Exploiting evanescent-wave amplification for subwavelength low-contrast particle detection

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DOI 10.1103/PhysRevA.96.013814
Publication date 2017
Document Version Final published version
Published in Physical Review A (Atomic, Molecular and Optical Physics)


Important note To cite this publication, please use the final published version (if applicable). Please check the document version above.

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The classical problem of subwavelength particle detection on a flat surface is especially challenging when the refractive index of the particle is close to that of the substrate. We demonstrate a method to improve the detection ability several times for such a situation, by enhancing the “forbidden” evanescent waves in the substrate using the principle of super-resolution with evanescent waves amplification. The working mechanism of the system and experimental validation from a design with a thin single dielectric layer is presented. The resulting system is a simple but complete example of evanescent-wave generation, amplification, and the consequent modulation of the far field. This principle can have far reaching impact in the field of particle detection in several applications ranging from contamination control to interferometric scattering microscopy for biological samples.

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The study of negative refractive index materials was initiated by Veselago [1] to understand whether such materials would, from a purely theoretical point of view, violate the founding laws of physics. A significant increase in interest among the research community in this subject occurred when Pendry [2] suggested that those materials would be capable of amplifying evanescent waves and eventually lead to unlimited spatial resolution. The crux of Pendry’s method was the use of a layer of negative-index media for restoration of otherwise damped evanescent waves. However, it has been shown from a theoretical viewpoint [3] that a slab of such a material works only if object and detector are both in the near field [4–6]. Far-field imaging with the evanescent-wave amplification has also been shown [7–11], for example, utilizing far-field superlenses and anisotropic metamaterials, although neither of these techniques had a simple construction like a thin slab. Alternatively, some authors [12,13] have doubted the mechanism of evanescent-wave amplification as detailed in Ref. [2]. It was, in fact, later shown that a dielectric layer is capable of doing similar amplification [14–16] for both parallel (p) and perpendicular (s) polarization, essentially triggering Fabry–Perot-like resonances. The existence of evanescent-wave amplification also for s-polarized light rules out the interpretation of the super-resolution effects through mimicking negative refraction in metals, as suggested in Ref. [2], because that case simply falls outside the theoretical framework of the negative-index-materials theory. Moving to dielectrics layers offers some simplicity from a fabrication point of view, especially on a large scale. However, these dielectric layers are also only effective in the near field on their own.

There has been little attention on using this principle for a problem which can significantly benefit from this concept: particle detection on a flat substrate. This problem is critical for substrate quality inspection in many important fields, such as semiconductors, organic polymers, optical-component manufacturing, the nanofabrication industry [17,18], and biological microscopy with nanoparticle markers, such as interferometric scattering microscopy [19]. Novotny showed that the “forbidden light” [20,21], i.e., light emitted by a dipole scatterer into supercritical angles inside the planar substrate under it [22], contains a significant amount of information about the scatterer. Although particle detection by evanescent waves is well known [23–25], the effect of using amplified evanescent waves for particle detection on a planar substrate is not well researched. A possible reason is the necessity of bringing the device converting the amplified evanescent waves into detectable far-field modulations very close to the sample. This is inconvenient for practical use and also is a source of further contamination. Thus, it is desired to have the evanescent modes originating from the particle to get amplified and detected in the far field without the presence of anything other than the amplifying media in the near field, combining both the ideas into “amplified forbidden light” with a practical and useful design.

We investigate here the effects of evanescent-wave amplification for detection of particles on a flat substrate coated with a very thin (≈λ/30) evanescent-wave amplifying layer. We consider subwavelength particles which are almost perfectly index matched to the substrate, which is a challenging situation for particle detection [26,27], and show that the detection sensitivity is significantly improved (almost 500% signal-to-noise improvement). This implies that, by this technique, compared with the not-enhanced case, particles that are nearly undetectable can be clearly detected. We present the working mechanism and numerical analysis of the principle, followed by experimental validation.

The evanescent waves, which are produced by a probe interacting with a target, are usually not available in a technique when the detector is located in the far field. In our case the optical probe consists of a field focused by a microscope objective and contains no evanescent waves. The way we circumvent this limitation and still exploit the advantages of near-field optics, is by using the evanescent part of the field scattered by the target itself, when illuminated by the incident optical field, as a new secondary optical probe. To realize this all one needs to do is to modify the properties of the physical support where the target is placed in a way that a large part of the evanescent waves generated...
some of those waves by amplifying them and then letting
they do not directly reach the detector. It is possible to recover
large amount of the scattered waves are evanescent, and so
amplified by the substrate. For an isolated small particle, a
probe, is essentially reflected back and can be eventually
the particle. This reflected scattered field, being the secondary
the direct scattered field with the substrate and rescattered by
and (3) a indirect scattered field, produced by the interaction of
produced by the scattering between particle and incident field,
field with the bare substrate only, (2) the direct scattered field,
(a) The main constituents of the outgoing
field in air for a particle on a substrate in air. In the normal case
(b), the incident field is scattered by the particle, but the evanescent
modes decay quickly in the substrate and in air. It does not contribute
significantly when they are rescattered to propagating modes in air.
The situation changes when the evanescent modes are amplified
(c) by a thin enhancing layer and the scattered field is boosted by a
large contribution from rescattered evanescent waves. As indicated in
panel (c), the enhancement results in increase in field at the substrate
side as well. The $z$ axis coincides with the optical axis of scanning
system, with $z > 0$ in air, and $z = 0$ at air interface.

by the scattering process between target and incident field
is reflected back by the support and redirected towards the
scatterer. Depending on the support, this secondary probe,
containing evanescent waves this time, interacts again with
the target and the new scattered field can be recorded in the
far field. More importantly, the support can be realized in such
a way that the amplitude of the evanescent waves, produced by
the first interaction between target and incident field, is
actually increased, resulting in an improved signal-to-noise ratio (SNR) of the recorded signal. In our work, the target
is represented by small dielectric particle on a flat substrate
which is illuminated by a focused optical field. The resulting
scattered field is recorded by a detector placed in the far field.
Generally speaking, once illuminated by a focused field, the
scattered field in a specific direction consists of mainly three components [28], as shown in Fig. 1(a). These are (1) the specular reflection, mostly due to the interaction of the incident field with the bare substrate only, (2) the direct scattered field, produced by the scattering between particle and incident field, and (3) a indirect scattered field, produced by the interaction of the direct scattered field with the substrate and rescattered by the particle. This reflected scattered field, being the secondary probe, is essentially reflected back and can be eventually amplified by the substrate. For an isolated small particle, a large amount of the scattered waves are evanescent, and so they do not directly reach the detector. It is possible to recover some of those waves by amplifying them and then letting the

particle rescatter them into propagating modes. The steps of
the working mechanism in short are as follows:
(i) The illuminating field is first scattered by the nanoparti-
cle which generates the evanescent field. Some of the scattered
field propagates from the particle towards the substrate.
(ii) Propagating and evanescent waves, directed towards
the substrate, hit the substrate. This interaction gives rise to a
reflected field, which still contains propagating and evanescent
waves. The substrate can eventually modify the amplitude of
the waves and enhance the amplitude of evanescent waves.
With proper design, the enhancing layer can be made to have a
good $Q$ factor with large full width at half maximum (FWHM),
so that a broad band of spatial frequencies can be amplified.
(iii) Such a back-reflected field interacts again with the
particle and gives rise to a new scattering process.
(iv) The scattered field is collected by the detector.
In this construction, the particle not only represents the
target but also plays the role of the seed for evanescent-
wave generation, and the waves are further enhanced by the
engineered substrate.

To verify the feasibility of such approach, two samples
were prepared. On the first sample, polystyrene latex (PSL),
particles 200 nm diameter were deposited on a flat glass plate (UV grade fused silica, flatness less than 20 nm,
5 mm thick). The second one was a 600 μm glass plate of the same material with a layer of 20 nm InSb on top,
which functions as an evanescent-wave enhancing layer. The
thickness of the evanescent-wave enhancing layer is less
critical for us than situations where spatially narrow-band
evanescent waves are generated by the object which needs
to be amplified, such as in the case of the grating studied in
Ref. [5]. To show that this specific layer can function as an
enhancement layer for evanescent waves, simulations were
performed. The simulations were done in two steps. At first,
an analytic but rigorous model [29] was used to verify the
response of thin film stack only, without any scatterer. In
Figs. 2(a)–2(d), the modulus of the complex reflectance as
a function of normalized wave vector ($k_s/k_\text{air}$) and distance $z$ from the air-substrate interface is shown. The enhancement of
evanescent modes can be seen if Figs 2(a) and 2(b) are compared with Figs. 2(c) and 2(d). The enhancement is larger
for an $s$-polarized field, which is more clearly seen from
Fig. 2(g), where the difference between the amplitudes of the
complex reflection coefficients of enhanced and not-enhanced
samples are plotted for a specific distance from the air interface ($z = 10$ nm). This metric shows the comparison of amplification
of two amplifiers, without and with enhancing layer, for
each polarization as a function of spatial frequency. A positive
value of this difference for approximately $1.4 \leq k_s/k_\text{air} \leq 5$
indicates that the amplification of the enhanced sample is
better. The peak amplification is around $k_s/k_\text{air} = 1.8$, for
$s$-polarized light, with about 60% enhancement. This indicates
that the design is capable of amplifying evanescent waves in the
near field and as a result can produce a higher SNR compared
with the standard sample without enhancing layer. To verify
the assumptions yet more rigorously, a model of the actual
experimental arrangement was created by using the finite
element method (FEM) [30], and the $x$-polarized electric-field
distribution in the $x$-$z$ plane is shown for a not-enhanced
[Fig. 2(h)] and enhanced [Fig. 2(i)] sample. Simulations are
FIG. 2. The modulus of reflectance (|r|) for parallel (p) and perpendicular (s) polarized waves are simulated respectively for a substrate (a), (b) with and (c), (d) without enhancement layer of InSb. In each case the reflectance is shown against the normalized \( x \) component of the wave vector (\( k_x/k_{air} \)) and the distance \( z \) from the air interface. In panels (e) and (f), the variation of |r| with wave vector at the air-interface (\( z = 0 \)) is shown. The Brewster’s angle for air-glass interface is seen at \( k_x/k_{air} \approx 0.82 \) in panel (f). The effect of evanescent-wave amplification by the InSb layer is clearly seen from panels (e) and (f). In panel (g), the differences between the |r| for enhanced and not-enhanced samples are plotted for each polarization with \( k_x/k_{air} \) for \( z = 10 \) nm. This value of \( z \) was chosen arbitrarily, since the particle will scatter light over a large range of \( z \) (0 \( \leq z \leq 200 \) nm). In panels (h) and (i) the x-polarized electric field, in the \( x-z \) plane, is shown when a focused x-polarized beam is incident on the sample-air interface.

FIG. 3. The differential detection principle is shown in panel (a). In panels (b) and (c) the far-field maps of the sample without and with the enhancement layer are shown. The figures under panels (b) and (c) show the three-dimensional view of the signal maps near the particle. Please note the change in scale for the not-enhanced case, which is necessary to show the signal from the particle. (d) Signals can be quantitatively compared by plotting the cross sections. The noise of the two measurements are compared in panel (e), which have mean \(+3\sigma \approx -0.09 + 0.42\) (without enhancement layer) and \(-0.2 + 0.42\) (with enhancement layer). Particle localization is not possible without the enhancement layer.

shown for each substrate (enhanced and not-enhanced), in accordance with the coordinate system described in Fig. 1, using a simulation volume of 1.3 \( \mu \)m\(^3\). We used an InSb layer and substrate refractive index 4.28 + 1.81\( i \) and 1.48. Particle material refractive index was 1.58. While both the plots use the same scale, a visual inspection clearly shows the effect of the enhancing layer. The choice of \( x-z \) plane is only for representation; the final effect, when all the other planes are considered, will be much larger.
To make a fair comparison between the two samples it is necessary to eliminate the effect of the increased background reflection level resulting from the increase in reflectance for the propagating modes ($k_x < k_{an}$) when the layer is present. For this, differential detection is performed by subtraction of the detected intensities in the two halves of the detector [Fig. 3(a)]. To do this, linearly polarized He-Ne laser light ($\lambda = 632$ nm) is incident onto an objective with numerical aperture (NA) of 0.9 was used to focus the light on the air-substrate interface. The substrate is scanned in the lateral ($x$-$y$) direction and the reflected light is captured by the same objective. A beam splitter was used to divert the outgoing field such that the back focal plane (spectrum plane) is captured by a differential silicon detector [Fig. 3(a)]. The sample was placed on a Physik Instrumente piezo-electric actuator operating within its linear range. The actuator can move the sample in the $x$-$y$ plane [31,32].

With this differential detection principle the source power variation is no longer a problem, also, the localization accuracy and SNR with differential detection is significantly higher even with a low incident power and relatively fast scanning. For example, a properly chosen material for the enhancement layer is absent. The increase in SNR can be seen more clearly if a cross section is taken, which is shown in Fig. 3(e), where comparison of noise dependent, so a suitable polarization scheme, such as radially polarized illumination [34], can be used for an enhancing layer designed to amplify $p$-polarized light, giving a better SNR due to elimination of the polarization component which is not amplified.

The authors acknowledge Roland Horsten and Thim Zuidwijk of the Delft University of Technology for the electronics and mechanical design of the experimental system. Christiaan Hollemans of TNO, Delft is acknowledged for his contribution in preparing the samples. S. Roy acknowledges the Seventh Framework Program (No. FP7/2007-2013 of the European Union) under Grant Agreement No. 281027 for funding. Xukang Wei acknowledges the School of Physics, Nankai University for financing his stay in the Netherlands.

[6] Strictly speaking, we should say when the distance between object and image plane is twice the distance of the thickness of the amplifying slab.