\mu$m are shifted towards longer propagation length and smaller effective mode index, while points for $w = 30$ and 60 nm are shifted in opposite way).

![Fig. 6. Dispersion properties of the SR-SPP mode, expressed in terms of the effective mode index and propagation length. The experimental results are shown with points and compared to the simulation results, conducted for default parameters ($t = 30$ nm, $\varepsilon_{\text{gold}} = -108 + 10.4i$ [15]; solid black line) and modified parameters: $t = 35$ nm (dashed black line), $\varepsilon_{\text{gold}} = -90 + 10.1i$ [16] (cyan line). The point shape represents the strip width: $w = 30$ (square), 60 (circle), 100 (upward triangle), 200 (downward triangle), 500 (rhomb), and 1500 nm (star).](image)

The experimental results for fundamental mode are summarized in Table 1 below. The accuracy of fitting is expressed in terms of standard deviation $\sigma$:

$$
\sigma = \frac{1}{k_0} \sqrt{\frac{1}{N} \sum_{m=1}^{N} \left( \beta_m - \bar{\beta} \right)^2}, \quad \bar{\beta} = \frac{1}{N} \sum_{m=1}^{N} \beta_m.
$$

One can see from the last two columns that the accuracy of fitting does not strongly depend on mode characteristics and only influenced by the length of the measured waveguide, $L$. The second column from the right shows that the accuracy of fitting is $\sim 15$ times better than the accuracy of Fourier analysis. The accuracy was also checked by exciting the mode from the op-
posite site (using the second grating) for \( w = 60 \text{ nm} \). The results for direct and reverse excitation are depicted in Fig. 6 as a half-filled circles.

| \( w \), \( \mu \text{m} \) | \( L \), \( \mu \text{m} \) | \( \frac{\beta}{k_0} \), Re | \( \frac{\beta}{k_0} \), Im | \( L_{\text{prop}}, \mu \text{m} \) | \( \sigma_{\text{Re}} \) | \( \sigma_{\text{Im}} \) | \( \frac{\lambda_0}{L_{\sigma_{\text{Re}}}} \) | \( \frac{\lambda_0}{L_{\sigma_{\text{Im}}}} \) |
|---|---|---|---|---|---|---|---|---|
| 30 | 10 | 100/72 | 2.24/1.99 | 0.102/0.069 | 1.2/1.7 | 1.2 \times 10^{-2} | 3.6 \times 10^{-3} | 13 | 42 |
| 60 | 10 | 131/105 | 1.74/1.70 | (4.3/4.2) \times 10^{-2} | 2.8/2.9 | 1.0 \times 10^{-2} | 2.2 \times 10^{-3} | 15 | 68 |
| 100 | 10 | 172/147 | 1.595/1.583 | (2.9/2.9) \times 10^{-2} | 4.1/4.2 | 6 \times 10^{-3} | 2.1 \times 10^{-3} | 25 | 71 |
| 200 | 10 | 278/249 | 1.490/1.502 | (1.2/1.7) \times 10^{-2} | 9.8/6.9 | 9 \times 10^{-3} | 2.2 \times 10^{-3} | 17 | 68 |
| 500 | 10 | 580/550 | 1.464/1.467 | (4.5/9.3) \times 10^{-3} | 26/13 | 9 \times 10^{-3} | 1.9 \times 10^{-3} | 17 | 79 |
| 1500 | 20 | 1580/1551 | 1.473/1.463 | (2.4/5.4) \times 10^{-3} | 50/22 | 6 \times 10^{-3} | 5 \times 10^{-4} | 19 | 150 |

4. Conclusion

In this work, we have investigated SR-SPP modes supported by the 30-nm-thick gold strip on the silica substrate for various strip widths (from 30 to 1500 nm) at the free-space wavelength of 1500 nm. The main mode characteristics (effective mode index, propagation length, mode profile, and mode width), determined by fitting the experimental amplitude- and phase-resolved near-field maps, agree well with numerical simulations. The mode supported by the narrowest strip is found to be laterally confined within \( \sim 100 \text{ nm} \) (\( \sim \lambda_0/15 \)) at the air side, having the wavelength \( \sim 670 \text{ nm} \) and propagation length \( \sim 1.2 \mu\text{m} \). A strong mode confinement and relatively low propagation losses, together with wide tunability and rather easy fabrication, makes strip metal waveguide the most popular among other designs of plasmonic waveguides used by researchers and promising for industrial applications. The results of this work are especially valuable for applications utilizing the ultimate field enhancement achieved by nanofocusing, since the knowledge of evolution of mode properties for progressively narrow strip widths is crucial for optimum design of nanofocusing configurations.

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