Tuning of defects embedded within three-dimensional photonic crystals

Michael. J. Ventura, Martin Straub, and Min Gu.
Centre for Micro-Photonics and
Centre for Ultrahigh-bandwidth Devices for Optical Systems (CUDOS),
Faculty of Engineering and Industrial Sciences, Mail 38,
Swinburne University of Technology, P.O. Box 218, Hawthorn, Victoria 3122, Australia
mventura@swin.edu.au
Phone: +61 3 9214 4303
Fax: +61 3 9214 5435

Abstract: Tuneable microcavities embedded in woodpile photonic crystals were generated by femtosecond-laser direct writing in a solid polymer. Analogous to a simple Fabry-Perot etalon cavity size and angular dependence were observed experimentally and confirmed using supercell calculations. The addition of one and two-dimensional lattices to the cavity allows for additional fine-tuning.

Exhibiting a photonic bandgap in which propagating electromagnetic modes cannot exist at all or only for certain directions, photonic crystals allow for the highly efficient manipulation of light at wavelengths on the scale of their dielectric periodicity. Along with numerous other attributes they are seen by many as the fundamental building block by which the optical integrated circuit of the future will be realized. Fabrication of precisely tuneable microcavities in three-dimensional photonic crystals is of great important towards this goal, as they are key elements of photonic crystal microlasers. Presently the fabrication of controlled defects within a three-dimensional lattice has been extremely difficult and results have been mixed. In this paper we demonstrate the ability to fabricate high quality cavities in a single step process by femtosecond-laser direct writing of void channels in solid photopolymer resin.

Femtosecond-laser direct writing of submicron-size voids into a solid polymer host [1,2] is a single step process which allow for the generation of arbitary non-overlapping channel arrangements and requires no chemical post-processing. Controlled defects can be introduced at any location within the lattice geometry. Microcavities were fabricated at the centre of a twenty-four layered woodpile structure by the introduction of a displacement Δd of all layers beyond the twelfth [Fig. 1(a)]. Such a system is analogous to a Fabry-Perot etalon consisting of two parallel quarter-wave stacks, in which each layer of void channels contributes two quarter-wave layers of different average dielectric constants, one containing the channels and another one consisting entirely of cured resin.

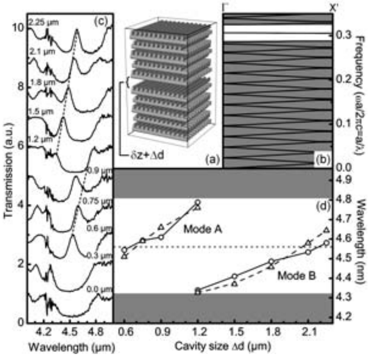

Fig. 1. (a) Sketch of a twenty four-layer woodpile structure with a microcavity of size Δd in its centre. (b) Supercell calculation of photonic bands for a structure with a cavity size Δd of 2.1 μm. Shaded regions are frequencies outside the bandgap. The flat band within the bandgap denotes the cavity mode. (c) Infrared transmission spectra in the stacking direction for Δd from 0.3 to 2.25 μm. (d) Variation of experimental (circles) and calculated (triangles) cavity mode wavelengths with the cavity size.

Figure 1(b) shows the band diagram for a Δd of 2.1 μm, within the stop gap a flat band at normalized frequency 0.306 (4.57 μm) demonstrates the existence of a localised defect mode. Figure 1(c) shows the resultant spectra. The dip in transmission centered around 4.5 μm is due to the main photonic stop gap of the woodpile photonic crystal lattice and agrees well with our calculations. The striking feature

0-7803-9217-5/05/$20.00©2005 IEEE

which is apparent in all samples except the structure without a defect is a sharp peak within the stop gap region for Δd = 0.6 to 0.9 μm and again 1.5 to 2.25 μm constituting two successive cavity modes A and B, respectively.

Figure 1(d) compares the spectroscopy results (circles) with the eigenmode calculations (triangles). The calculations reproduce the experimental results extremely well. With increasing cavity size both modes move from the lower to the upper gap edge. As with typical quarter-wave stack Fabry-Perot filters our microcavities provide a first cavity mode at a cavity size of approximately a quarter-wave layer as well as a spacing between subsequent modes of 1.5 μm corresponding to half the light wavelength in the dielectric.

Spectral measurements yielding an angular dependence further highlight the analogy to the Fabry-Perot etalon. For a cavity size of Δd = 0.6 μm over a range of angles of incidence of 0 - 10° a shift of the cavity mode to shorter wavelengths by approximately 20 nm was observed

Supercell calculations not only reproduce the cavity size dependence of the mode wavelengths, but also demonstrate the degree of localization of the modes inside the cavity. Figure 2 plots the intensity of both modes along the stacking direction relative to the cavity position with the dielectric visualized by the shaded areas (a, b). The corresponding channel arrangement perpendicular to the stacking direction is illustrated above them (c, d). Mode A reveals a strong intensity maximum in the centre of the cavity, whereas mode B features two maxima with a central node. High intensity is confined to the cavity position and to a lesser extent to the adjacent dielectric. For both modes A and B modal confinement is strongest near the midgap wavelength, whereas closer to the gap edges the modes extend deeper into the surrounding lattice.

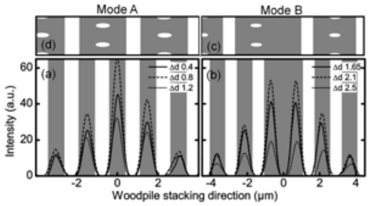

Fig. 2. (a,b) Calculated intensity mode profiles for a variety of cavity sizes for both modes A and B. A representative structure is overlayed to show the alternating dielectric set up by the lattice periodicity [grey: dielectric, white: void channels; additional illustration in (c,d)]. Close to the midgap wavelength (mode A: Δd = 0.8 μm, mode B: 2.1 μm) modes are localized more strongly within the cavity than close to the stop band edges.

Further optical confinement and tailoring of modes was achieved through the addition of one and two-dimensional crystal lattices to the Fabry-Perot cavities. The introduction of these elements allowed for the confinement of modes perpendicular to the stacking direction therefore confining modes in all three dimensions. This additional degree of freedom allowed for precise tuning of mode quality, position and the number of modes allowed to exist.

In conclusion, the ability to fabricate high quality defects within a three-dimensional photonic crystal was demonstrated. Infrared transmission measurements revealed pronounced cavity mode peaks within the photonic stop band yielding a characteristic dependence of the fundamental and second-order cavity mode wavelengths on the cavity size and the angle of incidence. Experimental results were explained by a quarter-wave stack and a simple reflective surface Fabry-Perot model as well as supercell calculations, which demonstrate the high degree of mode localization in the cavity.

Acknowledgments

This work was produced with the assistance of the Australian Research Council under the ARC Centres of Excellence program. CUDOS (the Centre for Ultrahigh-bandwidth Devices for Optical Systems) is an ARC Centre of Excellence.

Reference List

[1] M. J. Ventura, M. Straub, and M. Gu, Appl. Phys. Lett. **82**, 1649 (2003).

[2] M. Straub, M. Ventura, and M. Gu, Thin Solid Films, 521 (2004).