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Abstract. Employing rigorous electromagnetic theory we investigate optical the near-field imaging of two interacting dipole-like objects with metal and slightly lossy metamaterial nanoslab superlenses. Our analysis indicates that the dipole emission is suppressed by near-field interactions when the objects are close to the lens or each other. This strongly influences the image quality, in particular with objects of small size and high polarizability. The interference from two nearby objects also affects the resolution and subwavelength definition can only be obtained for objects with dipole moments predominantly orthogonal to the slab. Such an optimal imaging condition is achieved with excitation by total internal reflection. With simulations we show that in these circumstances, subwavelength resolutions of about $\lambda/5$ for silver superlens and $\lambda/10$ for metamaterial slab are reached.

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1. Introduction

In conventional optical imaging, resolution is limited by the light’s wavelength $\lambda$ and the numerical aperture (NA) of the system. Optical imaging beyond the classic Rayleigh–Abbe diffraction limit of $\lambda/2$ in spatial definition has for a long time attracted the attention of scientists, and several approaches for overcoming this limit have been developed. In biomedical imaging, high-resolution far-field techniques, such as stimulated emission depletion microscopy [1], have been demonstrated. Advances in computed imaging have allowed experimental high-definition reconstruction of three-dimensional (3D) samples; examples of recent methods include tomographic diffraction microscopy [2] and interferometric synthetic aperture microscopy [3] based on inverse scattering. In nanophotonics, on the other hand, an entirely different and widely employed approach is optical near-field microscopy [4], which makes use of (scanning) local probes and near-field imaging elements. The imaging device is placed at a subwavelength distance from the object, enabling detection of the evanescent field created by the object and thereby increasing the effective NA. Such nanophotonic microscopy includes evanescent-wave and multiple scattering effects, but the close proximity of the sample and the detector also leads to near-field interactions between the device and the object. These interactions may distort the image and are an inherent feature of nanoscale imaging techniques.

In near-field imaging metallic and metamaterial superlenses [5] providing subwavelength image resolution have inspired an increasing number of both theoretical [6–13] and experimental [14–19] works following the suggestion of the ‘perfect lens’ by Pendry [20] in 2000. The perfect lens is a lossless nanoslab of negative-index material (NIM) that would work as a non-interacting imaging device delivering an undistorted image with unlimited definition. However, any realistic metamaterial is necessarily lossy leading to absorption of the object radiation and to interactions between the lens and the object. Still, they evidently allow subwavelength resolution [10–13]. Despite the rapid progress in the field of metamaterials [21–28], experimental NIM-lens realizations are few [19]. Besides NIM lenses, subwavelength nanophotonic imaging of 2D objects can be achieved with physically realizable metallic nanoslabs exhibiting plasmon resonances [14, 15, 18].

Making use of a rigorous electromagnetic theory for near-field imaging of a dipolar emitter by metallic and slightly absorbing metamaterial superlenses [11, 12], in this work we consider such a nanophotonic imaging of two interacting point-like objects. Our analysis also
accounts fully for the influence of the imaging device on the objects [13]. The object–lens and object–object interactions lead to several remarkable and physically important effects. In close proximity to the metal or NIM slab the dipole moment of the emitter is strongly reduced, as can be explained in terms of a mirror-image dipole in the quasistatic limit [13]. The near-field interactions between two adjacent dipoles suppress the emission of both dipoles as they come closer together, thereby considerably attenuating the intensity of their images. We further show that two interacting dipoles can be unambiguously resolved with subwavelength resolution only when the dipole moments are predominantly oriented orthogonal to the nanoslab. Such a near-field imaging arrangement can be created through excitation by total internal reflection. Our results also indicate that the imaging capabilities of NIM superlenses are superior to those of plasmonic (metallic) nanoslabs, owing to the weaker reflections and stronger enhancement of evanescent waves by metamaterials.

2. Imaging geometry

The imaging geometry is illustrated in figure 1. Radiation from an external source is incident into half-space $z < 0$ (medium I). A transversally infinite slab of thickness $d$ (medium II), located within $0 < z < d$, works as a near-field imaging lens. The slab is followed by another half-space $z > d$ (medium III). As the objects, we use two polarizable point-like emitters described by their dipole moments $q_1$ and $q_2$. The emitters are located in the ‘object plane’ $z = z_0$ in front of the slab and the image is considered in the ‘observation plane’ a distance $b$ behind the slab. The objects are excited by a normally or perpendicularly incident, monochromatic, p-polarized plane wave $E_{ex}(r, \omega)$, where $\omega$ is the angular frequency. The fields generated as
a result of the (multiple) interactions of the incident wave with the dipole objects and the slab, including the image field $E_{im}(\mathbf{r}, \omega)$ exiting into medium III, are all based on the exact boundary conditions of electromagnetic fields [13]. The time-dependent parts $e^{-i\omega t}$ of all fields are suppressed.

We consider two different imaging schemes [11–13]. The first is a metallic superlens structure: a thin silver (Ag) sheet is sandwiched between two dielectric materials. Medium I is composed of polymethyl methacrylate (PMMA), while medium III is a photoresist (PR). For a good impedance match between the materials we take the excitation wavelength as $\lambda = 35$ nm, which has been demonstrated to be an appropriate value in recent experimental [14, 15] and theoretical [13] studies. To ensure that the contribution of the near-field components of the object radiation remains strong in the observation plane, we consider the image intensity distribution in the PR immediately behind the silver film ($b = 2$ nm). The second imaging geometry is a near-perfect lens structure in which a slightly absorbing NIM slab is surrounded by vacuum. In this case, we choose the excitation wavelength as $\lambda = 633$ nm and the effective material parameters of the slab as $\epsilon_{r2} = -1 + i\epsilon''_{r2}$ and $\mu_{r2} = -1 + i\mu''_{r2}$, where $\epsilon''_{r2}$ and $\mu''_{r2}$ are small positive numbers. For the slab thickness we use $d = 35$ nm, and in line with the perfect lens structure we consider the image at the distance $d/2$ behind the metamaterial slab.

3. Emission properties of interacting point-like objects

3.1. Dipole moments for coupled emitters

We consider interacting dipole-like objects in the vicinity of the imaging slab. The electric field at point $\mathbf{r} = (x, y, z)$ generated by a point dipole located at $\mathbf{r}_0 = (x_0, y_0, z_0)$ in a homogeneous, linear and isotropic medium is [13, 30]

$$E(\mathbf{r}, \omega) = \mu_0 \mu_0 \omega^2 \overrightarrow{G} (\mathbf{r}, \mathbf{r}_0, \omega) \cdot \mathbf{q},$$

(1)

where $\mu_0$ is the vacuum permeability, $\overrightarrow{G} (\mathbf{r}, \mathbf{r}_0, \omega)$ is the outgoing infinite-space dyadic Green function and $\mathbf{q}$ is the dipole moment. The dipole moment of a polarizable point dipole is determined through a relation

$$\mathbf{q} = \mathbf{\alpha} \cdot E_{tot}(\mathbf{r}_0, \omega),$$

(2)

where $\mathbf{\alpha}$ is the polarizability and $E_{tot}(\mathbf{r}_0, \omega)$ is the total electric field at the location of the dipole. In our geometry (see figure 1), the first dipole $\mathbf{q}_1$ is located at $\mathbf{r}_1 = (x_1, y_1, z_1)$ and the second dipole $\mathbf{q}_2$ at $\mathbf{r}_2 = (x_2, y_2, z_2)$. We choose $x_2 > x_1 = 0$, $y_1 = y_2 = 0$, and take the dipoles at equal distance from the slab, i.e. $z_1 = z_2 = z_0 < 0$. We further assume that the polarizability of both dipoles is isotropic, i.e. $\mathbf{\alpha} = \alpha \mathbf{1}$, where $\alpha$ is a scalar quantity, $\mathbf{1}$ is the unit tensor and $i = 1, 2$. The total electric field at the position of each dipole consists of the exciting field, $E_{ex}(\mathbf{r}_i, \omega)$, the part of this field that is reflected from the slab, say $E_{exr}(\mathbf{r}_i, \omega)$, and the dipole field itself scattered back from the slab. In addition, the dipole field propagated straight from the adjacent dipole, as well as reflected from the slab, contribute to the total field. Hence, we can write
self-consistent relations for the dipole moments

\[
\mathbf{q}_i = \alpha \{ \mathbf{E}_{\text{ex}}(\mathbf{r}_i, \omega) + \mathbf{E}_{\text{ex},t}(\mathbf{r}_i, \omega) + \mu_0 \mu_0 \omega^2 \mathbf{G}_{ti}(\mathbf{r}_i, \mathbf{r}_i, \omega) \cdot \mathbf{q} + \mathbf{G}_j(\mathbf{r}_i, \mathbf{r}_j, \omega) \cdot \mathbf{q}_j \nonumber \\
+ \mathbf{G}_{ij}(\mathbf{r}_i, \mathbf{r}_j, \omega) \cdot \mathbf{q}_j \}, \quad i, j \in \{1, 2\}, \quad i \neq j,
\]

(3)

where \( \mathbf{G}_{ti}(\mathbf{r}, \mathbf{r}_i, \omega) \) and \( \mathbf{G}_i(\mathbf{r}, \mathbf{r}_i, \omega) \) denote the reflection Green tensor and the free-space Green tensor, respectively, for the dipole located at \( \mathbf{r}_i \). The explicit forms of the Green tensors were worked out in detail in our earlier study [13] (see also [31, 32]). We note that (3) does not account for the radiation reaction of the dipole. While this effect could readily be included, amounting to a small correction [30, 33, 34] to the polarizability \( \alpha \), it is not of importance in our analysis since we only consider some characteristic values of \( \alpha \).

In the case of normal incidence, the exciting field is \( \mathbf{E}_{\text{ex}}(\mathbf{r}, \omega) = \mathbf{E}_0 e^{i k_1 z} \), with \( \mathbf{E}_0 = (1, 0, 0) \) and \( k_1 \) denoting the \( z \)-component of the wave vector in medium I. For the perpendicular incidence \( \mathbf{E}_{\text{ex}}(\mathbf{r}, \omega) = \mathbf{E}_0 e^{i k_2 z} \), where \( \mathbf{E}_0 = (0, 0, 1) \) and \( k_2 \) is the wave vector of a plane wave propagating in the +\( x \)-direction. For the normal incidence, the reflected exciting field at the dipole site is \( \mathbf{E}_{\text{ex},t}(\mathbf{r}_i, \omega) = -R_p \mathbf{E}_0 e^{-i k_1 z_0} \), where \( R_p \) is the slab reflection coefficient for \( p \)-polarization. The minus sign originates from the choice of the unit vectors for the polarization components [13]. For the perpendicular incidence, \( \mathbf{E}_{\text{ex},t}(\mathbf{r}_i, \omega) = 0 \). Noting further that \( \mathbf{G}_{ti}(\mathbf{r}_1, \mathbf{r}_1, \omega) = \mathbf{G}_{t2}(\mathbf{r}_2, \mathbf{r}_2, \omega) \), we can solve for the dipole moments

\[
\mathbf{q}_i = [\mathbf{A} - \mathbf{B}_j \mathbf{A} \mathbf{B}_j]^{-1}[\mathbf{b}_j + \mathbf{B}_j \mathbf{A} \mathbf{b}_j], \quad i, j \in \{1, 2\}, \quad i \neq j,
\]

(4)

where

\[
\mathbf{A} = -\alpha \mu_1 \mu_0 \omega^2 \mathbf{G}_{ti}(\mathbf{r}_i, \mathbf{r}_i, \omega), \quad i = 1, 2,
\]

(5a)

\[
\mathbf{B}_j = \alpha \mu_1 \mu_0 \omega^2 [\mathbf{G}_j(\mathbf{r}_i, \mathbf{r}_j, \omega) + \mathbf{G}_{ij}(\mathbf{r}_i, \mathbf{r}_j, \omega)], \quad i, j \in \{1, 2\}, \quad i \neq j,
\]

(5b)

\[
\mathbf{b}_j = \alpha [\mathbf{E}_{\text{ex}}(\mathbf{r}_j, \omega) + \mathbf{E}_{\text{ex},t}(\mathbf{r}_i, \omega)], \quad i = 1, 2.
\]

(5c)

For the normally incident excitation, \( \mathbf{E}_{\text{ex}}(\mathbf{r}_1, \omega) = \mathbf{E}_{\text{ex}}(\mathbf{r}_2, \omega) \) and \( \mathbf{E}_{\text{ex},t}(\mathbf{r}_1, \omega) = \mathbf{E}_{\text{ex},t}(\mathbf{r}_2, \omega) \), implying that \( \mathbf{b}_1 = \mathbf{b}_2 \). In contrast, for the perpendicular excitation \( \mathbf{E}_{\text{ex}}(\mathbf{r}_1, \omega) \) and \( \mathbf{E}_{\text{ex}}(\mathbf{r}_2, \omega) \) differ from each other by a phase factor. One may also notice that \( \mathbf{G}_{ti}(\mathbf{r}_2, \mathbf{r}_1, \omega) = \mathbf{G}_{t2}(\mathbf{r}_1, \mathbf{r}_2, \omega) \) in the case of both excitations.

### 3.2. Influence of the dipole–dipole and dipole–slab interactions

Using (4) we now investigate the dipole–dipole and dipole–slab interactions. We calculate the dipole moments of the point emitters as a function of their distance from the slab, as well as their distance from each other. For \( \alpha \) we use the values \( 5 \times 10^{-33} \) and \( 5 \times 10^{-35} \) cm\(^2\) V\(^{-1}\) that, according to the Clausius–Mossotti relation [35], characterize the polarizabilities of a metallic sphere of radius \( \sim 20 \) nm and a glass sphere of radius \( \sim 10 \) nm, respectively, in vacuum or PMMA. We also study the interactions with molecule-like objects, for which we take \( \alpha = 1 \times 10^{-30} \) cm\(^2\) V\(^{-1}\), consistent with atomic dipole moments and unit-amplitude incident electric field. We focus on the near-field effects, so the distances of the emitters from the slab and from each other are within the ranges \( 10 \) nm \( \lesssim |z_0| \lesssim \lambda_1/2 \) and \( 10 \) nm \( \lesssim \Delta x \lesssim \lambda_1/2 \),
Figure 2. Magnitudes of the dipole moment components as a function of the dipole–slab distance $z_0$ and the separation $\Delta x$ of the dipoles. The imaging structure is (a, b) a silver slab surrounded by PMMA and PR ($\lambda = 365$ nm, $\epsilon_{r1} = 2.3$, $\epsilon_{r2} = -2.4 + i0.2$, $\epsilon_{r3} = 2.9$) and (c, d) an absorbing metamaterial layer in vacuum environment ($\lambda = 633$ nm, $\epsilon_{r2} = \mu_{r2} = -1 + i0.1$). The objects are excited by (a, c) a normally and (b, d) a perpendicularly incident p-polarized plane wave. The other parameters are $d = 35$ nm and $\alpha = 5 \times 10^{-33}$ Cm$^2$ V$^{-1}$ in all cases.

respectively, where $\Delta x = x_2 - x_1$ and $\lambda_1$ is the excitation wavelength in medium I. Figures 2(a) and (b) illustrate the magnitudes of the dipole moment components in the case of the silver slab structure. Figure 2(a) shows $|q_{x1}|$ with normal illumination ($|q_{x2}| = |q_{x1}|$), and figure 2(b) shows the value of $|q_{z1}|$ for the perpendicular excitation ($|q_{z2}| \approx |q_{z1}|$). Likewise, figures 2(c) and (d) contain the magnitudes of the dipole moment components when a slightly lossy NIM slab is used as the imaging element ($\epsilon_{r2} = \mu_{r2} = -1 + i0.1$). These parameters correspond to a figure of merit (FOM) equal to 10, which is close to the FOM = 8.5 of a recently proposed low-loss NIM structure working at 650 nm [28]. Figure 2 (c) depicts the value of $|q_{x1}|$ for the normally incident excitation, whereas figure 2(d) shows $|q_{z1}|$ with perpendicular illumination.

The dipole–slab near-field interaction manifests itself in figure 2 as the decrease of $|q_{x1}|$ and $|q_{z1}|$ ($i = 1, 2$) when the objects approach the silver or NIM superlens. In the case of the silver slab structure and normal excitation (see figure 2(a)) $|q_{x1}|$ (and $|q_{x2}|$) shows an oscillatory behavior as a function of $z_0$. This phenomenon results from the interference of the exciting field with the backscattered part of the exciting field. In contrast, due to the good impedance match of the NIM superlens the reflections from the slab in that case are weak, making $|q_{x1}|$ (and $|q_{z2}|$) approach quickly the constant value of $\alpha$ cm$^2$ V$^{-1}$ when $|z_0|$ increases (see figure 2(c)). Regular oscillations as a function of $z_0$ are also absent when the objects are illuminated perpendicularly.
(see figures 2(b) and (d)), because $E_{\text{ex},r}(r_i, \omega) = 0$. All these effects are consistent with (and discussed more deeply in) our earlier study, in which we considered the interaction of a single dipolar object with imaging devices of this type [13].

The interaction of the objects with each other is also visible in figure 2. In all these graphs one can note an interesting (and unexpected) phenomenon: if two point-like emitters are placed very close to each other, their dipole moments die out. This effect happens even when the dipoles are located so far from the slab that the backscattered near-field components of the dipole radiation are insignificant. Thus the effect is only a consequence of the straight near-field interaction of the adjacent dipoles. Although not explicitly shown here, this result can be derived analytically from (4). The same phenomenon appears, at least indirectly, also in earlier studies [34, 36, 37], but the vanishing of the dipole moments is conventionally avoided by considering small spheres which cannot be closer to each other than $2R_s$, where $R_s$ is the radius of the spheres. The peaks and ridges in 2(b) and (d) arise from the configurational resonances [38] of the system, i.e. when $\det(\mathbf{A} - \mathbf{B}_i \mathbf{A} \mathbf{B}_j) \approx 0$ (see (4)). The resonances are narrower and more pronounced in conditions where the quasistatic approximation holds; otherwise (as in figures 2(a) and (c)) they are smeared out.

When metallic nanospheres are near the slab ($|z_0| \lesssim 60 \text{ nm}$) and close to each other ($|\Delta x| \lesssim 60 \text{ nm}$), the near field radiated by the adjacent emitter and reflected from the slab contributes to the emission of the objects. With normal illumination this interaction induces small $q_{x1}$ and $q_{x2}$ components. Similarly, small $q_{y1}$ and $q_{y2}$ components for the emitters emerge when the objects are excited perpendicularly. In the NIM-slab case these effects are negligible, but for the more reflective silver slab the minor dipole moment components show a clear influence on the electric fields of the emitters. The object–object and the object–slab interactions depend strongly on the polarizability of the objects. For $\alpha = 5 \times 10^{-35} \text{ cm}^2 \text{ V}^{-1}$ (small glass sphere) it is found that the interactions effectively vanish. With $\alpha = 1 \times 10^{-30} \text{ cm}^2 \text{ V}^{-1}$ (characteristic of a molecule) the interactions, in turn, are stronger than with $\alpha = 5 \times 10^{-33} \text{ cm}^2 \text{ V}^{-1}$ (small metal sphere) and extend over the whole near-field range.

By virtue of the above discussions we can conclude that unless the two metallic or glass nano objects are in very close proximity to each other (i.e. $\Delta x < 3R_s$) or to a silver or NIM slab (i.e. $|z_0| < 3R_s$), the object–object and object–slab interactions do not strongly influence the emission properties of the objects. However, if two molecules of high polarizability are brought to within near-field distances from each other ($\Delta x < \lambda_1/2$) or the imaging slab ($|z_0| < \lambda_1/2$), then the effects of the interactions within dipole approximation, such as the suppression of emission, are strong.

4. Imaging capability of metallic and metamaterial superlenses

Next we analyze the imaging capabilities of both superlens structures in terms of image resolution. The field of each dipole at the observation region in half-space $z > d$ is

$$
E_{\text{d},i}(\mathbf{r}, \omega) = \mu_{r1}(\mathbf{r}_i, \omega)^2 \mathbf{g}_i(\mathbf{r}, \mathbf{r}_i, \omega) \cdot \mathbf{q}_i, \quad i = 1, 2,
$$

where $\mathbf{g}_i(\mathbf{r}, \mathbf{r}_i, \omega)$ is the Green tensor for transmission across the slab [13] and $\mathbf{q}_i$ can be calculated from (4). A part of the exciting field is also transmitted through the slab when the objects are illuminated by a normally incident wave. Hence, the total field in the observation

plane is

\[ E_{\text{im}}(\mathbf{r}, \omega) = E_{d1,1}(\mathbf{r}, \omega) + E_{d2,1}(\mathbf{r}, \omega) + T_p E_0 e^{i k z}, \]  

(7)

where \( T_p \) is the slab’s transmission coefficient for p-polarization \([13]\) and \( k_{z3} \) denotes the z-component of the wave vector in medium III. In the case of perpendicular illumination the last term in (7) is absent.

Owing to the dominant \( q_z \)-components, the fields generated by normally excited objects closely resemble those created by purely \( x \)-oriented point dipoles. Consequently, the near-field intensity distribution in the observation plane \((x, y)\) is elongated along the \( x \)-axis and contains two peaks with a dent in the middle \([11, 12]\). On the other hand, with perpendicular excitation the near-field image intensity profiles are circularly symmetric due to the major \( q_z \)-components \([11, 12]\). When the emitters are close to each other and close to the silver slab, the \( q_z \)-components with normal illumination and \( q_x \)-components for the perpendicular excitation also contribute to the emission, as discussed above. The total near-field image-intensity distribution in the observation plane, \( |E_{\text{im}}(\mathbf{r}, \omega)|^2 \), contains the interference of two correlated point-like objects. Figure 3 shows the image profiles along the \( x \)-axis in the observation plane when a metallic ((a) and (b)) or a slightly lossy metamaterial ((c) and (d)) slab is used as the imaging element (see figure 1). Figures 3(a) and (c) correspond to normal excitation (\( x \)-oriented dipoles), while figures 3(b) and (d) represent perpendicular illumination (\( z \)-oriented dipoles). The system parameters are given in the figure caption.

Figures 3(a) and (c) show that the interference of two normally excited point-like objects makes the image intensity profiles obscure with multiple maxima. From the intensity distributions one can recognize two point emitters if they are separated by a distance of \( \lambda_1 \) (black dotted lines), but already when \( \Delta x = \lambda_1/2 \) it is hardly possible to identify two objects from the image (blue dashed-dotted lines). The simulations show that unlike the case of uncorrelated dipoles \([11, 12]\), subwavelength near-field imaging of two correlated point-like emitters is not possible if the objects are excited in such a way that their dipole moments are predominantly parallel to the surface of the imaging element. However, when the objects are illuminated by a perpendicularly incident plane wave (see figures 3(b) and (d)), the interference does not disturb the imaging as much: two clear intensity peaks form in the observation plane and their positions match with the object locations in the object plane. In this case we are able to define the resolution of the image as follows: two-point objects are resolved if the central dent in the \( |E_{\text{im}}(\mathbf{r}, \omega)|^2 \) distribution is less than 81% of the lower maximum of the profile (the Rayleigh criterion). According to this criterion we find here resolutions of \(~\lambda_1/5\) and \(~\lambda_1/10\) for the metallic and metamaterial superlens structures, respectively (green solid lines in figures 3(b) and (d)). The corresponding 3D intensity distributions in the observation plane are shown in figure 4.

The image definition obtained for the silver superlens is close to the experimentally reached resolutions of \( \lambda/6 \) and \( \lambda/7 \) for the same kind of imaging systems but for 2D objects \([14, 15]\). Recently, a resolution of \( \lambda/12 \) for a 2D grating object was achieved using an ultra-thin and smooth silver superlens \([18]\). However, these experiments are not directly comparable with our imaging system: the dipole emission is three dimensional containing both s- and p-polarization components, whereas in the experiments with 2D objects only p-polarized light is present. The silver slab enhances the p-polarized evanescent waves due to the surface plasmons. The better resolution for the metamaterial superlens originates from the lower losses in NIM and the greater enhancement of evanescent wave components of the object radiation in transmission across the
Figure 3. Image-intensity distributions along the x-axis in the observation plane for (a, b) a PMMA-Ag-PR superlens ($\lambda = 365 \text{ nm}$, $d = 35 \text{ nm}$, $b = 2 \text{ nm}$, $\epsilon_{r1} = 2.3$, $\epsilon_{r2} = -2.4 + i0.2$, $\epsilon_{r3} = 2.9$) and (c, d) an absorbing NIM lens in vacuum ($\lambda = 633 \text{ nm}$, $d = 35 \text{ nm}$, $b = d/2$, $\epsilon_{r2} = \mu_r = -1 + i0.1$). The objects are excited by (a, c) a normally or (b, d) a perpendicularly incident plane wave and located at $r_1 = (0, 0, -40 \text{ nm})$ and $r_2 = (x_2, 0, -40 \text{ nm})$, with $\lambda_1/10 < x_2 < \lambda_1$. The polarizability of the objects is $\alpha = 5 \times 10^{-33} \text{ cm}^2 \text{ V}^{-1}$ (typical of a metallic sphere with a radius of $\sim 20 \text{ nm}$).

We also calculated the resolution of the imaging systems when the point emitters had the polarizability characterizing a molecule, but did not find any significant difference in resolution compared to the metallic nano objects. However, the brightness of the images was approximately 10–20 times higher for molecular-like emitters, which is a result of two competing phenomena: the larger polarizability increases the strength of the dipole but also leads to stronger near-field interactions, decreasing the emission. In addition, we analyzed the imaging of metal nanospheres and molecule-like objects with a silver superlens having slab thicknesses of 25 and 15 nm [18]. However, there was no remarkable improvement in the resolution, and the only benefit was an increase in image brightness. Furthermore, we verified with simulations that lowering the absorption of NIM leads to better resolution and higher image
Figure 4. Image-intensity profiles in the observation plane. Two point-like objects are separated (a) by \( \lambda_1 / 5 \) \( (\mathbf{r}_1 = (0, 0, -40 \, \text{nm}), \mathbf{r}_2 = (50 \, \text{nm}, 0, -40 \, \text{nm})) \) and the imaging element is a PMMA-Ag-PR superlens, and (b) by \( \lambda_1 / 10 \) \( (\mathbf{r}_1 = (0, 0, -40 \, \text{nm}), \mathbf{r}_2 = (60 \, \text{nm}, 0, -40 \, \text{nm})) \), imaged with a slightly absorbing NIM lens. The objects are excited by a perpendicularly (from below) incident plane wave. Other system parameters are the same as in figure 3.

Figure 5. Schematic illustration of excitation with a prism. A p-polarized wave is incident on the interface between the prism and medium I \((n_p > n_1)\) at an angle that is slightly larger than the critical angle. The exciting field in medium I then is an evanescent wave traveling along the \( x \)-axis and decaying in the \( z \)-direction. Its electric field component is effectively perpendicular to the surface of the imaging element (medium II).

brightness because the evanescent wave components of the object radiation are enhanced much more and in a wider spatial-frequency range in the transmission through the slab [11].

On the basis of the above results we conclude that near-field imaging beyond the conventional resolution limit of \( \lambda/2 \) is achievable with the silver and absorbing NIM superlens structures. To obtain subwavelength definition the excitation has to be such that the dipoles oscillate predominantly orthogonal to the imaging element. This situation can be arranged, for instance, by placing a prism of refractive index \( n_p \) near the objects (see figure 5). In this setup, a p-polarized wave \( \mathbf{E}_{\text{inc}} \) is incident on the surface between the prism and medium I containing the objects \((n_p > n_1)\) with an angle of incidence \( \theta \) larger than the critical angle \( \theta_c \). Consequently, the exciting field in medium I is an evanescent wave traveling along the interface (\( x \)-direction)
and having a $z$-dependence \[ [39] \]

\[ E_{\text{ex}}(z) = E_{\text{inc}} \frac{2 \cos \theta e^{-z/d_p}}{n^2 \cos \theta + i (\sin^2 \theta - n^2)^{1/2}} \left[ -i (\sin^2 \theta - n^2)^{1/2} \hat{u}_x + \sin \theta \hat{u}_z \right], \] (8)

where $n = n_1/n_p$, and $\hat{u}_x, \hat{u}_z$ are the Cartesian unit vectors. The parameter $d_p$ denotes the penetration depth \[ [39] \]

\[ d_p = \frac{\lambda}{2\pi (n_p^2 \sin^2 \theta - n^2)^{1/2}}, \] (9)

which corresponds to the distance at which the evanescent wave has decreased by a factor of $1/e$ from its value at the interface. One can readily see from (8) that when $\theta$ is only slightly larger than $\theta_c$, the exciting evanescent wave has an electric field substantially in the $z$-direction. With an appropriate choice of prism material this wave can be made to nearly vanish before the surface of the imaging slab. Consequently, the reflected part of the exciting field is zero as taken in our simulations with perpendicular illumination. As an example, in the silver superlens case, by choosing $n_p = 1.7$ ($n_1 = 1.52$ for PMMA) we have $\theta_c = 63^\circ$. Then, using $\theta = 66^\circ$ with $\lambda = 365$ nm the penetration depth takes on the value 170 nm, which is suitable for our system where the objects are located 40 nm from the lens. With these parameters the $z$-component of the exciting field is five times as large as the component in the $x$-direction. This kind of excitation corresponds well to the situation, analyzed by simulations above, in which the object dipoles are aligned orthogonal to the imaging slab.

5. Conclusions

In summary, we have studied the near-field imaging of two interacting nanoscale objects with metallic and metamaterial superlenses using exact electromagnetic theory. Our main aim was to determine how the near-field interactions of the objects with each other and with the imaging element affect their emission properties and the image resolution. These issues play a significant role in nanophotonic near-field imaging applications.

We found that the near-field interactions in the dipole model suppress the emission of the objects when the emitters approach the imaging slab. Likewise, the dipole moments of the emitters vanish when the objects are in very close proximity to each other. At certain distances from each other and from the slab, the dipole moments exhibit a peak-like behavior as a result of configurational resonances. The effects that arise from the object–slab interactions are weaker and do not reach as far with the NIM slab structure as they do with the metallic imaging element, a consequence of the good impedance match between the slightly lossy NIM and its surroundings. The observed phenomena depend on the polarizability of the objects: for molecular-like emitters of high polarizability, the influence of the interactions on the object emission extends over the entire near-field range, whereas for metallic or glass nanospheres of lower polarizability, the interactions are insignificant unless the objects are nearly in contact with each other or the imaging slab.

We showed that both lens systems can provide image resolutions beyond the classic diffraction limit of $\lambda/2$. However, the interference of the fields from two correlated point-like emitters affects the resolution in an essential way. Subwavelength definition cannot be achieved if the object dipoles oscillate mostly parallel to the imaging element. In contrast, if the emitters are excited such that their dipole moments are orthogonal to the slab surface, we obtain the
resolutions of about $\lambda/5$ and $\lambda/10$ for the metallic and slightly lossy metamaterial superlens structures, respectively.

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**References**
