Tuning the transmission of surface plasmon polaritons across nano and micro gaps in gold stripes

GOLALEH GHAFOORI, JOHANNES BONEBERG, PAUL LEIDERER, AND ELKE SCHEER*

Department of Physics, University of Konstanz, 78457 Konstanz, Germany
*elke.scheer@uni-konstanz.de

Abstract: We applied a far-field technique to measure the surface plasmon propagation over a wide range of gap sizes in thin gold stripes. This is realized with a grating technique which allows the excitation and out coupling of surface plasmon polaritons (SPPs). With this method the intensity can be monitored before and after the gap. The observations show that the SPPs can transmit over gaps with a width of 1 μm with a probability of about 40% for Au stripe-waveguides (7 μm width) at a wavelength of 780 nm. The transmission decays exponentially above a gap size of 1 μm. The results also demonstrate that the transmission has non-monotonic behavior for gap sizes smaller than 1 μm that we attribute to excitation of Fabry-Perot modes and resonant localized plasmons within the gap. The experimental results are supported by numerical simulations using a Finite-Difference Time-Domain (FDTD) approach.

References and links


1. Introduction

For the development of integrated optical devices the functionality of which depends on the combination of optical signals with electronics, the ability to guide and manipulate light propagation at very small scales is crucial. However, minimizing optical waveguides is limited because the confinement of light is restricted to the diffraction limit. One way to overcome this issue is using surface plasmon polaritons (SPPs) on metallic structures [1–3]. The unique properties of SPPs such as high confinement and high speed signal transmission enable various applications, such as plasmon wave guides [4–8] imaging [5], nanophotonics [9] and biosensors [10]. For these structures, an important issue is the transmission of SPPs between two guiding elements. Investigation on how the light can transmit and interact with discontinuities in restricted elements was investigated extensively theoretically and experimentally [11–21]. In some experiments it might be desirable to thermally decouple the excitation area from the actual measurement area. This might be realized by a gap in the system, but it has to be determined to what extent the SPP can couple across a gap of a given width. Previous gap measurements employed near-field scanning optical microscopy techniques for gap sizes from 200 to 500 nm [15, 21] and far-field techniques for gap sizes from 30 nm to 16 μm [20].

In this work we present a comprehensive study on propagation and transmission of surface plasmons over gaps with size $d_{gap}$ from about 100 nm to 5 μm in a narrow and thin gold stripe. Our findings with the help of far-field technique extends the existing literature [16, 20] by a detailed study for $d_{gap} = 110$ nm to 1 μm revealing that the transmission has a non-monotonic dependence on the gap size [21, 22].
2. Results and discussion

For the excitation of SPPs we used the grating method, i.e. we engrave a series of line grooves into the metal stripe. We optimized the grating parameters (number, width, depth and distance of grating grooves) with the help of Finite-Difference Time-Domain (FDTD) simulations. When the gratings’ geometrical parameters are correctly chosen, the corrugations can provide the correct momentum difference to achieve efficient coupling between incident photons and propagating SPPs at the gold-air interface. These SPPs propagate along the gold stripe and further gratings allow converting them back into photons which can be detected in the far-field. The propagation of SPPs on a metallic stripe and their transmission can be measured and the decay length can thus be determined [23–25]. This experimental technique also allows measuring the transmission of SPPs across different gap sizes by monitoring the intensity before and after the gap. Further details on sample fabrication and experimental setup can be found in the supporting information (SI).

First we investigate the SPPs’ propagation length for Au stripes with 100 nm thickness and two different widths ($w = 4$ and $7 \mu m$). We find decay lengths of $9.4 \pm 1.1 \mu m$ and $11.1 \pm 2 \mu m$ for the samples of $w = 4$ and $7 \mu m$. The reduction of the propagation length compared with previous findings is attributed to the fact that in our case we excite the SPPs within a restricted stripe, while for 70 nm thick but wide gold films an SPP decay length of about 40 $\mu m$ was reported for the same wavelength [7]. The experimentally determined SPP decay length in narrow stripes is smaller than in extended films, in good agreement with the simulations for the given geometry and in accord with literature for gold films with comparable dimensions [23, 25] (see SI).

In the next step we fabricated a series of samples with different gap sizes (see SI) and studied the transmission over the gap by comparing the far-field intensity before and after each gap. For that purpose the excitation grating (grating 1) and the first measurement grating (grating 2) were on one side, while the second measurement grating (grating 3) was on the other side of the gap (see Fig. 1(a)).

Figure 1(b) indicates the far-field image of the sample under 780 nm laser diode illumination, which shows the back-scattered light of the SSP propagating in the gold stripe with $w = 7 \mu m$. The main high intensity peak is related to the excitation grating (grating 1). In addition clearly visible light contributions at the two other gratings (grating 2 and 3) can be found for the polarization along the stripe (p polarization). A sharp increase of intensity at the edge of the gap shows that the first edge causes the SPP to couple to free space electromagnetic modes, leading to partial radiation of the SPP intensity. The intensity loss measured after the second gap edge is used to quantify the transmission for each gap width. For s polarization (Fig. 1(c)), a much smaller, but still detectable light intensity is found at grating 2 and at the gap edge. We attribute this unexpected signal for the s polarization to the excitation of SPPs because of the roughness of the grating lines due to the milling. By scattering and reflection at the rim of the Au stripe these SPPs may reach grating 2. Figure 1(d) shows the cross section intensity of the far-field image of the sample as obtained from Figs. 1(b) and 1(c). This shows the decay of SPP intensity with distance from the point of excitation which is interrupted by the gap.
We follow the concept of [25] and calculate the transmission over different gap width by measuring the intensity at grating 2 and 3 when illuminating at grating 1. The transmission over a gap with width $d_{\text{gap}}$ is given by:

$$T_s = \frac{I_{3,1}}{I_{2,1}} \exp\left(-\frac{d_{2,3}-d_{\text{gap}}}{l}\right)$$  \hspace{1cm} (1)

Here, the distance $d_{2,3}$ between the positions of grating 2 and 3 is reduced by the gap size $d_{\text{gap}}$ to only account for the decay along the stripe with constant width. $I_{3,1}$ ($I_{2,1}$) is the intensity measured at grating 3 (2) when irradiating grating 1. We evaluate the transmission probabilities separately for each $d_{\text{gap}}$ and $w$ and plot them in Fig. 2.

For a further interpretation of the findings, we carried out FDTD numerical simulations. Here we use the refractive index of gold material in the FDTD database (Gold Palik). A small mesh size of 6 nm was chosen to accurately capture the SPP propagation. Perfectly matched layer boundary conditions were used on all sides of the calculation domain. More details on FDTD simulations can be found in the SI. Figure 3 shows the corresponding simulation results on the gold surface, when the sample design is equal to the real sample width of 7 μm. The cross section intensity of the sample features all elements, including the incidence point, the out-coupling grating and the gap.
The simulation also shows the intensity in the gap and in the gratings. The SPPs clearly decay along the stripe over distance. From the comparison between the experimental (Fig. 1(d)) and simulation results (Fig. 3(b)) one can recognize that, in contrast to the experiment, in the simulation the edges of the intensity are sharp for each trench and the gap. However, this difference can be due to the fact that the experiment is in the far-field, but the FDTD intensity is simulated at a distance of 20 nm above the surface (near field).

A quantitative measurement of SPP transmission over the gap in gold metal stripes as a function of gap length is shown in Fig. 2. The experimental results in Fig. 2(a) show the exponential decay with increasing gap length above 1 μm for two samples with a width of 4 μm and 7 μm. This decay arises from scattering of the radiation into the substrate and into the air (see FDTD simulation in the SI for a side view). The simulated transmission values are not determined directly from the curve shown in Fig. 3(b), but are calculated by averaging the intensities at monitors placed in y-z planes at fixed distance in front and behind the gap, as described section 4.2 in the SI. The uncertainties arising from the choice of the monitor distance are in the order of a few %. Figures 2(b)-2(d) present the comparison between simulation and experimental results for all three samples under investigation (one sample with \( w = 4 \) μm and two with \( w = 7 \) μm). For the wider stripe the experimental and simulated transmission values agree very well with each other except for small variations that we attribute to experimental uncertainties. For the narrow sample the simulated transmissions for \( d_{\text{gap}} \geq 1000 \) nm are systematically lower than found in the experiment. Since the comparison of the simulation results shows no systematic difference for both stripe widths, we argue that
details of the samples, like the film quality and the edge roughness created by the FIB milling
or the electron beam lithography are at the origin of this discrepancy. Still, in view of these
unavoidable fabrication tolerances and experimental errors the agreement can be considered
as good. Note that, in fact, SPPs are excited both at the air/metal and metal/substrate interface
(see SI). In the simulations we see that the intensity of the SPPs at the metal/substrate
interface is much smaller (several orders of magnitude) than the SPPs at the air/metal
interface, but in the experiment we cannot distinguish between the two contributions.

![Simulation results](image)

**Fig. 3.** (a) FDTD simulation results of the intensity distribution on the gold surface for a
geometry corresponding to the real sample but with ideally flat surfaces and edges (b) Average
intensity cross sections along the long axis over the grating size for $w = 7 \mu m$ and $d_{gap} = 700$

nm.

We performed a detailed study for small gap sizes $d_{gap} < 1 \mu m$ for a stripe a sample with $w = 7 \mu m$. Figure 2(d) shows the experimental (blue curve) and simulation (red curve) results
for this range which reveals a non-monotonic dependence of $T_g$ on the gap size. Such a
behavior had been predicted theoretically before [22] and found experimentally in [21] for
silver films with a thickness of 60 nm by the attenuated total reflection (ATR) method. The
authors showed that the transmission is higher for a 500 nm groove than for a 420 nm groove.
They compared their results with theoretical predictions based on a system which was treated
as a waveguide structure sandwiched between two metal boundaries and concluded that the
complex transmission behavior is due to the existence of certain groove width supporting
electromagnetic modes in the gap region [22]. Further experimental indications for non-
monotonic gap size dependence have been reported in [20], but could not be retrieved in
finite-element simulations.

Our simulations clearly reproduce the non-monotonic behavior. However, the amplitude
of the non-monotonous part is smaller than observed experimentally. We attribute this
difference to experimental uncertainties of the sample geometries. The precision, with which
the grating profile and the gap width can be defined, is in the order of 50 nm. The roughness
of the gap edges is in the order of 20 nm, the surface roughness amounts to 5 nm, neither one
is taken into account in the simulations. We estimated by test simulations on simplified
geometries that the variation of these parameters may result in a variation of the transmission
of 5-7%. Finally, the SPP propagation depends on the dielectric constant of the metal which is known to depend on the fabrication as well [26]. These simulation results are also in good agreement with those of [16], where the authors estimated a high transmission probability of 80% over a 5 μm gap for a 40 nm thick gold film embedded between two dielectric layers with equal refractive index \(n = 1.47\), illuminated at 785 nm for a symmetrical geometry.

We attribute the non-monotonic behavior for small gaps to the excitation of Fabry-Perot modes in the gap. Figure 4 compares the transmission behavior for two idealized samples with a width of (a) \(w = 4 \text{ μm}\) and (b) \(w = 7 \text{ μm}\) as a function of gap size calculated with the Fabry-Perot theory (see SI) on the other hand. For the calculation of the Fabry-Perot modes we have to take into account that the reflection on an absorbing metal induces a phase shift [27]. This phase shift can be calculated [28] by:

\[
\tan \phi = \frac{-2k_1n_2}{-n_1^2 + n_2^2 + k_2^2}
\]

where the index 1 refers to air and the index 2 to the gold. For the wavelength of 780 nm \((n_2 = 0.14, k_2 = 4.543)\) we found a shift of 24.8°. This corresponds to an apparent reflection at \((24.8°/360°) \times 780 \text{ nm} = 53.7 \text{ nm}\) inside the gold. Taking this effect into account on both sides of the gap region we obtain very good agreement between simulation and Fabry-Perot calculation. The maxima in all cases appear close to gap widths that are integer multiples of half the incident wavelength (780 nm). This behavior is similar to the oscillations which are found in thin film Fabry-Perot interferometers [22,29,30] or optical dipole antennas [31,32]. According to the Fabry-Perot theory, constructive or destructive interference occurs and cause high or low transmission probability for different gap sizes. For both samples \((w = 4 \text{ μm}\) with gap step size of 100 nm and \(w = 7 \text{ μm}\) with the gap step size of 50 nm) the transmission for the gap size of 400 nm and 800 nm are higher than for the adjacent gap sizes. This agreement between Fabry-Perot theory and FDTD simulation results suggests that the Fabry-Perot mechanism is at the origin of the non-monotonic transmission function. It also underlines the validity of the FDTD simulations.

3. Conclusion

In conclusion, we have presented a comprehensive study of surface plasmon polariton propagation across a gap with widths between 100 nm to 5 μm in thin and narrow gold stripes. We used a far-field measuring technique and as well as excitation and detection of the plasmons by gratings. Our observations demonstrate that the surface plasmon poloritons can transmit over gaps with sizes up to 1 μm with a transmission probability in the order of 40%.
For gap sizes bigger than 1 μm the transmissivity decays exponentially because the radiation is out-coupled into the substrate and the air. A more detailed study on gap sizes smaller than 1 μm also reveals that the transmission depends non-monotonically on the size of the gaps because of the formation of Fabry-Perot modes in the gap. Quantitative agreement between experimental results and FDTD modeling is obtained when taking into account the finite skin depth of the electromagnetic waves in metals. Our findings are important for designing nanoplasmonic functional devices, since they can be used to maximize or to minimize the transmission according to the envisaged functionality of the device.

Acknowledgments

We are indebted to Matthias Hagner for help in sample preparation and to Daniel Benner for his support in the early phase of the project. We gratefully acknowledge financial support from the Deutsche Forschungsgemeinschaft through the Strategic Japanese-German Cooperative Program of the JST and DFG on Nanoelectronics and from the Center of Applied Photonics funded from the Ministry of Science and Arts Baden-Württemberg and the German Excellence Initiative.