

Achieving superresolution in near-field optical data readout systems using surface plasmons

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The effects of surface plasmons and enhanced transmission on the readout contrast in a superresolving near-field optical data system are studied numerically using an exact Green’s tensor formulation. It is shown that plasmon effects can both help and hinder such a readout system, and the system geometry must be chosen carefully to produce optimal effects. Under certain conditions, the system can have a readout contrast approaching 50% and a resolution of at least $\lambda/3$. © 2005 American Institute of Physics. [DOI: 10.1063/1.2128061]

Since the discovery of enhanced transmission through subwavelength-size hole arrays in metal plates,¹ there has been much interest in the optical transmission properties of both hole arrays and single subwavelength apertures.² This enhancement is generally credited to surface plasmons (although enhancement can also be observed in certain configurations which excite no plasmons)^{3,4} which, under proper circumstances,⁵ create large field amplitudes at the edges of the aperture, and consequently result in more light throughput. The transmission can be further increased by incorporating surface features such as ridges around the outside of the aperture to couple and reflect more plasmons back into it.⁶

Although it has been suggested that the phenomenon of enhanced transmission could be useful in near-field optics, nanolithography and near-field optical data readout systems (super optical disk systems), little work has been done to study such possible applications theoretically (although surface plasmons have been used in other ways in readout systems, in so-called super-RENS systems).^{7,8} In this letter, we consider the application of enhanced transmission effects in superresolving near-field optical readout systems, and demonstrate that surface plasmons may drastically improve or degrade the readout contrast, depending on the specific configuration.

The configuration of the simulated readout system is illustrated in Fig. 1. A monochromatic electromagnetic wave is normally incident upon a silver plate of finite conductivity and thickness t_2 which contains a single subwavelength slit of width $2a$ that acts as the readout system probe. The metal plate is situated a short distance t_3 away from a semi-infinite data layer which serves the role of an optical disk. In our simulations, we consider one or more data structures (“pits” or “bumps”) on the surface of the data layer, taken to be either silver or silicon. Furthermore, to study the effects of enhanced transmission and plasmon resonances, we consider the effect of placing a pair of surface features on the metal plate, either on the light side or the dark side, referred to as “plasmon pits.” These pits allow the coupling of light to the surface plasmons. The position of the pits from the center of

the slit is specified by γ . In nearly all cases, the plate is taken to be evaporated silver.

The field in the vicinity of the readout system was calculated using a Green’s tensor formulation which allows an exact numerical solution of Maxwell’s equations; this method has been described in some detail elsewhere.^{3,4,9} In short, the method involves the numerical solution of an integral equation for the electric field of the form:

$$E_i(x, z) = E_i^{(\text{inc})}(x, z) - i\omega \int_D \Delta \epsilon(x', z') G_{ij}^E(x, z; x', z') E_j(x', z') dx' dz', \quad (1)$$

where E_i represents the i th component ($i=x, y, z$) of the total electric field, $E_i^{(\text{inc})}$ represents the incident field which would propagate in the system in the absence of the slit, data structure, and plasmon pits, G_{ij}^E is the electric Green’s tensor of the ideal layered medium, which can be calculated exactly (to within a spatial Fourier transform). The integral is over all regions D (slit, data structure, plasmon pits) in which the system deviates from the ideal layered geometry. This equation can be solved numerically within the “deviant” regions by the collocation method with piecewise-constant basis functions. The field everywhere else may then be calculated by substitution back into Eq. (1). We consider transverse

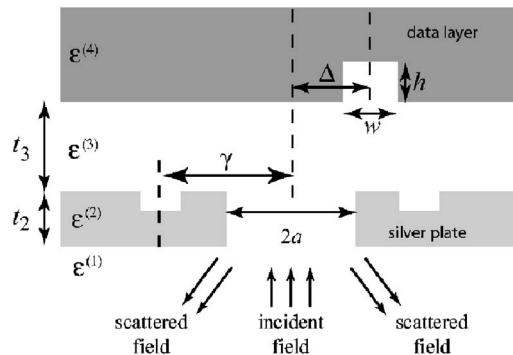


FIG. 1. Illustrating the readout system configuration.

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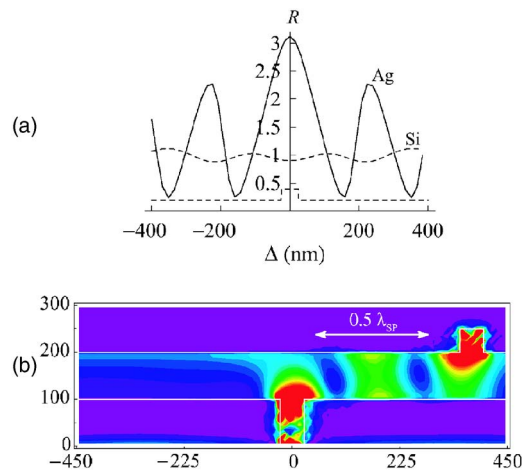


FIG. 2. (Color online) (a) The reflected power R as a function of data position; the effective profile of the data structure is shown as a dashed line. The solid line is the result for a plate and data surface both consisting of evaporated silver; the dashed line is for both consisting of silicon. Here, $t_2 = 100$ nm, $t_3 = 100$ nm, $a = 25$ nm, $\lambda = 500$ nm, and the data structure is taken to be a pit in the data surface with $w = h = 50$ nm. (b) Plot of the time-averaged electric energy density in the neighborhood of the slit and data structure, with the plate and surface both taken to be evaporated silver. The data have been plotted on a logarithmic scale to enhance visibility of the plasmon standing wave. Redder regions correspond to a higher-energy density. Here $\Delta = 375$ nm. To the right of the slit, alternating bright and dark regions indicate the presence of a plasmon standing wave. λ_{sp} indicates the plasmon wavelength. The figure scale is in nanometers.

magnetic (TM) polarization of the incident field as this is the only polarization which results in surface plasmons.

We have used this method to numerically analyze the effect of surface plasmons and enhanced transmission schemes on the ability to detect and superresolve individual data “bits” on the surface of an optical disk. The detection process was simulated by calculating the total power scattered from the readout system, neglecting the power which would be directly reflected back from a smooth planar surface. Such a system could be implemented in practice by measuring only the power scattered in directions away from the normal to the surface. Two criteria are considered in looking for the optimal readout system: The readout contrast (the percentage difference in reflected power when a pit is near the slit versus when none is present) and the resolution (the effective measured full width half maximum of the data structure as it is being scanned past the slit). This latter criterion assumes that the actual binary data are encoded by the *edges* of the data structure, not by the data structure itself; this is the method of data encoding in a conventional compact disk player (Ref. 10, Chap. 3).

A typical result for a TM-polarized incident field, without plasmon pits, is shown in Fig. 2(a), for a system with the plate and the disk both composed of either evaporated silver or silicon. The quantity R is the power scattered from the readout system normalized by the power scattered when no data pit is present; it is to be noted that this quantity can exceed unity. Surprisingly, in both cases, it is found that the scattered power oscillates as a function of data structure position, completely obscuring any possible readout of the data. This effect can be attributed to two causes: Ordinary waveguide modes and surface plasmon modes. In both cases, light couples into propagating modes which reflect from the data structure and return to the slit, where they can couple into the backscattered field. This field may constructively or destruc-

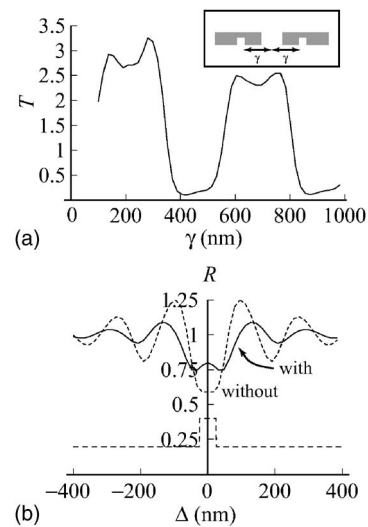


FIG. 3. (a) Transmitted power T as a function of plasmon pit location, for pits on the illuminated side of the plate. The inset shows the system configuration. (b) The reflected power as a function of data position, both with and without the plasmon pits on the illuminated side of the silver plate. Here, $t_3 = 30$ nm, $\gamma = 150$ nm, and the data surface is silicon; all other parameters are the same as in Fig. 2(a).

tively interfere with the backscattered field which is directly reflected from the data layer, resulting in an oscillation of the reflected power as a function of data structure position. For silver, the plasmon standing wave is dominant, as can be seen explicitly by plotting the electric energy density in the neighborhood of the data structure and slit; an example is shown in Fig. 2(b). The energy density is strongest near the surface, indicating the presence of surface plasmons.

A number of strategies were employed to suppress these oscillations. First, it is to be noted that a judicious choice of the data surface material will remove the ability of plasmons to propagate on that surface. By using a silicon data surface, the plasmon oscillations are significantly reduced. Second, different surface features (plasmon pits) of the type used to enhance transmission may be placed on the plate. The purpose of the plasmon pits is twofold, and depends on their placement on the illuminated or dark side of the plate: (1) On the illuminated or dark side, they can increase the amount of energy coupled into light on the dark side of the plate, and (2) on the dark side, they can restrict the region around the slit within which plasmons and waveguide modes can propagate.

We first considered plasmon pits on the illuminated side of the plate, in an attempt to increase light throughput; the configuration is shown in the inset of Fig. 3(a). The transmission T of light through the slit, without the disk present, as a function of pit position is plotted in Fig. 3(a), and a position with high transmission was chosen. The transmission T is normalized by the power geometrically incident on the slit; it is to be noted that systems with T greater than unity correspond to enhanced transmission. In Fig. 3(b), the normalized scattered power R is plotted as a function of data structure position. It can be seen that the readout contrast gets *worse* with the presence of the plasmon pits; this arises from the fact that although more light is being coupled into the slit, the throughput is relatively small compared to the light which is directly backscattered by the pits themselves. For a reflection readout system (such as we are considering), this results in a decrease in the contrast; for a transmission

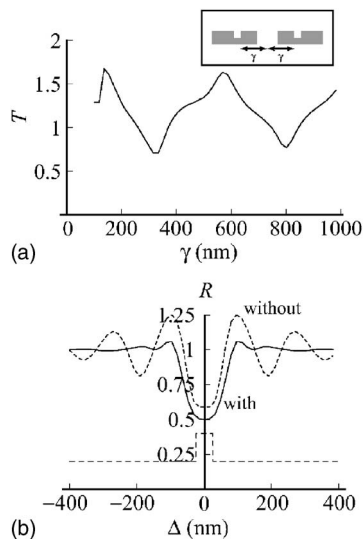


FIG. 4. (a) Transmitted power as a function of plasmon pit location, for pits on the dark side of the plate. The inset shows the system configuration. (b) The reflected power as a function of data position, both with and without the plasmon pits on the dark side of the silver plate. Here, $t_3=30$ nm, $\gamma=125$ nm, and the data surface is silicon; all other parameters are the same as in Fig. 2(a).

readout system, this configuration may result in an improvement.

The other possibility is the placement of plasmon pits on the dark side of the plate, in an attempt to limit the propagation range of the plasmons and waveguide modes in the region between the plate and the disk. In Fig. 4(a), the transmission as a function of pit position is plotted, and the first peak of transmission was chosen based on the desire to both keep the transmission high and the plasmons localized. In Fig. 4(b), we find a quite surprising result: The oscillations are completely suppressed and, in fact, the readout contrast takes on a value of roughly 50%. The width of the reflection minimum is wider than the data structure itself, but significantly smaller than the wavelength of light: The readout process can be said to be superresolving. The resolution takes on the value of 150 nm, or roughly 0.3λ .

These investigations suggest that surface plasmons and plasmon manipulation techniques can be used to significantly

improve the behavior of near-field optical readout systems, but that a careless application of plasmon effects can, in fact, degrade the system performance. It is to be noted that one could extend the results of this letter and add multiple pits to the surface of the metal plate, creating a surface Bragg grating which could be used to further enhance the plasmon effects. Because of the large number of free parameters in the design of such a readout system, much more work must be done to find what sort of configurations would be optimal. Furthermore, one could extend the results to a three-dimensional geometry in which the aperture is a hole rather than a slit; such a configuration could result in higher data storage density, since the light is confined in two dimensions rather than in one dimension. It is expected that most of the results of this letter (poor performance of plasmon pits on the illuminated side of the plate and plasmon standing waves on the dark side of the plate) will qualitatively hold in three dimensions, but additional effects are also expected (crosstalk between different rows of data). We hope to address these issues in future work.

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