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Design of a chalcogenide-based 2D photonic crystal nanobeam cavity

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Original Research

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Abstract:

This article introduces the development and enhancement of a side-coupled chalcogenide-based 2D PhC nanobeam cavity in the mid-IR spectral range. The structure configuration consists of 2D PhC nanobeam and side-coupled bending bus waveguide for efficient light coupling. Through numerical simulation and optimization, we optimized three key parameters: the number of mirror holes, the radius of the central hole of the nanobeam cavity, and the optimized coupling gap size, improving the quality factor of the primary mode of the cavity. The cavities exhibit high Q factors and low modal volumes, making them attractive for various applications, including laser, sensing, nonlinear optics, optical trapping, and quantum technologies. Regarding applications, this allows us to compare optical devices with each other.

Keywords: Photonic crystal; Chalcogenide; Wavelength; Quality factor; mid-IR

1. Introduction

Photonic crystal cavities (PhC), for confining light in the mid-IR spectral range, are of great interest due to many potential applications, including biomedical imaging and medical and environmental sensors to security and food quality analysis [1–8]. Made chalcogenide photonic crystal slabs (PCSs) using focused ion beam milling [9]. A narrow band filter selects a narrow frequency band signal from incoming light. Chalcogenide is compared with conventional Si material regarding applications as a feasible material for optical devices [10]. Chalcogenide Waveguide Amplifier Based on a Photonic Crystal with Compound LatticeThe photonic crystal waveguide can allow light to travel at both wavelengths of 1530 nm for signal and 980 nm for pump [11]. Chalcogenide phase change materials (PCMs) are considered highly promising owing to the nonvolatile nature of their phase change. Chalcogenide PCM nanophotonics can be broadly classified into integrated photonics (with guided wave light propagation) and Meta-optics (with free space light propagation) [12]. Te-enriched chalcogenide glass $Ge_{15}As_{25}Se_{15}Te_{45}$ (GAST) is synthesized, thermo-optically characterized, and used to fabricate a one-dimensional photonic crystal cavity mode dynamically and reversibly tuned by temperature modulation. Broad and dynamical spectral tuning of low bandgap chalcogenide glasses via temperature modulation can be utilized in photonic crystal-based integrated optics, quantum dot resonance matching, solid state and gas laser components, and infrared photonic crystal fibers [13]. fabrication of 2D photonic crystal nanobeam cavities with optical resonances around 800 nm, compatible with rubidium, cesium, or argon atomic transitions. The cavities are made of indium gallium phosphide material, a III-V semiconductor compound that has an extensive index of refraction ($n = 3.3$) favoring strong optical confinement and small mode volumes [14].

Enhancing the light-matter interaction is important for integrated photonic circuits where light must be effectively confined and controlled [15]. Phononic crystal nanocavities (PhC) have a unique ability to encapsulate and manipulate light, so they can be used to build and develop new resonance-based photonic integrated circuits. The performance of resonant optical cavities is usually characterized by quality factor (Q) and mode volume (V).
Two primary resonant optical cavities exist: whispering mode resonators and photonic crystal cavities. Light is confined within resonator configurations of whispering modes, like disc-shaped or microring structures, through total internal reflection [16, 17]. These structures exhibit minimal losses. Conversely, the one-dimensional nanobeam photonic crystal nanocavity has garnered significant interest within the realm of photonic crystal cavities. Such cavity structures showcase a high-quality factor and low mode volume, making them appealing for applications like lasers, sensors, nonlinear optics, optical trapping, and quantum technologies [18–21]. Nevertheless, effectively monitoring 2D PhC nanocavities presents hurdles, notably in efficiently exciting the primary resonant mode linearly. These constraints hinder their integration into most photonic systems-on-chips, demanding superior detection resolution. To overcome these challenges, coupling configurations have been investigated in which a 2D PhC nanocavity is laterally coupled to a direct waveguide. These configurations reveal resonant modes as dips in the transmission spectrum passing through the direct waveguide [22–24].
Optical resonant cavities with micro- or nanoscale dimensions are fundamental building blocks in photonic integrated circuits (PICs), serving as key enablers for a wide range of applications in photonics. These compact cavities facilitate essential functionalities such as light confinement, wavelength filtering, and enhancement of light-matter interactions, making them indispensable in optical communications, sensing, and quantum photonics. The mode volume quantifies the spatial extent of optical field confinement, typically corresponding to a small region on a few cubic wavelengths. This parameter is crucial for achieving strong light-matter interactions, as tighter confinement increases the interaction density between photons and the material. Simultaneously, the quality factor (Q) measures the photon lifetime within the cavity, indicating how effectively the cavity can store optical energy. A high Q factor reduces energy losses, allowing light to circulate within the cavity for an extended period, enhancing resonance effects and interaction efficiency.
The interplay between the mode volume and the quality factor is paramount in optimizing the performance of optical resonant cavities. Minimizing the mode volume while maintaining a high Q factor is a persistent challenge in cavity design, as it directly impacts the efficiency of devices such as lasers, modulators, and sensors. These parameters are critical benchmarks in developing advanced photonic systems, driving innovation in integrated photonics, and expanding the boundaries of what is achievable in modern optical technologies.
Using chalcogenide materials, we introduce a highly effective side-coupling setup designed to excite resonant modes of nanobeam cavities within 2D PhCs. This setup promises heightened light-matter interactions, opening avenues for cutting-edge applications in integrated photonics and processing. Not only does this configuration guarantee superior performance, but it also enhances design adaptability, surmounting the constraints of traditional in-line coupling arrangements. This innovative method involves finely adjusting.

2. Design of photonic crystal nanobeam cavity

This section focuses on creating a 2D Fabry–Perot cavity using the framework of a 2D PhC nanocavity. The Fabry–Perot cavity houses two opposing defect modes moving between two Bragg mirrors, generating stationary modes within the cavity. Conversely, the photonic crystal nanobeam cavity has a consistent pattern of air openings along a waveguide. Light confinement within this structure results from a dual mechanism—transverse mode restriction through total internal reflection and propagation mode determination based on the photonic bandgap.
By introducing a local defect in 2D PhC, nanocavity is created. Light loss comes from two contributions in photonic crystal nanocavities: loss outside the waveguide plane and loss inside the structure. The loss inside the cavity structure results from mismatching the defect region's propagation mode and the listener's fading mode in the Bragg reflection mirror region.
The proposed configuration holds significant potential due to its ability to introduce new degrees of freedom, thereby paving the way for advancements in the development of light sources and optical sensors. One of its key contributions is enhancing design flexibility by moving beyond conventional in-line coupling methods. This novel approach provides a versatile framework for researchers and engineers, enabling the exploration of a broader range of parameters and configurations. Such flexibility is essential for addressing the limitations inherent in traditional coupling techniques, thereby expanding the scope of achievable functionalities.
Additionally, the side-coupling configuration plays a pivotal role in efficiently exciting the fundamental resonance mode of the one-dimensional photonic crystal (2D PhC) nanobeam cavity. By optimizing the interaction between the input waveguide and the cavity, this approach ensures more substantial and more efficient mode excitation, which is critical for achieving high-quality optical performance. Collectively, these attributes make the proposed configuration a promising innovation for advancing the capabilities of integrated photonic systems in applications such as sensing, signal processing, and light generation.
Properties of chalcogenide materials in photonic crystals: High refractive index, functionalities. Nonlinear optical behavior, conversion, flexible manufacturing.
This taper facilitates gradual mode-gap modulation while minimizing losses in the mode profile. In the conical section, it gradually decreases. Ensuring smooth optical transitions. The taper mirror section, designed for uniformity, consists of air holes with radii identical to the outermost holes in the

taper section. Additional mirror holes are incorporated to enhance optical confinement within the cavity further and maximize the Q factor. This strategic design ensures robust light confinement, reduced radiative losses, and improved resonance properties, making it an optimal structure for high-performance optical applications.
The bottom shape illustrates a one-dimensional Fabry-Perot style 2D PhC nanobeam cavity design. Following the methodology described in citation [25], figure 1 a one-dimensional Gaussian-shaped nanocavity is crafted using air holes, showcasing symmetry around the central air cavity. This nanocavity comprises three components: The central nanocavity, the conical segment, and the Bragg mirror reflection conical portion, symmetrically positioned on both sides of the central cavity. A parabolic cone section (tapered cone) is employed to gradually adjust mode spacing and reduce the loss of mode profiles to achieve high-Q resonant modes within the nanobeam cavity.

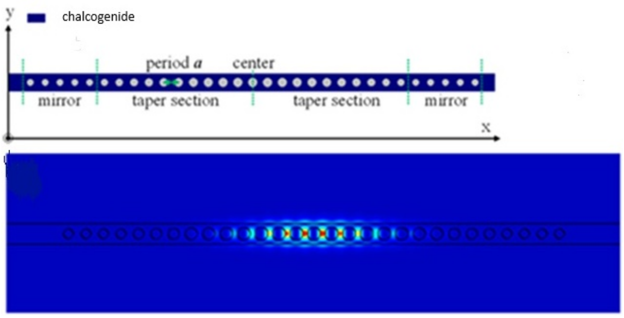

Figure 1. Design of Photonic Crystal with circular holesomprising the tapered and mirrored portions. The entire configuration exhibits symmetry relative to the center of the cavity.

3. Simulations and results

Figure 2 illustrates the schematic representation of the primary simulation setup. The simulation of the 2D PhC nanocavity, utilizing the advanced computational features of Lumerical FDTD software, requires a methodical strategy. The simulation process mandates the precise specification of the nanocavity's geometric attributes, including the width, height, and length of the waveguides, in coordination with the specific material configuration surrounding the 360 nm lattice constant. This setup includes 20 mirror components and 10 taper elements, each with a bending radius of 3.0 μm. The bus waveguide maintains a fixed width of 450 nm and a height of 220 nm, with LS set at 7000 nm and yspom at 8000 nm.

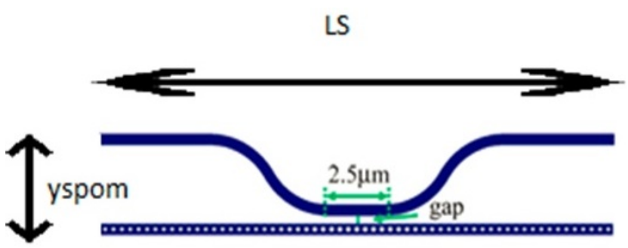

Figure 2. Schematic of side-coupled of 1D PhC nanobeam cavity using chalcogenide material.

Additionally, the central circle radius is 110 nm, with the predominant material being chalcogenide. The refractive index of the chalcogenide material is assumed to be 2.63 for the simulation.
Additionally, the design of the associated waveguide structure is carefully incorporated into the model to accurately reflect real-world conditions.
A critical factor in achieving high simulation accuracy is the selection of an appropriate grid resolution. The grid resolution must be fine enough to capture the intricate spatial variations of the electromagnetic fields within the nanobeam cavity. This ensures that the numerical model can resolve key features of the cavity's resonant modes and optical interactions without introducing significant numerical dispersion or errors.
By leveraging the robust functionality of Lumerical FDTD, this meticulous simulation approach enables detailed analysis of the nanobeam cavity's performance, such as its quality factor (Q-factor), mode profiles, and coupling efficiencies. These insights are essential for guiding the design and optimization of photonic devices and supporting the development of next-generation optical systems for applications in sensing, communications, and integrated photonics.
This innovative design facilitates precise regulation of the coupling strength while effectively mitigating parasitic losses typically associated with the bus waveguide. By optimizing the interaction between the waveguide and the cavity modes, the design not only enhances overall efficiency but also demonstrates the capability to suppress the coupling of higher-order cavity modes. These modes, which exhibit minimal spatial overlap with the fundamental waveguide mode, are thereby selectively filtered, contributing to improved mode purity and system performance. Such advancements underline the potential of this approach for applications requiring high-fidelity optical signal transmission and mode control.
Today, many chips are designed using photonic crystals, often including optical communication, biosensing, quantum photonics, nonlinear optics, and optical signal processing.
The reduction in the speed of light within photonic waveguides is inherently restricted by propagation losses, which establish a boundary on the degree to which interactions between light and matter can be intensified. This limitation underscores the critical importance of managing and minimizing losses in photonic waveguides to optimize the enhancement of light-matter interactions. By addressing and mitigating propagation losses effectively, researchers can potentially unlock greater opportunities for enhancing the efficiency and functionality of photonic devices and systems. These losses restrict the ability to achieve prolonged light confinement and interaction, thereby hindering efforts to optimize the performance of photonic devices. In response to this obstacle and to bolster light-matter coupling, scholars have progressively leaned towards employing optical resonant cavities. These cavities establish exceptionally tailored settings wherein light waves are constrained and resonate for prolonged durations, fostering intensified and more effective interactions with matter. The adoption of

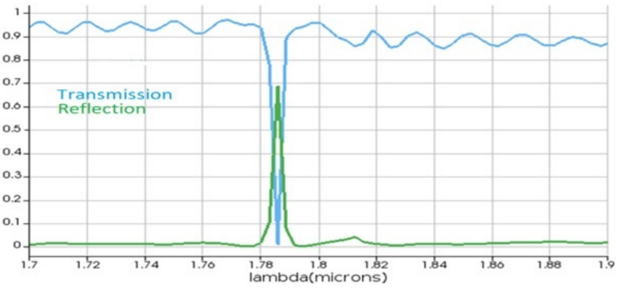

Figure 3. FDTD simulation reflection and passage.

optical resonant cavities represents a strategic approach to enhancing the manipulation of light at the nanoscale, enabling researchers to delve deeper into the intricacies of light-matter interactions and potentially unveil novel avenues for technological advancements in photonics and optoelectronics.

The unique properties of resonant structures, such as their high quality (Q) factors and tailored mode volumes, enable significant amplification of light-matter interaction strength. By effectively trapping light within a small spatial region, these cavities allow for repeated interactions between photons and the material, thereby overcoming the limitations imposed by conventional photonic waveguides. This enhanced interaction not only improves the sensitivity and performance of optical devices but also unlocks new opportunities for the miniaturization and integration of photonic circuits.

The integration of resonant cavities into photonic systems has profound implications for advancing technologies in a wide range of fields, including quantum computing, optical sensing, and telecommunication. By leveraging these structures, researchers can achieve unprecedented levels of efficiency and functionality, driving transformative progress in the development of next-generation integrated photonic circuits.

The transmission and reflection spectra of cavity modes are simulated to evaluate the cavity quality performance figure 3. This design is such that with changes in the bending radius, width, and height of the bus waveguide and changes in the lattice constant, the number of holes in tapered and mirror parts of the PhC nanobeam, and the amount of reflection and light transmission spectrum at the output and input at the wavelength of 1781 nm, the cavity quality performance will be obtained in an ideal state.

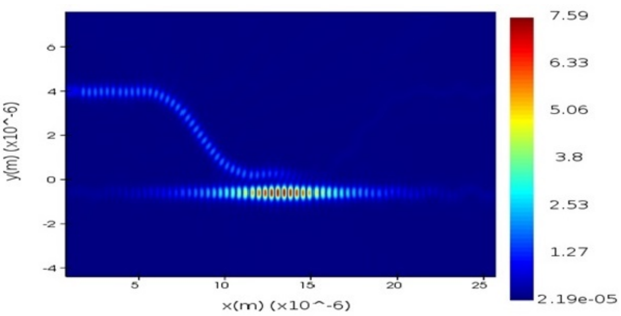

Figure 4. Distribution of electric field intensity within the entire structure.

According to coupled-mode theory [19, 25–27], the transmission and reflection coefficients at cavity resonance are obtained by:

$$R=\left(\frac{1-Q_{tot}}{Q_{int}}\right)^2,\ T=\left(\frac{Q_{tot}}{Q_{int}}\right)^2 \tag{1}$$

$$\frac{1}{Q_{tot}}=\frac{1}{Q_{int}}+\frac{1}{Q_w} \tag{2}$$

Figure 4 depicts the distribution of electrical intensity and confinement of coupled 2D PhC nanobeam cavity with a fundamental mode at a wavelength of 1781 nm.

Simulating nanobeam cavities using the advanced computational functionalities offered by Lumerical FDTD software necessitates a comprehensive and exacting methodology. The simulation procedure initiates with a meticulous delineation of the geometric attributes of the nanobeam cavity, which includes parameters such as width, height, and length. Typically, silicon and the waveguide structure.

At the core of ensuring simulation precision lies the critical selection of an optimal grid resolution, often specified as a fraction of the wavelength of the light being studied. This grid resolution, characterized by parameters like $dx=\lambda/10$, dictates the spatial discretization within the simulation domain. To comprehensively cover the cavity structure, we have elucidated the mesh dimensions by implementing a 40 nm mesh across the entirety of the structure and a finer 5 nm mesh specifically within the cavity region to enhance precision in capturing field variations. Additionally, the auto shutoff parameter has been configured to 1×10^{-5}. These meticulous configurations and parameters are essential for accurately modeling the source interactions within the nanobeam cavity, thereby advancing our understanding of nanophotonic devices.

One of the capabilities of this design is that by FDTD simulation, the number of mirror holes, the fundamental cavity resonance mode, and the quality factor can be changed. Figure 5 shows the transmission spectrum with a different number of mirror holes. As shown in figure 5, the bandwidth of the fundamental mode is increased by decreasing the number of mirror holes. It is shown in figure 5 when the number of these holes is 5, giving more bandwidth than when the number of holes is 15 or 10.

An additional observation we make is that quality factor diminishes as the number of holes decreases. With 5 mirror holes, the quality factor measures 227. This value increases to 353 with 10 mirror holes and further rises to 467 with 15 mirror holes.

One notable finding from this simulation is that altering the radius of the central hole in the cavity induces changes in the wavelength of the resonance mode. Illustrated in Fig. 6, reducing the radius of the central hole causes a shift in the wavelength of the resonance modes towards higher values, as depicted in figure 6 (a). With a radius of 120 nm, the fundamental resonance mode occurs at a wavelength of 1563 nm. Decreasing the central hole radius to 115 nm shifts the fundamental resonance mode to 1570 nm (figure 6 (b)). Furthermore, as demonstrated in figure 6 (c), reducing the central radius to 110 nm results in fundamental resonance mode appearing at a wavelength of 1577 nm.

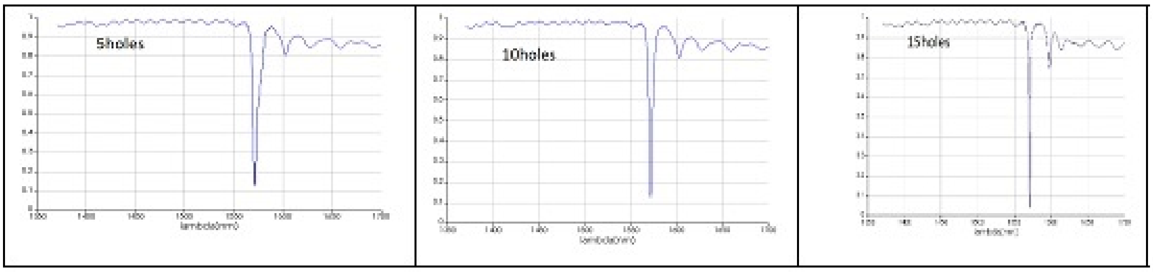

Figure 5. Fundamental cavity mode and corresponding bandwidth for the number of mirror holes of 15, 10 and 5.

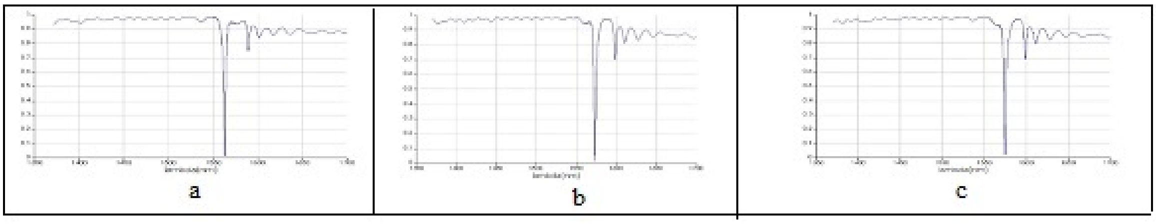

Figure 6. The transmission spectra with cavity central hole radius of (a) 120 nm (b) 115 nm (c) 110 nm (c) 450 nm.

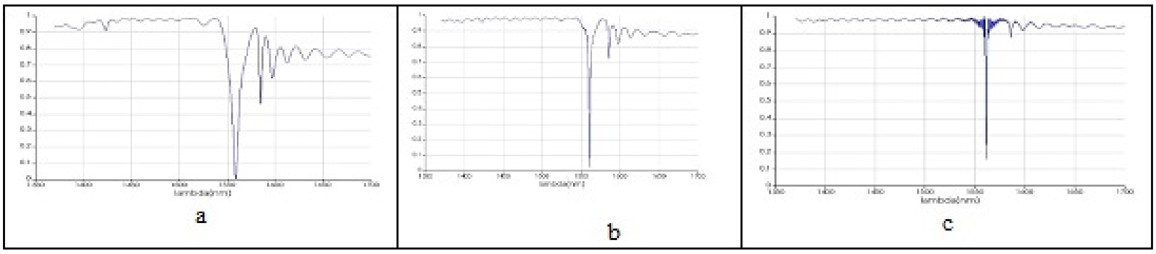

Figure 7. The transmission spectra featuring the primary cavity resonance mode for different coupling gaps of (a) 250 nm (b) 350 nm (c) 450 nm.

The corresponding fundamental cavity resonance wavelengths are 1563 nm, 1570 nm, and 1577 nm, respectively. Our last investigation was about the coupling gap value; the quality factor increases as the coupling gap value increases. In figure 7 (a), the transmission spectrum is displayed with a coupling gap of 250 nm, showcasing a fundamental resonance mode with a quality factor (Q) of approximately 250. Fig. 7 (b) illustrates the transmission spectrum with a coupling gap of 350 nm, where the Q factor of the fundamental resonance mode is around 689. Finally, figure 7 (c) presents the transmission spectrum with a coupling gap of 450 nm, revealing a Q factor of about 2010 for the fundamental resonance mode. As shown in the bandwidth of Fig. 7 (c), the transmission dip is less than that dips in Fig. 7 (a) and Fig. 7 (b) due to the more considerable coupling gap value.

4. Conclusion

Our study presented a systematic optimization approach for designing a 2D PhC nanobeam cavity using chalcogenide materials, leading to enhanced light transmission. Additionally, we investigated the mid-infrared wavelengths within this structure, obtaining a resonance wavelength of 1781 nanometers where the electric field is wholly confined within the cavity due to precise optimization of critical parameters such as the number of holes, central cavity radius, and optimal gap size. This improved design shows excellent potential in various fields. Our structured method offers a valuable resource for developing efficient and optimal 2D Photonic Crystal cavities.

Authors contributions
Authors have contributed equally in preparing and writing the manuscript.

Availability of data and materials
The data that support the findings of this study are available from the corresponding author upon reasonable request.

Conflict of interests
The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

References

[1] J. S. Foresi, P. R. Villeneuve, J. Ferrera, E. R. Thoen, G. Steinmeyer, S. Fan, J. D. Joannopoulos, L. C. Kimerling, H. I. Smith, and E. P. Ippen. "**Photonic-bandgap microcavities in optical waveguides**.". 390:143, 1997.
DOI: https://doi.org/10.1038/36514.

[2] Y. Akahane, T. Asano, and B. S. Song S. Noda. "**High-Q photonic nanocavity in a two-dimensional photonic crystal**.". *Nature*, 425: 944, 2003.
DOI: https://doi.org/10.1038/nature02063.

[3] E. Kuramochi, M. Notomi, S. Mitsugi, A. Shinya, T. Tanabe, and T. Watan abe. "**Ultrahigh-Q photonic crystal nanocavities realized by the local width modulation of a line defect**.". *Appl. Phys. Lett.*,

88:041112, 2006.
DOI: https://doi.org/10.1063/1.2167801.

[4] P. Lalanne, C. Sauvan, and J. P. Hugonin. "**Photon confinement in photonic crystal nanocavities**.". *Laser Photonics Rev.*, 2:514, 2008.
DOI: https://doi.org/10.1002/lpor.200810018.

[5] M. Notomi, E. Kuramochi, and H. Taniyama. "**Ultrahigh-Q nanocavity with 1D photonic gap**.". *Opt. Express*, 16:11095, 2008.
DOI: https://doi.org/10.1364/OE.16.011095.

[6] T. Asano, Y. Ochi, Y. Takahashi, K. Kishimoto, and S. Noda. "**Photonic crystal nanocavity with a Q factor exceeding eleven million**.". *Optics Express*, 25(3):1769–1777, 2017.
DOI: https://doi.org/10.1364/OE.25.001769.

[7] S. Tomljenovic-Hanic, C. M. De Sterke, B. J. Eggleton, D. Freeman, C. Grillet, B. Luther-Davies, and M. J. Steel. "**Design, Fabrication and Characterisation of Chalcogenide-Based Photonic Crystal Slabs**.". *International Conference on Transparent Optical Networks*, 2:108–111, 2006.
DOI: https://doi.org/10.1109/ICTON.2006.248350.

[8] B. Suthar and A. Bhargava. "**Chalcogenide photonic crystal filters for optical communication**.". *AIP Conference Proceedings*, 1393 (1), 2011.
DOI: https://doi.org/10.1063/1.3653715.

[9] S. Tomljenovic-Hanic et al. "**Design, Fabrication and Characterisation of Chalcogenide-Based Photonic Crystal Slabs**.". *International Conference on Transparent Optical Networks*, 2, 2006.
DOI: https://doi.org/10.1109/ICTON.2006.248350.

[10] B. Suthar and A. Bhargava. "**Chalcogenide photonic crystal filters for optical communication**.". *AIP Conference Proceedings*, 1393 (1):502001, 2011.
DOI: https://doi.org/10.1063/1.3653715.

[11] D. Yuzhou, S. Li, and C. Liang. "**Design of a Chalcogenide Waveguide Amplifier Based on a Photonic Crystal with Compound Lattice**.". *Asia Communications and Photonics Conference. Optica Publishing Group*, 2013.
DOI: https://doi.org/10.1364/ACPC.2013.AW4B.2.

[12] D. Tripathi et al. "**Recent developments in chalcogenide phase change material-based nanophotonics**.". *Nanotechnology*, 34(50): 502001, 2023.
DOI: https://doi.org/10.1088/1361-6528/acf1a7.

[13] Y. Mecit, H. E. Kondakci, and M. Bayindir. "**Large and dynamical tuning of a chalcogenide Fabry-Perot cavity mode by temperature modulation**.". *Optics express*, 18(3):3168–3173, 2010.
DOI: https://doi.org/10.1364/OE.18.003168.

[14] S. Ivens et al. "**Photonic crystal nanobeam cavities with optical resonances around 800 nm**.". *JOSA B*, 36(7):1823–1828, 2019.
DOI: https://doi.org/10.1364/JOSAB.36.001823.

[15] S. Abbaslou, R. Gatdula, M. Lu, A. Stein, R. A. Soref, and W. Jiang. "**High-spectral-contrast symmetric modes in photonic crystal dual nanobeam resonators**.". *IEEE Photonics Technol. Lett.*, 28: 2137–2140, 2016.
DOI: https://doi.org/10.1109/LPT.2016.2582641.

[16] V. M. Passaro, B. Troia, M. La Notte, and F. De Leonardis. "**Photonic resonant microcavities for chemical and biochemical sensing**.". *RSC Advances*, 31:25–44, 2013.
DOI: https://doi.org/10.1039/C2RA21984K.

[17] Y. Takahashi, Y. Inui, M. Chihara, T. Asano, R. Terawaki, and S. Noda. "**A micrometre-scale Raman silicon laser with a microwatt threshold**.". *Nature*, 498:470, 2013.
DOI: https://doi.org/10.1038/nature12237.

[18] R. V. Nair and R. Vijaya. "**Photonic crystal sensors: An overview**.". *Prog Quantum Electron*, 34(3):89–134, 2010.
DOI: https://doi.org/10.1016/j.pquantelec.2010.01.001.

[19] M. Hosseinzadeh Sani, H. Saghaei, M. A. Mehranpour, and A. Asgariyan Tabrizi. "**A novel all-optical sensor design based on a tunable resonant nanocavity in photonic crystal microstructure applicable in MEMS accelerometers**.". *Photonic Sensors*, 11(4): 457–471, 2021.
DOI: https://doi.org/10.1007/s13320-020-0607-0.

[20] F. Parandin, F. Heidari, Z. Rahimi, and S. Olyaee. "**Two-Dimensional photonic crystal Biosensors: A review**.". *Opt Laser Technol*, 144:107397, 2021.
DOI: https://doi.org/10.1016/j.optlastec.2021.107397.

[21] Y. Ueda, T. Fujisawa, S. Kanazawa, W. Kobayashi, K. Takahata, and H. Ishii. "**Very-low-voltage operation of Mach-Zehnder interferometer-type electroabsorption modulator using asymmetric couplers**.". *Opt Express*, 22(12):14610, 2014.
DOI: https://doi.org/10.1364/OE.22.014610.

[22] F. O. Afzal, S. I. Halimi, and S. M. Weiss. "**Efficient side-coupling to photonic crystal nanobeam cavities via state-space overlap**.". *JOSA B.*, 36:585–595, 2019.
DOI: https://doi.org/10.1364/JOSAB.36.000585.

[23] S. I. Halimi, S. Hu, F. O. Afzal, and S. M. Weiss. "**Realizing high transmission intensity in photonic crystal nanobeams using a side-coupling waveguide**.". *Opt Lett.*, 43:4260–4263, 2018.
DOI: https://doi.org/10.1364/OL.43.004260.

[24] Y. Xu, Y. Li, R.K. Lee, and A. Yariv. "**Scattering-theory analysis of waveguide-resonator coupling**.". *Phys Rev E.*, 62:7389, 2000.
DOI: https://doi.org/10.1103/PhysRevE.62.7389.

[25] W. Xie, P. Verheyen, M. Pantouvaki, J. Van Campenhout, and D. Van Thourhout. "**Efficient resonance management in ultrahigh-Q 1D photonic crystal nanocavities fabricated on 300 mm SOI CMOS platform**.". *Laser Photon Rev.*, 15:2000317, 2021.
DOI: https://doi.org/10.1002/lpor.202000317.

[26] L. Kassa-Baghdouche. "**Optical properties of a point-defect nanocavity-based elliptical-hole photonic crystal for mid-infrared liquid sensing**.". *Phys. Scr.*, 95:015502, 2019.
DOI: https://doi.org/10.1088/1402-4896/ab474a.

[27] S. M. Zare et al. "**Efficient side-coupling configuration for photonic crystal nanobeam cavities with micro-ring resonators**.". *Optical and Quantum Electronics*, 56(4):692, 2024.
DOI: https://doi.org/10.1007/s11082-024-06478-5.