High Sensitivity And Ultra-High Quality Factor For An All-Optical Temperature Sensor Based On Photonic Crystal Technology

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Research Article

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Abstract

In our work, we propose a novel temperature sensor design based on a two-dimensional (2D) photonic crystal resonant cavity structure designed to detect and monitor temperature under very harsh environmental conditions from 0 °C to 500 ºC. The sensitivity of the proposed structure is 109.8 pm/ºC, an ultra-high quality factor, high transmission efficiency and ultra-compact size. The characteristics of the proposed sensor under different temperatures are simulated using the Plane Wave Expansion (PWE) method and Finite Difference Time Domain (FDTD) method to calculate, respectively, the Photonic Band Gap (PBG) and transmission efficiency. The results obtained show that the wavelength of the resonant cavity increases linearly with increasing temperature. Our sensor is suitable for applications based on nanotechnology.

Introduction

In recent years, Photonic Crystal (PhC) has attracted a lot of attention because of its more important properties for controlling and manipulating light through crystal [1]. Based on this characteristic, many scientists are finding designs and applications for various optical devices, such as optical decoders [2], logic gates [3,4], sensors [5], etc.

Due to their several advantages such as bandwidth properties and the flexibility of miniaturization, PhC-based devices are now playing a very important role in new fields such as optical sensing [6].

Recently, optical sensors have attracted the attention of researchers because of their advantage over electronic sensors, which are limited in transferring large data at a very higher speed, which can be solved by all-optical sensors, optical switches, and the tunable filter [7–11]. Optical sensors have been used effectively in many applications to detect various parameters such as pressure [12], biochemical sensors [13], gas [14], electric field [15], and temperature [16]. Temperature measurements are very important and are widely used in the risk control application of the petrochemical industry, automotive industry, avionics, industrial safety, biomedicine [17–20], and in many other applications.

Different optical temperature sensors based on 2D-PhC can be realized by ring resonators [21] and waveguides structure [22]. Although nanosensors based on ring resonators offer high normalized transmission efficiency, high sensitivity, and high-quality factor [23]. PhC waveguide-based nano-sensors have a good standardized transmission efficiency but a very low- quality factor [24].

In the present work, we have proposed a new hexagonal nanosensor based on a resonant cavity to detect the temperature in the range of 0°C to 500°C. The proposed temperature sensor has a wide range of applications in the defense, chemical, civil, metal production, semiconductor industry, and other fields. Temperature monitoring is also important for estimating the structural health of the device. The proposed design is more compact and simpler. Also, it offers a very high-quality factor and high sensitivity.

Bandgap Analysis

In this section, we proposed the initial temperature sensor structure based on 2D PhC, with a hexagonal array of circular silicon pillars whose the refractive index is equal to 3.42 suspended in the air. The numbers of the pillars in the x and z directions are respectively 23 and 17 and the ratio between the radius « R » and the lattice constant « a » is 0.3 (Fig. 1a).

In general, we use the PWE method to obtain the photonic bandgap which depends on three major parameters such as the lattice constant, the permittivity of dielectric materials, and the radius of the pillars. As shown in Fig. 1b, there are three PBG regions for the Transverse Electric (TE) mode. The normalized frequency (a/λ) ranges for the three regions are [0.23–0.32], [0.42–0.54], and [0.64–0.75]. The second wavelength range of the PBG is between 1481.48 and 1904.76 nm, which is suitable for the proposed sensor design because it belongs to the third window of optical telecommunications.

Analysis Of Temperature Effects

The detection operation of an all-optical temperature sensor is based on the refractive index variation as a function of the thermo-optical effect. The refractive index will be modified according to the temperature, which allows the photonic band gap and the center wavelength of the structure to be changed, and this variation is given as [25]:

$$n = n_0 + \alpha \Delta T$$

n_0 is the refractive index of the medium at zero temperature (0°C), α is the thermo-optical coefficient is given by 2.4×10^{-4}/°C for silicon [26] and ΔT is the temperature difference.

Results And Discussion

The designed temperature sensor structure of the 2D hexagonal shape based on the resonant cavity is showed in the figure (2). Our sensor is composed of two quasi-waveguides in the horizontal in-line direction, and a resonant cavity is located between them. The in-line quasi-waveguides are created by removing nine silicon pillars for both sides as input and output. The resonant cavity is created by optimizing rays of some internal pillars such as black rod (R*1.3), blue rods (R*0.5), green rods (R*0.45) placed in the hexagonal array to couple the light signal into quasi-in-line waveguides from the input to the output. The resonance wavelength is observed using the monitor which is placed at the sensor output. The total size of our sensor is 18 μm×12 μm.

This section describes the optical detection results obtained for the proposed sensor structure. The Fig. 3 shows the electric field distribution of resonant cavity for the wavelength 1682.1 nm at the output of our proposed device in the temperature range of 0°C to 500°C with a 50°C step size. This result is obtained by the use of the FDTD method. The Fig. 4 graphically represents the normalized transmission at the output of the proposed sensor at a zero temperature (0°C) which corresponds to an intensity of 81.5 % at the wavelength 1682.1 nm. On the other hand, the relationship of resonance wavelengths as a function of temperature has been illustrated in Fig. 5 and recapitulated in the Table 1. The necessary functional parameters of our designed temperature sensor are compared with the already mentioned sensors, which are summarized in Table 2. It indicates that the dynamic range, quality factor (Q) = $\lambda 0/\Delta\lambda$, and sensitivity (S) = $\partial\lambda/\partial T$ of the proposed temperature sensor are better than those of the previously existing sensor [25, 27, 28, 29, 30, 31, 32].

Table 1
Functional Parameters for the Temperature Sensor at Different Temperature Levels

Temperature (°C)	Refractive index (RIU)	Resonance wavelength (nm)	Transmission efficiency (%)	Quality factor	Wavelength shift
0	3.42	1682.1	81.5	17 156	/
50	3.432	1687.5	62.0	14 688	5.4 nm
100	3.444	1693.2	64.6	12 525	5.7 nm
150	3.456	1698.6	89.6	10 943	5.4 nm
200	3.468	1704.1	92.2	10 182	5.5 nm
250	3.48	1709.7	66.7	10 412	5.6 nm
300	3.492	1714.9	96.8	11 707	5.2 nm
350	3.504	1720.6	98.0	14 027	5.7 nm
400	3.516	1725.9	50.8	17 234	5.3 nm
450	3.528	1731.6	53	21 105	5.7 nm
500	3.54	1737.0	50.1	25 349	5.4 nm

Table 2. The Proposed Functional Parameters of the Temperature Sensor Compared with the previous works

Reference	Dynamic Range (°C)	Quality factor	Temperature sensitivity (pm/°C)
Present work	0 to 500	17 156	109.8
[25]	0 to 100	/	6.6
[27]	25 to 200	214	/
[28]	0 to 450	738.7	59.25
[29]	0 to 80	2506.5	93.61
[30]	20 to 90	/	84
[31]	20 to 70	415.7	88.7
[32]	0 to 360	/	92.3

Conclusion

In this paper, we presented a two-dimensional hexagonal structure based on the resonant cavity designed for temperature sensing applications. The presence of the thermo-optical effect of the 'Si' material plays a very important role in the all-optical temperature sensor. The results of the PWE simulation show that the resonance frequency is shifted to a lower frequency by increasing the temperature. The study all the functional characteristics of our proposed sensor, is realized by using the PWE and FDTD methods. For temperature detection, the resonant cavity structure has a maximum quality factor of 17 156, a very high sensitivity of about 109.8 pm/°C, the dynamic range is 0°C to 500°C, and a size of 216 μm2. It is therefore a design is simple, stable, and suitable for various applications in integrated optics.

Declarations

Ethics approval and consent to participate

(Not applicable)

Consent for publication

(Not applicable)

Availability of data and materials

(Not applicable)

Competing interests

(Not applicable)

Funding

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Authors' contributions

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Disclosure of potential conflicts of interest

The authors have no conflicts of interest to declare that are relevant to the content of this article.

Research involving Human Participants and/or Animals

(Not applicable)

Informed consent

(Not applicable)

References

1. Joannopoulos JD, Johnson SG, Winn JN (2008) and R.D. Meade. Photonic Crystals - Molding the Flow of Light. Princeton University Press, Princeton
2. Ouahab I, Naoum R (2016) A novel all optical 4× 2 encoder switch based on photonic crystal ring resonators. Optik 127(19):7835–7841
3. Kouddad E, Naoum R (2020) Optimization of an all-optical photonic crystal NOT logic gate using switch based on nonlinear Kerr effect and ring resonator. Sensor Letters 18(2):89–94
4. Kouddad E, Naoum R. A novel proposal based on 2D linear resonant cavity photonic crystals for all-optical NOT, XOR and XNOR logic gates. Journal of Optical Communications, 1(ahead-of-print), 2020
5. Biswas U, Rakshit JK, Das J, Bharti GK, Suthar B, Amphawan A, Najjar M (2020) Design of an Ultra-Compact and Highly-Sensitive Temperature Sensor Using Photonic Crystal Based Single Micro-Ring Resonator and Cascaded Micro-Ring Resonator. Silicon, pp 1–8
6. Radhouene M, Chhipa MK, Najjar M (2017) and al. Novel Design of Ring Resonator Based Temperature Sensor Using Photonics Technology. Photonic Sensors 7:311–316
7. Wang HZ, Zhou WM, Zheng JP (2010) A 2D rods-in-air square-lattice photonic crystal optical switch. Optik 121(21):1988–1993
8. Radhouene M, Monia N, Janyani V. Tunable photonic crystal switch based on ring resonators with improved crosstalk and Q-factor. In International Conference on Optical and Photonics Engineering (icOPEN 2016) (Vol. 10250, p. 102500Z). International Society for Optics and Photonics, 2017
9. Chhipa Mk, Radhouene M, Robinson S, Suthar B (2017) Improved dropping efficiency in two-dimensional photonic crystal-based channel drop filter for coarse wavelength division multiplexing application. Opt Eng 56(1):015107
10. Suthar B (2015) Tuning of guided mode in two dimensional chalcogenide based photonic crystal waveguide. Optik 126(22):3429–3431
11. Park I, Lee HS, Kim HJ, Moon KM, Lee SG (2004) and al. Photonic crystal power-splitter based on directional coupling. Opt Express 12(15):3599–3604
12. Shanthi KV, Robinson S (2014) Two-dimensional photonic crystal based sensor for pressure sensing. Photonic sensors 4(3):248–253
13. Sharma P, Sharan P (2014) Photonic crystal based ring resonator sensor for detection of glucose concentration for biomedical applications. International Journal of Emerging Technology Advanced Engineering 4(30):702–706

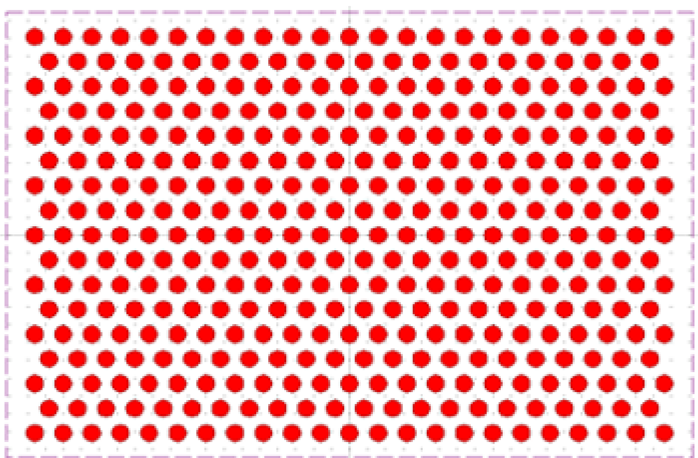
14. Qian X, Zhao Y, Zhang YN, Wang Q (2016) Theoretical research of gas sensing method based on photonic crystal cavity and fiber loop ring-down technique. Sens Actuators B 228:665–672
15. Zhao Y, Zhang YN, Lv RQ, Li J (2017) Electric field sensor based on photonic crystal cavity with liquid crystal infiltration. J Lightwave Technol 35(16):3440–3446
16. Tinker MT, Lee JB (2005) Thermal and optical simulation of a photonic crystal light modulator based on the thermo-optic shift of the cut-off frequency. Optics express 13(18):7174–7188
17. Zhang Y, Huang J, Lan X, Yuan L, Xiao H (2014) Simultaneous measurement of temperature and pressure with cascaded extrinsic Fabry–Perot interferometer and intrinsic Fabry–Perot interferometer sensors. Opt Eng 53(6):067101
18. Wu C, Zhang Y and B. O. Guan. Pressure and temperature discrimination based on dual-FBG written in microstructured fiber and standard fiber. In 21st International Conference on Optical Fiber Sensors (Vol. 7753, p. 775398). International Society for Optics and Photonics, 2011
19. Anuszkiewicz A, Statkiewicz-Barabach G, Borsukowski T (2012) and al. Sensing characteristics of the rocking filters in microstructured fibers optimized for hydrostatic pressure measurements. Opt Express 20(21):23320–23330
20. Xu H, Hafezi M, Fan J, Taylor JM, Strouse GF, Ahmed Z (2014) Ultra-sensitive chip-based photonic temperature sensor using ring resonator structures. Opt Express 22(3):3098–3104
21. Sharma P, Sharan P (2014) Photonic crystal based ring resonator sensor for detection of glucose concentration for biomedical applications. International Journal of Emerging Technology Advanced Engineering 4(30):702–706
22. Goyal AK, Pal S (2015) Design and simulation of high sensitive photonic crystal waveguide sensor. Optik 126(2):240–243
23. Huang L, Tian H, Yang D, Zhou J, Liu Q, Zhang P, Ji Y (2014) Optimization of figure of merit in label-free biochemical sensors by designing a ring defect coupled resonator. Opt Commun 332:42–49
24. Jindal S, Sobti S, Kumar M, Sharma S, Pal MK (2016) Nanocavity-coupled photonic crystal waveguide as highly sensitive platform for cancer detection. IEEE Sens J 16(10):3705–3710
25. Fu HW, Zhao H, Qiao XG, Li Y (2011) D. Z. Zhao and Z. Yong. Study on a novel photonic crystal temperature sensor. Optoelectron Lett 7(6):419–422
26. Tinker MT, Lee JB (2005) Thermal and optical simulation of a photonic crystal light modulator based on the thermo-optic shift of the cut-off frequency. Opt Express 13(18):7174–7188
27. J.Boruah Y, Kalra, Sinha RK (2014) Demonstration of temperature resilient properties of 2D silicon carbide photonic crystal structures and cavity modes. Optik 125(5):1663–1666
28. Rajasekar R, Robinson S (2019) Nano-pressure and temperature sensor based on hexagonal photonic crystal ring resonator. Plasmonics 14(1):3–15
29. Bounaas F, Labbani A (2020) High Sensitivity Temperature Sensor Based on Photonic Crystal Resonant Cavity. Progress In Electromagnetics Research 90:85–90

30. Hocini A, Harhouz A (2016) Modeling and analysis of the temperature sensitivity in two-dimensional photonic crystal microcavity. J Nanophotonics 10(1):016007

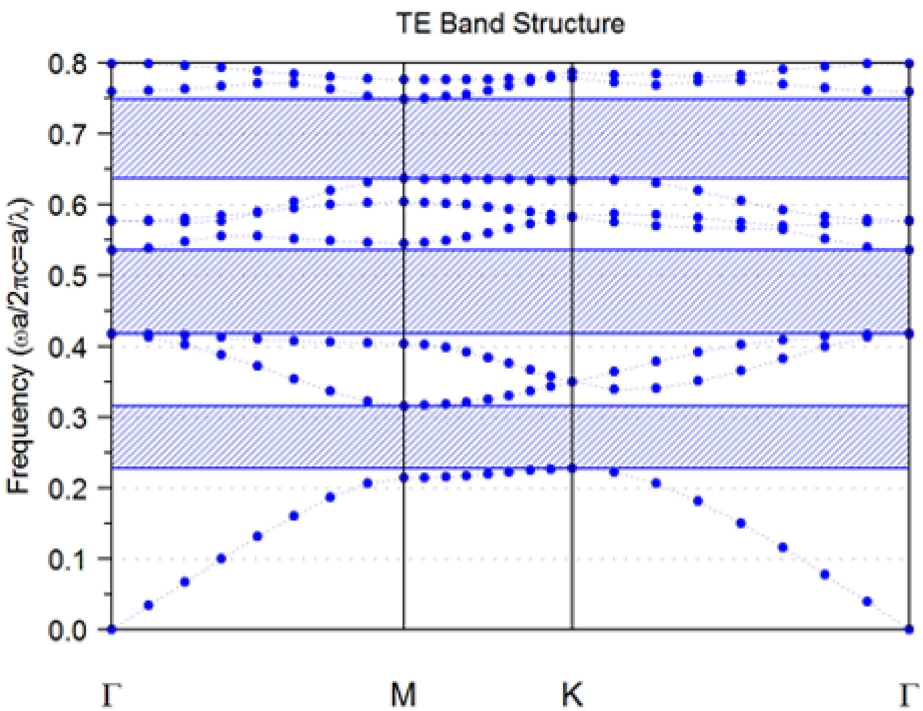
31. Chen YH, Shi WH, Feng L, Xu XY, Shang-Guan MY (2019) Study on simultaneous sensing of gas concentration and temperature in one-dimensional photonic crystal. Superlattices Microstruct 131:53–58

32. Zegadi R, Ziet L, Zegadi A (2019) Design of high sensitive temperature sensor based on two-dimensional photonic crystal. Silicon, pp 1–7

Figures



(a)



(b)

Figure 1

Initial Structure (a) Pillars in the air (hexagonal lattice) (b) Band Gap Structure for the TE Mode

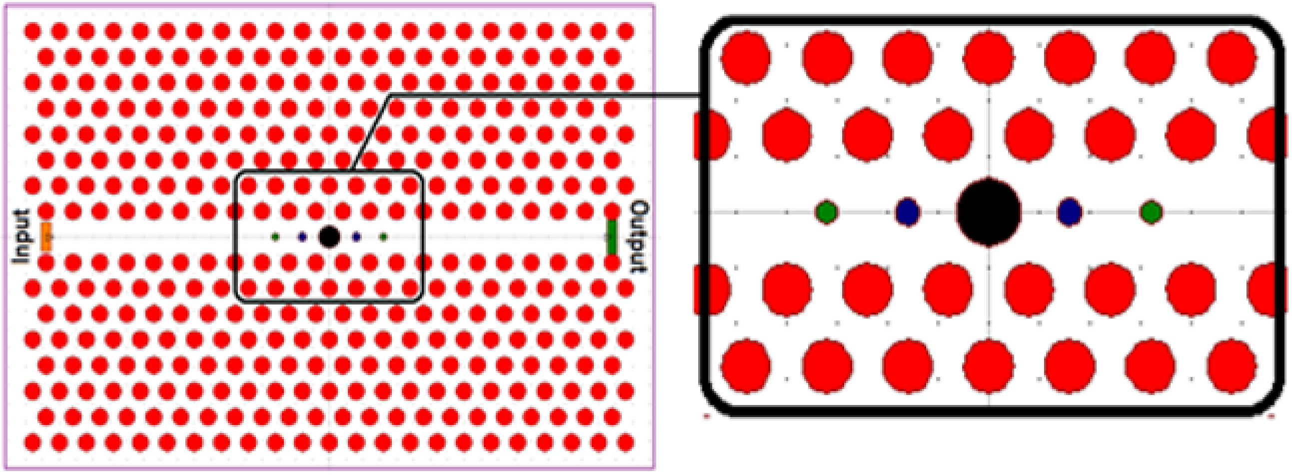


Figure 2

Proposed Design for the Temperature Sensor

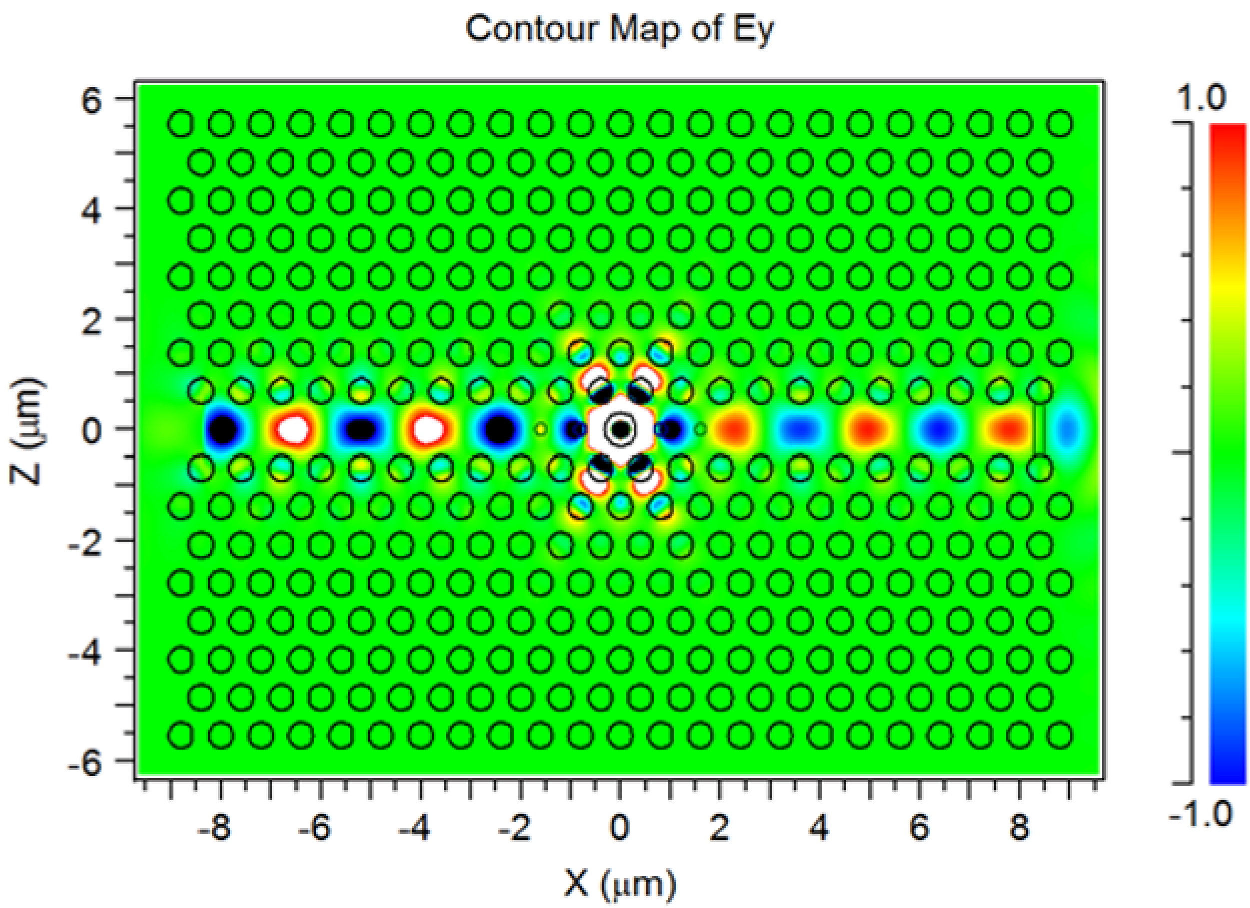


Figure 3

Electric Field Distribution of Resonant Cavity at 1682.1 nm

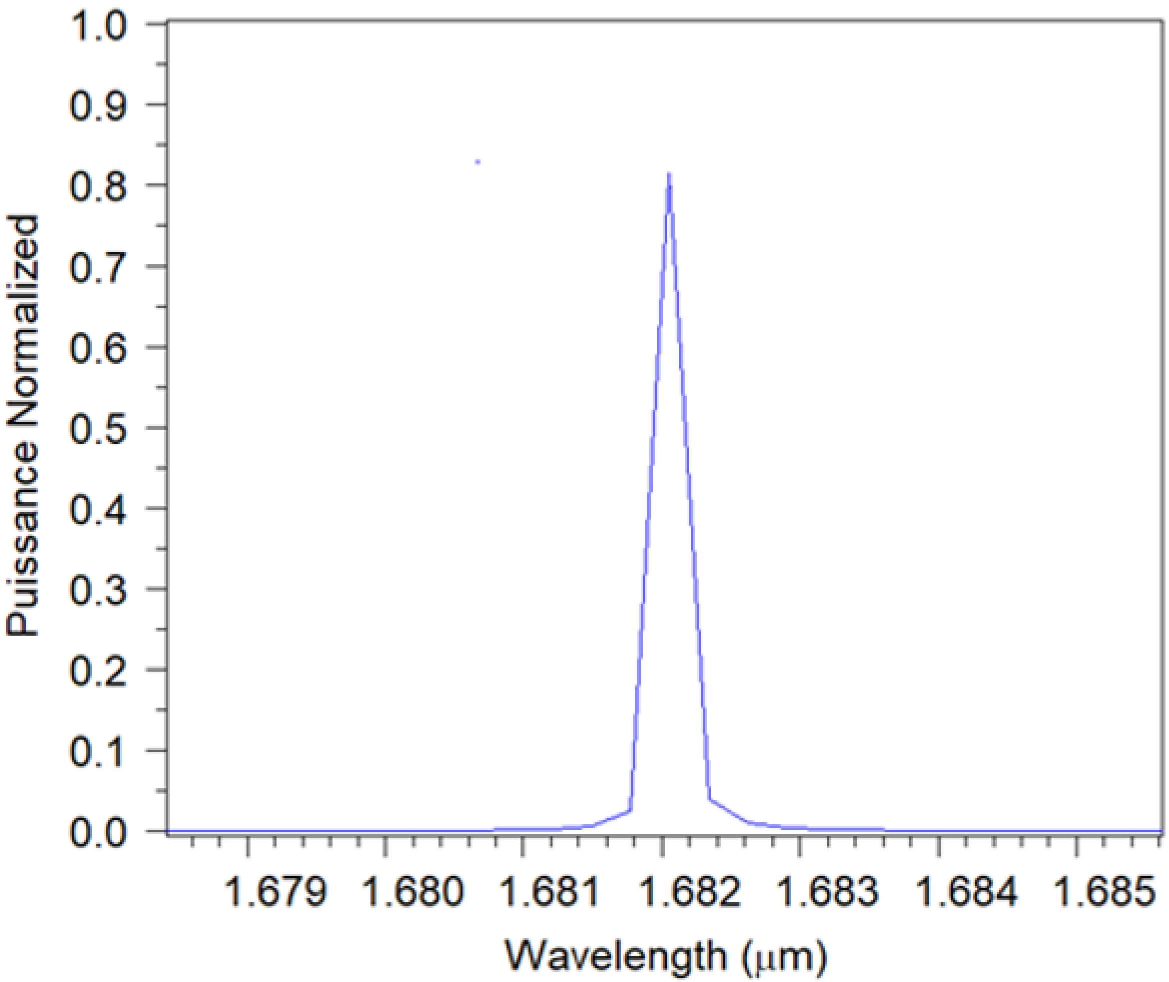


Figure 4

Resonant Wavelength of a Resonant Cavity at 0 °C

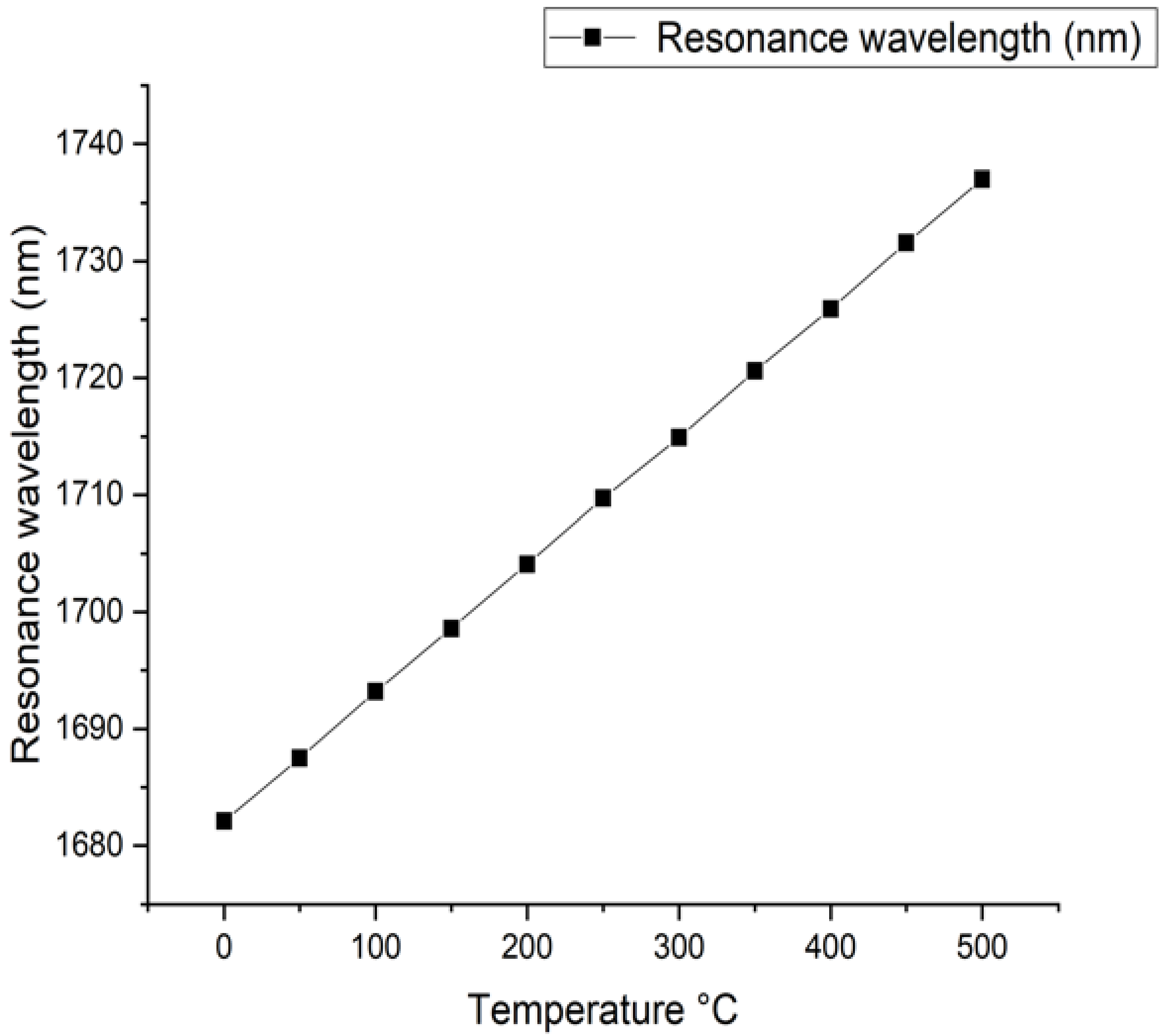


Figure 5

The Linear Relation between Resonant Wavelengths and Temperature