Extended Abstracts of the 2019 International Conference on Solid State Devices and Materials, Nagoya, 2019, pp91-92

Photonic Crystal Nanolasers with Enhanced Wavelength Tunability by Waveguides

Tsan-Wen Lu, Cheng-Han Lai and Po-Tsung Lee

National Chiao Tung Univ.
Rm. 401 CPT Building, 1001 Ta-Hsueh Road, Hsinchu 30010, Taiwan.
Phone: +886-3-5712121-59341, E-mail: tsanwenlu@gmail.com

An idea of integrating waveguides with 1D photonic crystal (PhC) tunable nanolasers in polydimethylsiloxane for local strain enhancement is proposed and demonstrated. The resulted enlarged wavelength tunability by strain can provide further optimization and possibilities for different tunable PhC devices in soft photonic circuits.

1. Background and Motivation

In recent years, embedding semiconductor-based PhC resonators in different soft materials [1] have been utilized for different functional devices in flexible photonic integrated circuits (PICs). Generally, the embedded PhCs can be with various continuous and discontinuous lattice structures for different stable and tunable optical properties under applied strain. In the latter one, the changes of resonance modes (usually in wavelength) caused by lattice deformation can be served as the basis of tunable devices or quantity for optical sensing, for example, tunable nanolasers [2], dynamic filters [3], strain sensors [4], and so on. In these applications, their performances are highly related to the wavelength responses of resonance modes inside to the applied strain (R_s, defined as wavelength shift for every percentage strain variation). Unfortunately, once the lattice structure and resonance mode are chosen, the R_s is given and further optimizations become very tough, which is usually limited in the range of 2–7 nm.

To break this limitation, locally enhancing the strain within core region of the devices in other research fields [5-6] would be a feasible solution. In our unpublished works, we have proposed and demonstrate a design of "nanoclamps" setting nearby 1D PhC nanocavity embedded in deformable polydimethylsiloxane (PDMS). The induced film-edge strain [7] of nanoclamps owing to significant stiffness variation between semiconductor and PDMS can shape and enhance the strain distribution within the nanocavity, which increase the R_s under the same applied strain to the entire structure. However, our previous design is with very delicate parameters and unable to be applied for compressive and stretching strain simultaneously. In this report, we propose and demonstrate that significant R_s enhancement can also be achieved by simply integrating waveguides with 1D PhC nanocavity, while above shortcomings can be made up.

2. Proposal and Simulation Results

To simply explain our proposal in finite-element simulation, we first set two InGaAsP optical waveguides with finite length L, width of 1 μm, and thickness of 0.22 μm within PDMS, as shown in Fig. 1(a). They are separated by a distance d of 10 μm along x-direction. With different L of 5 and 10 μm, the simulated strain in the x-direction (x-strain) under total strain (ξ_{tot}, the ratio between total structural length after and before applying stress) of 1.05 and 0.95 along the x-axis are shown in Figs. 1(b) and (c). For both cases, the x-strain of PDMS outside the waveguide remain constant, while the enhanced strain within the gap resulted from the induced strain near the ends of each waveguide are observed. For the cases with L of 5 μm, the strain within the gap (ξ_{int}) are enhanced to average values of 1.08 and 0.92 respectively. For the case with longer L of 10 μm in Fig. 1(c), they are further enhanced to 1.11 and 0.89. Therefore, it is reasonable that an enhanced R_s can be obtained from PhC nanocavity set within above strain-enhanced region between waveguides.

Figure 2(a) shows our proposed 1D PhC nanocavity with above waveguides (L = 5 μm) embedded in PDMS, whose mode-gap confinement is given by the PhCs with linearly increased lattice width w_n and constant a_n (both in 10-nm increments) from the center to the outer regions. By applying compressive (ξ_{tot} = 0.95) and stretching (ξ_{tot} = 1.05) strain to this design, their ξ_{int} between lattices in the central (cavity) region show extreme values of than 0.82 and 1.18 respectively, as shown in Fig. 2(b). These enhanced ξ_{int} distributions are directly reflected on their lattice constant shifts in Fig. 2(c), which lead to enlarged R_s of −9.7 and 9.3 nm than that (−8.1 and 7.8 nm) in nanocavity without waveguides. In addition, the small differences in mode distributions and high quality factors (Q) in Fig. 2(c) guarantee that inserting waveguides

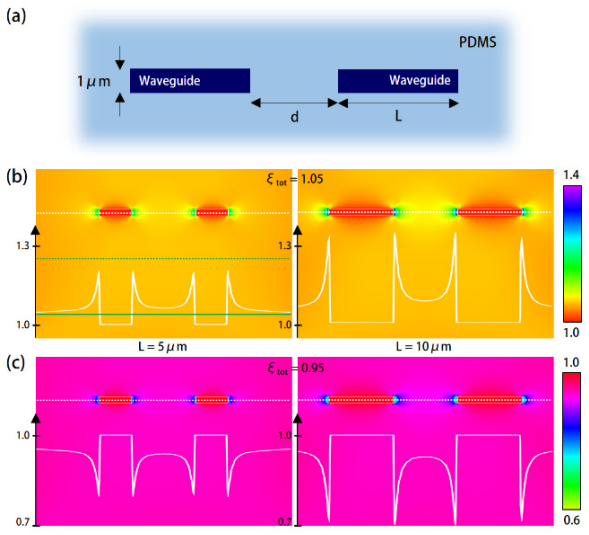

Fig. 1 (a) Scheme and parameters of two waveguides embedded within PDMS and (b) (c) their theoretical x-strain distributions under different L and ξ_{tot}.

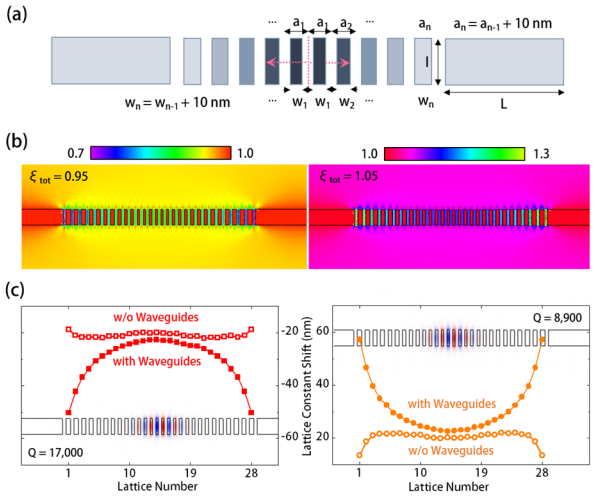

Fig. 2 (a) Design of 1D PhC nanocavity with waveguides and their (b) theoretical *x*-strain, (c) lattice shift distributions, and optical mode profiles (in E_y fields) inside under ξ_{tot} of 0.95 and 1.05.

shows no significant optical degradation to the mode inside because of uniform strain enhancement near the cavity region.

3. Experimental Results

Figure 3(a) simply shows the flowchart of manufacturing our proposed design. The devices are fabricated on the InGaAsP multi-quantum wells (MQWs) by a series of electron beam lithography and dry etching processes, as shown by the top- and tilt-view SEM pictures in Fig. 3(b). The nanocavity is then embedded into a PDMS substrate by bonding with PDMS, removing the InP substrate, and sealed by PDMS in sequence. Figure 3(c) illustrates the optical microscopic (OM) images of the finished device before and after compression (ξ_{tot} = 1.00 and 0.95). The length L of the waveguides are almost invariant, while that of the PhCs is significantly compressed. This is the direct evidence of local strain enhancement we theoretically predicted above.

In the measurements, the devices with different L shown in Fig. 4(a) are excited by optical pulse at room temperature under different compressive ξ_{tot}, whose lasing spectra are shown in Fig. 4(b). It is clearly that the total wavelength shifts increase with L, which is attributed to the enhanced ξ_{int} with

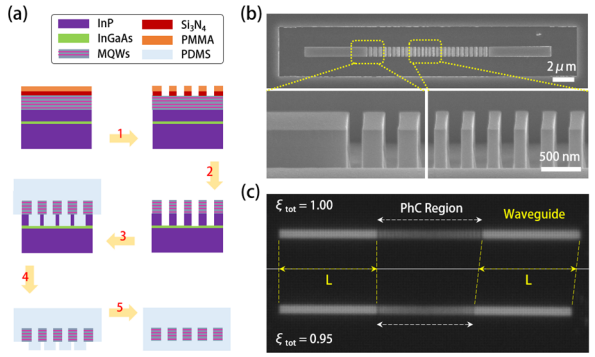

Fig. 3 (a) Flowchart of manufacturing PhC nanocavity with waveguides buried in a PDMS substrate. (b) Top- and tilt-views SEM pictures and (c) OM images of nanocavity before and after compressing.

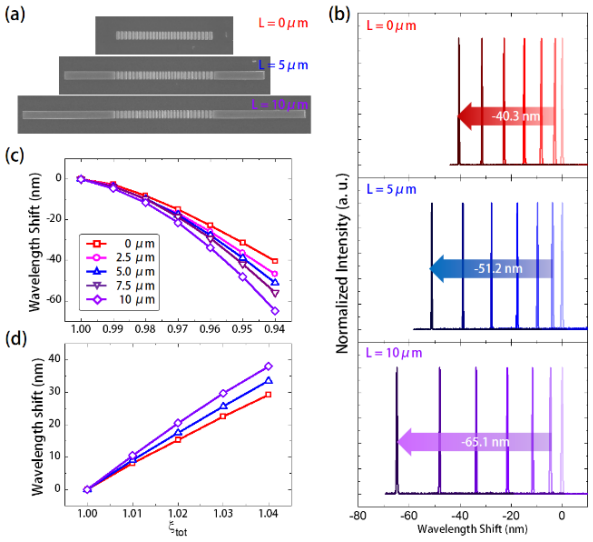

Fig. 4 (a) SEM images of nanocavities with different L and their (b) lasing spectra, and (c) (d) recorded wavelength shifts of under ξ_{tot} of 1.00−0.94 and 1.00−1.04.

L we predicted in Figs. 1(b) and (c). Their recorded wavelength shifts from devices with L = 0−10 μm under ξ_{tot} of 1.00 to 0.94 in Fig. 4(c) agree with our simulation results quite well. When L = 10 μm and ξ_{tot} = 0.94, a total wavelength shift of −65.1 nm is obtained, which corresponds to an enhanced R_s of −10.8 nm. In addition, the same devices are also excited under stretching ξ_{tot} from 1.00 to 1.04. The recorded wavelength shifts shown in Fig. 4(d) also agree with out simulation results. With L = 10μm, an enhanced R_s of 9.7nm is confirmed.

4. Conclusion

We have proposed and initially demonstrated the idea of enhancing wavelength tunability of PhC nanocavity in PDMS by simply setting waveguides nearby. Enhanced R_s of −10.8 and 9.7 nm are experimentally obtained under compressive and stretching strain, which provide further optimization for tunable PhC devices and more possibilities in soft PICs.

Acknowledgements

The authors acknowledge the financial support from Ministry of Science and Technology (MOST), Taiwan, under 106-2221-E-009-124-MY2. We also sincerely thank the Center for Nano Science and Technology of NCTU for assistance in the fabrication facilities.

References

[1] J. Hu, L. Li, H. Lin, P. Zhang, W. Zhou, and Z. Ma, Opt. Mater. Express **3**, (2013) 1313.

[2] T. W. Lu, C. Wang, and P. T. Lee, Nanoscale **8** (2016) 16769.

[3] L. Zhu, J. Kapraun, J. Ferrara, and C. J. Chang-Hasnain, Optica **2** (2015) 255.

[4] T. W. Lu, C. C. Wu, and P. T. Lee, ACS Photonics **5** (2018) 2762.

[5] H. P. Phan, T. Dinh, T. Kozeki, T. K. Nguyen, A. Qamar, T. Namazu, N. T. Nguyen, and D. V. Dao, Appl. Phys. Lett. **109** (2016) 123502.

[6] A. H. Ghadimi, S. A. Fedorov, N. J. Engelsen, M. J. Bereyhi, R. Schilling, D. J. Wilson, and T. J. Kippenberg, Science **360** (2018) 764.

[7] S. M. Hu, J. Appl. Phys. **50**, (1979) 4661.