

Measurement of the linear thermo-optical coefficient of $\text{Ga}_{0.51}\text{In}_{0.49}\text{P}$ using photonic crystal nanocavities

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$\text{Ga}_{0.51}\text{In}_{0.49}\text{P}$ is a promising candidate for thermally tunable nanophotonic devices due to its low thermal conductivity. In this work we study its thermo-optical response. We obtain the linear thermo-optical coefficient $dn/dT = 2.0 \pm 0.3 \cdot 10^{-4} \text{ K}^{-1}$ by investigating the transmission properties of a single mode-gap photonic crystal nanocavity. © 2017 Optical Society of America

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1. INTRODUCTION

Several III-V semiconductors are used for nanophotonic devices, such as GaAs [1], GaP [2], and InP [3] for their specific properties such as optical tunability. Local tuning of the refractive index has been proposed as a method to create localized resonances in a waveguide [4] and to tune complex localized states [5,6]. For local thermal tuning, the high thermal conductivity of Si or Si_3N_4 is unfavorable. A potential material for thermally tunable nanophotonic devices is GaInP, which became popular during recent years [7–11]. Its thermal conductivity [12] is more than 6 times smaller than for Si and Si_3N_4 , so in addition to the absence of two-photon absorption at 1550 nm and favorable nonlinear properties [10] it is a promising candidate for thermally tunable photonics where multiple closely spaced elements have to be tuned independently. The thermo-optical coefficient of this material has indirectly been obtained before as a result of a series of complex measurements and heat diffusion calculations in Ref. [7], implying the need of a more direct measurement. To the best of our knowledge, the precise value of dn/dT has not been reported in the literature. Therefore, in this work we investigate the thermal response of a single photonic crystal nanocavity made of $\text{Ga}_{0.51}\text{In}_{0.49}\text{P}$ for a homogeneously heated sample where the temperature of the sample is directly measured. Our rigorous analysis allows us to obtain the precise value of the thermo-optical coefficient of the refractive index for this material.

2. SAMPLE AND EXPERIMENTAL SETUP

To experimentally measure the thermo-optical coefficient of the $\text{Ga}_{0.51}\text{In}_{0.49}\text{P}$, a nanophotonic sample containing photonic crystal nanocavities was mounted on a thermally controlled stage, so the sample was homogeneously heated, and the temperature of the stage was locked with a precision of $\pm 0.001 \text{ K}$.

The temperature drop between the stage and the sample was measured in a separate run using a PT-100 temperature sensor placed in the position of the photonic crystal. It was found that temperature drop varied from 1.1 to 1.4 K linearly for stage temperatures between 27.5°C and 77.5°C. All temperatures mentioned from here are sample temperatures corrected for this temperature drop and measured with an absolute precision of 0.3 K as verified with a calibrated digital thermometer.

The sample is an air-suspended photonic crystal membrane with a linear array of 10 directly coupled mode-gap photonic crystal nanocavities made of $\text{Ga}_{0.51}\text{In}_{0.49}\text{P}$. The thickness of the semiconductor membrane is 180 nm. The structure of a single cavity is presented as the inset in Fig. 1. It is made in a photonic crystal waveguide with width $W_0 = 0.98\sqrt{3}a$ where $a = 485 \text{ nm}$ is a period of a triangular photonic crystal lattice. Red holes are shifted away from the waveguide by 6 nm, green holes by 4 nm, and purple holes by 2 nm to create a cavity mode. Such cavities are known for large experimentally measured Q factors [13,14], and therefore they are suitable for precise thermal measurements. The first and last cavities in the

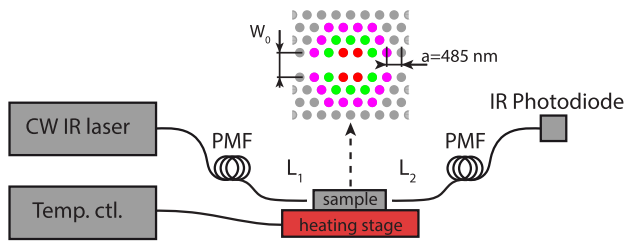


Fig. 1. Experimental setup. Transmission through the sample is measured. The sample temperature is locked to $\pm 0.001^\circ\text{C}$ using a temperature controller. Inset shows the cavity structure. Holes are represented with circles. Different colors correspond to different hole shifts.

array are coupled to input and output photonic crystal waveguides with width $W_1 = 1.1\sqrt{3}a$. The waveguides are used to launch and collect light from the structure.

The structure was probed by IR light with a wavelength of around 1550 nm from the CW tunable laser. The light was coupled into and out from the structure with polarization-maintaining lensed fibers L_1 and L_2 with $\text{NA} = 0.55$. The out-coupled light was collected on an IR photodiode for transmission measurements. The sample was kept in nitrogen atmosphere to avoid oxidation [15,16]. The resonance frequencies of cavities are perturbed by unavoidable disorder, which breaks the resonance hybridization. This normally undesired effect allowed us to pick an isolated single cavity resonance. We picked the single resonance corresponding to the third cavity in the array, verified by our pump line-scan technique [7,8,17]. The transmission spectrum of the resonance at 48.7°C is presented in Fig. 2. The spectrum has a clear Fano-like lineshape due to the interference with transmitted TM light. The spectrum is fitted with a Fano lineshape function [18,19] and a 1st order polynomial for the background. The lineshape is perfectly described by the fit, so it is used to obtain line parameters. The loaded Q factor of the resonance is $Q = 1.6 \pm 0.1 \cdot 10^5$.

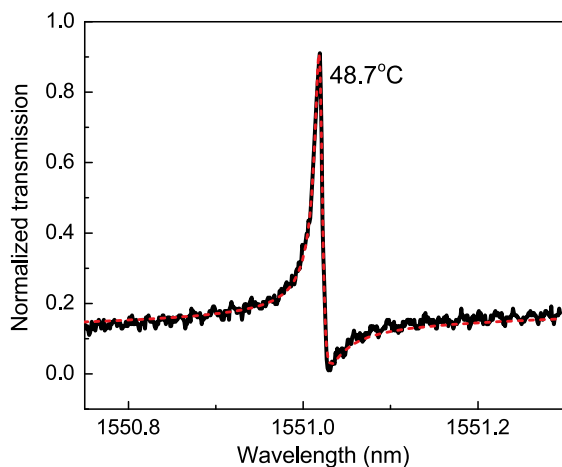


Fig. 2. Transmission spectrum. Transmission spectra of the sample at 48.7°C . Dashed line represents Fano lineshape fit.

3. EXPERIMENT DESCRIPTION

For the measurement of the thermo-optical coefficient the resonance wavelength was measured for several temperatures of the sample ranging from 26.4°C to 76°C . Spectra for all temperatures are presented in Fig. 3. The resonance experiences a redshift, signifying that the material has a positive thermo-optical response. All spectra have a Fano-like lineshape. There was no systematic change of the Q factor which signifies that within this temperature range the mode profile of the cavity does not change. In total, the resonance redshifts by about 4.5 nm when the temperature rises by approximately 49.7°C . The dependence of resonance wavelength on the temperature of the sample is presented in Fig. 4. The resonance wavelength changes linearly with increasing temperature, as shown by the fit.

When a sample is heated, there is always an extra resonance shift as a result of the evaporation of the water film from the surface of the sample [15] in addition to the redshift due the increase in temperature. The exact magnitude of this extra shift

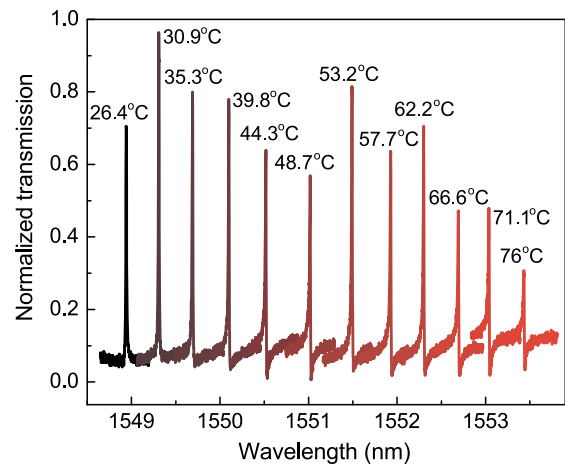


Fig. 3. Transmission spectra. Patched graph showing all transmission spectra collected in this experiment. The color of the lines changes from black to red to emphasize the temperature difference.

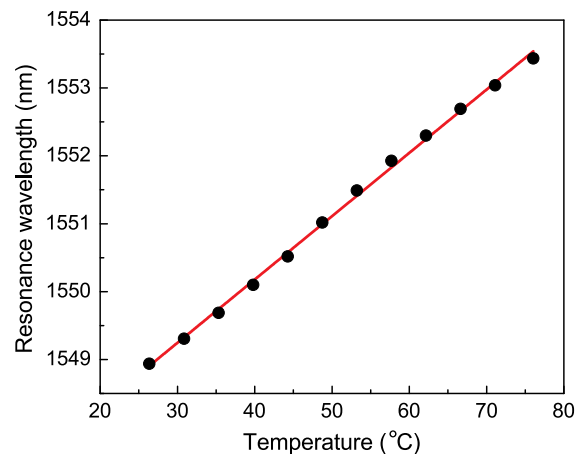


Fig. 4. Resonance wavelength versus temperature of the sample. The red line represents a line fit of the experimental data. The error for temperature is smaller than the datapoint size.

depends on details of the surface condition. In laser heating experiments with similar temperature changes and resonance shifts we have observed this extra shift to be about 0.6 nm or less. As a worst case estimate we add an additional error term to the error of the linear fit that corresponds to the extra change of the resonance wavelength by 0.6 nm when temperature is increased by 49.7°C. The resulting tuning slope is $d\lambda/dT = 9 \pm 1 \cdot 10^{-2}$ nm/K.

Using perturbation theory and scaling of Maxwell equations one can get a precise value of linear thermo-optic coefficient dn/dT of the refractive index of $\text{Ga}_{0.51}\text{In}_{0.49}\text{P}$. To the 1st order, the following equation for relative resonance wavelength shift can be applied [20], as follows:

$$\frac{\Delta\lambda}{\lambda} = \frac{\Delta\lambda_n}{\lambda} + \frac{\Delta\lambda_a}{\lambda}. \quad (1)$$

Here, $\Delta\lambda_n/\lambda$ and $\Delta\lambda_a/\lambda$ are relative resonance wavelength changes caused by two processes: refractive index increase and sample expansion due to heating. The first term is a direct result of the 1st order perturbation theory [20], while the second term comes as a consequence of the scaling nature of Maxwell equations [20], as follows:

$$\frac{\Delta\lambda_n}{\lambda} = \frac{\Delta n}{n} \cdot \frac{\int_{\text{membrane}} \epsilon |\mathbf{E}(\mathbf{r})|^2 d\mathbf{r}}{\int_{\text{all}} \epsilon |\mathbf{E}(\mathbf{r})|^2 d\mathbf{r}} = \frac{1}{n} \frac{dn}{dT} \Delta T \mathcal{E}_m \quad (2)$$

$$\frac{\Delta\lambda_a}{\lambda} = \frac{\Delta a}{a} = \alpha_T \Delta T. \quad (3)$$

Here Δn is the refractive index change due to temperature increase ΔT , ϵ and n are the dielectric constant and refractive index of the membrane material, and $\mathbf{E}(\mathbf{r})$ is the electric field of the cavity mode. $\mathcal{E}_m$ is the fraction of the electric-field energy inside the membrane. In Eq. (2) we considered that the change in the refractive index of ambient nitrogen is negligible [21] in comparison to the change of the refractive index of the semiconductor. According to our 3D FDTD calculations, the fraction of electric-field energy in the membrane is 0.88. In Eq. (3) $\Delta a/a$ is the relative change of the photonic crystal lattice, and α_T is the thermal expansion coefficient. Finally, the dn/dT value can be obtained from

$$\frac{dn}{dT} = \frac{n}{\lambda \mathcal{E}_m} \left(\frac{d\lambda}{dT} - \alpha_T \lambda \right). \quad (4)$$

The thermal expansion coefficient [22] α_T for $\text{Ga}_{0.51}\text{In}_{0.49}\text{P}$ is equal to $5.4 \pm 0.3 \cdot 10^{-6}$ K⁻¹. The experimentally measured value of dn/dT is then equal to $dn/dT = 2.0 \pm 0.3 \cdot 10^{-4}$ K⁻¹. We note that in the case of GaInP, linear expansion gives a noticeable contribution to the tuning slope of the cavity resonance. Without accounting for that effect, the value of dn/dT would be about 10% larger.

In Ref. [7] we used complex modeling to estimate dn/dT for a locally laser heated membrane, where the temperature was calculated from absolute power, thermal conductivity, and absorptivity, thereby introducing many uncertainties. In addition, due to the local heating the membrane in that experiment was thermally stressed. The present experiment uses a direct temperature measurement with much less uncertain parameter performed on an unstressed membrane.

4. CONCLUSION

In conclusion, we investigated the thermo-optical effect of the refractive index for $\text{Ga}_{0.51}\text{In}_{0.49}\text{P}$. Our measurement took place for a freely expanding membrane, and we accounted for the effect of thermal expansion of the material. We found no significant Q factor change during our measurement, guaranteeing that the working wavelength of photonic devices based on nanocavities made of $\text{Ga}_{0.51}\text{In}_{0.49}\text{P}$ can be safely biased with temperature within the range of about 5 nm. This work enables precise thermal tuning of GaInP-based photonic devices, making GaInP one of the lowest thermal conductivity semiconductors used in photonics.

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REFERENCES

1. A. Faraon, D. Englund, D. Bulla, B. Luther-Davies, B. J. Eggleton, N. Stoltz, P. Petroff, and J. Vučković, "Local tuning of photonic crystal cavities using chalcogenide glasses," *Appl. Phys. Lett.* **92**, 043123 (2008).
2. K. Rivoire, Z. Lin, F. Hatami, and J. Vučković, "Sum-frequency generation in doubly resonant GaP photonic crystal nanocavities," *Appl. Phys. Lett.* **97**, 043103 (2010).
3. Y. Yu, E. Palushani, M. Heuck, N. Kuznetsova, P. Trøst, S. Ek, D. Vukovic, C. Peucheret, L. Katsuo, S. Combré, A. D. Rossi, K. Yvind, and J. Mørk, "Switching characteristics of an InP photonic crystal nanocavity: experiment and theory," *Opt. Express* **21**, 9221–9231 (2013).
4. M. Notomi and H. Taniyama, "On-demand ultrahigh-Q cavity formation and photon pinning via dynamic waveguide tuning," *Opt. Express* **16**, 18657–18666 (2008).
5. F. Riboli, N. Caselli, S. Vignolini, F. Intonti, K. Vynck, P. Barthelemy, A. Gerardino, L. Balet, L. Li, A. Fiore, M. Gurioli, and D. Wiersma, "Engineering of light confinement in strongly scattering disordered media," *Nat. Mater.* **13**, 720–725 (2014).
6. J. Pan, Y. Huo, K. Yamanaka, S. Sandhu, L. Scaccabarozzi, R. Timp, M. L. Povinelli, S. Fan, M. M. Fejer, and J. S. Harris, "Aligning microcavity resonances in silicon photonic-crystal slabs using laser-pumped thermal tuning," *Appl. Phys. Lett.* **92**, 103114 (2008).
7. S. Sokolov, J. Lian, E. Yüce, S. Combré, G. Lehoucq, A. De Rossi, and A. P. Mosk, "Local thermal resonance control of GaInP photonic crystal membrane cavities using ambient gas cooling," *Appl. Phys. Lett.* **106**, 171113 (2015).
8. J. Lian, S. Sokolov, E. Yüce, S. Combré, A. De Rossi, and A. P. Mosk, "Measurement of the profiles of disorder-induced localized resonances by local tuning," *Opt. Express* **24**, 21939–21947 (2016).
9. A. Martin, G. Moille, S. Combré, G. Lehoucq, T. Debuisschert, J. Lian, S. Sokolov, A. P. Mosk, and A. De Rossi, "Triply-resonant continuous wave parametric source with a microwatt pump," *ArXiv:1602.04833* (2016).
10. S. Combré, Q. V. Tran, A. De Rossi, C. Husko, and P. Colman, "High quality GaInP nonlinear photonic crystals with minimized nonlinear absorption," *Appl. Phys. Lett.* **95**, 221108 (2009).
11. A. S. Clark, C. Husko, M. J. Collins, G. Lehoucq, S. Xavier, A. D. De Rossi, S. Combré, C. Xiong, and B. J. Eggleton, "Heralded single-photon source in a III-V photonic crystal," *Opt. Lett.* **38**, 649–651 (2013).

12. S. Adachi, "Lattice thermal conductivity of group-IV and III-V semiconductor alloys," *J. Appl. Phys.* **102**, 063502 (2007).
13. E. Kuramochi, M. Notomi, S. Mitsugi, A. Shinya, T. Tanabe, and T. Watanabe, "Ultrahigh-Q photonic crystal nanocavities realized by the local width modulation of a line defect," *Appl. Phys. Lett.* **88**, 041112 (2006).
14. S. Combr  , A. De Rossi, Q. V. Tran, and H. Benisty, "GaAs photonic crystal cavity with ultrahigh Q: microwatt nonlinearity at 1.55 μm ," *Opt. Lett.* **33**, 1908–1910 (2008).
15. C. J. Chen, J. Zheng, T. Gu, J. F. McMillan, M. Yu, G. Lo, D. Kwong, and C. W. Wong, "Selective tuning of high-Q silicon photonic crystal nanocavities via laser-assisted local oxydation," *Opt. Express* **19**, 12480–12489 (2011).
16. K. Navr, "Thermal oxidation of gallium arsenide," *Czech. J. Phys. B* **18**, 266–274 (1968).
17. S. Sokolov, J. Lian, E. Y  ce, S. Combr  , A. De Rossi, and A. P. Mosk, "Tuning out disorder-induced localization in nanophotonic cavity arrays," *Opt. Express* **25**, 4598–4606 (2017).
18. U. Fano, "Effects of configuration interaction on intensities and phase shifts," *Phys. Rev.* **124**, 1866–1878 (1961).
19. W. Zhou, D. Zhao, Y. C. Shuai, H. Yang, S. Chuwongin, A. Chadha, J. H. Seo, K. X. Wang, V. Liu, Z. Ma, and S. Fan, "Progress in 2D photonic crystal Fano resonance photonics," *Prog. Quantum Electron.* **38**, 1–74 (2014).
20. J. Joannopoulos, S. G. Johnson, J. N. Winn, and R. D. Meade, *Photonic Crystals: Molding the Flow of Light* (Princeton University, 2008).
21. J. Zhang, P. Huang, Y. Li, and H. Wei, "Design and performance of an absolute gas refractometer based on a synthetic pseudo-wavelength method," *Appl. Opt.* **52**, 3671–3679 (2013).
22. I. Kudman and R. J. Paff, "Thermal expansion of $\text{In}_x\text{Ga}_{1-x}\text{P}$ alloys," *J. Appl. Phys.* **43**, 3760–3762 (1972).