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Atomic Defects in Diamond Unveil a New Class of Efficient Optical Antennas

Novel optical antennas based on atomic defects in solids show up to one-million-fold intensity enhancement for the electromagnetic field emitted at close distances. The study reveals their remarkable capability to concentrate optical energy, to sense and manipulate their proximal environment.

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Over a century after the invention of radio antennas by Henrich Hertz, and in the era where the miniaturization of technological devices is absolutely widespread, it is hardly surprising that a nanoscale version of regular antennas has emerged.

These optical nanoantennas, as they are called, can concentrate a large amount of radiative optical energy, massively increasing the intensity of an electromagnetic signal. This is quite analogous to how radio antennas work, but in this case operating at higher frequencies and much smaller sizes.

Nowadays, these nanoantennas face two important challenges. To start with, their miniaturization cannot achieve arbitrarily reduced dimensions, since they suffer large losses when they are made as small as a nanometer (one billionth of a meter). And moreover, the fact that the antenna is in a solid state can be detrimental to the signal: interactions with phonons (collective excitations in solids) or other fluctuations can severely limit the overall efficiency.

Now, a team led by the University of Chicago and with the contribution of Argonne National Laboratory and ICFO researchers **Dr. Francesco Andreoli** and **ICREA Prof. Darrick Chang**, has reported in Nature Photonics on a new optical antenna in a solid that circumvents these obstacles. They propose the use of color centers in diamond, specifically Germanium-Vacancy centers (GeV), as **surgically precise (both spectrally and spatially) and efficient optical nanoantennas.**

Germanium vacancy centers become optical nanoantennas

A color center is a defect in the regular spacing of atoms within a solid that absorbs and emits visible light of a particular color or infrared or ultraviolet radiation. A germanium-vacancy center in a diamond is a particular case of a color center, where two missing carbons are replaced by a germanium atom.

The presented study has shown both theoretically and experimentally that GeVs, when illuminated by light with a particular frequency (the resonant frequency), can function as an efficient antenna. More importantly, they show up to one-million-fold intensity enhancement in the near-field (that is, in the signal emitted or absorbed at close distances).

Furthermore, they demonstrated that GeVs can be used for both active manipulation and sensing of its proximal environment, which showcases the power of these novel nanoantennas and their unique properties.

Shedding light into charge fluctuations in nearby vacancies

In this type of material, it can happen, by chance, that other vacancies (that is, missing carbon atoms) are created close to the GeV. Those vacancies can locally capture or release electrons from the surrounding carbon atoms that form the diamond, changing their own charge as a consequence.

The fluctuations in the charge state of randomly created nearby vacancies alter the behavior of the GeV in a manner that is detrimental for many applications, as long as it is not controlled (for instance, for entanglement generation between solid-state qubits). One of the landmarks the team accomplished was to detect, manipulate and even induce for the first time these charge variations in the carbon vacancies.?

According to Dr. Francesco Andreoli: ï¿½This detrimental effect had been already observ d, but it wasn't clear up to now its cause and how to deal with it. In our study, we offer an explanation and a possible path to control this problemï

GeVs versus traditional nanoantennas: a complementary approach

The researchers highlight how GeV nanoantennas are very different from traditional nanoantennas.

On the one hand, standard nanoantennas are made of enough atoms that their optical response is dictated by that of the bulk material, while the structure of a GeV resembles that of a single atom. Consequently, a nanoantenna smaller than (roughly) ten nanometers experiences bulk absorption, causing it to drastically lose its efficiency and maximum field enhancement. On the contrary, the efficiency of a GeV as an optical antenna is given by its quantum coherence, which is effectively decoupled from its physical size. This makes the GeV perfectly compatible with nanometric distances, leading to the large field enhancements reported in the study.

On the other hand, this very same mechanism yields very different bandwidths at which each of them can operate. Traditional nanoantennas are suitable for broad bandwidths, while GeVs can only function within narrower ones. Although for some applications a large bandwidth is highly desirable (as it guarantees a broadband driving ability), GeVs' small bandwidth offers remarkable sensitivity to weak perturbations that would otherwise remain unnoticed.

New directions for optical antennas

Given that field enhancements are often used in photochemistry, a potential application of GeV nanoantennas could be to improve the detection of molecules via Raman spectroscopy or other light-based techniques. Optical sensing and quantum technologies could also benefit from them, for instance to control decoherence in solid-state qubits.

In summary, this study opens unexplored paths for optical nanoantennas, whose typical regime of operation was largely different, both at a technical level and on a more conceptual and long-term ground.

i¿½The large near-field generated at close distances allows to concentrate massive energy n a remarkably small volume, increasing the optical efficiencies and enabling high spati l precisioni¿½, emphasizes Andreoli about the demonstrated nanoantennas. i¿½Bu on a broader ground, this just shows a specific example of how our novel perspective on color centers might open new directions for optical nanoantennas towards yet unex lored regim

Bibliographic reference:

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