Rapid growth of evanescent wave by a silver superlens

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Recent theoretical work suggested the possibility of constructing a super-resolution diffraction-free lens by using a negative refractive index medium (NRIM). The key proposition is that evanescent waves can be greatly enhanced by increasing the thickness of the NRIM. We report here experimental evidence that confirms that the transmission of evanescent waves rapidly grows with the film thickness up to about 50 nm, after which it decays as loss becomes significant. These findings represent the first step toward the understanding and realization of a diffraction-free lens. © 2003 American Institute of Physics. [DOI: 10.1063/1.1636250]

It has been shown in theory by Veselago in 1968[1] and in recent experiments by Shelby *et al.*,[2] that materials with simultaneous negative permittivity and permeability (and thus possessing a negative refractive index n), can exist without violating any physical laws. This class of material, denoted as left-handed medium or "negative refractive index medium" (NRIM), can lead to many unusual phenomena, such as negative Cerenkov radiation,[3] reversed Doppler effect, etc.

As recently pointed out by J. B. Pendry,[4] the unique properties of NRIM allow a single slab of it to be used as a superlens, capable of focusing all Fourier components from the object onto a two-dimensional image with a resolution far below the diffraction limit. Two counterintuitive propositions form the foundation of Pendry's superlens theory. The first proposition states that in the NRIM, the wave front advances in the opposite direction of energy flow, therefore causing a negative bending of the incident light. This negative refraction phenomenon was observed experimentally by Shelby *et al.* at microwave frequencies in a wedge-shaped NRIM.[2] Even more striking is the second proposition: the evanescent waves that would normally decay away from the object in positive index materials instead grow exponentially through the NRIM, compensating for the decay in the rest of optical path outside of NRIM. This provides the possibility of reconstructing a diffraction-free image by collecting all Fourier components, including these evanescent waves at image plane.

Artificial NRIM in optical wavelength has yet a long way in the designer's roadmap. Nevertheless, the very unique properties of evanescent waves allow us to examine and validate the second proposition of superlens theory by illuminating a p-polarization light on materials that only have a negative permittivity. In the electrostatic limit, the p-polarized light, dependence on μ is eliminated and only ε is relevant.[4] Therefore, in this letter, we experimentally demonstrate a key precursor for an optical superlens; regeneration of evanescent field can be achieved by carefully choosing a metal film.

The concept of enhancing evanescent waves by exciting the bounded surface states has been known for decades in optics and surface sciences. However, the realization that surface plasmons could be used to reproduce sub-diffraction-limited image components has not been explored until Pendry's recent proposal. The fundamental conjecture of the superlens, evanescent field regeneration, has long been under a hot debate.[5,6] Yet, we will show that by studying films of varying thickness d, a rapid growing transmission coefficient $T_p(k_x,d)$ can indeed be observed under the appropriate conditions. While still far from producing a coherent high-resolution image, this work provides direct evidence that the foundation of superlensing is solid, and suggests the path that will enable the observation of superlensing at optical wavelengths.

In Pendry's theoretical paper, a perfectly flat silver film at $\varepsilon = -1 + 0.4i$ is employed as a superlens to capture all of the evanescent waves from a near-field source. However, for simplicity without loss of generality, in this work, we introduce a pristine silver film with natural roughness (Fig. 1), which can excite a plethora of evanescent waves for studying the superlensing properties. The advantage of this method, in comparison to the lithographic gratings, is that the small modulation amplitude ensures negligible perturbation to the evanescent field, thus a linear coupling scheme is satisfied.[7] Given a specific evanescent component k_x, we then focus on quantitatively determining the transmission coefficient $T_p(k_x,d)$.

In prior research efforts on evanescent enhancement such as in attenuated total reflection (ATR),[7,8] the surface roughness was considered rather as a noise that spreads the transmitted evanescent field. Conventionally, the estimation
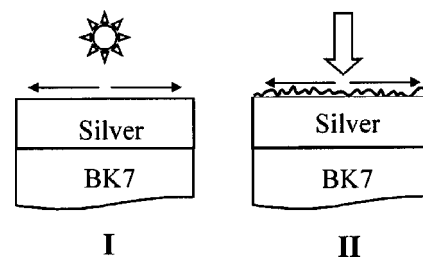

FIG. 1. I: Superimaging configuration in Pendry's paper (see Ref. 4). The evanescent waves are supplied by a near-field source (star). II: Experimental configuration in our evanescent wave enhancement measurement. The evanescent waves are supplied by a roughness coupling mechanism.

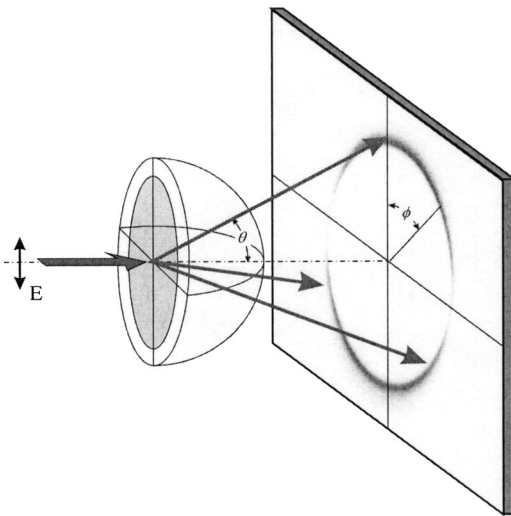[a)]Electronic mail: xiang@seas.ucla.edu

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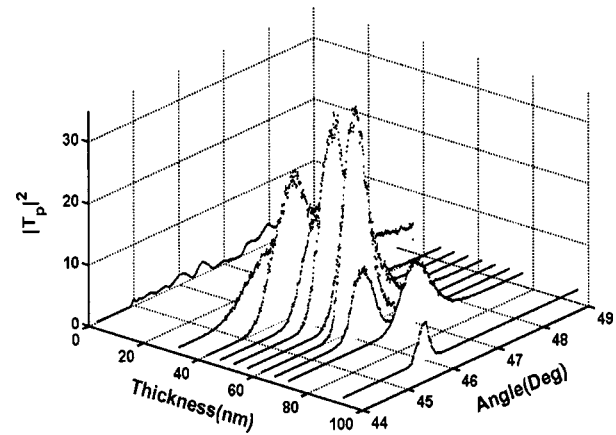FIG. 2. RATR setup for measuring the relative transmissivity of evanescent waves.

FIG. 3. The measured relative power transmissivity $|T_p|^2$ vs azimuthal angle (θ) for silver films with thickness ranging from 30 to 90 nm. The wavelength of incident light is 514.5 nm.

of surface roughness spectrum is barely extrapolated from some simplified model, without other careful justifications. Similar studies on thickness dependence of enhanced light-emission efficiencies were reported,[9] but the film roughness was not quantified and only integrated intensity signals were given. In this work, we extracted a spectrum of surface roughness $|s(k_x)|$ with all k_x of interest by an accurate characterization with an atomic force microscope (AFM). This allowed us to actively employ the random surface roughness of metal films as a natural grating with precisely determined Fourier components used for coupling light waves into the metal films.

The experimental setup, a reversed ATR (RATR) scheme,[10] is shown in Fig. 2. Silver films were deposited on the flat surfaces of semispherical BK7 glass prisms (refractive index $n_p = 1.52$). A collimated Ar$^+$ laser beam (polarization $\phi = 0°$) with wavelength λ and diameter <1.5 mm is incident normally on the center of semispherical prism from the flat side. At the air/silver interface, a portion of the incident beam is converted from propagating wave to evanescent waves by the natural roughness with all possible spatial modulations, characterized by lateral wave vectors $k_x > 2\pi/\lambda$. These evanescent waves transmit through the silver film and are allowed to be converted back to propagating waves in the semispherical glass prism when $k_x \leq 2\pi n_p/\lambda$. Therefore, this far-field experiment allows us to probe the near-field information at air/metal interface.

A 8 mm$\times$6 mm CCD camera is placed about 5 cm away from the center of BK7 prism to measure the spatial angular distribution of relative light intensity nearby θ_{sp} (the surface plasmon coupling angle), while ϕ is centered at zero. The direct transmission at the center of the ring is blocked by a mask. To further enhance intensity resolution, the intensity profiles captured by CCD are averaged in $-3° < \phi < 3°$. The angular resolution and repeatability in the setup is calibrated within 0.1°.

The far-field light intensity dI per solid angle element $d\Omega$ normalized by incident intensity I_0 can be written as[11,12]

$$\frac{dI}{I_0 d\Omega} = 4\left(\frac{\pi}{\lambda}\right)^4 |T_p(k_x,d)|^2 |s(k_x)|^2 |W(\theta,\phi)|^2, \quad (1)$$

with T_p being the p-polarization transmission coefficient through the silver film, λ the incident wavelength, $|s(k_x)|$ the roughness Fourier spectrum of the silver/air interface, and $W(\theta,\phi)$ the dipole function. Equation (1) assumes the scattering occurs only once at the air/metal side, the roughness at the metal/prism interface and the scattering inside metal films does not contribute to the collection of evanescent waves. According to reference,[11] the scattering due to bulk inhomogeneities in similar deposition condition is far below the comparable level of air/metal interface, which means our approximation is reasonable. This is also verified by the $\phi = 90°$ dips in the scattered cone, which excludes the polarization mixing due to volume scattering. Therefore, the conversion to evanescent waves at first surface is measured.

Systematic studies on surface characteristics were performed on a commercial atomic force microscope (Dimension 3100, Veeco Digital Instrument). In our experiment, the samples have ten different thicknesses: 20, 30, 40, 45, 50, 55, 60, 65, 70, and 90 nm. $|S(k_{sp})|^2$ of each sample can be obtained by Fourier transformed AFM image and averaged in radial direction. For certain k_{sp}, excitation wavelength is 514.5 nm as an example, the averaged $|S(k_{sp})|^2$ with different thicknesses in an arbitrary unit are 1.8, 6.1, 4.8, 4.4, 3.6, 3.5, 3.3, 2.6, 11, and 1.7, respectively. This careful justification of $|S(k_{sp})|^2$ in samples is the key to a reliable extraction of enhancement factor $|T_p|^2$.

By applying Eq. (1), we are now able to extract the measured relative transmissivity $|T_p|^2$ dependence on azimuthal angle θ with sample thicknesses (Fig. 3). This is done by taking into account the measured roughness modulation spectrum $|s(k_x)|$, as well as the computed dipole function $|W(\theta,\phi)|$. Physically, the enhanced transmission of these evanescent components occurs only in a finite band centered at a surface plasmon wavevector $k_x = k_{sp} \equiv (\omega/c)\sqrt{\varepsilon(\omega)/[1+\varepsilon(\omega)]}$ known in metal optics and surface sciences. At this wave vector and frequency, the photon impinging on the metal surface can excite the collective oscillation of conductive electrons; that is, surface plasmon with maximum efficiency. Therefore, coupling by a hemispherical lens in our case, a transmitted hollow cone can be seen using a screen (Fig. 1).[13]

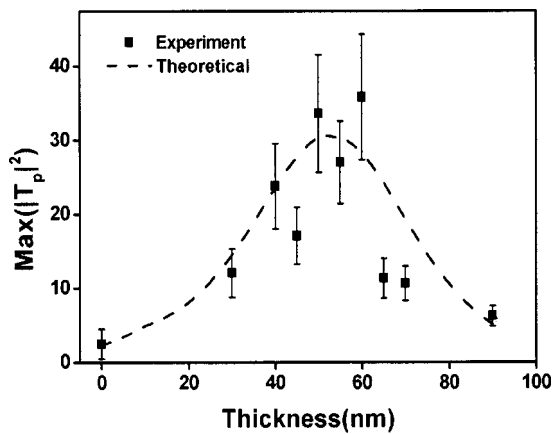In Fig. 4, the peak enhancement is plotted as a function

FIG. 4. Measured peak field enhancement $|T_p|^2$ vs the thickness of silver films at $\lambda = 514.5$ nm. The dashed line is the calculated value by Fresnel equation using $\varepsilon_{Ag} = -10.8 + 0.42i$.

of sample thickness. We found that the enhancement factor $|T_p|^2$ rapidly grows with increasing silver thickness up to 50 nm. Above 50 nm, the enhancement is sharply suppressed due to the intrinsic loss inside the silver film,[14] so that the transmissivity decays as film thickness further increases. Accordingly, our experimental results provide direct evidence of the thickness dependence of enhanced evanescent field across the silver film, a key prediction in Pendry's superlens theory.

For comparison, in both Figs. 3 and 4, a bare prism (zero silver film thickness) is chosen as a normalization reference of scattered light by roughness of the glass surface (at order of a few Å). The peak values are selected (Fig. 4) in replacement of the values corresponding to each k_x, mainly to remove the peak shift in k_x which may occur due to possible aspherical deformation of each prism from fabrication variations. The silver film thickness is chosen to be larger than 30 nm, ensuring that the bulk optical properties of silver can be applied in the calculations.[15]

To verify that the evanescent field enhancement is indeed attributed to the surface plasmon in materials with negative ε, we also tested two groups of samples by substituting silver to gold and silicon. Very similar light cones have been obtained for the gold samples, and no light cone is observed in silicon samples. We also compared two samples with the same silver thickness but very different roughness Fourier spectra ($\sim$one order's difference), and the deviation of the measured $|T_p|^2$ is within 20%, comparable with the statistical error of surface roughness. The agreement implies a negligible effect of electromagnetic resonances induced by the corrugation.

In order to realize a perfect lens, the allowed bandwidth of k_x for the enhancement of evanescence wave in the me-

dium should extend to infinity. However, in real metallic films, there exists finite bandwidth of k_x in which enhancement can be realized.[16] In order to achieve a relative large bandwidth of enhanced k_x spectrum and obtain a superlens, we already studied the bandwidth broadening effect when the excitation frequency approaches to surface plasmon resonance frequency.[17] For example, at a photon energy equal to 3.68 eV, where $\varepsilon(\omega) \approx -1 + 0.33i$, the enhancement for evanescence extends over a broad spectrum of $k_x(\sim 6k_p)$, thus allowing more detailed image reconstruction.

The superlens theory lifts the resolution restriction inherent in conventional optics, with new avenues to optical imaging using metal[18,19] and dielectric structures.[20] However, to realize a true far-field super-resolution imaging, we have yet to solve many challenges. For example, a special coupling mechanism is needed to convert a large band of these enhanced evanescent waves to propagating waves. With future engineered metamaterials that allow a broader k_x bandwidth to be coupled to a far field, one should be optimistic that the realization of a superlens is no longer a dream.

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