High intensity gap light coupling of nano-antenna to high Purcell factor photonic crystal nano cavity

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An efficient hybrid photonic-plasmonic structure which combines the resonant mode of an ultrahigh Purcell factor photonic crystal nano-cavity with plasmonic resonance of a bowtie nano-antenna with a high accuracy has been presented in this article. The consequential enormous light intensity enhancement of ~3×10^6 times in the gap region of the bowtie nano-antenna (in the coupled structure with respect to the incoming exciting light), originated from the effective optical resonance combination, is realized by subtle optimization of nano-cavity's geometrical parameters. The designed coupled structure holds great promise for many applications and purposes trusting on strong confinement and enhancement of optical field in the volumes of nano-scale, including antennas, optical trapping and manipulation, sensors, data storage, nonlinear optics, lasers, etc.

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1. Introduction

Theoretical predictions indicate that optical field can be concentrated without being subjected to the diffraction limit by employing sub-wavelength metallic objects [1-4]. This branch of optics is well identified in the very interesting field of plasmonic-photonic crystals [5-9]. This field typically introduces hybrid architectures which combine the light concentration and manipulation features of dielectric photonic crystal cavities with the strong light confinement and significantly light field enhancing properties of the optical nano-antennas. The concept of the optical nano-antennas historically was initiated from near-field optics using metal nanoparticles due to their ability to capture and focusing propagating electromagnetic energy into sub-diffraction-limited areas [10-12]. The hybrid structures enable generation of optical devices with extraordinary light harvesting features directly appropriate for various domains and fields such as antennas, information and communication technologies, optical trapping, nonlinear optics, lasers, etc [13-16].

Regarding the unique possibility of acquiring the strongly improved optical energy of the light confined within the tiny gap between two coupled metal nano-antennas and the capability of exploitation and development of this optical field, the nano-antennas have attracted excessive research attention in the recent years [17-20]. On the other hand, photonic crystal nano-cavities, due to their attractive aptitude to harvest the light field concentrated into the spaces of nanometer dimension, are considered as an acceptable and suitable pattern for the ultra-integrated architectures and devices [21-24]. Over the past 10 years, several research works have been performed aiming at increasing the quality factor of photonic crystal cavities, while decreasing the mode volume for improving the Q/V figure of merit(Purcell factor) to enhance light-matter interaction. In this regard, the most efforts and competitions have been allocated to declining the mode volume [25-28].

Optical hybrid structures that couple a photonic crystal micro/nano cavity to a nano-antenna have been introduced by different groups, recently [1-4], [9]. These approaches are based on increasing the distance between photonic crystal and nano-antenna to enhance the coupling efficiency which needs a high practical accuracy.

In the proper distance the efficient coupling results higher optical field in the gap region of the nano-antenna. In this work, we investigate the coupling between an ultrahigh Purcell factor photonic crystal nano-cavity and a bowtie nano-antenna. The design of the dielectric cavity is conducted to attain an effective high Purcell factor for improving the coupling efficiency between the nano-antenna and the photonic crystal to achieve considerably large intensity of optical field in the gap region of the nano-antenna. For this purpose, with optimized photonic crystal structure geometries, we realize an efficient and instructive coupling between the nano-antenna and the low mode volume photonic crystal nano-cavity. In this direction choosing the optimized geometries for photonic crystal cavity avoids breaking the cavity resonance in presence of the antenna. Therefore, effectively insures a critical coupling characterized by an ultra-huge light intensity in the gap region of the nano-antenna. In addition, by directly positioning the nano-antenna on the photonic crystal, we exclude the difficulty of removing the antenna away from the photonic crystal substrate that has been proposed in [1-4] and [9] to improve the coupling capability.

2. Ultrahigh purcell factor PC cavity design

The first fundamental substructure of the hybrid structure, the photonic crystal nano-cavity, consists of two sections of H-type defect as cladding and core, sketched in Fig. 1.

Both sections include 2D triangular arrays of air holes drilled through the thin silicon membrane with the thickness of 220 nm, with different hole radius and lattice constants in order to spatially trap the optical energy. It is worth mentioning that the central air hole of the core area has been removed in order to create the defect to confine the light and for that purpose, the central hole and the first ring of the holes of the cladding zone have been also eliminated. Finite difference time domain (FDTD) based optimization tools lead choosing the following geometries for the photonic crystal cavity in order to achieve an efficiently high Purcell factor.The optimum structural parameters of the photonic crystal nano-cavity are as follow. The cladding section lattice constant, a=439 nm and air hole radius R=144 nm and these characteristics for the core of the photonic crystal cavity are a=426 nm and R=75 nm, respectively. The nano-cavity is excited by an electric dipole located within the structure, polarized along the x-direction. The structure is designed and intended to attain the fundamental mode resonant at λ=1.55µm. The optical properties and responses of the nano-cavity which is simulated applying 3D-FDTD method with the exploitation of perfectly matched layer boundary conditions, also discloses that the considered PC structure consists of the resonance fundamental mode at λ=1.55µm. The resonant mode has the small volume of V= $0.00011(\lambda/n)^3$ (n is the refractive index of silicon) and the quality factor of resonant wavelength Q=2700, is corresponding to a relatively strong resonance. The obtained Purcell factor of the nano-cavity is about PF =Q/V = $24.5\times10^6(\lambda/n)^{-3}$. The ultrahigh value of Purcell factor makes the photonic crystal nano-cavity a very suitable medium for providing the efficient optical field for the nano-antenna.

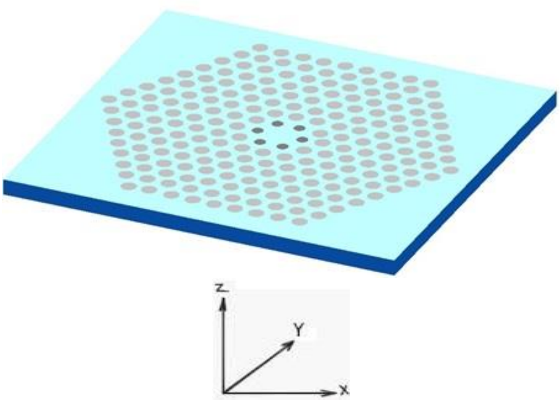

Fig. 1. 3D view of the photonic crystal cavity (The core area of the photonic crystal nano-cavity is depicted in dark gray and the cladding section is in light gray. The core and cladding parts are created in the silicon substrate, demonstrated in blue). The desired directions are indicated at the bottom

The calculated intensity distributions of the diverse components of the optical electric field, $|E_x|^2$, $|E_y|^2$ and $|E_z|^2$, obtained exactly at the surface of the nano-cavity, along with the wavelength spectrum of the nano-cavity mode are demonstrated in Fig. 2(a-d) while Fig. 2(a) proves a sharp resonance at λ =1.55µm.

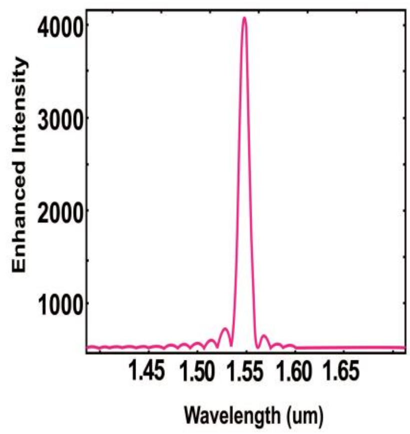

Fig. 2(a). The spectrum of the photonic crystal nano-cavity-mode

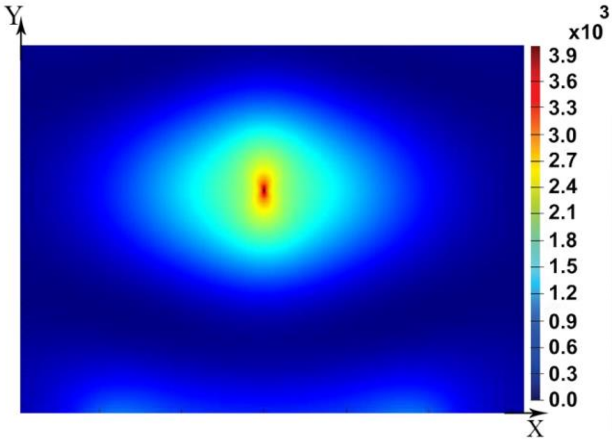

Fig. 2(b). The corresponding X component of the electric field intensity at resonance wavelength

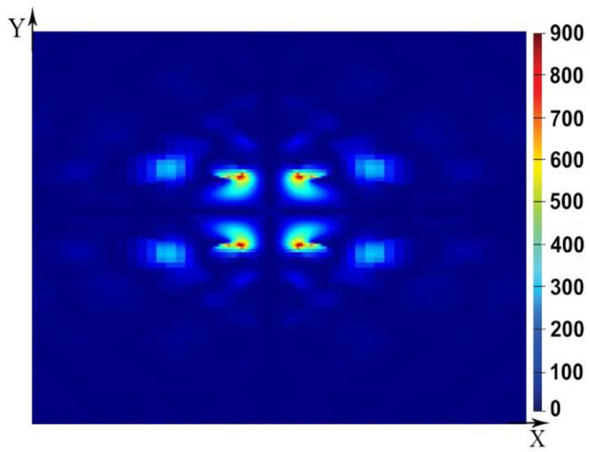

Fig. 2(c). The corresponding Y component of the electric field intensity at resonance wavelength

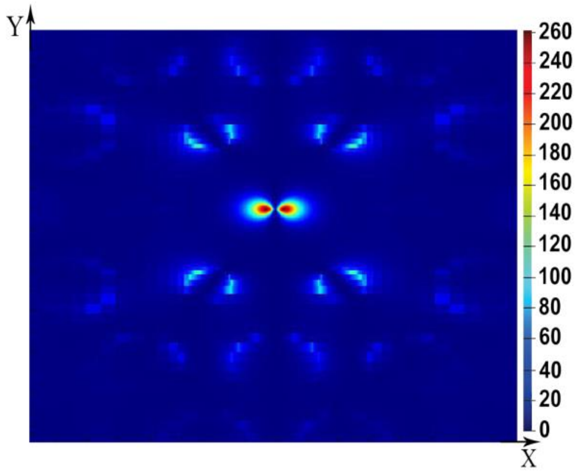

Fig. 2(d). The corresponding Z component of the electric field intensity at resonance wavelength

3. Bowtie nano-antenna design

The second basic building block of the coupled structure, the optical bowtie nano antenna, comprises two opposing tip-to-tip gold triangles with defined length, width and thickness, split by a tiny gap of 20 nm. The structure of the nano antenna is illustrated in Fig. 3(a).

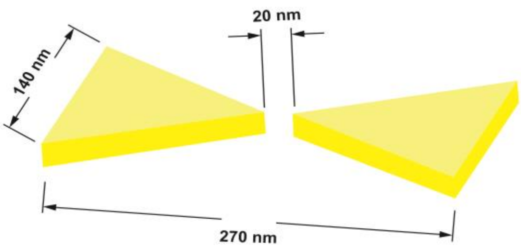

Fig.3(a). 3D schematic of the bowtie nano antenna with its structural parameters

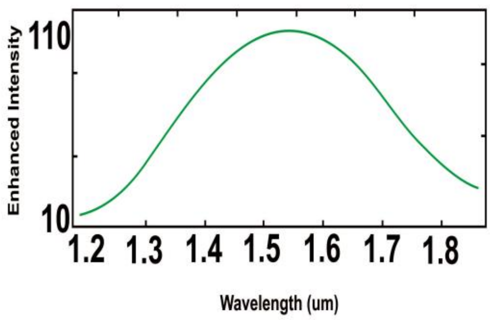

Fig. 3(b). Spectral response of the bowtie nano-antenna

Geometrical parameters of the nano-antenna have been methodically designed in order to insure an acceptable wavelength and spectral matching between the plasmonic resonant mode of the optical nano-antenna and the resonant mode of the photonic crystal nano-cavity. Fig. 3(b) illustrates the spectrum of the nano-antenna's plasmonic mode.

4. Hybrid structure - study of coupling

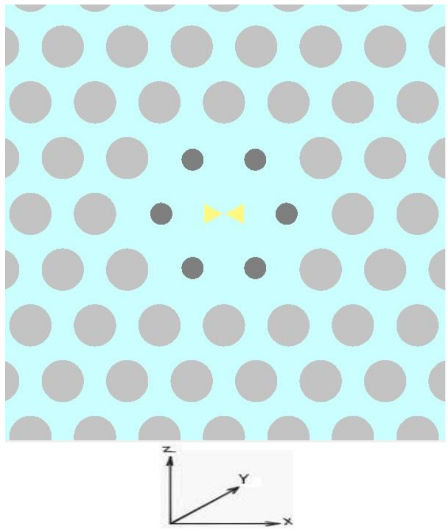

Fig. 4(a). Schematic view of the analyzed hybrid structure .The golden bowtie nano-antenna is positioned exactly at the center of the nano-cavity surface, along the x direction. The desired directions are indicated at the bottom

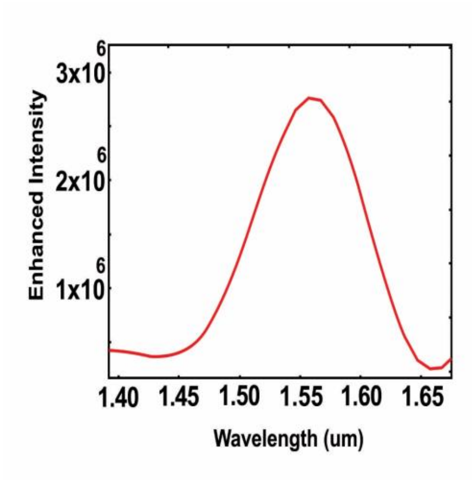

Fig. 4(b). The wavelength spectrum of the hybrid structure mode

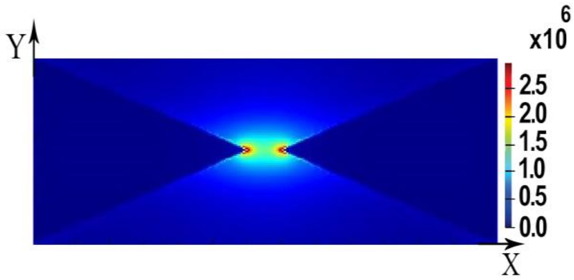

Fig. 4(c). Calculated enhancement of the electric field intensity distribution $|E|^2$ at resonance wavelength

The 1D view of the whole structure in which the bowtie nano-antenna is positioned on the surface of the PC cavity, is demonstrated in Fig. 4(a) in which the PC nano-cavity geometries have been accurately optimized by applying the fully qualified 3D-FDTD method to achieve an optimum coupling between the nano-cavity and the antenna. The design is optimized to achieve a high PF providing an optimum amount of optical energy density in the suitable vicinity of the nano-antenna to improve the light-matter interaction; Therefore, fulfilling the efficient coupling of optical field to the gap region of nano-antenna. Particularly, the meticulously optimized structure of the PC cavity preserves the optical characteristics of the cavity in presence of the nano-antenna, insuring constructive coupling between the cavity and the antenna, strongly improves the optical resonance combination. Furthermore, the resonant frequency of the antenna coincides with the band gap of the PC cavity in order that, the stored light energy within the cavity will excite the nano-antenna's resonance. Moreover, the results of the numerical calculations lead us to accurately determine the feasible position for the nano-antenna on top of the PC cavity surface in order to achieve the enhanced coupling efficiency between the plasmonic resonant mode of the nano-antenna and the fundamental resonant mode of the nano-cavity. In fact, the coupling can be much more effective provided that the nano-antenna (the gap zone) is correctly placed at a spatial location where the electric field generated by the PC cavity exhibits the proper polarization. In other words, the antenna axis should be oriented along the efficient component of the electric field of the optical energy transferred to its gap vicinity from PC cavity to be induced resonantly. It can be seen from Fig. 2(b- d) that the bowtie antenna must be located at the center of the PC cavity surface, exactly at the field maxima of the cavity mode. In addition, the nano-antenna arms must be oriented along the x-direction and not along the other transverse directions. Because, as it is apparent from Fig. 2(b-d), in this case the x component of the electromagnetic field has the most desired polarization belonging to the predominant optical electric field component to resonantly excite the nano-antenna. As it is observed in Fig. 4(b-c), a considerably large enhancement of light intensity of about 3×10^6 , normalized to the input source, is achieved exactly in the gap center of the nano-antenna. This gained outcome witnesses that the light traveled from the PC nano-cavity toward the nano-antenna has been efficiently and instructively coupled to the subwavelength gap of the bowtie antenna, without destructively affecting the resonance characteristics of the PC substrate. Actually, the end results of the numerical analysis clarify an improved coupling efficiency. This consequence decisively confirms a constructive near field interaction and effective optical coupling between the PC nano-cavity and the bowtie nano-antenna; improving the challenging mismatches between the light and objects of subwavelength and nano-scale dimensions. It should be declared that however, these parameters for a sample non-optimized structure, are R_{core}=100nm, R_{clad}=120nm, and a_{core}=420nm, respectively, resulting in the low light enhancement of about 25×10^3 times respect to the input light at the resonant wavelength of about 1.54μm.

5. Conclusion

In this paper, a hybrid structure that couples the optimized ultrahigh Purcell factor photonic crystal nano-cavity to a bowtie nano-antenna was proposed. The introduced hybrid resonance architecture benefits the 3D-FDTD-based optimization tools to optimize the photonic crystal nano-cavity geometries in order to achieve the strongly improved optical coupling and therefore, substantially enhances the optical energy of light in the gap space of the nano-antenna.

Furthermore, the presented structure eliminates the need for desperate efforts in accuracy adjustment of nano-antenna position regarding the photonic crystal cavity via direct coupling of the nano-antenna to the cavity. Moreover, the designed architecture provides the possibility of realizing the ultra-compact optical structures.

Whereas, in the previous reports, authors had tried to enhance the coupling efficiency (that is obvious in the high intensity of light in the gap region of the nano-antenna) in the hybrid structure by varying the distance between the antenna and the cavity in order to get the optimum distance at which the field intensity of light is high in the gap space of the nano-antenna, admitting the difficulty and lack of sufficient accuracy for this method. The highest enhancement of the light intensity in the gap region of the antenna in the coupled structures introduced by the references [1-4] and [9], is reported by the reference [4], that is about 11000.

The achieved considerably high intensity field at the output of the hybrid structure (10 nm above the structure in the gap zone of the nano-antenna), can provide an indispensable alternative to the common and recently introduced coupled systems; suitably applicable in diverse fields of applications directly proportional to the light intensity and strong trapping of the light field in the subwavelength spaces as well, including antennas, nonlinear optics, data storage, optical trapping and development of nanometer size objects, information and communication.

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