Coupled-cavity two-dimensional photonic crystal waveguide ring laser

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Coupled-cavity hexagonal ringlike photonic crystal lasers are fabricated as a class of single mode photonic crystal laser light sources. The structures are formed by placing one missing hole nanocavity (H1 type) between each two segments at 60° that form the hexagonal ringlike photonic crystal laser. The H1 cavities act as a mode filter, clamping the frequency of emission of the laser device. The emission frequency in these rings with cavities varies as the filling factor is changed, allowing the tuning of the laser emission. Stable single mode lasing occurs with side mode suppression greater than 20 dB. This kind of devices may be used as an efficient selective filter of modes and may have important applications in future photonic devices for optical communications and optical sensing. © 2006 American Institute of Physics. [DOI: 10.1063/1.2345374]

During the last years, much attention has been paid to two-dimensional (2D) photonic crystal^{1,2} (PC) fabricated in dielectric slabs.³ This particularly important class of photonic crystal consists of a two-dimensionally periodic index contrast introduced into a high-index guiding layer. The introduction of structural defects and waveguides is also possible, and this aspect has been the matter of intense studies. Adding these ideas to the maturity of current planar fabrication technology, an important number of works have been carried out such as single defect lasers,⁴ photonic crystal waveguides,⁵ and the integration of photonic crystal waveguides with microcavities.⁶ This is particularly interesting in the case of photonic crystal ring resonators due to their efficient coupling to photonic crystal linear waveguides and shows its potential as a light source or as a filter in photonic crystal circuits.⁷ Also, the low group velocity of some modes of the PC waveguide that forms the ring resonator can be used to enhance nonlinear and optical sensing effects. This photonic crystal ring resonators have been used for laser emission since they have a close analogy to microdisk lasers⁸ and to photonic wire lasers.⁹ In the microdisk laser, the whispering-gallery modes are guided by total internal reflection, whereas in the photonic crystal ring laser, the ring-type resonant modes operate by the photonic band gap. Optical confinement by the photonic band gap is more efficient than that by the total internal reflection, especially for wavelength-size small structures. In this way, the resonant mode is expected to have similar properties to the guided mode of photonic crystal waveguides.⁷

The first photonic crystal ring laser was demonstrated by Kim *et al.*,⁷ who analyzed hexagonal ringlike structures composed of six waveguides with 60° bends. The devices emitted in a double-degenerate emission pattern. By varying the pumping condition, the lasing mode could be switched to a neighboring mode. Nevertheless, for the future integrated PC circuits and nanophotonic devices it is very important to obtain single mode emission in order to couple to PC

waveguides or fibers, thus requiring additional efforts for mode conversion.¹⁰

In this letter, the effect of the introduction of an H1 cavity¹¹ located in the six corners of a hexagonal waveguide ringlike resonator is studied. We use R8 to call the structure without cavities, where the number denotes the amount of holes removed per side and R8H1 for the structure with cavities in the corners. The device is integrated in a periodic lattice of holes formed in dielectric slab with triangular symmetry that supports only modes for the TE polarization.¹² Since the H1 cavity has a double-degenerate single defect state well inside the photonic band gap,¹³ it may be possible to use this defect state for the selection of the wavelength of the emission mode in an otherwise multimode ringlike hexagonal photonic structure.

A 2D PC structure with a triangular lattice of cylindrical air holes has been fabricated on an InP slab incorporating an active medium composed of four $\text{In}_{0.65}\text{As}_{0.35}\text{P}/\text{InP}$ quantum wells, with a total thickness of 237 nm. The heterostructure is transferred onto a heat sinking silicon wafer bonding (SiO_2 thickness = $0.9 \pm 0.1 \mu\text{m}$).¹⁴ This structure gives rise to strong photoluminescence spectra centered around 1500 nm at room temperature. Processing of the PC structures was done by electron-beam lithography of a polymethylmethacrylate layer on top of a SiO_2 layer (120 nm thick).¹⁵ Reactive ion etching was used to open the holes in the SiO_2 and the semiconductor by CHF_3 and $\text{CH}_4:\text{H}_2$ reactive gases.¹⁶ In order to design the ring resonator, eight holes in each of the six sides of a hexagon have been removed giving rise to a hexagonal ringlike structure (R8). The lattice parameter a is 450 nm and different values of the radius of the holes r around $0.33a$ have been used. The variation of the radius is estimated from the scanning electron microscopy (SEM) pictures, being below 5%. With this choice of parameters a large band gap exists for the TE mode between the normalized frequencies of $\omega \sim 0.28$ and $\omega \sim 0.36$, which corresponds to the wavelength range of 1250–1600 nm. Figure 1 shows a scanning electron microscopy picture of an R8H1 structure. The fabricated structures are optically pumped with a 780 nm laser

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FIG. 1. SEM image of a ringlike photonic crystal waveguide structure with six H1 cavities in the six corners of the structure (R8H1). The lattice parameter is $a=450$ nm and the r/a is around 0.33.

diode pulsed to 1 MHz and a 20% duty cycle. An objective lens (0.40 numerical aperture) is used to focus the excitation spot that covers the whole PC fabricated structure. The emitted laser light at room temperature is collected through an optical fiber connected to an optical spectrum analyzer.

The L - L curve (collected power at the lasing wavelength versus incident peak pump power) measured in our optical setup shows a threshold pump power around 0.3 mW for these structures with Q factors typically around 2000. Figure 2(a) shows the typical spectrum above threshold for the case of R8 structures. Several peaks are observed, corresponding to modes of the R8 structure, with the peak at lowest energy centered at $\omega=0.30$ (1500 nm). Varying the pumping conditions the relative intensity of the modes can be changed, in a similar way of a multimode diode laser.

Figure 2(b) shows the typical spectrum above threshold for an R8H1 structure. Single mode emission is observed for

FIG. 2. (a) Spectrum above threshold for a ringlike waveguide structure without cavities on the corners (R8). Inset: below-threshold spectrum. (b) Spectrum above threshold for a ring structure with H1 cavities in the corners (R8H1). Inset: below-threshold spectrum. For both structures $a=450$ nm and r is around 0.33a.

FIG. 3. 3D PWE calculation of the photonic bands of the single defect waveguide with $a=450$ nm, $d=0.527a$, and $r=0.33a$. The region above the light line (for SiO_2 , i.e., $n=1.46$) where leaky modes can couple to SiO_2 layer is marked in light gray. The frequency of the measured laser emission for the R8H1 structure is marked with an arrow.

a frequency $\omega=0.297$ (1515 nm) with side mode suppression greater than 20 dB. This emission can be explained by the filtering of the modes of the R8 structure when cavities are fabricated in the corners. The reduction on the lasing frequency when the H1 cavity is introduced comes from the slight variation on the r/a value due to the fabrication process (around a 3% in r/a).

Figure 3 shows the photonic bands of the one missing hole waveguide obtained by three-dimensional (3D) plane wave expansion (PWE) with $r=450$ nm, $d=0.527a$, and $r/a=0.33$. The region marked in light gray corresponds to the area where leaky modes can couple to the SiO_2 layer (i.e., the light cone for $n=1.46$) whereas the band gap is marked by the gray regions.

The quasiflat mode around $a/\lambda=0.297$ has even symmetry with respect to the mirror plane perpendicular to the slab and parallel to the waveguide, taking the other mode odd symmetry. The values of the lasing frequency for the R8H1 structure is found to be very close to the minimum of the even mode, situated at the K point of the reciprocal lattice. The lasing frequencies for the R8 structures differ slightly (from 1% to 3%) from them, due to the experimental variation of the radius of the holes.

The defect mode of the H1 cavity has a dipolar symmetry for the two degenerated states in the middle of the gap.¹³ The compatible symmetry between the waveguide and the cavity mode has been found to be very important for the transmission of light through coupled-cavity structures.^{6,17,18} The H -field distribution of the double-degenerated H1 mode presents a symmetry which benefits the coupling between the waveguide modes and the resonant cavity mode at the 60° bend.⁶ Due to this, the doubly degenerate dipole of the H1 cavity can couple to the even mode of the waveguide.

Figure 4 shows the tunability of the device through the variation of the filling factor. The figure shows the change in the spectra above threshold with the r/a value for the R8H1 structures. A clear shift of the laser emission toward higher

FIG. 4. Variation of the spectra above threshold with the r/a value for the coupled-cavity ringlike structures (R8H1). Inset: normalized frequencies of the lasing mode for the R8H1 structures (squares) vs the r/a value. Dashed line: calculated frequencies of the defect level in an H1 cavity. Solid line: calculated frequencies of the even mode of the single defect waveguide at the K point of a perfect triangular lattice.

energies is observed as the r/a value increases. Figure 4 inset shows the variation in the frequency of the lasing mode for the R8H1 structure with the r/a and the calculated frequencies of the even mode of the single defect waveguide at the K point in a perfect triangular lattice for the same values of r/a . Both experimental and calculated data are in very good agreement. The calculated shift with r/a of the defect level in an H1 cavity is shown also. The discrepancy in the absolute values of the frequencies between both are probably due to the not perfect confinement of the H1 cavity in the rings, but the trend of the variation in the emission for the H1 defect mode and the experimentally measured R8H1 structures is practically the same (7 nm per 0.01 of variation in the filling factor f for the H1 and ~ 7.5 nm per 0.01 of variation in f , for the band-edge mode).

In summary, we have fabricated a coupled-cavity ringlike photonic crystal laser. The device exhibits stable single mode emission with side mode suppression higher than 20 dBm in respect to rings without cavities. As the filling fraction is increased, the lasing mode of these structures shifts parallel to the even mode of the single defect waveguide. The results are in good agreement with 3D PWE simulations carried out. This kind of devices may be used as efficient selective filters of modes and may have important

applications in the future photonic devices for optical communications and optical sensing.

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