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► **To cite this version:**

Martin Berthel, Quanbo Jiang, Aline Pham, Joël Bellessa, Cyriaque Genet, et al.. Directional Local Density of States of Classical and Quantum Propagating Surface Plasmons. *Physical Review Applied*, 2017, 7 (1), pp.014021. 10.1103/PhysRevApplied.7.014021 . hal-01627769

HAL Id: hal-01627769

<https://hal.science/hal-01627769>

Submitted on 12 Feb 2021

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Local Density of States of Classical and Quantum Propagating Surface Plasmons

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(Received 25 May 2016; revised manuscript received 10 October 2016)

We theoretically and experimentally introduce the concept of the local density of states (LDOS) associated with propagative surface plasmons (PSPs) launched along a structured thin gold film (a concept we call PSP LDOS). The alternative method couples a near-field optical microscope, in either the classical or the quantum regime of excitation, to a far-field leakage-radiation microscope. This method allows for selecting and collecting a very narrow portion of the directional SP wave vectors, thereby offering sufficient resolution to probe the collimation efficiency of a SP beam for a source near the focal point of a Bragg parabolic reflector. We are able to build and image the PSP LDOS in a fully integrated quantum SP launcher by depositing a diamond nanocrystal hosting nitrogen-vacancy centers at the focal point of the mirror. Our demonstration of the PSP LDOS with quantized SPs offers alternative prospects in the field of quantum plasmonics.

DOI:

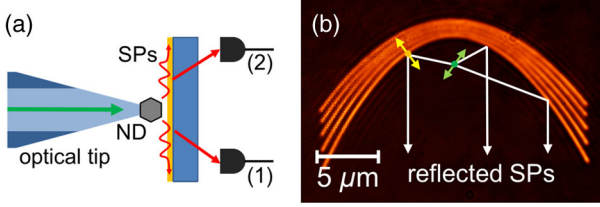
I. INTRODUCTION

Controlling the emission of a pointlike dipole in a complex environment is a central issue for nanophotonics and nanoplasmonics [1–6]. In this context, the key quantity to be measured is the local density of states (LDOS), which generalizes the concept of the Purcell factor [7]. The LDOS defines the ability of a dipole to populate the various optical modes available in a given environment [8,9]. Since the environment is complex in nanophotonics, both in composition and geometry, the LDOS strongly depends on the dipole location and orientation. This dependence entails the peculiar role played by evanescent waves dressing the objects. In recent years, the photonic LDOS was explored in nanostructures supporting resonant or localized surface plasmon (LSP) modes by means of near-field optical microscopes (NSOMs) [10,11] that allow for an acute position control of a dipolar pointlike tip in the optical near field [12–14]. Alternative powerful methods have been developed to record these LSP-LDOS near-metal nanoparticles [15–18], colloidal-particle networks [19], or single nanoholes [20]. However, to date, no method has been proposed to operate precise studies of propagative SP (PSP) LDOS on extended and nanostructured metal-dielectric planar systems, where propagating SPs are natural information vehicles for photons along micrometers. Since propagative SPs offer a range of technological applications for two-dimensional information transfer, it becomes crucial to define a protocol for recording PSP LDOS. This issue is the first to be considered in this article. Moreover, in

the context of quantum-information processing, one would ultimately like to control and map these PSP LDOS using a quantum fluorescent emitter scanning over the plasmonic system [21]. This knowledge is indeed particularly relevant since current research focuses on the coupling of quantum emitters to metal nanoantennas [10,14], waveguides [1,22], or structured metal films [23,24], for the ultimate purpose of developing fully integrated and optimized single-SP sources. This issue is the second one that we tackle in this work.

In this article, we introduce a general experimental and theoretical scheme for mapping the PSP LDOS in extended and planar devices using a NSOM coupled to resolved back-focal-plane imaging [see Fig. 1(a)]. We demonstrate that this association provides the high contrast and resolution needed for PSP-LDOS measurements. As a second step, we exploit the PSP-LDOS protocol to implement an optimized SP collimator working in the quantum regime. For the purpose of this work, we consider two types of NSOM probes, made of either a classical 100-nm aperture tip or a quantum nitrogen-vacancy- (NV) based optical tip. The latter [25] provides a way to accurately position a single-photon source in a complex environment, spatially limited by the 80-nm nanodiamond that hosts the NVs. Both sorts of tips are placed in the near field of a gold film to convert the light they emit into propagative SPs. In order to map the SP propagation, we use a leakage-radiation microscope (LRM) that records the coupled light transmitted through the thin metal layer in the glass substrate [24,26–31]. Briefly, an elementary SP characterized by its in-plane wave vector \mathbf{k}_{SP} leaks into the glass [see Fig. 1(a)] and couples to light of in-plane wave vector \mathbf{k} , matching the

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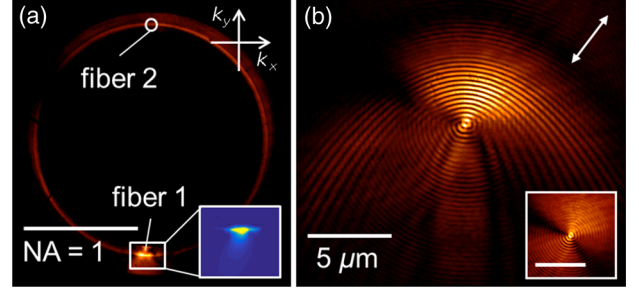
F1:1 FIG. 1. Principle of the experiment. (a) Either a classical-
 F1:2 aperture NSOM tip (not shown here) or an active NV-based
 F1:3 NSOM tip excites SPs on a 50-nm-thick gold film evaporated on
 F1:4 a glass substrate. Leakage radiation of the emitted SPs in the
 F1:5 Fourier plane (1) in a given direction or (2) collected with a high-
 F1:6 numerical-aperture (NA) microscope objective. (b) Image of the
 F1:7 direct plane of the structured gold film in transmission under
 F1:8 global illumination. Five confocal parabolic slits, each of 150 nm
 F1:9 width, are milled by a FIB. Most SPs emitted by a dipole located
 F1:10 at the focus point (the green double arrow) are reflected in the
 F1:11 same direction by the parabolas' induced dipoles (the yellow
 F1:12 double arrow), giving a collimated SP beam.

79 real part of \mathbf{k}_{SP} . Leaky waves are emitted at the
 80 fixed angle Θ_{LRM} defined by the condition $\text{Re}[k_{\text{SP}}] =$
 81 $(2\pi/\lambda)n_g \sin(\Theta_{\text{LRM}})$ (where n_g is the glass-substrate optical
 82 index and λ the optical wavelength). Being a far-field
 83 method, a LRM is powerful in mapping SP propagation
 84 over a metal film and has been applied in the context of
 85 quantum plasmonics, i.e., for the demonstration of single-
 86 SP launching, a wave-particle-duality test, and a measure-
 87 ment of second-order temporal and spatial coherence
 88 [23,32]. Furthermore, the LRM also provides a way for
 89 determining the plane-wave angular spectrum associated
 90 with the intensity distribution $I_{\text{SP}}(\mathbf{k}_{\text{SP}})$ in the Fourier space
 91 [24,26,29–31]. This approach defines a methodology for
 92 mapping the PSP LDOS in the \mathbf{k}_{SP} space, as demon-
 93 strated below.

94 II. PROOF OF PRINCIPLE

95 The plasmonic device we consider is a Bragg parabolic
 96 mirror [28] made of five confocal slits (each with a 150 nm
 97 width) milled using a *focused ion beam* (FIB) in a 50-nm-
 98 thick gold film. The Bragg condition is such that a pointlike
 99 source located near the focus excites propagative SPs
 100 subsequently reflected along the symmetry axis of the
 101 in-plane mirror. An optical image of the structure recorded
 102 using a far-field illumination is displayed in Fig. 1(b).

103 Prior to going to the PSP-LDOS measurements, it is
 104 necessary to interpret the LRM images of the parabolic
 105 reflector (see also Ref. [32]), first with the classical tip
 106 used for excitation ($\lambda_{\text{exc}} = 633$ nm). Typical LRM images
 107 recorded by a camera capturing the SP propagation in the
 108 Fourier plane of an oil-immersion objective are displayed in
 109 Fig. 2(a) and in the direct image plane in Fig. 2(b). The tip
 110 is located above the metal film (the tip-surface distance is
 111 kept at $h \approx 20$ nm) near the parabolas' common focus F .
 112 The thin ring observed in the Fourier plane is the typical



F2:1 FIG. 2. LRM images [recorded, respectively, in the (a) Fourier
 F2:2 and (b) direct planes] with a classical NSOM tip facing the gold
 F2:3 film at the focus of the parabolas. The inset in (a) is an
 F2:4 enlargement of the simulation for the Fourier-plane zone col-
 F2:5 lected by fiber 1. The inset in (b) is a LRM image obtained with
 F2:6 the same NSOM tip along the plain metal film (500 nm is the
 F2:7 scale bar for the inset). In (a) NA stands for numerical aperture. In
 F2:8 (b), a double white arrow indicates the dipole orientation. The
 F2:9 closest parabola to the focus point F is represented by a white
 F2:10 dashed curve.

signature of the leaky SPs launched by the NSOM tip [26].
 In the direct plane, the 2D profile shows a SP wave
 generated by an in-plane electric dipole which is also
 visible in Fig. 2(a) as an anisotropy in the radiation profile.
 When the tip is positioned at F , the emitted SPs reflected by
 the Bragg mirror are strongly collimated along a specific \mathbf{k}
 direction [see Fig. 2(a)]. The same behavior is observed in
 the direct-plane image as shown in Fig. 2(b), where several
 fringes are also superposed to the initial SP wave induced
 by the NSOM tip for SPs launched by the same NSOM tip
 on a plain gold film [see the inset of Fig. 2(b)].

18 In order to theoretically describe LRM images, we use a
 modal expansion into transverse-magnetic (TM) and -
 electric (TE) waves [24,29]. Considering an oscillating
 pointlike electric dipole $\boldsymbol{\mu}e^{-i\omega t}$ (with $(\omega/c) = (2\pi/\lambda)$)
 located at a height h above the air-gold interface, we
 express the radiated intensity in the Fourier plane as a
 function of the in-plane wave vector \mathbf{k} of the radiated light.
 Here, the TM term dominates [24,29] and we have

$$I_{\text{TM}}(\mathbf{k}) \approx \eta \left| \frac{\boldsymbol{\mu} \cdot \hat{\mathbf{z}}}{\sqrt{(2\pi/\lambda)^2 - k^2}} - \frac{\boldsymbol{\mu} \cdot \mathbf{k}}{k^2} \right|^2 F_{\text{SP}}(\mathbf{k}), \quad (1)$$

where $\hat{\mathbf{z}}$ is a unit vector along the z -optical axis, η is an
 overall detection efficiency taking into account the trans-
 mission of the microscope objective, and $F_{\text{SP}}(\mathbf{k})$ is a
 resonant SP Lorentzian profile [29]. In order to simulate
 the Fourier-plane image of Fig. 2(a), we coherently add to
 the field generated by the NSOM tip the contribution due
 to the Bragg mirror. We describe this additional term as a
 sum of N elementary electric dipoles $\boldsymbol{\mu}_p$ ($p = 1, 2, \dots, N$)
 obtained by discretizing the parabolic mirrors (the method
 is explained in Ref. [24]). Each $\boldsymbol{\mu}_p$ is excited by the SP

142 field $\mathbf{E}_{\text{SP}}(\mathbf{x}_p, \mathbf{x}_0)$ acting at the dipole location $\mathbf{x}_p :=$
 143 $[x_p, y_p, z_p = 0]$, while the tip is located at $\mathbf{x}_0 := [x_0, y_0, h]$.
 144 We model the coupling between $\boldsymbol{\mu}_p$ and $\mathbf{E}_{\text{SP}}(\mathbf{x}_p, \mathbf{x}_0)$ by a
 145 linear relation $\boldsymbol{\mu}_p = \xi[\mathbf{E}_{\text{SP}}(\mathbf{x}_p, \mathbf{x}_0) \cdot \hat{\mathbf{n}}_p]\hat{\mathbf{n}}_p$ where ξ is a
 146 constant polarizability and $\hat{\mathbf{n}}_p$ is an in-plane unit vector
 147 oriented along the normal to the parabola at \mathbf{x}_p .

148 We present, in the inset of Fig. 2(a), an enlargement of
 149 the simulated back-focal-plane image [24,29] obtained with
 150 the tip located at the parabola focus. It is in a very good
 151 agreement with the experiment.

152 We now turn on to the PSP-LDOS demonstration. The
 153 **19** principle [32] is sketched in Fig. 1(a). The tip brought in the
 154 near field of the metallic film shines on SPs, which leak and
 155 are recorded in the Fourier plane. Subsequently, after
 156 selecting and detecting only light leaking along a specific
 157 wave-vector direction, we map the partial PSP LDOS
 158 associated with this wave vector by scanning the tip while
 159 maintaining the detection direction fixed in the Fourier
 160 plane. As shown below, we unambiguously define the
 161 partial PSP LDOS with a high \mathbf{k} resolution in the
 162 Fourier space.

163 For this purpose, it is worth remembering that the full
 164 LDOS $\rho_{\text{LDOS}}(\omega, \mathbf{x}_0)$ associated with a dipole $\boldsymbol{\mu}e^{-i\omega t}$ is
 165 given by [8,12,33]

$$\rho_{\text{LDOS}}(\omega, \mathbf{x}_0) = \frac{3}{\pi\omega^2|\boldsymbol{\mu}|^2}P(\omega, \mathbf{x}_0), \quad (2)$$

166 where $P(\omega, \mathbf{x}_0)$ is the total energy rate of the oscillating
 167 dipole (including radiative and nonradiative exchanges
 168 with the environment). For a simple two-level quantum
 169 emitter [33], we have $P(\omega, \mathbf{x}_0) = \hbar\omega\Gamma(\omega, \mathbf{x}_0)$, where Γ is
 170 the full decay rate including dissipation in the metal. As
 171 the LRM only accounts for radiative SP modes, we
 172 define the partial PSP LDOS by integrating the radiative
 173 power along a fraction of the back focal plane intersect-
 174 ing the SP ring [see Fig. 2(a)]. The partial PSP-LDOS
 175 measurement is achieved using two motorized 50- μm
 176 multimode fibers placed in the back focal plane of the
 177 microscope [see also Ref. [32]]. We use these fibers to
 178 collect a fraction $\delta P(\omega, \mathbf{k}, \mathbf{x}_0)$ of the Fourier space in the
 179 area $\delta^2\mathbf{k}$. The radius of each fiber represents only a ratio
 180 $r = 3\%$ of the SP ring radius, meaning that only an
 181 angular ratio $r/\pi \approx 1\%$ of the total PSP LDOS is
 182 recorded. Therefore, this method provides a way to
 183 experimentally define an angularly resolved PSP LDOS
 184 with a resolution of 1% (which could be improved by
 185 reducing the collection-fiber diameter). We define the
 186 concept of partial PSP LDOS as

$$\delta\rho_{\text{PSP LDOS}}(\omega, \mathbf{k}, \mathbf{x}_0) \approx \frac{3}{\pi\omega^2|\boldsymbol{\mu}|^2}I_{\text{TM}}(\omega, \mathbf{k}, \mathbf{x}_0)\delta^2\mathbf{k}, \quad (3)$$

187 where $I_{\text{TM}}(\omega, \mathbf{k}, \mathbf{x}_0)$ includes the contributions of the
 188 NSOM tip and the Bragg mirror and $\delta^2\mathbf{k} \approx (\omega/c)^2\pi r^2$.

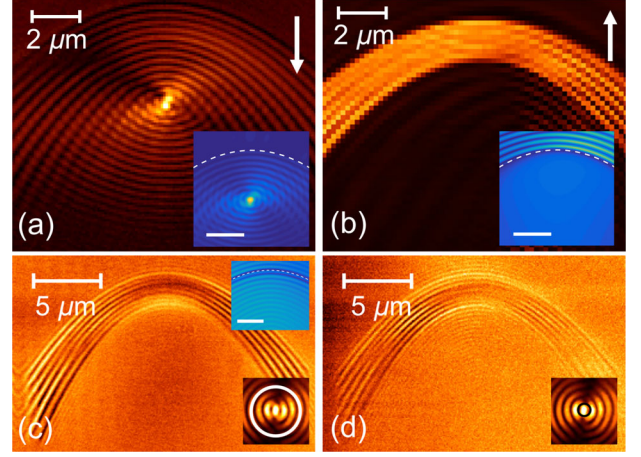
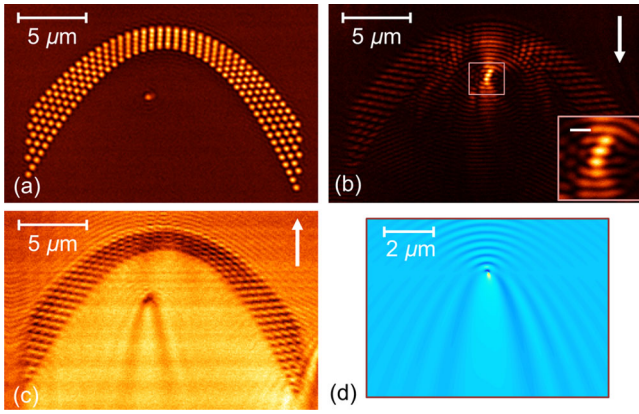


FIG. 3. (a),(b) Experimental partial PSP LDOS of the parabolic structures with an aperture NSOM tip in the classical regime for the collections in regions 1 and 2 of Fig. 2(a), respectively. The white arrow on the top-right corner indicates the collection direction. (Insets) Simulated partial PSP LDOS, scale bar 200 nm. The closest parabola to the focus point is represented by the white dashed curve. (c),(d) Experimental partial PSP LDOS obtained in the direct plane after \mathbf{k} filtering with a collection fiber of 200 and 50 μm diameter, respectively. The bottom insets in (c) and (d) show a \mathbf{k} -filtered direct-plane image, with the corresponding collection area, taking into account the X100 magnification of the optical setup. White circle in inset (c), 2 μm diameter; black circle in inset (d), 500 nm diameter. The top inset in (c) is a simulation of the total PSP LDOS.

Partial PSP LDOS associated with two SP directions can be simultaneously recorded by means of the two collection fibers while scanning the tip over the metal film, as illustrated in Figs. 1(a) and 2(a). Figures 3(a) and 3(b) show the PSP-LDOS measurements obtained by scanning the tip over the structure focus and associated with the directions (1) and (2) depicted in Fig. 1(a), i.e., the directions where SPs are strongly reflected or weakly transmitted along the symmetry axis of the parabolas. In Fig. 3(a), a strong contrast near the focus is observed, revealing that $\delta\rho_{\text{PSP LDOS}}(\omega, \mathbf{k}_1, \mathbf{x}_0)$ is strongly position dependent in this configuration due to the efficient SP collimation occurring with the source near the parabola focus [see Fig. 2(a)]. Conversely, $\delta\rho_{\text{PSP LDOS}}(\omega, \mathbf{k}_2, \mathbf{x}_0)$ in Fig. 3(b) appears rather flat away from the grooves and does not depend on \mathbf{x}_0 , in agreement with the fact that no SP collimation occurs in direction (2) [see Fig. 2(a)].

Theoretical maps of $\delta\rho_{\text{SP LDOS}}(\omega, \mathbf{k}_1, \mathbf{x}_0)$ and $\delta\rho_{\text{SP LDOS}}(\omega, \mathbf{k}_2, \mathbf{x}_0)$ are depicted in the insets of Figs. 3(a) and 3(b), respectively. For simplification, we modeled only one parabolic slit. The main features for each direction are very well reproduced by the simulations. $\delta\rho_{\text{SP LDOS}}(\omega, \mathbf{k}_1, \mathbf{x}_0)$ features a maximum of intensity localized at the focus point of the parabola surrounded by fringes, while $\delta\rho_{\text{SP LDOS}}(\omega, \mathbf{k}_2, \mathbf{x}_0)$ remains flat, in agreement with the experimental images.



F4:1 FIG. 4. (a) Unfiltered direct plane NSOM and (b),(c) partial
 F4:2 PSP-LDOS images of discretized slits forming a parabolic Bragg
 F4:3 mirror that includes a nanometric defect near the focus point. The
 F4:4 right arrow in the top-right corner in (b),(c) indicates the
 F4:5 collection direction. [Inset in (b)] Enlargement of the focus
 F4:6 point, scale bar 500 nm. (d) Simulation of PSP-LDOS images
 F4:7 (c) with the nanohole only.

215 A similar experiment is performed with discretized
 216 parabolas made of milled nanoholes (with the diameter
 217 $d = 200$ nm). The separation between adjacent holes in a
 218 given parabola is fixed at λ_{SPP} . We show in Fig. 4(a) a
 219 transmission image when the aperture tip is located at
 220 500 nm of the surface. We observe a defect in the metal
 221 forming a single nanohole near the focus point of the
 222 parabolas. Figures 4(b) and 4(c) present the partial PSP-
 223 LDOS measurements obtained by recording downward and
 224 upward plasmons, respectively. We see, in the first case,
 225 the same features as for the continuous parabolas of Fig. 3, i.e.,
 226 a bright spot on the focus point, demonstrating that SPs are
 227 strongly reflected by the structure in the downward
 228 direction. Moreover, the effect of this collimation is so
 229 intense that the defect has no influence at all. Looking at the
 230 second partial PSP-LDOS measurement in Fig. 4(c), we
 231 see, as with the continuous parabolas, a rather flat evolution
 232 of the intensity. However, we can additionally observe an
 233 effect of the nanohole, demonstrating a kind of “hyperbolic
 234 shadowing” that results from interference between different
 235 SP contributions. The partial PSP LDOS of such a nano-
 236 hole, approximated as a single dipole, has been simulated
 237 using the analytical method presented before. The resulting
 238 calculated image is shown in Fig. 4(d). The qualitative
 239 features—i.e., the hyperbolic shadowing—observed in
 240 Fig. 4(c) are again reproduced by our model.

241 Moreover, the above experiments can be analyzed using
 242 Lorentz’s reciprocity theorem [34], which helps us to
 243 understand the images features. Indeed, this theorem has
 244 been intensively studied in the case of electromagnetic
 245 waves [34–36]. It plays a central role in nano-optics to
 246 describe and connect various NSOM and LDOS measure-
 247 ments [14,35,36]. In our case, the tip radially excites SPs
 248 which can be reflected by the structures. While the structure

is scanned, the SPs emitted and reflected along one precise
 direction are collected. Applying the reciprocity theorem to
 this measurement amounts to exciting the structure with a
 (nearly perfect) plasmonic plane wave, coming from the
 actual collection direction. Finally, to complete the reci-
 procity, we have to imagine a NSOM tip in the detection
 mode that probes the plasmonic field above the chosen area.
 For parabolas, the plane wave would excite dipoles all
 along the slits, themselves exciting waves that would
 constructively interfere at the focus point. If we could scan
 a NSOM tip in detection mode over this area, we should
 obtain images very similar to what is measured in PSP
 LDOS (a problem which was recently analyzed using a
 partial NSOM in the detection mode [37]). For a single-hole
 structure, we would have a plane wave that excites a single
 dipole, creating a circular wave. The interference pattern
 obtained between a plane wave and a circular wave is
 typically the one obtained in Figs. 4(c) and 4(d), showing
 that the reciprocity theorem can be applied in this case.

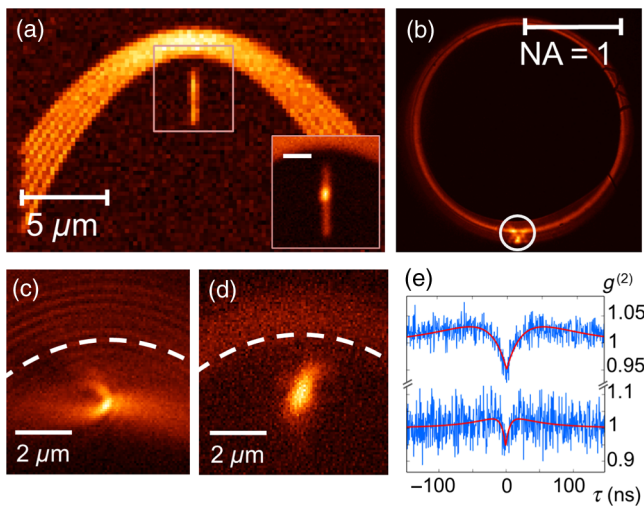
It is worth emphasizing that previous LDOS measure-
 ments using NSOMs mapped the full spectrum of radiative
 components emitted by the tip [9,10,13,14], sometimes
 after filtering to keep only the “forbidden” light compo-
 nents [8,9,11,26,27]. Here, however, the issue is to reach
 enough resolution in the Fourier plane to define and map
 properly the partial PSP LDOS associated with specific
 wave vectors \mathbf{k} . Reaching sufficient resolution is essential
 for our method to be able to select a restricted part of the
 SP ring in order to map the PSP LDOS near the parabola
 focus with a very good resolution. To confirm this belief,
 we implement a forbidden light-LDOS measurement by
 mapping in the direct plane the total intensity emitted by the
 tip and using a \mathbf{k} filter in the Fourier plane that removes
 components corresponding to $\text{NA} < 1$. Figures 3(c)
 and 3(d) show two such LDOS maps obtained with two
 different collection-fiber diameters. The rather flat signal
 confirms, in agreement with the theory [see the inset of
 Fig. 3(c)], that integration and averaging over the different
 available SP channels cancel the LDOS sensitivity to the tip
 position and demonstrate that the \mathbf{k} resolution considered
 in Figs. 3(a) and 3(b) is crucial for successful PSP-LDOS
 mapping.

The above experiments have a simple physical inter-
 pretation, and what we show is that there is actually no
 backaction from the reflected plasmons on the excitation
 dipole, whatever its position. This absence of backaction
 is indeed critical for the PSP-LDOS measurement since
 the PSP LDOS is defined for a fixed-dipole moment. Clearly,
 this assumption would not be correct if the tip were near
 the slits. However, for points near the focus, which are
 relevant here, we expect that the tip is not too disturbed
 by the structure. Here, the SP signal reflected by the
 mirror and coming back on the tip could affect, in turn,
 the tip emission, and this situation is monitored in our
 experiment by detecting photons emitted near the tip

304 [see Figs. 3(c) and 3(d)]. The collection fiber conjugated
 305 with the sample plane discriminates against those useful
 306 photons from the background and those coming from the
 307 structure. Here, the collection fiber is represented by a
 308 circular collection area centered on the dipole. The
 309 measurement has been done with a 200- μm (50- μm)
 310 collection fiber, shown in Fig. 3(c) [Fig. 3(d)]. The inset
 311 in each figure shows the collection area, taking into
 312 account the magnification of the setup, compared to the
 313 filtered direct-plane image of the tip. In both cases, we see
 314 that the signal remains nearly constant when the tip is far
 315 away from the slit, apart from very slight modulations.
 316 Therefore, the emitting power of the tip is unchanged
 317 when we scan the structure, including in the region of
 318 **24** interest, i.e., around the focus point.

319 III. APPLICATION IN THE QUANTUM REGIME

320 **25** We now are in position to turn on to the quantum regime
 321 of SP excitation. We show in Fig. 5(c) the corresponding
 322 PSP-LDOS measurement with the NV-based probe excited
 323 at 532 nm, revealing the same features as in Fig. 3(b). We
 324 emphasize that the concept of PSP LDOS remains valid in
 325 the quantum regime. Indeed, above an area far from the
 326 slits, the effective dipole associated with the tip is not
 327 significantly disturbed by the SP-reflected field and there-
 328 **26** fore remains independent of its position. This result is



F5:1 FIG. 5. Deposition of the ND at the focus point of confocal
 F5:2 parabolas. (a) NSOM image with the tip retracted (500 nm), with
 F5:3 a ND hosting 17 NV centers. The parabolas are the same as they
 F5:4 were previously, but with an additional 4- μm -long slit milled
 F5:5 through the focus point. (Inset) The ND is deposited on the slit.
 F5:6 Scale bar, 2 μm . (b) Fourier-plane image when the deposited ND
 F5:7 is excited. Scale bar, 2 μm . (c) Experimental quantum partial SP LDOS of the
 F5:8 parabolas without an additional slit with the NV-based tip.
 F5:9 (d) Scan on the structure with the deposited ND while collecting
 F5:10 the Fourier plane in the area marked by the white circle in (b).
 F5:11 (e) $g^{(2)}(\tau)$ functions of the ND (top chart) above glass and
 F5:12 (bottom chart) after a dropoff in gold.

329 confirmed by Fig. 3(d), which shows that the NSOM tip
 330 intensity remains constant along the plane surface, i.e., far
 331 from the slits. Moreover, for the quantum system, the NVs
 332 used as quantum emitters are in a saturation regime so that
 333 the emitted power remains constant [21].

334 An elaborated configuration is implemented in the
 335 quantum regime to be able to measure the quantum
 336 correlation function $g^{(2)}(\tau)$ when the ND is located at
 337 the focus point above gold. The signal being very weak in
 338 the previous configuration, acquiring a $g^{(2)}(\tau)$ function by
 339 leaving the NV-based tip in a near-field height above the
 340 focus point for hours would be very challenging. Therefore,
 341 we directly deposit the ND at the focus point to excite it
 342 with the tip from the far field. The precise dropoff of the
 343 ND is assisted by a supplementary slit 4 μm long and
 344 150 nm wide passing through the focal point and aligned
 345 with the parabola axis. Figure 5(a) presents a scan of this
 346 structure with the active tip retracted to the far field. With
 347 this tip, we catch a ND hosting 17 ± 1 NV centers [top
 348 chart of Fig. 5(e): $g^{(2)}(\tau)$ acquired above glass, showing an
 349 antibunching] and then release it at the focus point [the
 350 inset of Fig. 5(a) shows a zoom of the slit containing the
 351 ND after deposition].

352 In the Fourier plane image of Fig. 5(b), we still observe a
 353 strong SP collimation in the downward direction. The
 354 pattern here looks different, showing that the ND is slightly
 355 shifted away from the focus point [see the inset of
 356 Fig. 5(a)]. However, we are able to collect a large part
 357 of the collimated signal with a 200- μm -core collection fiber
 358 [the white circle in Fig. 5(b)]. The signal is strong enough
 359 to allow for a $g^{(2)}(\tau)$ measurement [the bottom chart of
 360 Fig. 5(e)]. An antibunching dip is seen, confirming that the
 361 quantum signature of the NVs has been conserved after the
 362 plasmonic propagation [22,23]. By scanning the structure
 363 in this configuration, we see in Fig. 5(d) a bright spot when
 364 the ND is excited. By fitting the $g^{(2)}(\tau)$ curves with a three-
 365 level model [38], we can extract the intrinsic photophysical
 366 parameters. The quantum efficiency Q on the glass is $Q_g =$
 367 0.40 and increases to $Q_f = 0.63$ when the ND is located at
 368 the focus point. Therefore, the metallic structure has a
 369 strong effect on the emitter photodynamics [1,32,39].

370 IV. CONCLUSIONS AND PERSPECTIVES

371 In this article, we introduce the concept of PSP LDOS. In
 372 analogy with its previously demonstrated capability of
 373 imaging LSP LDOS in confined corrals [11], we propose
 374 an effective way to map the PSP LDOS of a parabolic
 375 Bragg collimator by means of a NSOM and a \mathbf{k} -resolved
 376 LRM. Our scheme is tractable on any planar structure on a
 377 thin metal film. Using a quantum emitter and the very high
 378 contrast and resolution of our method, we are able to
 379 measure the quantum PSP LDOS and the correlation
 380 function $g^{(2)}(\tau)$, and to build a fully integrated quantum
 381 plasmonic collimator by controlling the deposition of

382 quantum emitters near the focus of the structure, where
 383 the PSP LDOS reaches its maximum. It is worth noting
 384 that this quantum plasmonic device is excitable in the
 385 far field using a laser source, thereby paving the way for
 386 many applications in the bottom-up development and
 387 optimization of quantum integrated devices involving
 388 SPs and quantum emitters. For instance, in addition to
 389 be well suited to probe the photodynamics of quantum
 390 emitters coupled to plasmonics systems, this method
 391 could definitely be useful in the frame of plasmon
 392 entanglement studies [40,41] and quantum nanophotonic
 393 circuitry [1,22,42].

ACKNOWLEDGMENTS

394
 395 **27** This work was supported by Agence Nationale de la
 396 Recherche (ANR), France, through SINPHONIE Grant
 397 No. ANR-12-NANO-0019 and PLACORE Grant
 398 No. ANR-13-BS10-0007. C.G. also thanks the ANR
 399 Equipex “Union” (Grant No. ANR-10-EQPX-52-01). The
 400 Ph.D. grants of A. P., by the Ministère de l’enseignement et
 401 la recherche, scientifique, and of Q. Jiang, by the Région
 402 Rhône-Alpes, are gratefully acknowledged. We thank J.-F.
 403 Motte and G. Julie, from the NANOFAB facility in Neel
 404 Institute, for sample and NSOM tip fabrication. The nano-
 405 diamond sample was provided by G. Dantelle and T. Gacoin.

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