Efficient suppression of radiation damping in resonant retardation-based plasmonic structures

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We propose an innovative approach to the design of retardation-based plasmonic structures allowing efficient suppression of radiation damping and increase in resonance quality (Q) factors. The underlying idea consists of conformal structure transformation suppressing its electric-dipole response in favor of magnetic-dipole one. We show that bending of plasmonic nanoantennas increases significantly their Q factors up to the electrostatic limit while preserving the nature of resonance along with its exceptional features such as linear size-dependent tunability and robust field enhancement.

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Nanometer-sized metal structures exhibit spectacular resonant properties in the visible and infrared spectra, which is in fact a counterintuitive feature given the fact that their dimensions are well below the optical wavelength. Probably the most intensively investigated resonances are the so-called electrostatic resonances, which are associated with resonant (localized) electron oscillations in metal nanostructures of different shapes and configurations (see Ref. 1, and references therein). These resonances feature scale-invariant resonant wavelengths (determined by shapes and dielectric responses of constituents) and shape-invariant quality (Q) factors, which are related to the radiation absorption and thus determined only by the complex dielectric function of metals used.[2] Resonances of another type, the so-called retardation-based resonances,[3] involve the excitation, propagation, and interference of surface electromagnetic excitations, i.e., surface-plasmon polariton (SPP) modes, resonantly coupled to collective electron oscillations at the metal surface.[4] The most remarkable feature of these resonances is their (almost) linear size-dependent tunability extending over a very broad range of wavelengths.[5,6] This behavior stems from both tight confinement and guiding (potentially with no cutoff[7]) of SPP fields by the same metal structure, allowing constructive interference of propagating back and forth SPP waves that are efficiently reflected by structure terminations. Being tightly confined to the metal and featuring large effective indexes (i.e., low phase velocities), these plasmonic modes are often referred to as slow SPPs (S-SPPs).[3] Nanoresonators and nanoantennas based on S-SPPs (Refs. 8–11) have been shown to exhibit anisotropic responses as well as strong field enhancements, making them potentially interesting for challenging applications in nano-optics.[12–16] Unfortunately, besides these superior features, retardation-based resonances exhibit a strong damping of the resonant oscillations, which is dominated by the electric-dipole radiation enhanced due to linear geometry of plasmonic currents oscillating along the structure longitudinal axis. Moreover, their relatively low Q factors decrease rapidly when the resonances are tuned to longer wavelengths because the electric-dipole moment also scales with the structure longitudinal size. Fundamentally, the main question posed[2] is whether the Q factor of an individual structure can be increased beyond the quasistatic limit when including the wave retardation. It was also suggested to consider plasmon resonances in which strong electric-dipole radiation, causing the additional (as compared to the quasistatic case) radiation loss, can be suppressed.[2]

In this Brief Report we propose and analyze an innovative approach to the control of resonance quality in retardation-based resonant nanostructures. The general idea is to suppress the electric-dipole response (primarily responsible for the radiation damping) in favor of a magnetic-dipole response by means of a conformal geometric transformation that preserves the nature of resonance.

For this purpose, we considered light scattering by 20-nm-thick silver strips having width w and different bending radii R surrounded by air (Fig. 1). The strip length along the z axis was assumed to be infinite, i.e., much longer than w, thus allowing a rigorous two-dimensional modeling in the xy plane based on the surface-integral equation method for the magnetic field.[17,18] The silver refractive index data were taken from Ref. 19.

In a first set of simulations, we computed the scattering cross-section spectra of several strips with the same width $w=300$ nm and different values of the bending radius R. The structures were excited by an incident p-polarized plane wave propagating at an angle of 90° with respect to the x axis (Fig. 2). It is seen that bent strips (solid lines), as com-

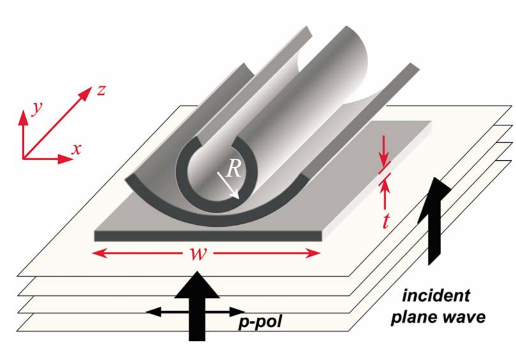

FIG. 1. (Color online) Schematic of the considered nanostructures obtained from a metal (silver) nanostrip by conformal bending transformation with different bending radii R. The strip thickness $t=20$ nm and the strip width w are in the range of few hundred nanometers. The strips are assumed to be infinitely long in the z direction.

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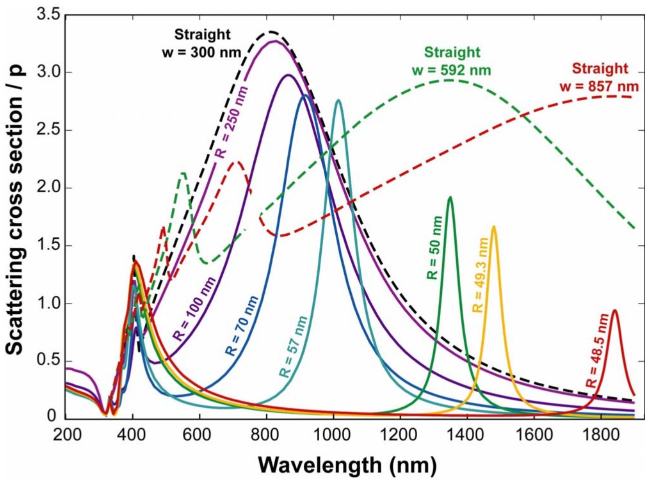

FIG. 2. (Color online) Scattering cross-section spectra (normalized to the semiperimeter p of the structures) for 20-nm-thick silver strips of different geometries: 300-nm-wide strips with different bending radii R (solid lines); straight strips of different widths w for comparison (dashed lines).

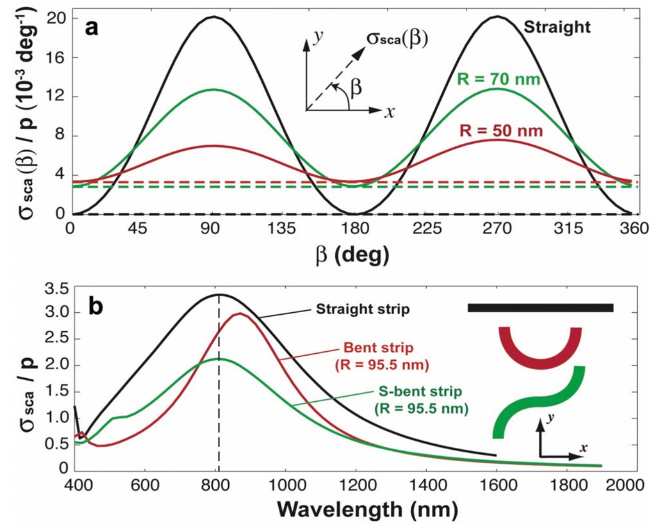

FIG. 3. (Color online) (a) Angular scattering cross section (with 1° resolution) under resonant excitation for three structures of different curvature. (b) Effect of the interaction between strip terminations on the redshift of the resonance.

pared to a straight strip (black dashed line), exhibit the following two distinctive features when the bending radius decreases: (i) the resonance wavelength (i.e., the peak wavelength λ_p in the scattering spectrum) is progressively redshifted; (ii) the Q factor (defined as the ratio between the resonance wavelength and the full width at half maximum of the scattering line) is progressively increased, albeit at the expense of a limited decrease in the peak value. For example, bent strips with the bend radii $R=50$ nm and $R=48.5$ nm exhibit the Q factor of 21 and 31, respectively, values to be compared with the Q factor of 1.4 for the straight geometry. The improvement achieved is even more evident if one relates these bent strips with straight strips tuned (by selecting their length) to the same resonance wavelengths, ~1350 and ~1841 nm, respectively (see green and red dashed lines in Fig. 2).

An explanation for such a drastic increase in the Q factor caused by the bending can be gained via monitoring of the evolution of differential (angular) scattering cross section under resonance excitation. It is seen (Fig. 3) that three structures of the same width $w=300$ nm and different curvatures, i.e., a straight strip, a bent strip with $R=70$ nm, and a bent strip with $R=50$ nm, exhibit very different contrasts in angular scattering spectra. Here, the resonant excitation was provided by a p-polarized plane wave at 815, 915, and 1350 nm, respectively. Note that for the straight strip the scattering cross section behaves as $\sin^2(\beta)$ just like an oscillating dipole oriented along the x axis.[20] It has in fact been noticed that the field pattern formed by a straight metal nanostrip corresponds to that of an electric dipole.[21] This behavior can be easily understood by considering that the S-SPP mode propagating back and forth along the strip axis corresponds to a longitudinal plasmonic current oscillating at the same mode frequency. On the contrary, bent strips exhibit a rather distinctive feature, showing a high constant (namely, β independent) contribution to the angular scattering diagram which is typical of a magnetic dipole with a dipole moment oscillating along the z axis.[20] We conclude that the bending of the strip axis, resulting in a bending of the plasmonic currents (partially closing in a loop by means of displacement currents in the gap between strip terminations), induces a magnetic-dipole response in the structure that forbids strong electric-dipole radiation. As a consequence, efficient suppression of radiation damping is achieved, resulting in a dramatic increase in the Q factor in an isolated (i.e., single) nanostructure.

We already noticed that the resonance wavelength in the scattering spectra of Fig. 2 is progressively redshifted as the curvature is increased even though the strip width is kept constant. This feature is seemingly in contrast with what would be expected from retardation-based resonances since, for example, in straight nanostrips, the (fundamental) resonance wavelength has been found to scale almost linearly with the strip width in accord with the Fabry-Perot-like resonance condition:

$$(w/\lambda_p) = (\pi - \phi)/2\pi n_{\mathrm{eff}}, \qquad (1)$$

where n_{eff} is the effective index of a S-SPP mode bound to and propagating along a metal film with the same thickness as the strip, and ϕ is a phase change (modulus π) due to reflection at strip terminations. Actually, the phase ϕ is a very critical parameter to take into account because not only are the S-SPPs incident at strip terminations but also near field and other (non-SPP) propagating field components generated at one strip termination, influencing the total field at the other termination and thus the reflection of S-SPPs. Therefore it is expected that ϕ should significantly change in bent strips with respect to the straight strip as the bending radius is decreased because of the strong interaction between strip terminations, with the outcome of a dramatic shift in the resonance wavelength. To check this point we compared the scattering cross sections of a straight, S-bend, and circularly bent strips having the same thickness $t=20$ nm, width w

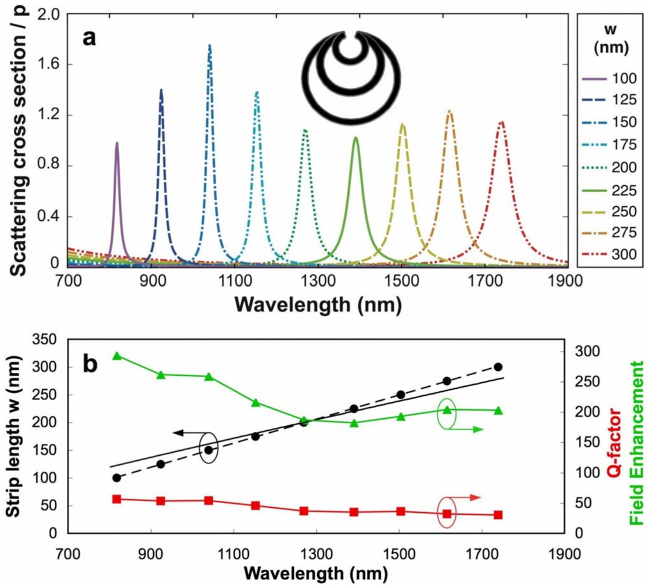

FIG. 4. (Color online) (a) Tuning of the plasmon resonance under a constant gap width $g=6$ nm. (b) Strip length (circles), Q factor (squares), and maximum field enhancement (triangles) as a function of the desired resonance wavelength. Black solid line represents the tuning curve derived from Eq. (1) assuming the effective formula reported in Ref. 21 and a reflection phase $\phi=2.12$ rad fitted on numerically computed data.

$=300$ nm, and curvature magnitude $R=95.5$ nm, except for the straight strip [Fig. 3(b)]. It is clearly seen that the S-bend strip, having the two terminations far apart from each other and thus allowing no interaction between them, different to the case of the circularly bent strip, exhibits no redshift in the resonance wavelength, thus precisely satisfying the resonance condition given by Eq. (1). This is another indication that the conformal transformation preserves the S-SPP mode, with full exploitation of retardation effects.

The aforementioned features of resonant scattering by bent nanostrips allowed us to deduce that, by imposing a constant gap size and achieving thereby an almost bending-independent phase change ϕ, the resonance wavelength of bent strips can be tuned linearly with the strip width [Eq. (1)]. The expected behavior was indeed found in calculations of the scattering cross-section spectra of bent strips of different width but with a constant gap $g=6$ nm measured along the circularly bent axis of the strip (Fig. 4). Note that in view of constant gap size, as the strip width increased the bending radius was accordingly increased to fulfill the condition $w=2\pi R-g$. It is seen that the resonance wavelength is almost linearly dependent on the strip width in a broad wavelength range as expected from Eq. (1) [Fig. 4(b)]. This linear scaling is similar to what has been reported for straight nanostrips[6] but with dramatically improved Q factors exhibiting only weak degradation with the wavelength increase [Fig. 4(b)]. This result demonstrates that our design allows efficient suppression of radiation damping at any wavelength in the near infrared. We also investigated the influence of the conformal transformation on field-enhancement effects under resonant excitation by considering the structures selected among the set reported in Fig. 2 (Fig. 5). As expected, for relatively large bending radii, the intensity pattern of the bent strip resembles the one of a straight strip after a conformal (bending) transformation in the xy plane [Fig. 5(a)], exhibiting maxima of the order of 20 located at strip terminations.[6,21] With the bending radius being further decreased, the field becomes more and more concentrated in the region between strip terminations, and field enhancement strongly increases as well [Fig. 5(b)]. Note also that as the gap region becomes a few nanometers wide, the maximum field enhancement turns to be very sensitive to the bending radius [see Figs. 5(b) and 5(c)], stepping from 120 for $R=50$ nm to 180 for $R=49.3$ nm, a sensitivity that might be related to a large variation in the gap width (from g

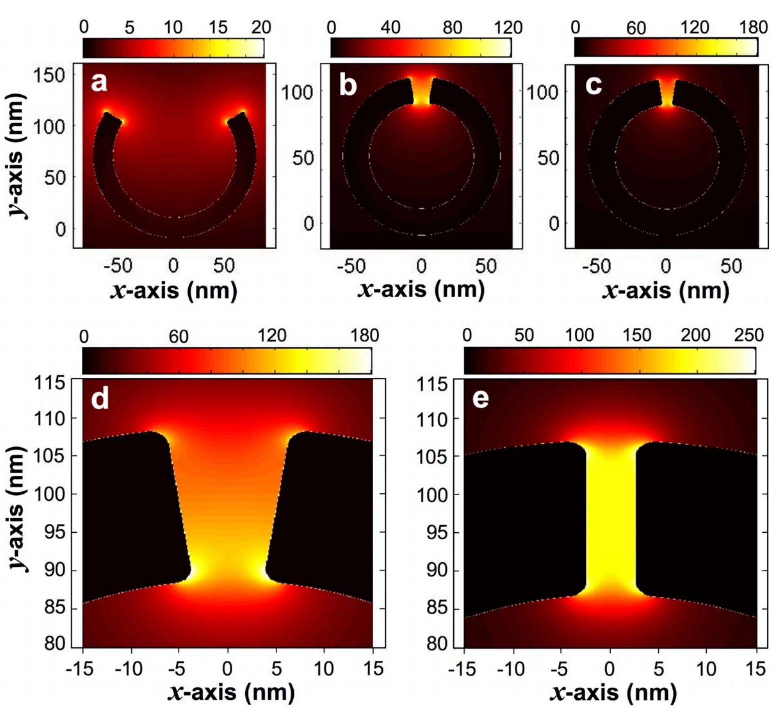

FIG. 5. (Color online) Field enhancement patterns for 300-nm-wide bent structures under resonance excitation: (a) $R=70$ nm, $\lambda=915$ nm; (b) $R=50$ nm, $\lambda=1350$ nm; (c) $R=49.3$ nm, $\lambda=1480$ nm; (d) detail of (c) in the gap area; (e) variant design of the gap. $R=48.54$ nm, $\lambda=1818$ nm.

$=14.2$ nm to $g=9.8$ nm). This behavior indicates that the maximum field enhancement achieved is mostly influenced by the strong interaction between strip terminations rather than by the geometrical curvature. In fact for a given gap width, the maximum field enhancement exhibits a limited variation as the strip width (and accordingly the bending radius) is varied in a wide wavelength range [Fig. 4(b)]. Detailed computations of the field distribution shown in Fig. 5(c) in the gap region reveals that the maximum field enhancement is achieved close to the bottom corners of the gap region although exhibiting relatively high values in the whole gap area. It should be emphasized that the observed field is not directly related to sharp metal corners. Thus, with a slightly different design of the gap employing parallel terminations, we found almost perfect uniformity of the field in the gap with an intensity enhancement of $\sim 4\times 10^4$ [Fig. 5(e)]. Furthermore, computation of the x and y components of the field (not shown here) confirmed that, as expected in view of the short-range nature of the plasmon mode excited (see Fig. 1 in Ref. 17), the field in the metal is completely dominated by the longitudinal component. As a consequence, the enhancement mechanism turns out to be intrinsically robust (i.e., virtually independent on the radius of curvature at the gap corners), being imposed by boundary conditions at the flat interface of strip terminations. Actually, the field is expected to experience a jump of about the absolute value of the silver dielectric constant [$\sim$175 for the case of Fig. 5(e)] when crossing the flat metal boundaries of the gap.

In conclusion, we have demonstrated an innovative design for retardation-based resonant nanostructures providing efficient suppression of radiation damping with a dramatic improvement in the Q factor of the plasmonic resonance. The underlying idea is to exploit the magnetic-dipole response induced in a metal-strip nanoantenna after a conformal bending transformation. Our simulations revealed that all the important features provided by retardation effects are preserved while the Q factor of the resonance was found approaching the electrostatic limit[2] in the near infrared. It is very interesting (and worth separate discussion) that virtually the same Q factor can be observed for electric-dipole-like metal nanostructures in the electrostatic limit[2] and retardation-based ones in the magnetic-dipole limit (considered in this work). We think that the Q factor of localized plasmon resonances found in the electrostatic limit[2] might turn out to be the fundamental limit for Q factors of plasmon resonances in nanostructures because it is related only to Ohmic loss in electron oscillations (i.e., to the absorption cross section) and can be only decreased with the radiation loss becoming important (i.e., with the increase in the scattering cross section). Furthermore, we found that, under a strong bending of structures, the resulting split-ring-shaped nanoantennas feature an intense field enhancement ($\sim 4\times 10^4$) in the whole gap area. Also, we believe that our design can be profitably applied to other kinds of plasmonic nanoantennas and nanoresonators based on retardation effects, such as metal nanorods and nanowires (which are the three-dimensional analogs of nanostrips) to enhance both the Q factor and the field enhancement of a single-structure nanoantenna with simultaneous control of the resonance tunability. Finally and more fundamentally, our analysis also contributes to the investigation of magnetic plasmon resonances in metamaterials (see, for example, Ref. 22 and references therein) by revealing that the magnetic response exhibited in the visible and infrared by C-shaped or split-ring-shaped metal nanostructures arises from the resonant excitation of plasmonic current loops associated with S-SPP modes, providing unique insight into the physics of single metamaterial atoms (that has been so far interpreted according to an electric circuit model[23]), and thus bridging in a sense the gap between metamaterials and plasmonics.

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