Designing the metallic superlens close to the cutoff of the long-range mode

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Abstract: The metallic superlens typically shows two peaks in its transfer function related to the long- and the short-range surface plasmon polariton (SPP) modes. These peaks are necessary to amplify the evanescent waves compensating the exponential decays, but enhance the spatial frequencies disproportionally, resulting in strong sidelobes in the image. We propose to design the metallic superlens with close to the cutoff condition of the long-range SPP mode to balance the SPP amplification and the flatness of the transfer function, and thus eliminating the sidelobes in the image. The design experiments for the Al superlens at 193 nm with both the transfer-matrix approach and the numerical finite difference in time domain method are shown.

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References and links

1. Introduction

Conventional images are formed by collecting the propagating object waves and then have a diffraction-limited resolution in the order of the wavelength. The superlens is a slab of negative index material (NIM) which restores the phase of propagating waves and the amplitude of the evanescent waves [1] to achieve the sub-wavelength resolution. In the ideal case all the media in the superlens structure are impedance-matched and lossless, so that perfect image recovery can be achieved. In practice however, the performances of the superlens are greatly reduced by the impedance mismatches at the interfaces and by the inherent absorption within the materials [2].

The metallic superlens is an alternative to the NIM lens made with noble metals like silver, gold and aluminum, which have a negative permittivity at operating optical frequency,
but a positive permeability close to unity. The metallic superlens is easier to implement and has been experimentally demonstrated and applied to lithography for recording sub-wavelength patterns in photoresist [3–5]. The principle of the metallic superlens is to amplify the evanescent waves by surface plasmons (SP) resonance to compensate for their exponential decay away from the object [1–7]. However, it was shown that for imaging purpose the SP resonance can be also detrimental by its disproportional enhancement of the spectral components of the field [8]. As a consequence, the images of isolated nanometric patterns can show strong sidelobes, which can be suppressed only by placing assistant features within the object [8]. In this paper, we propose to use the long-range mode cutoff technique [9–11] to trim the transfer function of the metallic superlens and to balance the amplification by the SP resonance and the flatness of the transfer function. Using both the transfer matrix approach [12] and the Finite Difference in Time Domain method (FDTD), we show that the image of a sub-wavelength two-slit pattern in an aluminum mask can be significantly improved with the superlens designed to approach the cutoff condition.

2. Imaging properties of the superlens

A simple metallic superlens consists of a thin noble metal slab of complex permittivity \( \varepsilon_m \) with \( \text{Re}\{\varepsilon_m\} < 0 \) at the operating optical frequency. The superlens is placed in between two semi-infinite and non-absorbing dielectric media of permittivities \( \varepsilon_1 \) and \( \varepsilon_3 \), where a planar object with nano-scaled detail and its image are parallel to the slab at the distance \( d_1 \) and \( d_3 \), respectively, as illustrated in Fig. 1. The illumination light is of TM-polarization.

![Fig. 1. Schematic representation of the superlens](image)

The imaging property of the superlens is conveniently described by the transfer function (TF), defined as the transmission coefficient for the Fourier components of the object at \( k_x \), which is the wave-vector component along the interfaces of the superlens. Considering the system depicted in Fig. 1 as a cascade of three subsystems, we can express the total TF from the object to the image plane as a product of the complex TFs through the three layers,

\[
TF(k_x) = \tau_1 \cdot \tau_m \cdot \tau_3,
\]

where \( \tau_n = \exp(ik_n d_n) \) for the dielectrics \( n = 1, 3 \) with \( k_n = \sqrt{\varepsilon_n k_0^2 - k_s^2} \) are the spatial filters of free space propagation and represent the exponential decay away normally from the plane \( z = 0 \) and \( z = d \), respectively, of the evanescent waves with \( k_s^2 > \varepsilon_s k_0^2 \), and \( \tau_m \) is the transmission coefficient through the metallic slab given by [1,7]

\[
\tau_m = \frac{t_m t_3 \exp(ik_m d)}{1 + r_0 r_d \exp(2ik_m d)}, \tag{1}
\]

where

\[
\begin{align*}
    r_0 &= \frac{\varepsilon_m k_{1m} - \varepsilon_1 k_m}{\varepsilon_m k_{1m} + \varepsilon_1 k_m},
    r_d &= \frac{\varepsilon_3 k_m - \varepsilon_m k_{3m}}{\varepsilon_3 k_m + \varepsilon_m k_{3m}},
    t_0 &= \frac{2\varepsilon_m k_{1m}}{\varepsilon_m k_{1m} + \varepsilon_1 k_m},
    t_d &= \frac{2\varepsilon_3 k_m}{\varepsilon_3 k_m + \varepsilon_m k_{3m}},
\end{align*}
\tag{2}
\]

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with \( k_{zm} = \sqrt{\varepsilon_m k_0^2 - k_i^2} \), are the Fresnel reflection and transmission coefficients of the interfaces of the metal slab with \( z = 0 \) and \( z = d \), respectively, for the optical field propagating along the \( +z \)-axis. The evanescent object waves carrying the nano-scale information would excite the surface plasmon polaritons (SPPs) at the metal-dielectric interfaces. It is well known [1,7] that the SPP can be amplified through the resonance of the multiply reflected field within the metallic slab. Indeed, in a simple symmetric structure \( \varepsilon_1 = \varepsilon_2 = \varepsilon_3 \) and supposing that \( \varepsilon_m = -\varepsilon_i \) according to Eqs. (1) and (2), the transmission coefficient \( t_m \) tends to \( \exp(-i k_{zm} d) \) \( \gg 1 \) for a large imaginary part of \( k_{zm} \).

As the superlens slab thickness is comparable with the SPP skin depth in the metal, the SPPs at the two interfaces of the slab are coupled, giving rise to the SPP modal field distributions. Typically, the transfer function of a metallic superlens contains two well defined feature peaks, corresponding to two excited SPP modes: a long-range mode associated to a narrow peak located at lower spatial frequencies near \( k_m = \sqrt{\varepsilon_i k_0} \), and a short-range mode associated to a broad peak at higher spatial frequencies. Indeed, in the symmetrical SPP waveguide structure with \( \varepsilon_1 = \varepsilon_3 \), the long-range mode corresponds to a symmetrical mode and the short-range mode corresponds to an anti-symmetrical mode [9]. In the case of metallic superlenses where the structure is usually asymmetric \( \varepsilon_1 \neq \varepsilon_3 \), the modes are not symmetrical, but can be still long-range and short range modes as their respectively symmetrical counterparts.

As \( t_1 \) and \( t_3 \) show exponential decays which increase with \( d_i \) for \( \kappa_i > \sqrt{\varepsilon_i k_0} \), \( d_i \neq 0 \) and \( d_i \neq 0 \), the short-range SPP mode at higher spatial frequencies is mostly suppressed. Therefore, the TF of the superlens structure contains mainly the long-range mode peak located in the lower portion of the evanescent spectrum. On one hand, this transmission peak provides the SPP amplification which is necessary for compensating its exponential decay along the \( z \)-axis. On the other hand, a narrow and too high transmission peak can cause strong sidelobes in the image of an isolated sub-wavelength object. In the simulation reported in [8], the metallic superlens failed to image an object of two 20 nm slits spaced by 40 nm, as it showed strong sidelobes that cannot be suppressed without using assistant features in the object mask. Therefore, the superlens structure parameters, such as the permittivities and thicknesses of the layers, must be optimized to balance the SPP amplification and the flatness of the TF of the superlens. This optimization is usually performed through numerical simulation by trials without rules to follow. In this paper, we propose to use the long-range mode cutoff technique to trim the TF in the design of the superlens.

In the SPP waveguide theory, the symmetrical mode is cutoff when the propagation constant, \( \beta \), obtained by numerical solution of the dispersion relation is purely real [9,10]. This occurs when the nature of the mode changes from attenuating (\( \text{Im}[\beta] > 0 \)) to growing (\( \text{Im}[\beta] < 0 \)) with the propagation along the metal layer, so that the mode cannot be excited by physical means. In the case of the three layer structure shown in Fig. 1, the symmetrical mode at the cutoff is a “Brewster mode”, for which a homogeneous plane wave in \( \varepsilon_i \) propagating at the grazing incidence \( (k_m = \sqrt{\varepsilon_i k_0}) \) feeds a SPP resonance localized at the \( \varepsilon_m-\varepsilon_3 \) interface with the incident energy totally dissipated in the metal such that the reflection of the metal layer, \( \rho_m \), is null. Thus, the cutoff condition is obtained from the condition \( \rho_m = 0 \). In the three-layer structure, according to [7] we have

\[
\rho_m = \frac{r_0 + r_2 \exp(2ik_{zm}d)}{1 + r_0r_2 \exp(2ik_{zm}d)},
\]

so that the symmetrical mode cutoff condition is

\[
-r_0/r_2 = \exp(2ik_{zm}d).
\]

This transcendent equation can be solved numerically for the propagation constant, \( \beta = \text{Re}(\beta) \) in the relations with the structural parameters \( \varepsilon_1, \varepsilon_2, \varepsilon_3 \) and \( d \). However, in the metallic
superlens design, we do not completely cutoff the long-range mode, but approach the cutoff condition to reduce amplification of the long range SPP mode at a convenient level. In addition for multi-dielectric-layer structures one cannot find the cut-off condition using Eq. (5). In practical design, starting from a given superlens structure, we approach the cutoff of the long-range mode by gradually increasing the asymmetry ratio \( \varepsilon_1/\varepsilon_3 \) or decreasing the metal layer thickness \( d \) for the given \( \varepsilon_1 \) and \( \varepsilon_3 \) and computing the \( t_m \) and the \( TF \) from Eq. (1), in the case of three-layer structure, or using the transfer-matrix approach, in the case of multiple-layer structure [12], to observe the long-range mode transmission peak decreasing with the peak location shifted toward \( k_x \approx \sqrt{\varepsilon_1 k_0} \).

3. Design examples

As an example, we consider a three-layer structure of a 13 nm-thick aluminum superlens \( \varepsilon_m = 4.43 + 0.42i \) at \( \lambda = 193 \) nm on a MgO substrate (\( \varepsilon_1 = 4.08 \)) in the symmetrical (\( \varepsilon_3 = \varepsilon_1 \)) configuration and a configuration close to the cutoff with a reduced value of \( \varepsilon_3 = 2.38 \). The object and image distances \( d_1 = d_3 = 10 \) nm. The magnitude of the metal slab transmission, \( t_m \), and of the total \( TF \) are plotted as a function of the normalized frequency \( k_x \approx k_x/\sqrt{\varepsilon_1 k_0} \) in Fig. 2. For comparison, the transmissions through free space over 13 nm for \( t_m \) and over 33 nm for \( TF \) are also plotted. In Fig. 2a for \( t_m \), the strong evanescent field amplification is shown in the symmetrical structure (green dotted line). The two peaks associated to the two SPP modes are clearly observable along with a transmission dip around \( k_x \approx 1 \). In the close-to-the-cutoff configuration (thick black line), the symmetrical mode peak is cutoff and \( t_m \) shows a near-flat amplification profile over a wide range \( 1 \leq k_x \leq 4 \) of the spectrum. In Fig. 2b for the \( TF \), the propagation over \( d_1 \) and \( d_3 \) strongly suppresses the evanescent field such that the broad anti-symmetrical mode peak is suppressed, and only the symmetrical mode peak at \( 1.2 < |k_x| < 2 \) is observable (green dotted line). In the close-to-the-cutoff configuration (thick black line), the symmetrical mode peak is strongly reduced, but the \( TF \) still shows enhancement of the evanescent waves over a range of \( 1 \leq k_x \leq 3 \) compared with that of free space propagation.

![Fig. 2. Metallic superlens transmission (a) and transfer function (b), for a 13 nm-thick Al superlens structures: \( \varepsilon_1 = \varepsilon_3 \) (green-dotted line) and close to the cutoff (thick black line). The transmission through free space over the same distances is plot in blue line.](image)

We then compute the images of a magnetic potential pattern comprising two 20 nm wide “slits” with a 40 nm spacing by this superlens in symmetrical and close-to-the-cutoff configurations by the inverse Fourier transform of the transmitted field spectrum through the \( TFs \) of the superlens. Figure 3 shows the image plane field intensity distributions. Although both superlens configurations give well-resolved images of the object, as shown in Fig. 3a and 3b, the image for the symmetrical structure shows sidelobes extending over a few hundredths of nanometres away from the slits in Fig. 3a, which is suppressed in the close-to-the-cutoff configuration in Fig. 3b. For the comparison, Fig. 3c gives the image without the superlens where the two slits are not resolved. Thus, the effect of trimming the evanescent field with the close-to-the-cutoff condition shown in Fig. 2b is evident. However, the middle peak between the two-slit is slightly increased in Fig. 3b, as the final \( TF \) shown in Fig. 2b is still not ideal.
Fig. 3. Intensity profile for a 20 nm two-slit object (green) using a) symmetrical superlens ($\varepsilon_1 = \varepsilon_3$); b) superlens close to the cutoff and c) free space propagation.

We now take the superlens implemented by Shi et al. which was optimized using an index matching layer to increase the optical throughput. This is a five layers structure at $\lambda = 193$ nm with a dielectric layer of $\varepsilon_1 = 2.4025$, a MgO index matching layer of $\varepsilon_2 = 4.08$, the aluminum layer of $\varepsilon_3 = -4.43 + 0.42i$ and the spacer and photoresist layers of $\varepsilon_4 = \varepsilon_5 = 2.89$, with the thicknesses of the layers $d_1 = d_2 = 10$ nm, $d_3 = 13$ nm, $d_4 = 8$ nm. The image is detected at the interface $\varepsilon_4$-$\varepsilon_5$. The superlens was effective in imaging a 20 nm ($\sim \lambda/10$) half-pitch periodic pattern in an aluminum mask, but failed to image a 20 nm two-slit pattern, as the simulation showed strong sidelobes as shown in Fig. 4.

To improve the imaging properties of this five-layer structure we first set the dielectric layer $\varepsilon_1$ as MgO with $\varepsilon_1 = \varepsilon_2 = 4.08$. Our numerical experiments showed that to approach the cutoff condition the medium $\varepsilon_1$ and $\varepsilon_2$ before the metal layer must be sufficiently dense optically. We then approached the cutoff condition by decreasing the permittivity of the spacer layer to $\varepsilon_4 = 1.9321$ ($n_4 = 1.39$). For an object made of a 20 nm-thick aluminum mask perforated by two slit of 20 nm width and spaced by 40 nm, the FDTD simulation was performed with a TM polarized normally incident wave. A periodic boundary condition (PBC) was used for the boundaries perpendicular to the slab interfaces to minimize the simulation noise. For the two other boundaries parallel to the slab interfaces, a perfectly matched layer (PML) condition was used. The grid size was 0.25 nm in both directions. The calculated energy distribution at the spacer-photoresist interface is shown in Fig. 4. The two sidelobes in the structure of Ref. 8 are suppressed significantly without using the assistant features.

The background noise shown in Fig. 4 as a “DC” component in the image is mostly due to the zero-order transmission of the incident field through the structure that could be suppressed by increasing the thickness of the metal object mask such that only the signal transmitted trough the slits contributes to the image.
4. Conclusion

Imaging with a metallic superlens is mediated by the recovery of evanescent waves through the excitation of the SPP modes of the structure. The SPP resonance gives rise to the peaks in the transfer function of the metallic superlens. These peaks are known to cause sidelobes in the image of isolated sub-wavelength patterns. Based on SPP waveguide theory, we have shown that an improved transfer function can be achieved by approaching the cutoff of the long-range mode. We designed a superlens close to the cutoff, based on an Al superlens structure at $\lambda = 193$ nm as proposed in Ref [8], which shows a strong suppression of the sidelobes in the image of an isolated two-slit nanometric pattern in an Al object mask.