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Sandwich-typed resonator cavity based on a regular photonic crystal nanobeam

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Abstract. The authors propose and numerically examine a two-component design of an optical nanocavity. The design utilizes the effective medium theory. Such a nanocavity consists, first, of a photonic crystal nanobeam, in which the photonic crystal unit cell is not changed. Second, the cavity contains a fragment of some supplementary material of the size of several or several tens of photonic crystal unit cells. This paper describes the cavity model in which the both components have an equal thickness and can be fabricated from the same silicon wafer. While combining the two components, the defect has formed, in which the resonant mode can be excited. The advantages of the proposed cavity model are reported, particularly the easiness with which the cavities array can be fabricated and the possibility of implementing electrically pumped light sources and amplifiers. The fabrication tolerances of the proposed nanocavity were investigated. It has been found that existing structural layers alignment technologies can be used for fabricating the suggested cavity.

1. Introduction

The ability of photonic crystal (PC) structures to localize light at subwavelength scale is used in a variety of nanophotonic devices. Nanocavity is a basic element of nanophotonics [1]. High Q-factor photonic-crystal nanocavities with small mode volume enable designing optical switches, filters, and low threshold-power light sources, as well as integrating the said components in microcircuits. With the optical cavities boosting the interaction of light with the propagation medium, they have found use for experimental research in quantum electrodynamics.

Before addressing the suggested nanocavity model, a number of issues that complicate the development of devices, based on PC nanocavities, are listed. Most of the existing technologies in use to create high-Q PC nanocavities suggest fine-tuning of the resonance chamber geometry by changing the parameters of the photonic crystal. Such parameters may be, for example, the radius of the hole in the photonic crystal period and/or the hole periodic spacing [2, 3]. This imposes strict limits on the fabrication tolerances of fine details of the PC structure. For creating an array of nanocavities [4], high fabrication tolerances should be provided in the entire area of the array. Another difficulty arises in fabrication of nonlinear nanophotonic devices. Increase in the degree of interaction between light and matter in a PC nanocavity makes effective use of non-linear optical materials and quantum dots. For introducing such materials in the area of the resonator, one needs to resort to complicated technologies [5]. The next important area of photonic nanocavity research is the development of light sources on the basis of PC structures integrated on-chip. To implement such a device, one needs to create an

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electrically pumped cavity [6]. Building dynamic systems, based on nanocavities, also requires complex technology solutions. In most cases, it involves mechanical impact directly on the PC structure [7]. Another example of the difficulties in creating some nanophotonic devices is the need for a given distribution of the radiation in the far field. This problem is commonly solved by fine-tuning of the minimum parts of the photonic crystal [8, 9].

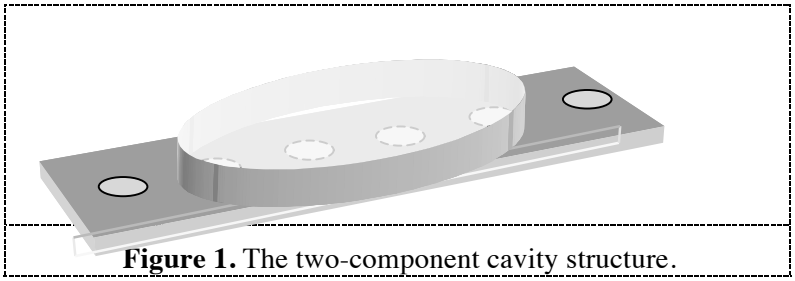


Figure 1. The two-component cavity structure.

2. The cavity model

To simplify the solutions for the problems cited, the authors theoretically investigated two-component PC cavity shown in Fig. 1. The first component of such a cavity is a periodic structure on the basis of a PC nanobeam. Compared with the two-dimensional structure on the basis of a PC slab [10, 11], the area of PC nanobeam is smaller and is naturally integrated into the waveguide geometry of connections on a chip. The second component is a fragment of a complementary material having an area of several lattice constant of the PC. The shape and size of the fragment were determined from the given parameters of PC cavity. While combining the two components, a defect forms in the resulting nanostructure. The resonant mode of the corresponding frequency can be excited in this defect.

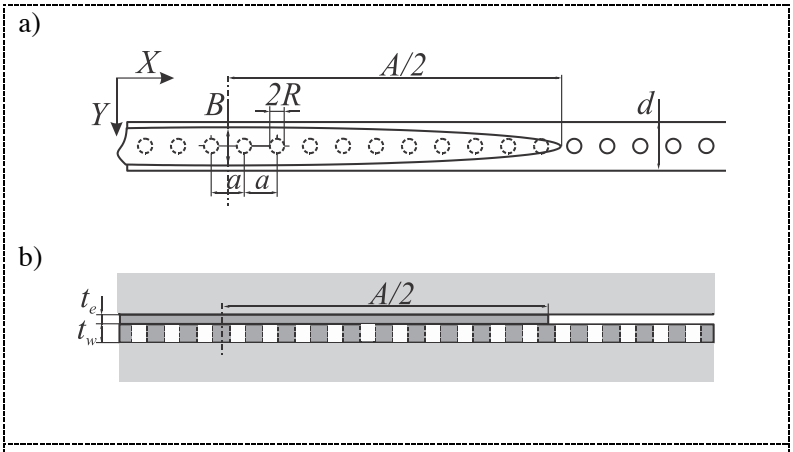


Figure 2. The geometry of the resonator calculated by (a) top view, (b) a side view. PC nanobeam (n = 3.46) lies on the substrate (n = 1.45). PC nanobeam width is d = 0.5 mm, thickness t_w = 0.26 um. Circular holes have a radius of R = 75 nm and filled with air, distance between holes a = 0.34 um. The elliptical shape (ellipse parameters A and B) (n = 3.46) lies on the substrate (n = 1.45). Thickness of ellipse t_e = 100 nm.

The proposed approach to creating two-component PC cavities is illustrated through the structure shown in Fig. 2. The first component of the resonator was a PC nanobeam. The nanobeam was made

of silicon and was placed on a silica substrate. The holes in the nanobeam were of the same radius; they were equidistant from each other and filled with air. PC nanobeam parameters are given in the legend to Fig. 2. With these parameters, PC band gap was created for TE- dominant polarization radiation in the wavelength range of 1.4-1.7 um. The second component of the nanocavity was an elliptical piece of silicon, placed on a silica substrate.

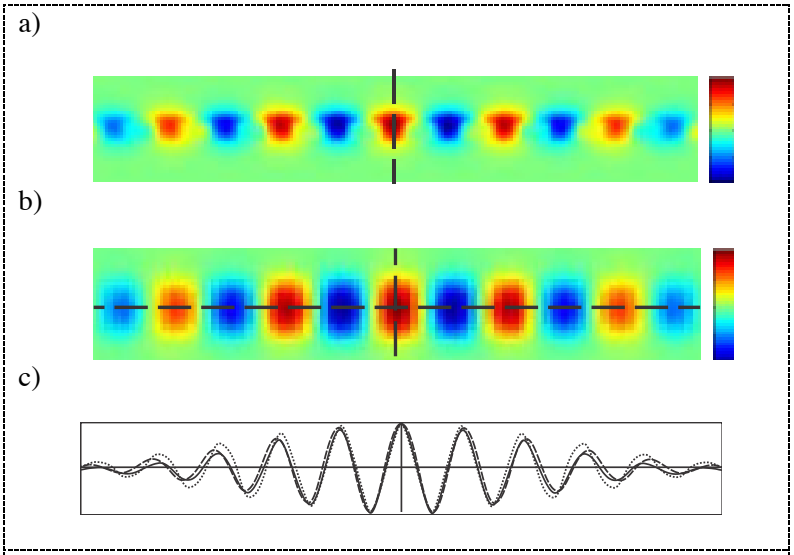


Figure 3. (a) the distribution of H_z in the vertical plane passing through the axis of the waveguide, (b) the distribution of H_z in the horizontal plane just above the elliptical fragment (in quartz), (c) the dotted line - H_z values along the line of intersection of the planes (a) and (b), the dashed line - H_z values just below PC nanobeam (in quartz), the solid line - function $\cos(\pi x/a)\exp(-\sigma x^2)$ for $\sigma = 0.23, a = 0.34$ um..

To create a high-Q nanocavity, it is necessary to reduce the radiation of the resonant mode in space. This was achieved by optimizing the shape of the envelope of the resonant mode. The spectrum of electromagnetic field distribution, directly above the waveguide, determines the energy distribution in the far zone. This spectrum consisted of two peaks. Energy was dissipated from the cavity through the light cone of the waveguide, which was located between the spectral peaks. Therefore, the width of the spectral peaks determines the nanocavity losses on scattering. In [11, 12], it is proposed that a resonant mode can be formed with an envelope matching the Gaussian function. The shape of the resonant mode's envelope depends, in particular, on the imaginary part γ of the wave vector of the PC structure. Gaussian shape of the envelope, provided by γ, varies linearly from one PC period to the next [12]. In the same paper [12], it has been shown that resonant mode with a Gaussian envelope can be realized by changing the PC nanobeam material fill factor (FF) quadratically. The elliptical shape of the defect proposed in this paper also enabled quadratic tapering of the PC nanocavity. In subsequent calculations, the thicknesses of the PC nanobeam and elliptical defect were assumed to be 260 nm and 100 nm, respectively. These thicknesses produced an optimal FF change in the cavity. Increasing the thickness of the nanobeam necessitates increase in the thickness of the elliptical defect.

3. Simulation

The resonance cavity characteristics were computed using the parallel FDTD method [13]. In particular, the cavity ($Q = 3.05 \times 10^4$) was calculated with the parameters of the ellipse A = 6.8 mm (20 holes below the ellipse) and B = 0.5. To achieve a high-Q nanocavity, five additional holes were

placed in the PC nanobeam at both ends of the ellipse. Thus, the total length of the cavity was (20 +5 x 2) x 0.34 = 10.2 um. Fig. 3a shows the distribution of H_z in the vertical plane passing through the axis of the nanobeam, and Fig. 3b the distribution in the horizontal plane, just above the elliptical silicon fragment (in quartz). H_z values along the intersection line of these two planes are represented by the dotted line in the graph of Fig. 3c, and the values directly below the PC nanobeam (in quartz) by the dashed line on the same chart. The solid line represents the function $\cos(\pi x/a)\exp(-\sigma x^2)$ with $\sigma = 0.23, a = 0.34$ microns. Good agreement between the distributions of H_z and an analytic function demonstrates that the shape of the resonant mode's envelope is Gaussian. Assuming a linear dependence of γ on x, the relation $\gamma(x) = a/\pi \int \sigma dx \approx x/40$ can be obtained. In [12, 14], quadratic tapering of PC nanobeam width was used to form the defect. In the paper [12], for a nanocavity with a length of 60 periods of the PC, the relation $\gamma(x) \approx x/120$ was implemented. Thus, it can be concluded that the two techniques used in creating a defect are almost equivalent. The nanocavity with an elliptical defect is 3 times shorter than the one with variable nanobeam width. Accordingly, the rate of change γ in the nanocavity with an elliptical defect is three times faster.

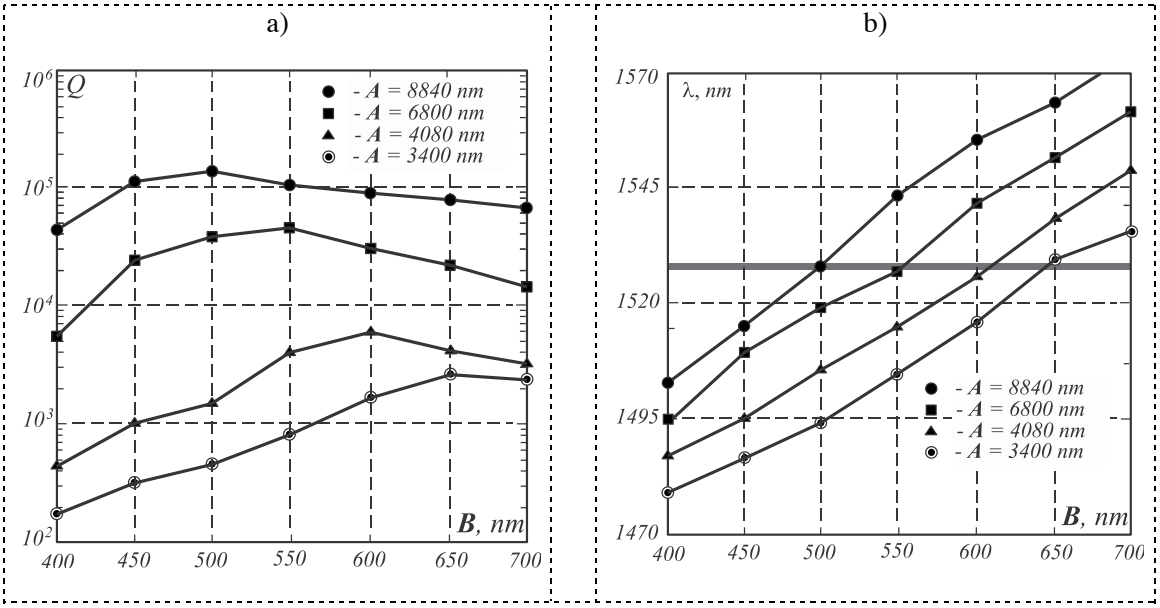


Figure 4. The dependence of Q-factor (s) and the resonance frequency (b) on the ellipse parameter A for different values of B.

Fig. 4 shows the simulation results of the proposed resonator for various parameters of the elliptical segment. For all simulations, five additional holes were placed in the PC nanobeam at both ends of the ellipse. It can be seen that the greater the length of the nanocavity, the greater is the Q-factor. For a resonator length of 12.24 um (36 holes - 26 of them are under the elliptical fragment), A = 8.84 um, B = 0.5 um, and Q-factor ~1.4 x10^5.

The minimum value of A, where the resonant mode with a Q-factor above 10^3 remains excited, is 3.4 um (10 holes are under the ellipse) and B = 0.65 um. The Q-factor of this resonator is 2.5 x10^3. The optimal values of B vary with the changing values of A. The optimal B values are 650, 600, 550, and 500 nm respectively for values of A equal to 3400, 4080, 6800 and 8840 nm. The frequency of the excited resonant mode is equal to 1.525 microns for A = 3400 nm and B = 650 nm (the horizontal gray line in Fig. 4b; the frequencies are almost the same for all the B values listed above). The changes in B value can be used to customize the resonant frequency of the cavity. For example, if the B value is

changed to be in the range 0.4-1.0 microns, then the resonant frequency varies from 1.485 to 1.535 microns (A = 4.08 um).

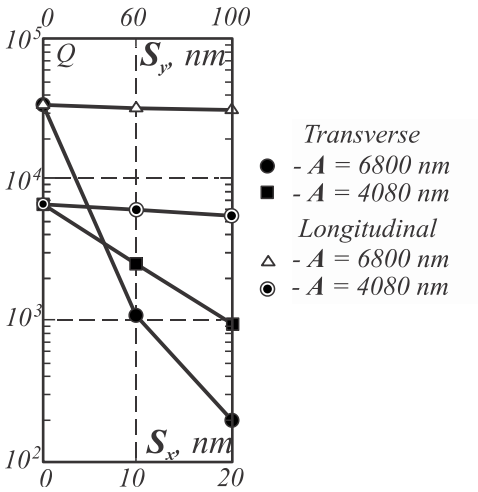


Figure 5. The dependence of the Q-factor for several values of A on transverse and longitudinal displacement of the two components of the cavity.

Fig. 5 shows the simulation results for horizontal displacement errors of the two components of the nanocavity with respect to each other. The greater the length of the resonator, the more accurate would be the combining of the two components. The misalignment offset of the ellipse, in the direction perpendicular to the axis of the waveguide, is most critical. Modern technologies allow combining structural layers within ~10 nm error [15]. Figure 4 shows that when the transverse displacement is only 20 nm, the Q-factor does not exceed 10^3 for A=4.08 um. The longitudinal direction is less critical to displacement errors. Fig. 4 also shows that longitudinal displacement of 100 nm results in a slow decrease of Q-factor. Such asymmetry of displacement tolerances in X and Y directions is useful, for example, for inexpensive alignment technology described in [16]. This technology allows combining of layers with an average displacement error of less than 60 nm in one axial direction and less than 10 nm in the other.

Another sandwich-typed cavity was also simulated. It is a cavity in which the both components have an equal thickness ($t_w = t_e = 0.22$ um) and can be fabricated from the same silicon wafer. PC nanobeam width is d = 0.6 mm. Circular holes have a radius of R = 90 nm and filled with air, distance between holes a = 0.38 um. Ellipse parameters are A = 6.80 um and B = 0.38 um. The remaining parameters are the same as for Fig. 2. The simulated Q-factor value of this cavity is about 20000.

4. Discussion

The two-component nanocavity proposed in this paper has several advantages when compared to existing solutions. First, it simplifies the manufacturing of nanocavities based on PC structures. At the heart of such a nanocavity is a regular structure. The formation of the defect does not need any change in the shape of the minimum parts of the structure(e.g., change in the period and/or size of the holes in a PC structure). The second component is a fairly large structure, whose construction is relatively simple.

Second, the proposed structure provides a natural way to form two-dimensional arrays of nanocavities. Two-component structure allows the use of relatively inexpensive technology of interferometric lithography (IL) for making arrays of resonators. Manufacturing the array of the first component of the structure (PC nanobeam) requires double-exposure IL [17], and that of the second

component (supplementary material) only single-exposure IL. The possibility for using IL is an additional advantage of the structure proposed in this paper as compared with the structures suggested in [12, 14].

Third, the proposed structure allows for the development of an integrated on-chip light source with vertical electrical pumping. The second component of the structure (supplementary material) can be doped with ions and, thus, be used as the basis for one (top) of the contact pads. The other (bottom) contact pad may be implemented, for example, by using the approach described in [18]. In this case, the bottom reflector may serve as both an electrical current pathway and a heat sink. Integrated on-chip light-emitting diodes with a laterally doped p-i-n structure, based on the nanobeam photonic crystal cavity, were demonstrated recently [6]. Using vertical electrical pumping, in comparison with lateral electrical pumping, allows, in particular, for reduction of the current threshold. This can be achieved by reducing the distance between the contact pads and the resonance cavity.

The authors note three more potential advantages, besides those cited above, in favor of the proposed nanocavity, which require proof through additional research. First, the creation of nanocavities with nonlinear properties is simplified. The supplementary component of the structure can be used to bring an optically nonlinear material directly into the nanocavity region. Second, the vertical radiation characteristics of the cavity can be controlled by varying the shapes of the second component of the resonator and its substrate. Third, the two-component structure of nanocavity permits dynamic control of its parameters. For example, the resonant frequency, Q-factor value and vertical radiation characteristics of the cavity can be varied by shifting one of the components of the nanocavity in the horizontal and/or vertical direction.

The cavity considered in this paper is based on the PC nanobeam. However, it is likely that the above approach to the construction of two-component PC cavities can be used for two-dimensional structures on the basis of a PC slab (e. g., for the L3-defect cavity [10] or for the line-defect cavity [11]. The validity of this assumption is also expected to check in our further studies.

5. Conclusion

The authors propose the two-component nanocavity model. In this model, the minimum details of the structure, which are the most difficult to fabricate, are found only in the periodic component of the resonator. Other advantages include the ease of forming arrays of nanocavities, a promising way to construct an electrically pumped photonic cavity, the ease of introducing non-linear optical materials in the area of the nanocavity, the possibility of formation of the desired energy distribution in the far zone, and the possibility to construct dynamic systems based on nanocavities.

The drawback of the proposed design of the nanocavity is its high sensitivity to the components' alignment errors. It is shown that to create a nanocavity with the Q-factor above 10^3, the latest technologies of structural layers alignment, within ~ 10 nm error, should be used.

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6. References

[1] K. J. Vahala, "Optical microcavities," Nature **424**, 839-846 (2003).
[2] Y. Akahane, T. Asano, B.-S. Song, and S. Noda, "Fine-tuned high-Q photonic-crystal nanocavity," Opt. Express **13**, 1202-1214 (2005).
[3] P. Velha, J. C. Rodier, P. Lalanne, J. P. Hugonin, D. Peyrade, E. Picard, T. Charvolin and E. Hadji, "Ultra-high-reflectivity photonic-bandgap mirrors in a ridge SOI waveguide," New J. Phys. (IOP) **8**, 1-13 (2006).
[4] A. Yariv, Y. Xu, R. K. Lee, and A. Scherer, "Coupled-resonator optical waveguide: a proposal and analysis," Opt. Lett. **24**, 711-713 (1999).
[5] F. Qin, Z.-M. Meng, X.-L. Zhong, Y. Liu, and Z.-Y. Li, "Fabrication of semiconductor-polymer compound nonlinear photonic crystal slab with highly uniform infiltration based on nano-imprint

lithography technique," Opt. Express **20**, 13091-13099 (2012).
[6] G. Shambat, B. Ellis, J. Petykiewicz, M. Mayer, T. Sarmiento, J. Harris, E. E. Haller, and J. Vuckovic, "Nanobeam photonic crystal cavity light-emitting diodes," Appl. Phys. Lett. **99**, 071105 (2011).
[7] I. W. Frank, P. B. Deotare, M. W. McCutcheon, and M. Lončar, "Programmable photonic crystal nanobeam cavities," Opt. Express **18**, 8705-8712 (2010).
[8] N.-V.-Q. Tran, S. Combrié, and A. De Rossi, "Directive emission from high-Q photonic crystal cavities through band folding," Phys. Rev. B **79**, 041101 (2009).
[9] S. L. Portalupi, M. Galli, C. Reardon, T. F. Krauss, L. O'Faolain, L. C. Andreani, and D. Gerace, "Planar photonic crystal cavities with far-field optimization for high coupling efficiency and quality factor," Opt. Express **18**, 16064–16073 (2010).
[10] Y. Akahane, T. Asano, B. S. Song, and S. Noda, "High-Q photonic nanocavity in a two-dimensional photonic crystal," Nature **425**, 944–947 (2003).
[11] B.-S. Song, S. Noda, T. Asano and Y. Akahane, "Ultra-high-Q photonic double-heterostructure nanocavity," Nature Materials **4**, 207-210 (2005).
[12] Q. Quan and M. Loncar, "Deterministic design of high Q, small mode volume photonic crystal nanobeam cavities," Opt. Express **19**, 18529–18542 (2011).
[13] A. Taflove and S. C. Hagness, Computational Electrodynamics: The Finite-Difference Time-Domain Method, 3rd ed. Norwood, MA: Artech House, 2005.
[14] B. H. Ahn, J. H. Kang, M. K. Kim, J. H. Song, B. Min, K. S. Kim, and Y. H. Lee, "One-dimensional parabolic beam photonic crystal laser," Opt. Express **18**, 5654-5660 (2010).
[15] N. Li, W. Wu, S. Y. Chou, "Sub-20-nm alignment in nanoimprint lithography using Moire fringe," Nano Letters **6**, 2626-2629 (2006).
[16] W. Wu, R. G. Walmsley, W.-D. Li, X. Li, R. S. Williams, "Nanoimprint lithography with ≤60 nm overlay precision," Applied Physics A. **106**, 767-772 (2012).
[17] S. R. J. Brueck, "Optical and Interferometric Lithography — Nanotechnology Enablers," Proc. IEEE **93**, 1704-1721 (2005).
[18] S.-H. Kim, J. Huang, and Axel Scherer, "From vertical-cavities to hybrid metal/photonic-crystal nanocavities: towards high-efficiency nanolasers," JOSA B **29**, 577-588 (2012).