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# 1 Highly directive Fabry-Perot Leaky-Wave nanoantennas based on optical 2 Partially Reflective Surfaces

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6 (Dated: 23 March 2015)

Nanoantennas enhance the conversion between highly localized electromagnetic fields and far-field radiation. Here, we investigate the response of a nano-patch Partially Reflective Surface backed with a silver mirror to an optical source embedded at the centre of the structure. Using full wave simulations, we demonstrate a two orders of magnitude increased directivity compared to the isotropic radiator, 50% power confinement to a  $13.8^\circ$  width beam and a  $\pm 16$  nm bandwidth. Our antenna does not rely on plasmonic phenomena thus reducing non-radiative losses and conserving source coherence.

7 During the last decades, nanotechnology has made  
8 a significant breakthrough in the development of novel  
9 optoelectronic devices allowing the accurate fabrication  
10 and integration of nanocomponents in flexible and inex-  
11 pensive materials.<sup>1</sup> The resulting nanodevices have had  
12 tremendous impact in optical communication, sensing,  
13 imaging and photovoltaic systems.<sup>2-4</sup> In the latter, the  
14 ability to enhance, confine, receive, and transmit optical  
15 fields, which are known basic functions of antennas, is  
16 required. Hence, the study of nanoantennas has become  
17 the subject of intensive research and a rapidly growing  
18 field of nanoscience. Nanoantennas are devices capable  
19 of connecting free-space far-field radiation and nanoscale  
20 optical signals. Their design methodology resembles  
21 that of its radio-frequency (RF) counterparts where its  
22 properties can be tailored to fulfill a specific function.  
23 However, conventional rules for light-matter interaction  
24 need to be re-examined to fit the different phenomena  
25 involved. One of the major differences is a dramatic  
26 change in behavior of metals which cannot be treated  
27 as (nearly) perfect conductors. Their optical response is  
28 described instead by a frequency-dependent complex dielectric  
29 function associated with material losses and non-  
30 negligible field penetration.<sup>5</sup> In addition, surface plasmon  
31 polaritons may be excited. Many designs inspired by  
32 well-established RF antennas can be found in the litera-  
33 ture. This is the case of: monopoles,<sup>6</sup> dipoles,<sup>4,7</sup> patch-  
34 antennas<sup>8,9</sup> and more interestingly arrays of these ele-  
35 ments (e.g. Yagi-Uda<sup>10,11</sup>). Nanoantenna arrays offer  
36 additional degrees of freedom for tailoring the radiation  
37 pattern such as the geometry of the individual elements,  
38 their relative positions, orientations and density; which  
39 makes them especially promising for spontaneous emis-  
40 sion enhancement, solar energy harvesting, 3D hologra-  
41 phy displays and enhancement of photodetectivity of in-  
42 frared detectors.<sup>11-14</sup>

43 In this context, we introduce a miniaturized Leaky  
44 Wave (LW) antenna operating in the near-infrared (NIR)  
45 offering up to 21.2 dBi directivity at broadside with a

46  $13.8^\circ$  beamwidth. The fractional bandwidth, defined as  
47 the frequency range for which the radiated power de-  
48 cays less than 50% of its maximum value normalized to  
49 the central frequency, is 2.8%. LW antennas have been  
50 extensively used to tailor the radiation pattern of low  
51 directive sources in the microwave regime. They are ca-  
52 pable of concentrating the radiated power into highly di-  
53 rective pencil-beams at the frequency of operation and  
54 conical beams above it.<sup>15</sup> A common type of 2-D LW an-  
55 tenna consists of a Partially Reflecting Surface (PRS)  
56 over a ground plane (GP) forming a half-wavelength  
57 Fabry-Pérot cavity. The cavity is excited by a horizontal  
58 hertzian electric dipole located at its center. At optical  
59 frequencies, such a source may consist in practice of a  
60 stimulated molecule or an embedded quantum dot. The  
61 periodic set of perturbations provided by the highly re-  
62 flective PRS allow the radiation to leak out, while the  
63 GP reflects all the incident power, avoiding power lost in  
64 the backward direction. As a result, multiple reflections  
65 appear inside the half-wavelength cavity which at the op-  
66 erating frequency of the antenna are in phase at the PRS  
67 plane and transmitted waves constructively interfere to-  
68 wards radiation.<sup>16</sup>

69 A PRS consisting of an infinite grating of square sil-  
70 ver nanopatches with thickness  $t = 20$  nm and side  
71  $l = 200$  nm arranged in a 2D square lattice with period-  
72 icity  $a = 250$  nm [Fig 1(a)] is considered. The dielectric  
73 function of silver is described using Drude's model with  
74 plasma frequency  $\omega_p = 1.39 \times 10^{16}$  rad/s and damping  
75 frequency  $\Gamma = 5.13$  THz.<sup>17</sup> The angular reflectivity spec-  
76 tra shows a maximum at about 300 THz for transverse-  
77 magnetic (TM) and transverse-electric (TE) polarized  
78 incident waves [Figs. 1(b) and 1(c), respectively]. At  
79 oblique incidence some important differences between the  
80 TM and TE spectra can be observed. For a TM polar-  
81 ized wave [Fig. 1(b)], a vertical band with almost zero  
82 reflectivity arises between 50 and 260 THz that is not  
83 present for TE polarization. This broadband extraordi-  
84 nary transmission effect has been attributed to anoma-  
85 lous perfect impedance matching of the impinging elec-  
86 tromagnetic radiation at the plasmonic Brewster's an-  
87 gle in optical plasmonic gratings and can be predicted  
88 using a transmission line model (TLM).<sup>18</sup> The condi-

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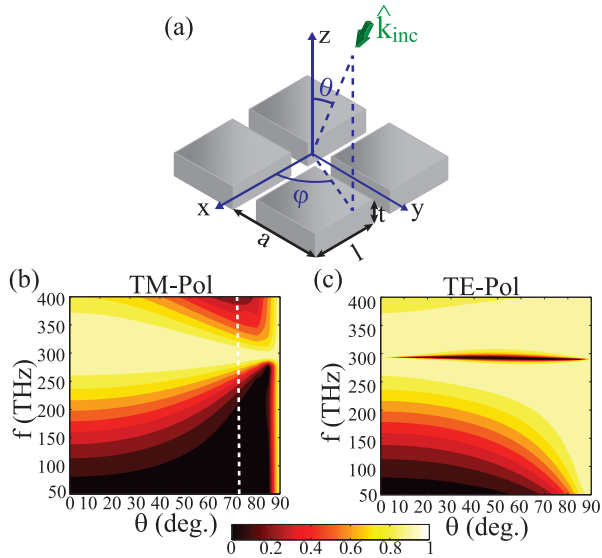


FIG. 1. (color online). (a) Proposed PRS. (b)-(c) Angular reflection spectra of a PRS with  $l = 200$  nm,  $a = 250$  nm and  $t = 20$  nm at  $\varphi = 0^\circ, 90^\circ$  for a (b) TM- and a (c) TE-polarized wave. The plasmonic Brewster's angle is indicated with a white dashed line.

tion for anomalous perfect matching is independent of the thickness of the grating, provided that it is optically thick enough. In our case, the metal particles are thinner than the skin depth allowing the incident E-field to penetrate into the metal while suffering very little absorption. As a result, transmission occurs not only through the gaps between adjacent nanopatches but also through the nanoparticles causing the angle of minimum reflectivity to appear deviated from that predicted by the TLM which is indicated by a dashed line in Fig. 1(b). When the wave impinging the PRS is TE polarized, a horizontal narrow band of zero reflectivity is observed [Fig. 1(c)]. This wide-angle resonance is originated by the excitation of a localized surface plasmon which splits the reflectivity maximum.<sup>19</sup>

The LW nanoantenna is formed by locating a sufficiently thick silver GP at  $h = 398$  nm ( $\sim \lambda/2$ ) from the PRS. Unless otherwise stated, the nanoantenna is completely embedded in silica,  $n_i = n_o = 1.45$ , in order to avoid any mismatch effect. The inhomogeneous case,  $n_i \neq n_o$ , will be discussed later in this Letter. The magnitude of the reflection coefficient of the PRS determines the maximum directivity of the nanoantenna while the pointing angle is related to its phase.<sup>16</sup> The height of the cavity  $h$  is slightly shorter than that expected from traditional antenna design due to the non-negligible field penetration into the metal.<sup>20</sup> A y-directed optical source emitting at 252 THz is placed at the center of the cavity formed [Fig. 2(a)]. Such a source emits electromagnetic waves as either  $TM_z$  or  $TE_z$  which determine the E- and H-planes of the antenna, respectively.<sup>21</sup> Our simulations show that the position of the source along the XY plane has very little effect on the radiation pattern,

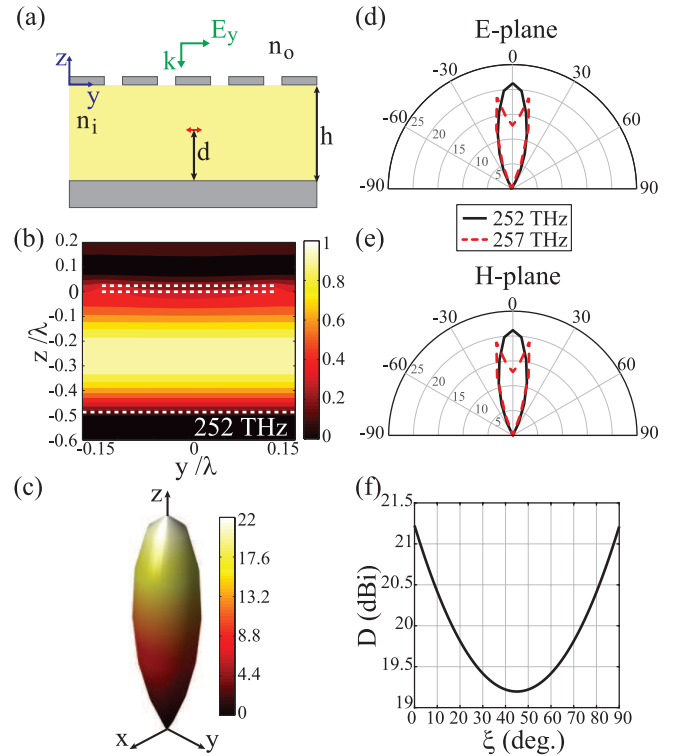


FIG. 2. (color online). (a) Side view of the LW nanoantenna. The horizontal optical source is shown with a red arrow. (b) Normalized E-field distribution at normal incidence. The position of a nanopatch and the GP are indicated with dashed white lines. (c) 3D-Directivity pattern (dBi) of the nanoantenna. (d)-(e) Directivity pattern at the (d) E- and (e) H-plane. (f) Directivity at broadside when the source is oriented at an angle from the y-axis.

in contrast to its vertical position [Fig. 2(b)]. Here, a perturbed version of the TM/TE first order mode of the corresponding parallel plate cavity is observed upon excitation of the source. At the frequency of operation, a standing wave in the transverse direction is formed, being the field maximum at  $d \sim h/2$ . The separation from the embedded source to the free surfaces is sufficient to avoid non-radiative recombinations associated with surface states thus conserving source coherence.<sup>22</sup>

The performance of the LW nanoantenna is analyzed using CST Microwave Studio together with reciprocity. According to the reciprocity theorem, the receiving pattern of an antenna equals that of its transmission pattern. Therefore, assuming a y-directed optical source at  $d$ , the problem of calculating the far-field radiated by the LW nanoantenna reduces to sampling the y-component of the electric near-field at the source position when a plane-wave impinges from any angle of incidence ( $\theta, \varphi$ ). The 3D directivity pattern [Fig. 2(c)] is then obtained as the ratio of the radiation intensity in each direction and the power emitted by the nanoantenna over the whole space<sup>23</sup>. As expected, a highly directive narrow pencil beam with  $13.8^\circ$  3dB-angular width is obtained at the

145 frequency of operation of the nanoantenna instead of the  
 146 dipole characteristic toroidal pattern. The directivity at  
 147 broadside ( $\theta = 0^\circ$ ) is 21.2 dBi. TM-polarized waves im-  
 148 pinging at the angle of minimum reflection [Fig. 1(b)] will  
 149 essentially contribute to the z-component of the E-field to  
 150 which a horizontal source cannot couple. As a result, no  
 151 side-lobes are observed regardless of the reflection mini-  
 152 mum in the angular spectra. However, it is worth men-  
 153 tioning that for those sources in which the z-component  
 154 plays an active role, for instance a vertical dipole, radia-  
 155 tion at the plasmonic Brewster's angle should be ex-  
 156 pected. On the other hand, the wide-angle zero reflectivity  
 157 band in the TE-polarization response of the PRS  
 158 [Fig. 1(c)] appears above the operating frequency of the  
 159 nano-antenna, not affecting its performance. The direc-  
 160 tivity patterns at E- and H-planes ( $\varphi = 90^\circ$  and  $\varphi = 0^\circ$ ,  
 161 respectively) for two different frequencies [Figs. 2(d) and  
 162 2(e)] are nearly symmetrical. As a result of increasing  
 163 the operating frequency, or equivalently employing higher  
 164 cavities, the resonant condition of the cavity is fulfilled  
 165 at oblique incidence. Consequently, the pointing angle  
 166 increases and the pencil beam turns into a conical beam.  
 167 This effect is shown with dashed red lines in Figs. 2(d)  
 168 and 2(e). Due to the nature of the sources needed to excite  
 169 this antennas, a precise control on their orientation in  
 170 the XY-plane is extremely challenging. Fig. 2(e) shows  
 171 that the directivity at broadside varies less than 2 dB  
 172 when the source is rotated an angle  $\xi$  with respect to the  
 173 y-axis, i.e. it is barely affected by orientation changes.

174 To gain a better understanding of the performance of  
 175 the nanoantenna, a parametric study of the PRS ge-  
 176 ometry was performed [Fig. 3]. The effect of vary-  
 177 ing the dimensions of the nanopatches is investigated  
 178 and presented in Figs. 3(a) and 3(b) for a periodicity  
 179  $a = 250$  nm. Silver's inherent losses are very low in this  
 180 frequency range. Therefore, larger nanopatches produce  
 181 more reflective PRSs while barely increasing the absorp-  
 182 tion [Fig. 3(a)] which in turn results in higher values of  
 183 directivity. For  $l = 200$  nm the directivity at broadside  
 184 is maximized. For larger values of  $l$ , the gaps between  
 185 adjacent nanopatches are significantly reduced. As a re-  
 186 sult, the operating frequency of the nano-antenna is red-  
 187 shifted. At higher frequencies, constructive interference  
 188 is achieved at angles different from broadside, resulting  
 189 in the beam splitting. Fig. 3(b) shows the directivity  
 190 at broadside for  $l = 180, 190$  and  $200$  nm. As a conse-  
 191 quence of increasing the size of the nanopatches up to  
 192 the optimum ( $l = 200$  nm) the 3dB-fractional bandwidth  
 193 is reduced. The coupling of the cavity to the incoming  
 194 plane wave decreases resulting in higher external qual-  
 195 ity factors and thus lower 3dB-fractional bandwidths. In  
 196 particular, for  $l = 200$  nm the 3dB-bandwidth is 2.8%  
 197 for a central frequency of 252 THz while for  $l = 190$  nm  
 198 and  $l = 180$  nm it is 3.7% and 5.1%, respectively. In  
 199 conclusion, there is a tradeoff between directivity and  
 200 bandwidth. The periodicity also plays a key role in the  
 201 performance of the nanoantenna. As long as the period  
 202 is below the first Bragg resonance, such as the case pre-

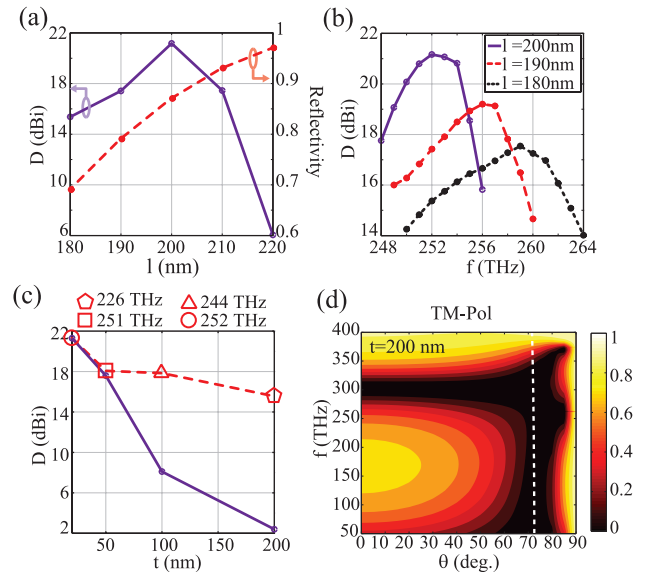


FIG. 3. (color online). (a) Directivity at broadside (right axis) and PRS reflectivity (left axis) when  $a = 250$  nm,  $t = 20$  nm,  $h = 398$  nm and  $l = 180 - 220$  nm. (b)-(c) Directivity at broadside when: (b)  $l = 180 - 200$  nm and (c)  $t = 20 - 200$  nm. The purple solid line in (c) is the directivity at 252 THz and the red dashed line at the frequencies at which the pencil beam is obtained (indicated in the legend). (d) TM Angular reflectivity spectra when  $t = 200$  nm. The plasmonic Brewster's angle is shown with a white dashed line.

203 sented in this Letter, only the zeroth diffraction order  
 204 is radiated. Thus, the effect of varying the periodicity  
 205 within this range (not shown here for the sake of brevity)  
 206 can be understood as complementary of that obtained  
 207 when changing the dimensions of the nanopatches. The  
 208 optimum periodicity was found to be  $a = 250$  nm.

209 Typically, when designing LW antennas in the mi-  
 210 crowave regime, metals are assumed to be good conduc-  
 211 tors with negligible thickness. This assumption is not  
 212 valid at the frequency range at hand. Furthermore, the  
 213 effective height of the cavity depends on the field pene-  
 214 tration and hence, on the thickness of the nanopatches.  
 215 The effect of the thickness of the metallic nanopatches  
 216 in the nanoantenna radiation performance is studied  
 217 in Fig. 3(c). The solid line shows the directivity at  
 218 broadside at 252 THz for a given cavity height. For  
 219  $t \neq 20$  nm the radiation pattern has a conical shape since  
 220 the nanoantenna is not tuned to the operating frequency.  
 221 The dashed line shows the directivity at the frequency at  
 222 which the pencil beam is obtained for the different thick-  
 223 nesses indicated in the figure. For thicker nanopatches,  
 224 the operating frequency is red-shifted. When the grating  
 225 is sufficiently thick, i.e. the nanopatches are thicker than  
 226 the penetration distance, the power is only transmitted  
 227 through the gaps, diminishing the directivity. Since the  
 228 field penetration which was not accounted for in the TLM  
 229 is negligible in this situation, the angle of minimum re-  
 230 flectivity and the plasmonic Brewster's angle calculated

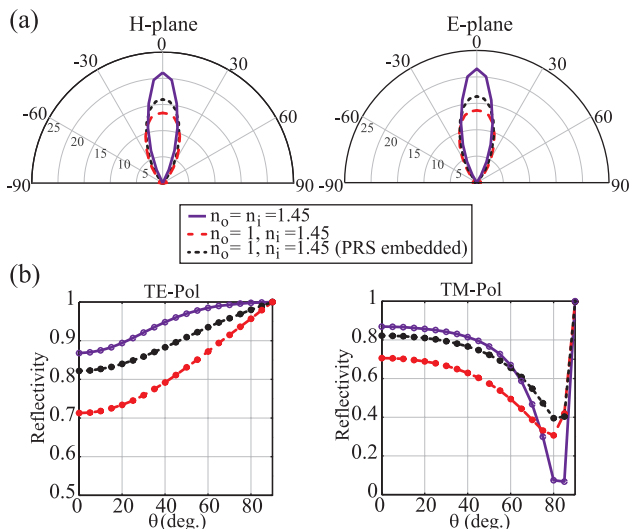


FIG. 4. (color online). (a) Directivity pattern (dBi) at the E- and H-plane when  $n_i \neq n_o$  and the PRS lies on top of the silica slab at 266 THz (red dashed line), and when embedded at 259 THz (black dotted line). The homogeneous case (purple solid line) is included for comparison. (b) PRS's angular reflectivity spectra for both incoming polarizations.

using the TLM agree excellently [Fig. 3(d)].

A more practical scenario may consist of a LW nanoantenna surrounded by an inhomogeneous dielectric medium so that the power radiated by the nanoantenna couples to free-space. In this case, the PRS is assumed to lay on a dielectric media with refractive index  $n_i$  while the surrounding space is vacuum. This situation is illustrated in Fig. 4(a) for two cases namely a PRS laying on top of a silica slab and a PRS embedded in silica. The dimensions of the nanoantenna are equal to those indicated in Figs. 1 and 2. For the sake of comparison, the LW nanoantenna pattern for  $n_i = n_o = 1.45$  is also included. The effect of the index mismatch results in a reduced directivity, increased beam-width and a blue-shift of the operating frequency. This can be explained by looking at the angular reflection spectra of the PRS in Fig. 4(b). The reflectance at normal incidence is much lower than that of the homogeneous media. As a consequence, the directivity is reduced by 8 dB. The performance can be moderately improved with the embedded PRS which shows a directivity of 16 dBi. Other techniques such as employing gradient index substrates may further enhance the directivity.<sup>24</sup>

In conclusion, we have shown that 2D-periodic FP cavity type LW nanoantennas can control the far-field emission of optical sources. They are capable of tailoring the radiation pattern of low directive emitters into very narrow highly-directive pencil beams. Its planar nature may ease its integration with slab embedded sources. In preparation for an experimental realization, we have also considered the case in which the nanoantenna is embedded in an inhomogeneous substrate. Our results

show that in this scenario, the nanoantenna still offers a very good performance. In addition, the nanoantenna does not rely on plasmonic effects, with the advantage of reduced non-radiative losses and higher separation to metallic parts than previously reported designs.<sup>9</sup> Such a device could find many exciting applications in the field of quantum communications and quantum cryptography. Despite the fractional bandwidth being small for the antenna to be considered broadband, a bandwidth of just a few THz is still enough for a broad variety of applications. Moreover, the bandwidth might be improved using similar techniques to those applied at microwaves.<sup>23</sup> Further investigation in this direction may be promising.

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