AQO

Thierry Grosjean, FEMTO-ST

You are about to study and quantify the dynamics of the photon emission of a single quantum emitter positioned in various structured environments. Your approach relies on classical electrodynamics via a commercial FDTD software.

- **Emission wavelength: 800 nm**
- Computation window: (2x2x2 µm^3 but not mandatory)
- Dipole at the coordinate origin (0,0), i.e., at the center of the window
- Meshgrid at 10 nm along X, Y and Z
- Time Limit for the FDTD simulations: 6 microns

I- Quantum emitter in air / 6 points

$\varepsilon_0 = 1/36/\pi * 10^{-9}$, $\mu_0 = 4\pi * 10^{-7}$

Lengths are turned in meters when ε_0 and μ_0 are used!!!

I-1 Power in vacuum

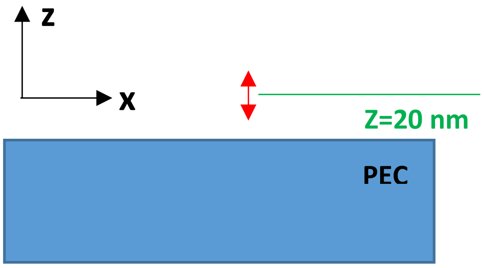
- *Q1: Calculate the power* ***P_0 in Watts*** *radiated by the dipole.* ***(3 points)***

I-2 Dipole moment / 3 points

- *Q2: what is the* ***amplitude*** *of the dipole moment* ***(in C.m)****?* ***(1 point)***
- *Q3: Calculate the two possible values of the phase difference φ between the dipole moment and the electric field at the dipole position.* ***(1.5 points)***
- *Q4: Give the two possible* ***complex values*** *of the dipole moment* ***(0.5 point).***
  ➔ express the phase term of **p** as : exp[i(phase_E - φ)]; "phase_E" is the phase term extracted from the FDTD.

II- Quantum emitter in air, close to a metal surface /9 points

II-A. Metal : perfect conductor / **6 points**



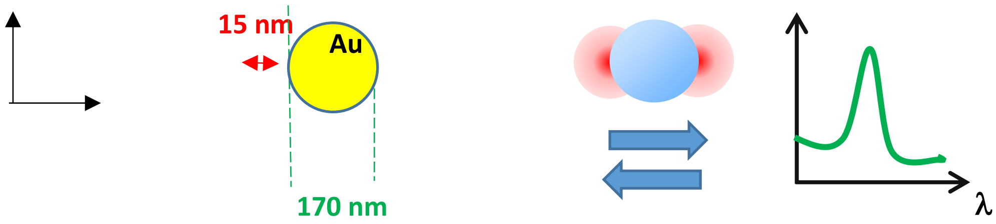
- *Q5: Give the two values of power radiated by the dipole based on the two previously calculated values of **p** (cf. Q4). What is the correct value of **p**, justify ?* ***1 point***
- *Q6: Calculate the enhancement of total decay rate of the quantum emitter **1 point***
- *Q7: Calculate the enhancement of radiative decay rate of the quantum emitter* ***1 point***
- *Q8: Calculate the change of absorption decay rate of the quantum emitter* ***0.5 point***
- *Q9: what is the quantum yield of the system ? **0.5 point***
- Conclusions, description of the phenomenon: **2 points**

II-B. Metal : gold / **3 points**

- *Q10: Calculate the enhancement of total decay rate of the quantum emitter* ***0.5 point***
- *Q11: Calculate the enhancement of radiative decay rate of the quantum emitter* ***0.5 point***
- *Q12: Calculate the change of absorption decay rate of the quantum emitter* ***0.5 point***
- *Q13: what is the quantum yield of the system ? **0.5 point***
- Conclusions, description of the phenomenon: **1 points**

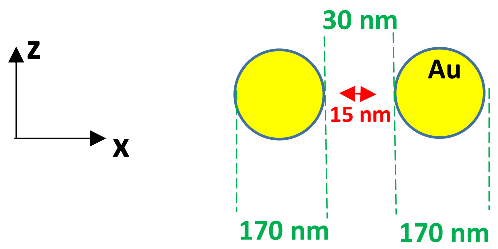
III- Dipole in air, in interaction with a plasmonic nanoantenna / 5 points

III-A. Nanoantenna : **gold nanosphere ➔** resonant dipole nanoantenna **/ 3 points**



- *Q18: Calculate the enhancement of total decay rate of the quantum emitter* ***0.5 point***
- *Q19: Calculate the enhancement of radiative decay rate of the quantum emitter* ***0.5 point***
- *Q20: Calculate the change of absorption decay rate of the quantum emitter* ***0.5 point***
- *Q21: what is the quantum yield of the system ?* ***0.5 point***
- Conclusions, description of the phenomenon: **2 points**

III-B. Nanoantenna : **couple of gold nanospheres ➔** resonant **"gap"** dipole nanoantenna / **2 points**



- *Q22: Calculate the enhancement of total decay rate of the quantum emitter* ***0.25 point***
- *Q23: Calculate the enhancement of radiative decay rate of the quantum emitter* ***0.25 point***
- *Q24: Calculate the change of absorption decay rate of the quantum emitter* ***0.25 point***
- *Q25: what is the quantum yield of the system ?* ***0.25 point***
- Conclusions, description of the phenomenon: **1 points**

Nanoantennas for Light Emission

Jean-Jacques Greffet

Nanoscience is by essence an interdisciplinary field in which traditional differences between disciplines vanish. On page 1607 of this issue, Mühlschlegel *et al.* (*1*) bridge the fields of electrical engineering and nanometer-scale optics to show that a thin, 100-nm-long metallic rod resonantly enhances light emission, just like an antenna enhances radio emission. The work paves the way for tailoring the light emission from nanometer-scale systems.

The emission of radio waves by antennas is discussed in many electrical engineering textbooks. On the other hand, emission of light by a single molecule is a cornerstone of nanooptics, with applications, for example, in quantum information processing or single-molecule spectroscopy. If the know-how from electrical engineering could be used for nanooptics applications, one might be able to enhance the optical emission rate and control the emission direction.

However, whereas for radio waves, a metal can be modeled by a perfect mirror, at optical frequencies the field can penetrate the material and can be absorbed. Moreover, absorption depends on the frequency of the light. Mühlschlegel *et al.* now show that ideas from electrical engineering can nevertheless be applied successfully to nanooptics.

A key issue in nanooptics is how the emission of light by a molecule can be modified. In a vacuum, an excited molecule releases its energy by emitting a photon at a rate that depends on its lifetime. Purcell showed in 1946 (*2*) that the amount of power emitted by an electromagnetic source depends on its environment. (This idea is commonly used for microwave emission, for example when a gun diode is placed in a resonant cavity connected to a waveguide to increase the emitted power.) In the same way, use of a wavelength-scale cavity modifies the emission rate of a single atom (*3*).

Another possibility for tailoring the optical emission is to create an environment that prevents the propagation of light. Because light is forbidden, an excited atom cannot generate a photon; the lifetime of the excited atom is thus increased. Light propagation can be prevented by using three-dimensionally periodic dielectric materials called photonic crystals (*4*). This concept has been used to modify the lifetime of an excited state (*5*).

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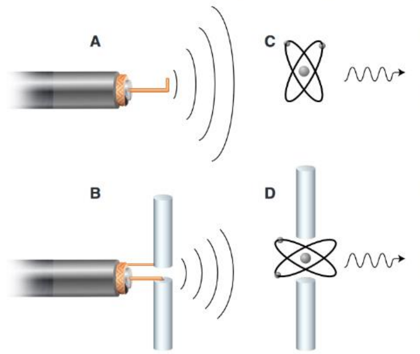

Radio and optical antennas. The end of a coaxial wire (**A**) is a source of radio waves. Connecting the wire to an antenna (**B**) amplifies the radio emission and modifies its direction. Light emission can be modified in a similar way by placing a light source such as an atom (**C**) between two rods (**D**). In (C), the photon is emitted in almost any direction, whereas in (D), the emission direction is concentrated in directions perpendicular to the antenna.

A third way of modifying the emission of radiation is routinely used in electrical engineering. Instead of inserting the source in a resonant cavity or in a photonic crystal, one can design an antenna (see the figure). An antenna modifies both the amount of energy emitted and the direction of emission. Let us consider a coaxial wire connected to a generator. Its end is a small dipolar antenna. By connecting the wire to a properly designed antenna, one can both increase the amount of radiated power and modify the angular emission pattern.

To understand the role of an antenna, consider the emission of acoustic waves by a guitar string. Without the guitar cavity, the string hardly emits any sound, showing clearly that the amount of emitted power strongly depends on the environment of the source. The antenna, like the guitar, can be viewed as an intermediate resonator that is efficiently coupled to both the source and the vacuum. From that point of view, there is not much difference between a microcavity and an antenna.

A key question for nanooptics is whether an antenna can be used to modify the emission of a single molecule. This can be achieved by bringing a metallic tip (such as those used for scanning tunneling microscopy) so close to a molecule that its radiation toward a detector is increased (*6*). Metallic-tip nanoantennas of this kind have been used to study the fluorescence or Raman scattering of nanometer-scale objects (*7–9*).

The next step is to improve the design and the performance of the nanoantennas. A possible approach is to reproduce classical radio antenna designs at the nanometer scale. Two groups have recently succeeded in building such nanoantennas. Schuck *et al.* obtained a strong enhancement of the field with a nanometer-scale bow-tie antenna (*10*). Mühlschlegel *et al.* (*1*) now report an optical version of the simplest radio antenna: a half-wave antenna. This antenna consists of a wire with a length of half a wavelength at the operating frequency; as a result, the current can resonate along the wire with a maximum at its center and zero current at both ends. The authors observe a resonant enhancement of the radiated power as the antenna length is varied, a behavior similar to the length dependence of a half-wave radio antenna.

Unlike radio antennas, the optical antenna strongly depends on electron resonances in the metal of the antenna (*11*). Taking advantage of these resonances is another promising approach to modify spontaneous emission. Antennas based on the excitation of surface waves (*12*), or on guided waves (*13*) that are subsequently diffracted, may be used to produce highly directional emission (or, to put it in electrical engineering terms, a large gain). This type of structure can also be used to substantially enhance the power emitted by fluorophores (*14*). Given the applications for light sources and quantum information, there is little doubt that research into nanoantennas will continue to grow rapidly.

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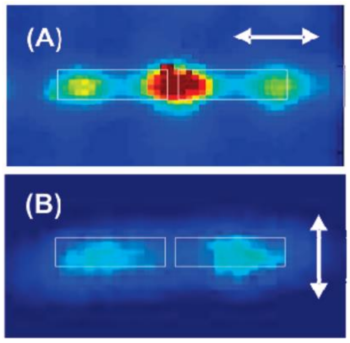

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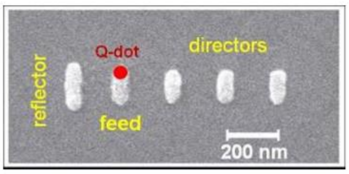
Low frequencies

Optics



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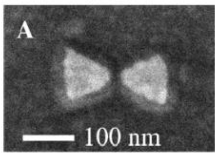

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