Current Optics and Photonics
Vol. 2, No. 1, February 2018, pp. 85-89

ISSN: 2508-7266(Print) / ISSN: 2508-7274(Online)
DOI: https://doi.org/10.3807/COPP.2018.2.1.085

Ultrahuge Light Intensity in the Gap Region of a Bowtie Nanoantenna Coupled to a Low-mode-volume Photonic-crystal Nanocavity

Nassibeh Ebadi[1]*, Reza Yadipour[1], and Hamed Baghban[2]

[1]Department of Electrical and Computer Engineering, University of Tabriz, Tabriz 51666, Iran
[2]School of Engineering-Emerging Technologies, University of Tabriz, Tabriz 51666, Iran

(Received December 5 2016 : revised November 5 2017 : accepted January 4 2018)

This paper presents a new, efficient hybrid photonic-plasmonic structure. The proposed structure efficiently and with very high accuracy combines the resonant mode of a low-mode-volume photonic-crystal nanocavity with a bowtie nanoantenna's plasmonic resonance. The resulting enormous enhancement of light intensity of about 1.1×10^7 in the gap region of the bowtie nanoantenna, due to the effective optical-resonance combination, is realized by subtle optimization of the nanocavity's optical characteristics. This coupled structure holds great promise for many applications relying on strong confinement and enhancement of optical field in nanoscale volumes, including antennas (communication and information), optical trapping and manipulation, sensors, data storage, nonlinear optics, and lasers.

Keywords : Photonic crystal (PC), Nanocavity, Low mode volume, Bowtie nanoantenna (BA), Coupling
OCIS codes : (190.4360) Nonlinear optics, devices; (230.4555) Coupled resonators; (230.5298) Photonic crystals

I. INTRODUCTION

In recent decades, Theoretical and practical studies indicate that light field can be concentrated without being subject to the diffraction limit, by employing subwavelength metallic objects. This interesting field typically introduces hybrid architectures of plasmonic-photonic crystal, which combine the light-concentrating and -manipulating features of a dielectric photonic-crystal (PC) cavity with the strong light-confining and significant optical-field-enhancing properties of an optical nanoantenna [1-3]. Such hybrid structures enable the design of optical devices directly appropriate for various domains and fields that rely on strong concentration and enhancement of light in subwavelength spaces, such as antennas, information and communication technologies, optical trapping, nonlinear optics, and lasers [4-8].

Regarding the capability of exploiting and developing the strongly improved optical energy of the light confined within the tiny gap between two coupled metal nanoparticles, nanoantennas have attracted much research attention in recent years [9-18]. On the other hand, PC nanocavities, due to their attractive aptitude to harvest the light field that is concentrated in spaces of nanometer dimensions, are considered as an acceptable and suitable pattern for ultraintegrated architectures and devices. Over the past 10 years, several research works have been performed with the aim of increasing the quality factors of PC cavities, while decreasing the mode volume to improve the *Q/V* figure of merit, to enhance light-matter interaction. In this regard, the most effort and competition has been allocated to reducing the mode volume [19-26].

In this work, we study the coupling between an ultralow-mode-volume PC nanocavity and a bowtie nanoantenna. The design of the dielectric cavity is conducted to improve the coupling efficiency between nanoantenna and PC. For this purpose, with optimization of the PC's optical properties in the presence of the nanoantenna, we realize an efficient and constructive coupling between the nanoantenna and the ultrasmall-mode-volume photonic-crystal nanocavity that is obvious in the high intensity of light realized in the gap

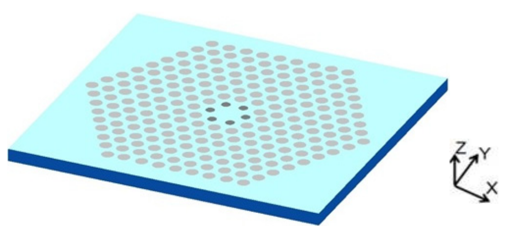
*Corresponding author: Ns-ebadi@tabrizu.ac.ir, ORCID 0000-0003-4991-0075
Color versions of one or more of the figures in this paper are available online.

space of the antenna. In addition, by directly positioning the antenna on the cavity, we avoid the difficulty of removing the antenna from the PC substrate, which has been proposed in references [1-3] and [8], to improve the coupling capability in the hybrid structures by varying the distance between antenna and cavity, to find the optimal distance at which the field intensity of light is high in the gap region of the nanoantenna.

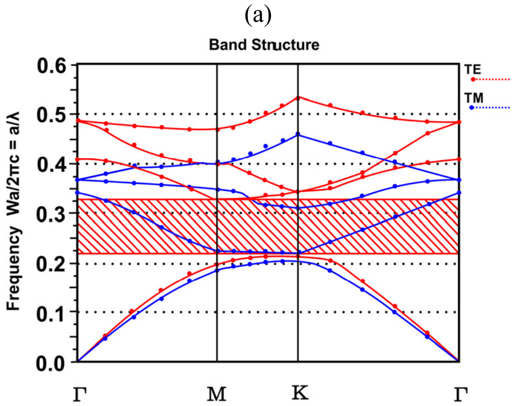
II. DESIGN OF LOW-MODE-VOLUME PHOTONIC-CRYSTAL CAVITY

One of the main substructures of the hybrid structure, the photonic-crystal nanocavity, consists of two sections of hexagonal-lattice PC as cladding and core areas, illustrated in Fig. 1(a). Both sections are two-dimensional triangular arrays of air holes drilled through a silicon membrane of thickness 220 nm, with different hole radii and lattice constants to spatially trap the optical energy of light. A finite-difference time-domain (FDTD) tool based on the particle swarm optimization algorithm leads to the choice of the following geometries for the PC cavity, so that its resonant properties will not be affected in the presence of the bowtie antenna (BA), for efficient coupling between PC and BA in spite of having a small resonant mode volume, calculated as $V_{pc} = 0.0014\ (\lambda/n)^3$. The optimal structural parameters of the nanocavity are as follows: for the claddingsection, lattice constant (the distance between the centers of any two neighboring holes) $a = 410$ nm and air-hole radius $R = 144$ nm, and for the core of the cavity, $a = 423$ nm and $R = 105$ nm.

The nanocavity is excited by an electric dipole located within the structure, polarized along the x-direction. The structure is designed to attain the fundamental mode, resonant at $\lambda = 1435$ nm. The optical properties and responses of the nanocavity, simulated with a 3D-FDTD method exploiting perfectly matched layer boundary conditions, also show that the considered structure has a resonant fundamental mode at $\lambda = 1435$ nm. The obtained wavelength of resonance belongs to the international *E*-band frequency range, extending from 1360 nm to 1460 nm. Systems operating at *E*-band frequencies have a unique characteristic not experienced by conventional lower-frequency devices: The high operational frequencies of an *E*-band system make an antenna highly directional. Furthermore, the optical field of nanoantennas

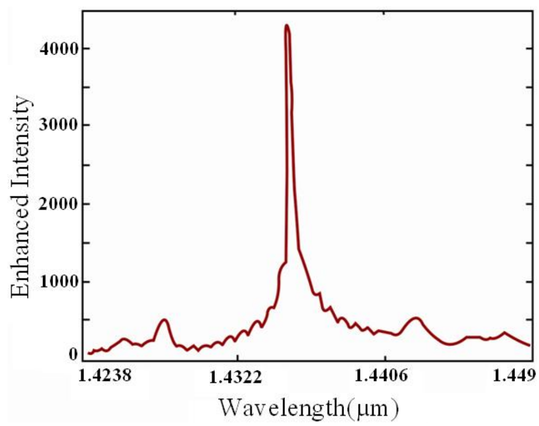


(a)

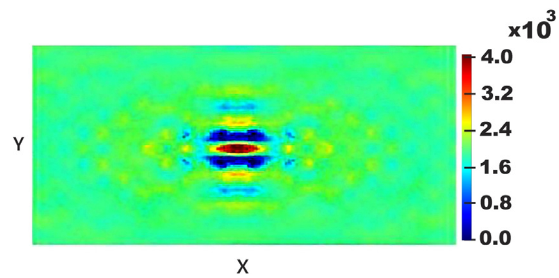


(b)

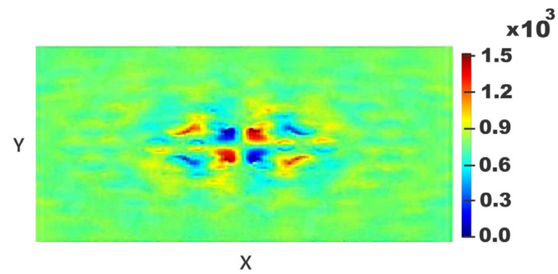
FIG. 1. (a) Three-dimensional view of the PC cavity (core area of PC nanocavity in dark gray, cladding in light gray), (b) band structure of the PC structure.



(a)



(b)



(c)

FIG. 2. (a) The spectrum of the PC nanocavity, (b) corresponding *x*-component of the electric-field intensity at the resonant wavelength, (c) corresponding *y*-component of the electric-field intensity at the resonant wavelength.

is improved more in this wide frequency band. The measured quality factor of the cavity at the wavelength of resonance is $Q = 4000$, corresponding to a relatively strong resonance. Figure 1(b) presents the frequency-band diagram of the PC structure, calculated utilizing the FDTD method. The vertical axis is normalized frequency ($\omega a/2\pi c$), and the curves in the graph represent the permitted propagation modes. According to this dispersion diagram, the normalized frequency of 0.29 relative to the frequency of the fundamental resonant mode of the nanocavity, 208.915 THz (corresponding to $\lambda = 1435$ nm), is located within the TE band gap (depicted as a red band).

The calculated intensity distributions of the different components of the optical electric field, $|E_x|^2$ and $|E_y|^2$, obtained exactly at the surface of the nanocavity, along with the wavelength spectrum of the nanocavity, are demonstrated in Fig. 2. Figure 2(a) proves that there is a relatively sharp resonance at $\lambda = 1.435$ μm.

III. BOWTIE NANOANTENNA DESIGN

The other basic building block of the coupled structure, the optical bowtie nanoantenna, comprises two sections of opposing tip-to-tip gold triangles, separated by a tiny gap of 25 nm. The structural parameters of the nanoantenna are illustrated in Fig. 3(a).

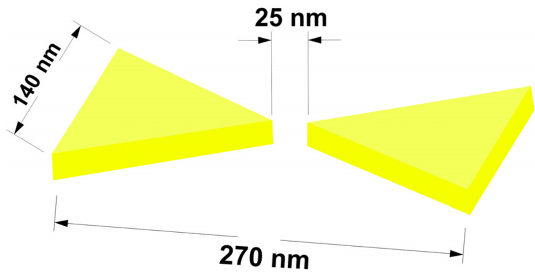
The geometrical parameters of the antenna have been methodically designed, to ensure acceptable wavelength and spectral matching between the plasmonic resonant mode of the antenna and the resonant mode of the PC nanocavity. Figure 3(b) illustrates the wavelength spectrum of the bowtie nanoantenna.

In fact, to achieve higher local field enhancement of the optical antenna, a small gaps spacing is required. Reducing the distance between the two opposing tips in a bowtie antenna results in even higher light intensity confined within its gap area. However, here the most important issue is that any change in the structural parameters of the antenna illustrated in Fig. 3(a) will result in a completely different resonant wavelength for the antenna.

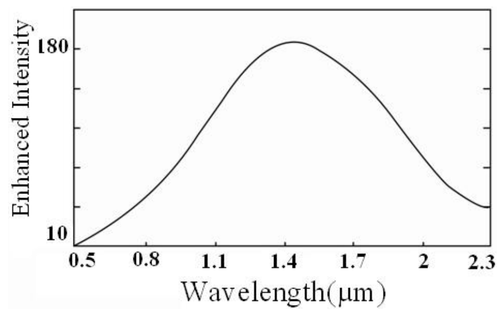
IV. STUDY OF COUPLING IN THE HYBRID STRUCTURE

A two-dimensional view of the coupled structure is shown in Fig. 4(a).

In this work, utilizing a 3D-FDTD-based optimization tool, the structural parameters and optical characteristics of the PC nanocavity have been accurately optimized in the presence of the nanoantenna to preserve the resonant properties of the PC cavity and avoid destructive coupling between antenna and cavity, to achieve an enhanced coupling characterized by a huge light intensity in the gap space of the nanoantenna. In particular, the meticulously optimized structure of the PC cavity strongly improves the optical-resonance combination. Furthermore, the resonant frequency of the antenna coincides with the band gap of the PC cavity, so that the stored light energy within the cavity will excite the nanoantenna's resonance. Regarding the polarization sensitivity of the BA, the results of the numerical calculations and simulations of Figs. 2(b) and 2(c) lead us to accurately determine the optimal position for the nanoantenna on top of the cavity. In fact, the coupling can be more effective if the nanoantenna's gap zone is correctly placed where the electric field generated by the PC cavity exhibits the proper polarization. In other words, the antenna's axis should be oriented along the efficient component of the electric field of the optical energy transferred to its gap from the cavity that is to be resonantly induced. It can be seen from Figs. 2(b) and 2(c) that the bowtie antenna must be located at the center of the cavity's surface, exactly where the cavity mode has maximum intensity. In addition, the nanoantenna's arms must be oriented solely along the *x*-direction, and not the transverse directions. As it is apparent from Figs. 2(b) and 2(c), in this case the *x*-component of the electromagnetic field has the appropriate intensity and polarization to resonantly excite the antenna. After directly depositing the bowtie antenna at the correct location on the surface of the nanocavity, to obtain forcible addressing of the antenna, the entire structure is illuminated by the *x*-polarized electric dipole located within the PC structure. The whole structure is analyzed employing the 3D-FDTD-based method, to



(a)



(b)

FIG. 3. (a) Three-dimensional schematic of the bowtie nanoantenna, (b) spectral response of the bowtie nanoantenna.

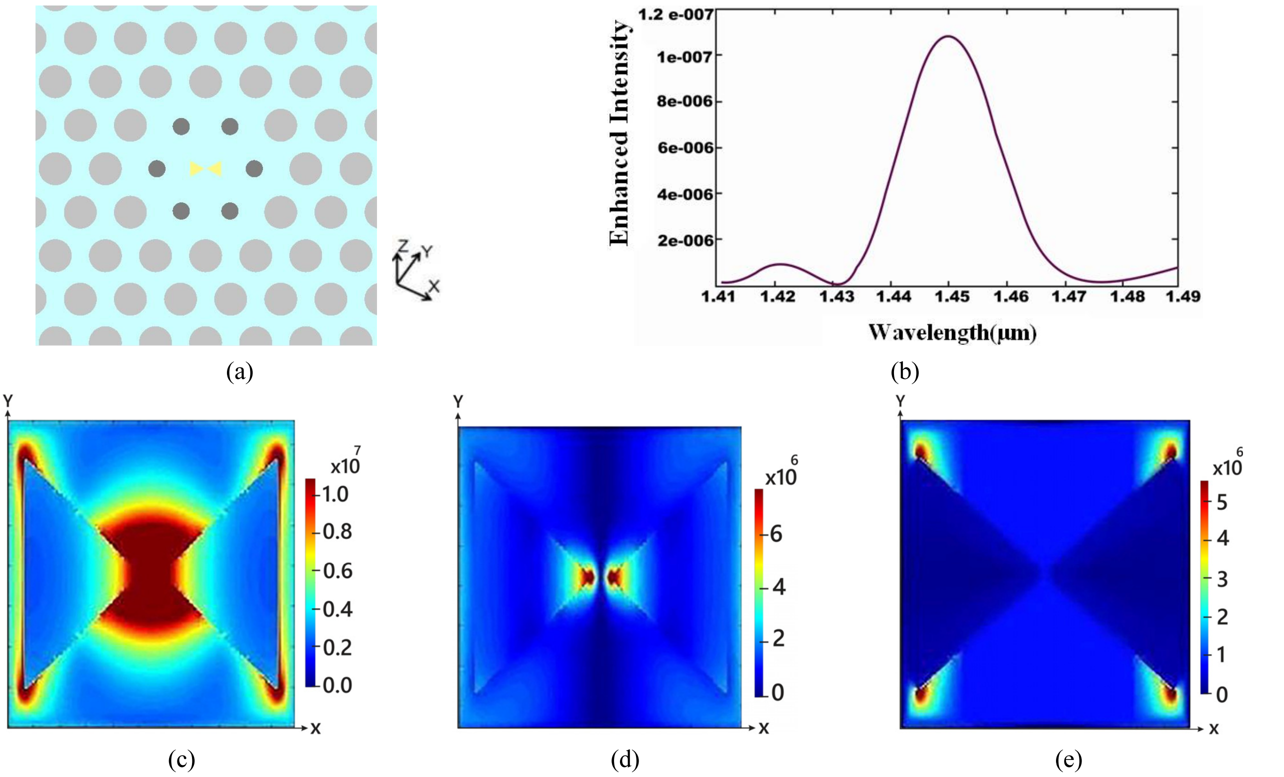


FIG. 4. (a) Two-dimensional view of the analyzed hybrid structure, (b) wavelength spectrum of the hybrid structure, (c) calculated enhancement of the electric field intensity distribution $|E|^2$ at the resonant wavelength, (d) calculated enhancement of the *x*-component of the electric-field intensity distribution $|E_x|^2$ at the resonant wavelength, (e) calculated *y*-component of the electric-field intensity distribution $|E_y|^2$ at the resonant wavelength.

simulate its optical and spectral responses. The resonant wavelength of the coupled structure is identified as $\lambda = 1450$ nm. The observed wavelength shifting (redshift) with respect to the resonant mode of the PC is naturally induced by the coupling phenomenon.

As it is observed in Figs. 4(b) and 4(c), a considerably large enhancement of light intensity, about 1.1×10^7, normalized to the input source and measured 10 nm above the structure, is achieved exactly in the gap area of the BA. This outcome witnesses that the light traveling from the nanocavity toward the nanoantenna has been strongly and constructively coupled to the subwavelength gap of the bowtie, without spoiling the resonant characteristics of the PC substrate. In fact, the final results of the numerical analysis clarify an improved coupling efficiency. This consequence confirms a constructive near-field interaction and optimal coupling between the PC cavity and the antenna, improving the challenging mismatches between light and objects of subwavelength dimensions.

Comparing this huge enhancement of optical field in the gap of the antenna in the hybrid structure to the enhancement in the bare antenna of Fig. 3(b) confirms that the PC cavity provides appropriate density of light energy in the vicinity of the BA to properly excite its resonance, through improved light-matter interaction.

From Fig. 4(d), as can be predicted, the *x*-component of the light field achieved by simulating the hybrid device is predominantly larger than the other, perpendicular component.

V. CONCLUSION

In this paper, a hybrid structure that couples an optimized low-mode-volume photonic-crystal nanocavity to a bowtie nanoantenna is proposed. This hybrid resonant architecture benefits from 3D-FDTD-based optimization to optimize the optical characteristics of the PC nanocavity in contact with the antenna, to achieve strongly improved optical coupling and therefore substantially enhanced energy of light in the gap space of the nanoantenna.

The proposed system takes advantage of the tiny mode volume of the PC structure to improve the light-matter interaction, reducing the energy required for the system. Moreover, the PC structure is created in a silicon membrane, which makes it very suitable and straightforward for fabrication. Furthermore, the presented structure eliminates the need for desperate efforts in accuracy adjustment of the nanoantenna's position relative to the PC cavity, via direct coupling of the antenna to the cavity. Additionally, the architecture designed here provides the possibility of realizing ultracompact optical structures.

The enormous strength of the light field at the output of the hybrid structure (10 nm above the structure, in the gap zone of the nanoantenna), compared to the intensity achieved by a PC structure without a bowtie antenna, can provide an indispensable alternative to the common and recently introduced coupled systems of references [1-3] and [8]. It is suitable for diverse applications that directly depend on light intensity and strong trapping of the optical field in subwavelength spaces as well, including antennas, nonlinear optics, data storage, high-sensitivity sensors, optical trapping and development of nanometer size objects, and information and communication.

REFERENCES

1. T. Zhang, S. Callard, C. Jamois, C. Chevalier, D. Feng, and A. Belarouci, "Plasmonic-photonic crystal coupled Nanolaser," Nanotechnol. **25,** 315201 (2014).
2. A. Belarouci, T. Benyattou, X. Letartre, and P. Viktorovitch, "3D light harnessing based on coupling engineering between 1D-2D Photonic Crystal membranes and metallic nanoantenna," Opt. Express **18**, A381-A394 (2010).
3. A. El Eter, T. Grosjean, P. Viktorovitch, X. Letartre, T. Benyattou, and F. I. Baida, "Huge light-enhancement by coupling a bowtie nanoantenna's plasmonic resonance to a photonic crystal mode," Opt. Express **22**, 14464-14472 (2014).
4. H. Pan, S. Assefa, W. M. J. Green, D. M. Kuchta, C. L. Schow, A. V. Rylyakov, B. G. Lee, C. W. Baks, S. M. Shank, and Y. A. Vlasov, "High-speed receiver based on waveguide germanium photodetector wire-bonded to 90nm SOI CMOS amplifier," Opt. Express **20**, 18145-18155 (2012).
5. H. Miao, K. Srinivasan, and V. Aksyuk, "A microelectro-mechanically controlled cavity optomechanical sensing system," New J. Phys. **14**, 075015 (2012).
6. H. A, Atwater, and A. Polman, "Plasmonics for improved photovoltaic devices," Nat. Mater. **9**, 205-213 (2010).
7. G. Shambat, B. Ellis, A. Majumdar, J. Petykiewicz, M. A. Mayer, T. Sarmiento, J. Harris, E. Haller, and J. Vuckovic, "Ultrafast direct modulation of a single-mode photonic crystal nanocavity light-emitting diode," Nat. Commun. **2**, 539 (2011).
8. M. Mivelle, P. Viktorovitch, F. I. Baida, A. El Eter, Z. Xie, T. P. Vo, E. Atie, G. W. Burr, D. Nedeljkovic, J. Y. Rauch, S. Callard, and T. Grosjean "Light funneling from a photonic crystal laser cavity to a nanoantenna: overcoming the diffraction limit in optical energy transfer down to the nanoscale," Opt. Express **22**, 15075-15087 (2014).
9. P. Mühlschlegel, H. J. Eisler, O. J. F. Martin, B. Hecht, and D. W. Pohl, "Resonant optical antennas," Sci. **308**, 1607-1609 (2005).
10. J. Aizpurua, G. W. Bryant, L. J. Richter, F. J. García de Abajo, B. K. Kelley, and T. Mallouk, "Optical properties of coupled metallic nanorods for field-enhanced spectroscopy," Phys. Rev. B **71**, 235420 (2005).
11. R. D. Grober, R. J. Schoelkopf, and D. E. Prober, "Optical antenna: Towards a unity efficiency near-field optical probe," Appl. Phys. Lett. **70**, 1354-1356 (1997).
12. P. J. Schuck, D. P. Fromm, A. Sundaramurthy, G. S. Kino, and W. E. Moerner, "Improving the mismatch between light and nanoscale objects with gold bowtie nanoantennas," Phys. Rev. Lett. **94**, 017402 (2005).
13. A. Alù and N. Engheta, "Hertzian plasmonic nanodimer as an efficient optical nanoantenna," Phys. Rev. B **78**, 195111 (2008).
14. O. L. Muskens, V. Giannini, J. A. Sánchez-Gil, and J. G. Rivas, "Optical scattering resonances of single and coupled dimmer plasmonic nanoantennas," Opt. Express **15**, 17736-17746 (2007).
15. L. Wang, S. M. Uppuluri, E. X. Jin, and X. Xu, "Nanolitho-graphy using high transmission nanoscale bowtie apertures," Nano Lett. **6**, 361-364 (2006).
16. W. L. Barnes, A. Dereux, and T. W. Ebbesen, "Surface plasmon subwavelength optics," Nat. **424**, 824-830 (2003).
17. H. Fischer and O. J. Martin, "Engineering the optical response of plasmonic nanoantennas," Opt. Express **16**, 9144-9154 (2008).
18. P. B. Johnson and R. W. Christy, "Optical constants of the noble metals," Phys. Rev. B **6**, 4370-4379 (1972).
19. Y. Lai, S. Pirotta, G. Urbinati, D. Gerace, M. Minkov, V. Savona, A. Badolato, and M. Galli, "Genetically designed L3 photonic crystal nanocavities with measured quality factor exceeding one million," Appl. Phys. Lett. **104**, 241101 (2014).
20. R. Miura, S. Imamura, R. Ohta, A. Ishii, X. Liu, T. Shimada, S. Iwamoto, Y. Arakawa, and Y. K. Kato, "Ultralow mode-volume photonic crystal nanobeam cavities for high-efficiency coupling to individual carbon nanotube emitters," Nat. Commun. **5**, 5580 (2014).
21. U. P. Dharanipathy, M. Minkov, M. Tonin, V. Savona, and R. Houdre, "High-Q silicon photonic crystal cavity for enhanced optical nonlinearities," Appl. Phys. Lett. **105**, 101101 (2014).
22. P. Barclay, K. Srinivasan, and O. Painter, "Nonlinear response of silicon photonic crystal microresonators excited via an integrated waveguide and fiber taper," Opt. Express **13**, 801-820 (2005).
23. D. Englund, D. Fattal, E. Waks, G. Solomon, B. Zhang, T. Nakaoka, Y. Arakawa, Y. Yamamoto, and J. Vuckovic, "Controlling the spontaneous emission rate of single quantum dots in a two-dimensional photonic crystal," Phys. Rev. Lett. **95**, 013904 (2005).
24. T. Yoshie, A. Scherer, J. Hendrickson, G. Khitrova, H. M. Gibbs, G. Rupper, C. Ell, O. B. Shchekin, and D. G. Deppe, "Vacuum Rabi splitting with a single quantum dot in a photonic crystal nanocavity," Nat. **432**, 200-203 (2004).
25. J. Vuckovic, M. Loncar, H. Mabuchi, and A. Scherer, "Design of photonic crystal microcavities for cavity QED," Phys. Rev. E **65**, 016608 (2001).
26. S. Aneja and M. Kumar, "Design of a three-hole defect photonic crystal nanocavity with high-quality and enhanced Purcell factor," Opt. Eng. **54**, 017106 (2015).