Quantum Dot Photonic Crystal Light Sources

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Invited Paper

The control and manipulation of light on a planar IC similar to that achieved for electrons in semiconductor chips on submicrometer and nanometer scales is an area of very active research today. While electronic device miniaturization is close to reaching its maximum possible potential, photonic devices have unique properties that have yet to be exploited. With increasing advances in nanofabrication techniques and the understanding of optical properties of semiconductors, several optical devices such as lasers, detectors, interferometers, and waveguides have been constantly shrinking in size. We have achieved very high speed integrated optical devices at 10–100-μm length scales. However, there is a need to further reduce the size of devices to make them competitive in size and cost to existing electronic devices and to utilize their potential and unique properties in a wide range of applications ranging from communications, displays to sensors. Photonic crystals have emerged as one of the best potential candidates that can achieve the goal of compact miniaturized photonic chips. In this paper, we describe the current efforts and advances made in the photonic crystal microcavity light sources and their future prospects.

Keywords—*Edge-emitting device, electrically injected, enhanced spontaneous emission, integrated optoelectronics, microcavity laser, photonic bandgap (PBG), photonic crystal (PC), Purcell effect, quality factor, quantum dots (QDs), quantum well heterostructure, stimulated emission, surface-emitting light source, waveguide.*

I. Introduction

The vision of miniaturized photonic devices, which function in a wide range of applications such as portable environmental sensors to detect hazardous compounds or to sample and analyze nanoscopic volumes of biological fluids with high speed, accuracy, and cost effectiveness, or ultracompact low-cost high-speed communication devices, will be realized only when we can sufficiently manipulate light (photons) on the submicrometer scale similar to what has been achieved for electrons in semiconductor devices. Photonic crystals (PCs)—or photonic bandgap (PBG) structures, as they are also called [1]–[3]—have emerged as feasible solutions to answer this need for a wide range of devices including single-photon sources, lasers, detectors, filters, waveguides, sensors, and optical interconnects. They provide both unique optical properties as well as great flexibility in the design, fabrication, and integration of these devices in various configurations as required for diverse photonic and optoelectronic applications.

PCs in the optical regime are periodic dielectric structures with variations in the refractive index on length scales of the order of the wavelength of light (a few hundred micrometers). Bragg diffraction in these periodic arrangements results in light interference manifested in photonic *bandgaps*, where propagation of certain frequencies of electromagnetic radiation is inhibited [see Fig. 1(a)]. Introducing point and line *defects* in the periodic photonic lattices give rise to localized modes within the bandgaps and hence allow us to confine and manipulate the flow of light in these structures. This behavior is analogous to that seen in crystalline semiconductors thereby making PCs excellent candidates for *PBG and defect engineering*. Since PCs were first described by Yablonovitch [1] and John [2] in 1987, extensive advances in micro- and nanofabrication have allowed us to construct PCs with bandgaps in the optical regime.

PC structures with their multiparameter design flexibility have been the subject of intense research and development over the past decade. The recent notable contributions of PCs to improvement of the existing conventional semiconductor light sources include, for example, replacement of the cleaved laser facets with PCs [4], enhancement of vertical extraction efficiency in LEDs [5], reduction of refractive index in vertical cavity surface-emitting lasers

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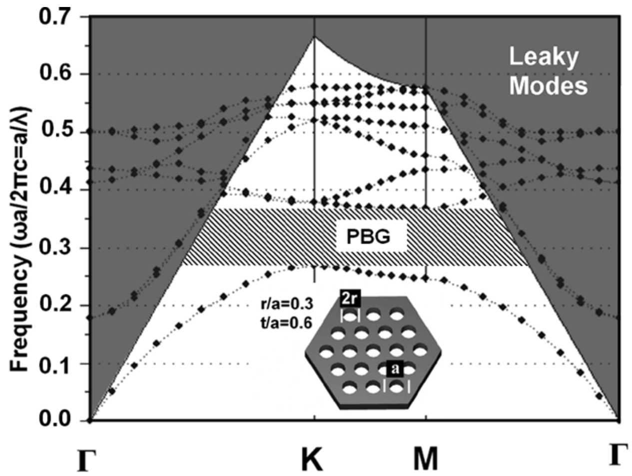

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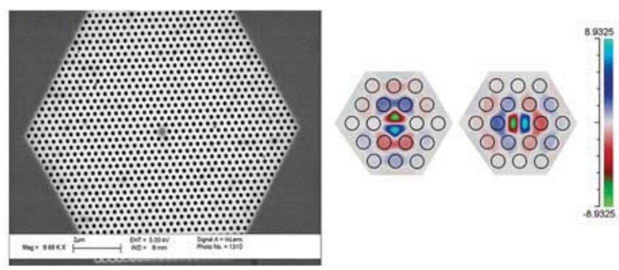


(b)

Fig. 1. (a) Calculated 3-D bandstructure of a PC formed by triangular lattice of air holes in dielectric slab of $0.6a$ thickness. The simulation shows a complete PBG for TE modes. (b) Scanning electron microscope (SEM) image of an single-cell microcavity (H1) supporting a doubly degenerate dipole mode.

(VCSELs) to improve the optical mode lateral confinement [6], development of practical mid- and far-IR PC-based quantum cascade lasers [7] for gas detection, etc. Equally important are the applications of PCs in the development of low-loss planar waveguides with sharp bends [8], [9], PC fibers [10], and nonlinear dispersive waveguiding and resonant mode-filtering components [11]. When integrated with submicrometer-scale light emitters and detectors, these components could eventually lead to the realization of functional ultrasmall high-density optoelectronic circuits for sensing and wavelength division multiplexing (WDM) applications [12], [13].

In this paper, we will focus on perhaps the most significant application of two-dimensional (2-D) PCs as a platform for a variety of microcavity light sources. We will discuss PBG defect mode engineering combined with the technology of self-organized quantum dots (QDs) as a means to develop advanced light emitters with single-mode operation, higher efficiency, lower thresholds, higher bandwidths, and increased output directionality. The evolution of microcavity optical resonators could advance toward PC nanolasers with a single embedded QD [14] that would provide many of the desired properties of advanced photon sources and eventually become the ultimate single photon turnstile sources capable of generating photons on demand [15]. The intensive development of such devices is propelled mainly by the prospect of studying strong-coupling cavity quantum electrodynamics (CQED) [16], [17] phenomena in semiconductor systems as well as a variety of promising applications in linear-optics quantum computation [18], quantum cryptography [19], and quantum teleportation [20].

II. Semiconductor Optical Microcavites

Spontaneous emission rate can be attributed to interaction of the dipole of the emitter (atom, molecule, or QD) with the surrounding vacuum electromagnetic field fluctuations. As such, the emission rate can be altered and controlled through modifying the electromagnetic environment parameters, for example, by introducing an optical microcavity that supports a single (or a few) resonance. The spontaneous emission rate can change depending on the overlap between the dipole and the cavity resonances. Recent advances in semiconductor microfabrication have allowed for sensitive cavity adjustments in the optical regime by lithographical tuning, which has led to microcavity resonators used to modify the spontaneous emission properties of matter through the Purcell effect [21], [22]. The enhancement in spontaneous emission for a particular cavity mode is given by

$$F_p = \left(\frac{3}{4\pi^2}\right)\left(\frac{\lambda_c}{n}\right)^3\left(\frac{Q}{V}\right) \tag{1}$$

where F_p is the Purcell factor, Q is the quality factor of the particular cavity mode, V is the effective modal volume, and λ_c/n is the wavelength of the resonant cavity mode in the medium with refractive index n. The Purcell factor has become a very useful figure of merit for a microcavity and in determining the strength of the cavity–emitter interaction. The development of optical microcavities is therefore driven by the desire to obtain the highest possible Q and the smallest possible modal volume V for maximum enhancement of light–matter interaction.

Several types of semiconductor optical microcavities including silica microspheres [23], toroid microcavities [24], microdisks [25]–[27], micropillar resonators [28], [29], Fabry–Pérot resonators [30], and cylindrical and oxide-confined microcavities [31] with various emission sources in the cavity have been investigated to study single-photon generation [24], strong- [23], [24] and weak-coupling CQED [25]–[29], and spontaneous emission enhancement (suppression) phenomena [23]–[27]. Excellent comprehensive reviews of optical microcavities in the context of CQED are available [32]–[35].

Strong-coupling phenomena in optical microcavities have been observed by Hood *et al.* on cesium atoms strongly coupled to electromagnetic fields in an ultrahigh-Q Fabry–Pérot cavity [30]. Experimentally demonstrated ultrahigh Q factors of microspheres ($Q \sim 8 \times 10^9$) [23] and toroid microcavities ($Q \sim 10^8$) [24] make these structures potential candidates for CQED experiments. Alternative versions of semiconductor optical microresonators such as micropillars have so far failed to deliver sufficiently high Q values for CQED, but have found an important application in triggered single-photon sources [28], [29], [36]. Since the idea was proposed by Gérard *et al.* [37], QDs with their atom-like density of states have gradually become the preferred emitter used in the more recent demonstrations, since, unlike neutral atoms, QDs can be confined in the high field density regions within the semiconductors. The demonstrated semiconductor single mode micropost devices with an embedded QD provide experimental evidence of weak coupling [28], [29] and up to 32-fold enhancement in spontaneous emission [38]. These results present several practical advantages such as single mode operation, narrow emission linewidth, lower (and potentially zero) threshold lasing, and higher collection efficiency when microcavity resonators are used as light emitters. The major challenge in obtaining high Q/V microcavities in the optical regime with the above techniques is that radiative losses increase with decreasing volume of the cavity. Such microcavities also routinely suffer from losses at the surfaces (hence lower Q). Furthermore, when the horizontal width of the cavity is reduced to approximately 1–2 μm (i.e., as the volume is reduced), the cavity Q varies widely even with slight geometry variations, and it is difficult to obtain repeatable performance. Finally, these techniques offer limited flexibility in designing the cavity mode profiles.

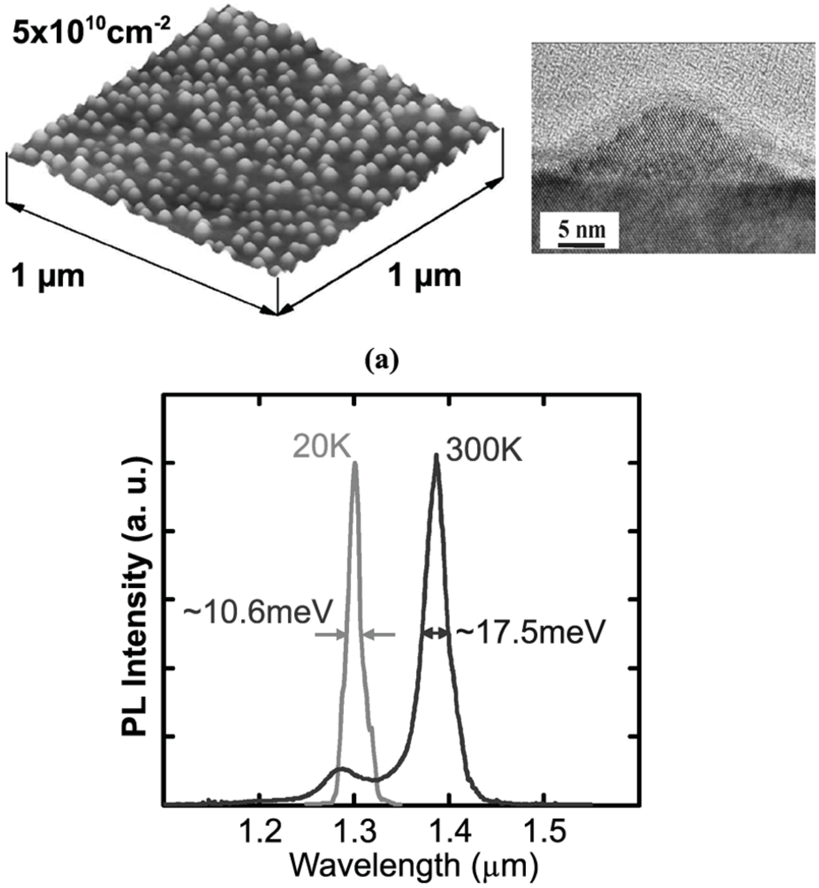
PC-based optical cavities have numerous advantages including superior mechanical stability, relaxed fabrication tolerances, and possibility of electrical excitation, over the above devices and have emerged as the preferred technology for building microcavity light sources. Optically pumped PCs have been used successfully to control the spontaneous emission rate of QDs [39], [40]. Several single-cell microcavity designs [41], [42] with sufficiently large theoretical Q values for QED experiments have been proposed, but have not yet been successfully fabricated and experimentally demonstrated. The recent report by Englund *et al.* [43] on the observation of fivefold enhancement of spontaneous emission rate of QDs placed in an optimized high-Q 2-D PC microcavity represents the first experimental demonstration of on demand single photon emission from an optical microresonator. Techniques are currently being developed to obtain a single InAs/InP self-assembled QD in a chosen location on the substrate [44] or position the PC cavities to single InAs QDs [45]. Further advances which incorporate such a single QD into a PC microcavity can be used to create single-photon sources for studying CQED processes in semiconductor systems such as strongly coupled dots and single dot lasing.

III. Self-Assembled Semiconductor QDs

Semiconductor QDs [46] with their high atom-like density of states, narrow emission linewidths, and size of the order of a *de Broglie* wavelength offer distinct advantages over quantum wells and bulk semiconductors. Self-organized QDs grown by molecular beam epitaxy (MBE) or metal–organic vapor phase epitaxy (MOVPE) have proven to be the best approach to obtain the desired properties of QDs [47], [48]. The self-organized growth techniques produce confined electronic islands of various shapes with fluctuations in size and composition. An atomic force microscopy (AFM) image of a layer of MBE-grown self organized InAs QDs and a transmission electron microscopy (TEM) image of a single InGaAs dot are shown in Fig. 2(a). Growth optimization to achieve control of dot size and hence emission wavelength, uniformity, and density is an area of active research. Fig. 2(b) shows an example of narrow photoluminescence spectra of InAs QDs with high size uniformity.

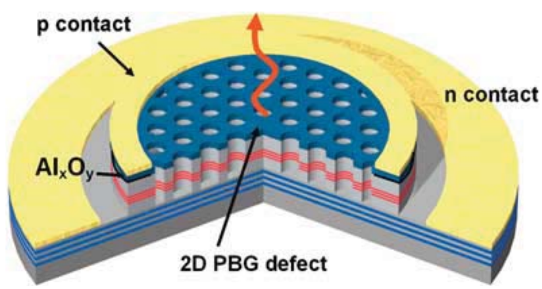
QDs exhibit lower absorption than bulk and quantum wells and hence contribute minimally to the degradation of the surrounding optical cavity, which is significant for microcavity applications. Much progress has already been reported on applications of self-organized QDs in semiconductor IR lasers that have shown lower threshold currents and low temperature sensitivity [49]. While the quantum yield of the quantum well devices is relatively low, the emission efficiency due to effective charge carrier capture, no defects within the dot, and lower nonradiative recombination from the QDs has already proved to be sufficient to observe single-photon phenomena [50]. Other notable QD features include high oscillator strength, large dipole moments, optical nonlinearities, and elimination of photon shelving [51].

When applied as active emitters in light sources, QDs provide three–dimensional (3-D) confinement for electrons while a 2-D PC slab microcavity provides 3-D confinement of photons. The advantages of both systems are



(b)

Fig. 2. (a) AFM image of self-organized MBE-grown InGaAs QDs and a TEM image of a single dot. (b) Photoluminescence spectra of highly uniform InAs QDs grown by MBE.



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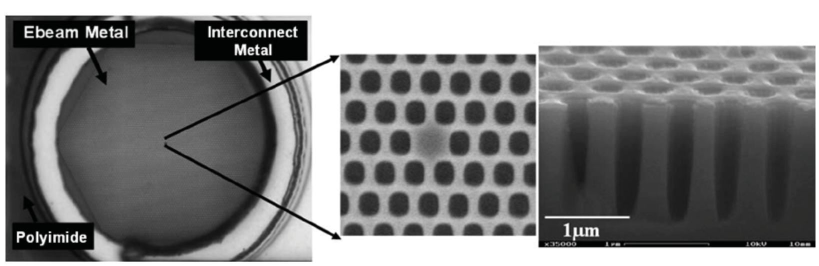


(b)

Fig. 3. (a) Schematic of a surface-emitting electrically injected device with 2-D PC horizontal confinement. The cavity is formed by a single defect in the 2-D PC. (b) SEM images of top view of a fabricated InP-based device with top electrical ohmic contact surrounding the PBG with the single defect magnified in the inset and cross-sectional image of the 2-D PBG slab.

simultaneously exploited to obtain greater enhancement in spontaneous emission rate, higher Purcell factors, and enhanced light-matter interaction in the strong coupling regime. While QDs provide intrinsically better performance than quantum wells, only a small fraction of QDs in a cavity actually contributes to the gain and spontaneous enhancement as the cavity Q is increased. A better control of the size, position, and number of QDs and higher Q cavities are needed to achieve the maximum potential of this system.

IV. Optically Pumped PC Microcavities

There are two methods of achieving excitation of the active material inside the cavity—optical pumping and electrical injection. Devices requiring optical pumping require relatively simple heterostructure design, are easier to fabricate, and provide clear comparisons with theoretical mode simulations. Two-dimensional PCs formed of a triangular lattice of air-holes in free-standing semiconductor slabs [52]–[54] have become most popular systems used to study PC microcavity effects due to their ability to accommodate an appropriate photoluminescent material within the high field regions. By selectively removing one or more air-holes and thereby introducing a defect mode(s) in a 2-D photonic lattice, or modifying the region near the cavity, a microcavity with a wide range of tailored modes excitable by the active material within the cavity can be created. Although these structures provide only quasi-3-D light confinement with the horizontal confinement provided by the PBG and the vertical confinement by total internal reflection provided by the cladding (air, oxide, or DBR), they are rather capable of confining light within small cavities with significantly high Q factors.

Ideally, a 3-D PC with a defect microcavity formed by a missing period in the lattice would provide the best confinement for a light emitter placed inside the cavity, due to the PBG confinement in all spatial dimensions. While there are interesting results on 3-D PCs in different material systems [55], it is practically difficult to fabricate cavities with sufficiently high Q in semiconductor-based 3-D PCs and, at the same time, incorporate a suitable active emitter within those cavities.

Two-dimensional PC defect microcavities can provide both sufficiently high Q as well as ultrasmall modal volumes (V) and hence a very high Q/V ratio—a necessary condition for achieving a high spontaneous emission rate enhancement. The quasi-3-D nature of these structures allows for mode coupling to the radiated modes in the vertical direction, which establishes a significant radiation loss mechanism and Q reduction in the cavities. A simple cavity in triangular lattice formed by removing one air-hole supports doubly degenerate dipole modes with a rather modest Q of a few hundreds. The Q can be improved by splitting the mode degeneracy by modifying the size or position of the PC holes around the cavity. Extensive numerical design work using 3-D finite-difference time-domain (FDTD) simulation tools performed by Scherer *et al.* at Caltech led to optimized single cell cavity designs in air-clad semiconductor slabs with large (Q/V) factors [41], [56], [57]. These and similar studies performed by other groups involved the optimization of the slab thickness [58], and modification of sizes and geometries of cavities embedded in both square and triangular lattice PCs [59], [60]. It should be noted that such flexibility in designing the geometry of optical microcavities is only offered by PCs. Similar work performed by Noda *et al.* resulted in the highest reported Q for a Si-based 2-D PC slab of 45 000 [52]. This was achieved by cautiously confining light in short linear cavities and by tuning the cavity dimensions to achieve the lowest radiation mode losses while slightly increasing modal volume. More systematic algorithmic Q-optimization studies of PC microcavities using the inverse-problem approach replacing previously used the trial-and-error methods have been applied by Geremia *et al.* [61].

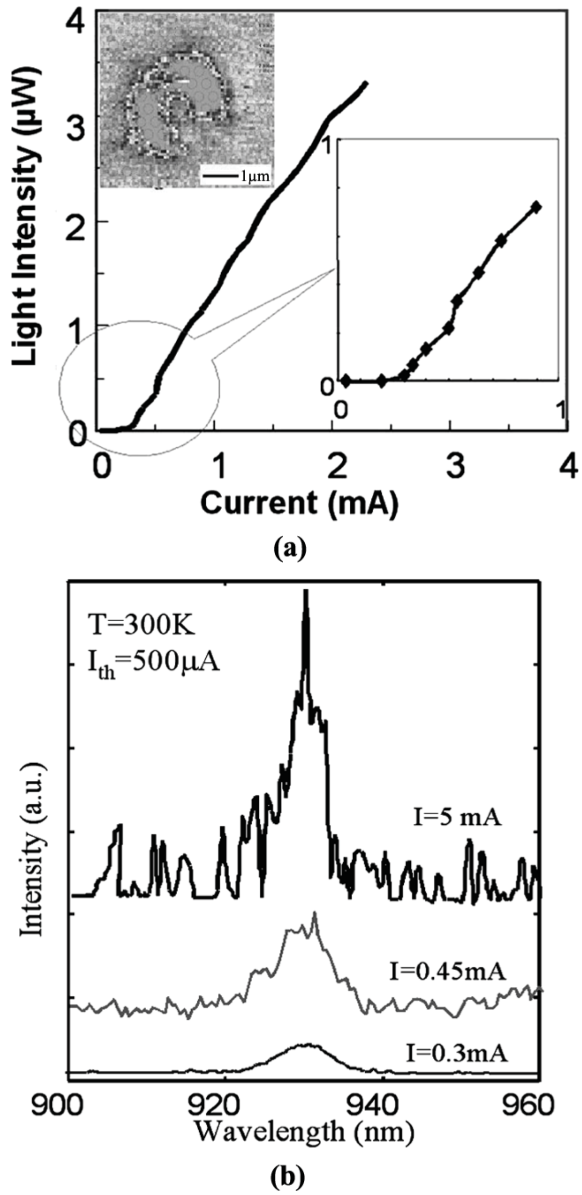
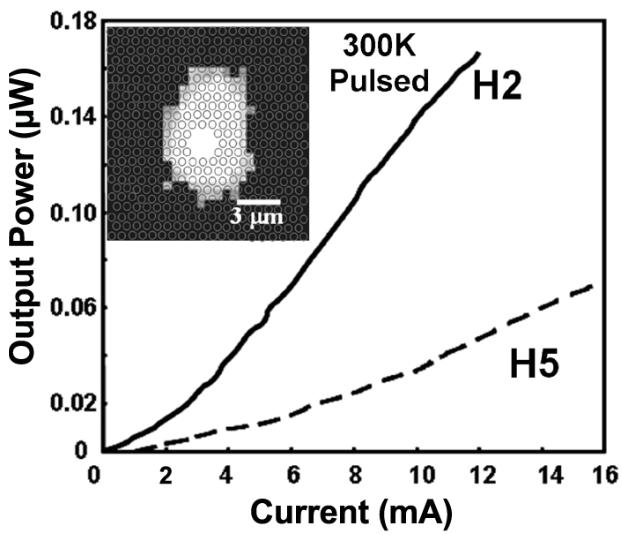


Fig. 4. (a) L–I characteristics of a single-defect GaAs-based quantum well device at 300 K in pulsed mode showing "soft" threshold current of 300 μA. (b) Spectral characteristics of the device under different current injection levels.

Gradual improvement of free-standing 2-D PC slab-based optical microcavities led to the development of submicrometer-scale low-threshold lasers. These ideally "thresholdless" lasers described by Yokohama [62] behave rather differently from their Fabry–Pérot counterparts, as they essentially eliminate the distinction between spontaneous and stimulated emission. In an ideal microcavity, all

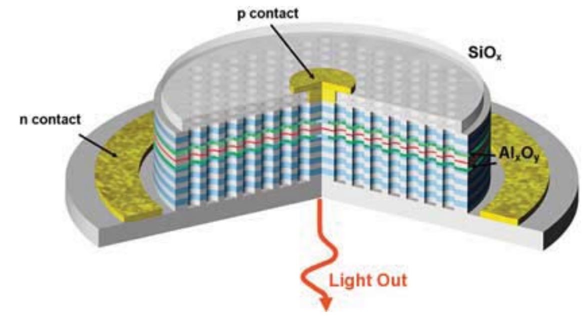
	GaAs	0.0746 μm	p+	2×10^{19}
	$Al_{0.8}Ga_{0.2}As$	0.0854 μm	p	2×10^{18}
	GaAs	0.0746 μm	p	2×10^{18}
	$Al_{0.96}Ga_{0.04}As$	0.0879 μm	p	2×10^{18}
	GaAs	0.1396 μm	i	------
	InGaAs dots	QD	i	
X4	GaAs barrier	20 Å	i	------
X4	InGaAs dots	QD	i	
	GaAs Spacer	0.1396 μm	i	------
	$Al_{0.96}Ga_{0.04}As$	0.0879 μm	n	2×10^{18}
X29	GaAs	0.0746 μm	n	2×10^{18}
X29	$Al_{0.8}Ga_{0.2}As$	0.0854 μm	n	2×10^{18}
	n+ GaAs (100) substrate and buffer			

(a)



(b)

Fig. 5. (a) Device heterostructure grown by MBE with an n-type lower $GaAs/Al_{0.8}Ga_{0.2}As$ DBR mirror, an undoped λ-cavity ($\lambda = 1.04$ μm) region with five layer InAs/GaAs QDs active region, and p-type AlGaAs and contact layers on the top. (b) L–I characteristics in pulsed-mode (1 μs with 1% duty cycle) of PC two- (H2) and five-defect (H5) period microcavity; inset shows the near-field image of two-defect period microcavity 1.38 mm surface diameter under 7.15 mA injection measured at a distance of 4 mm from the device surface.



(a)

0.084μm	p+	GaAs	
0.095μm	p	$Al_{0.80}Ga_{0.20}As$	
0.084μm	p	GaAs	
0.045μm	p	$Al_{0.80}Ga_{0.20}As$	
0.050μm	i	$Al_{0.98}Ga_{0.02}As$	
0.084μm	i	GaAs	
4× InGaAs QDs			
0.084μm	i	GaAs	
0.050μm	i	$Al_{0.98}Ga_{0.02}As$	
0.045μm	n	$Al_{0.80}Ga_{0.20}As$	
0.084μm	n	GaAs	×3
0.095μm	n	$Al_{0.80}Ga_{0.20}As$	×3
0.084μm	n	GaAs	
0.334μm	n+	GaAs	
GaAs S.I. Substrate			

(b)

Fig. 6. (a) Schematic representation of a bottom emitting PC QD device with the p-metal contact placed directly above the PC microcavity. (b) Device heterostructure grown by MBE.

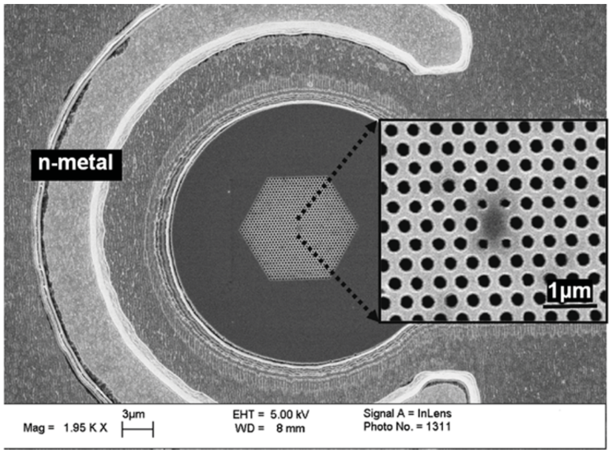
the photons are emitted into a single microcavity resonant mode and the loss to the free space is eliminated. As the excitation power is increased, there is no mode competition, and the single emission gradually shifts from spontaneous to stimulated without a sharp turn-on.

The first optically pumped single-mode PC microcavity laser with emission at 1.55 μm was reported by Painter *et al.* in 1999 [53]. The active region in this device was provided by compressively strained InGaAsP quantum wells enclosed in a single missing defect microcavity with split dipole degeneracy. Similar quantum well devices with improved microcavity designs, higher Q factors, and lower lasing thresholds were demonstrated by the same group at Caltech [63] and others [64]–[68]. Several authors have reviewed the design and fabrication of PC microcavity lasers [69]–[71].

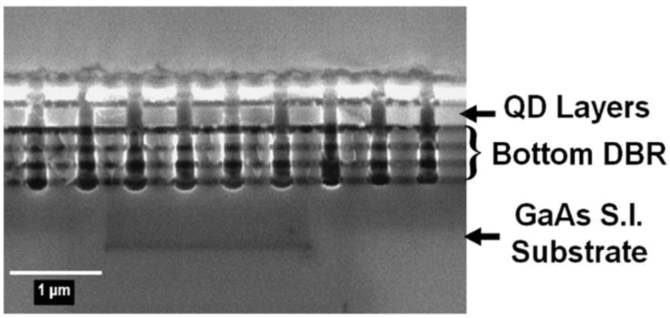
Recognizing the advantages of QDs over quantum wells in microcavity applications several groups attempted to incorporate them in the gain region of PC optical microcavities. Early promising results reported by Yoshie *et al.* [72] were followed by attempts to design and fabricate QD PC lasers [73]–[76] and optical microcavities for strong-coupling CQED [40], [77]. Many of the demonstrated devices exhibit QD spontaneous emission enhancement, but, to the best of our knowledge, to this date there is no experimental demonstration of strongly coupled QDs in PC microcavities or single-cell microcavity lasers. Lasing action has, however, been demonstrated by Scherer *et al.* in coupled cavities in square lattice PCs [78]. In this work, coupled cavity design was employed to increase optical gain of QDs. The difficulties associated with demonstration of QD nanolasers are mostly attributed to the relatively low optical gain of QDs due to lower emitter density and inhomogeneous emission broadening due to dot size variations and insufficient experimental Q factors of fabricated PC microcavities.

V. Electrically Injected PC Microcavity Light Sources

Several electrically injected lasers using the concept of PCs have been demonstrated [79]–[82]. The first 1.55-μm electrically injected laser was reported by Imada *et al.* [79]

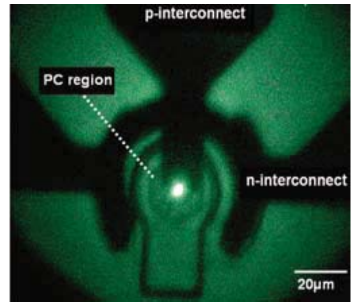


(a)



(b)

Fig. 7. (a) SEM image of the fabricated device before the passivaton and p-metal deposition. (b) Etched PC cross section.



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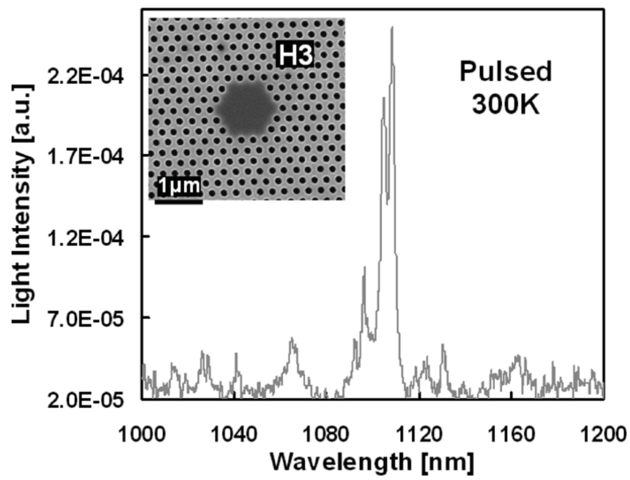


(b)

Fig. 8. (a) IR image of the output spot of a larger cavity H3 showing the light being emitted from the resonant cavity region. The biased device is illuminated from the top with a white light source and the image is taken from the bottom using 100× lens focused on the polished substrate. (b) Spectral characteristics of a H3 device showing multiple cavity resonances.

with InGaAsP/InP multiquantum well system using wafer fusion techniques. Lasing action was also observed in electrically injected PC cavity coupled edge emitters [80], and PC VCSELs [81]. The progress on electrically injected PC microcavity light sources [83] has been hampered mainly by difficulties associated with carrier injection into a small active region and elimination of surface-state recombination.

Various practical applications including device integration require high-Q PC microcavities that can be pumped electrically. Major challenges facing electrical injection include the complex heterostructure, difficult 3-D mode calculations, and relatively large etch depths compared to optically pumped PC free-standing slab structures. However, the most important consideration in designing electrically pumped microcavity light sources is the position of the electrical contacts. Unlike some other types of optical microresonators such as micropillars and microdiscs, PCs possess the necessary stability to allow for a relatively straightforward carrier injection scheme used usually in VCSELs [Fig. 3(a)]. However, this standard injection method allows for significant carrier loss mechanisms, and many of the devices demonstrated so far routinely suffer from high carrier losses in the surface states as the carriers have to transverse the etched surfaces of the PC to reach the active region [83].

A. Quantum Well Devices

To the best of our knowledge, our group demonstrated the first electrically injected surface-emitting 2-D PC microcavity light source with multiquantum well emission at 0.9 μm [84]. The approach to electrical injection pursued by our group involves using oxide clad structures and DBRs with doped posts for current injection defined under the PC microcavity. This configuration generally leads to lower Q factors due to the reduced refractive index contrast, but provides better mechanical stability and thermal conductivity. The device heterostructure, grown by MOVPE, consists of an undoped $\lambda/\text{n}-$ thick cavity gain region with a pair of 70-Å compressively strained $\text{In}_{0.15}\text{Ga}_{0.85}\text{As} - \text{GaAs}$ quantum wells and p-type $\text{Al}_{0.3}\text{Ga}_{0.7}\text{As}$ and contact layers on the top. N$-$ and p-type $\text{Al}_{0.96}\text{Ga}_{0.04}\text{As}$ layers were added for lateral oxidation to improve carrier injection into the microcavity region. The device configuration shown in Fig. 3(a) is similar to that of an oxide-confined VCSEL without the top mirror [85]. The single-cell microcavity was designed with a 2-D PBG for TE-like modes encompassing the quantum well photoluminescence peak at 0.94 μm. We used calculations based on plane-wave expansion and effective index method to obtain the final design parameters of 0.4 μm for the lattice period and 0.13 μm for the hole diameter. The L–I measurement results and spectral characteristics obtained from this device shown in Fig. 4 indicate a gradual turn-on, or a "soft" threshold, typical of optical microcavity devices with a few modes or a single mode [85]. The maximum measured output power in these devices is 14.4 μW, and

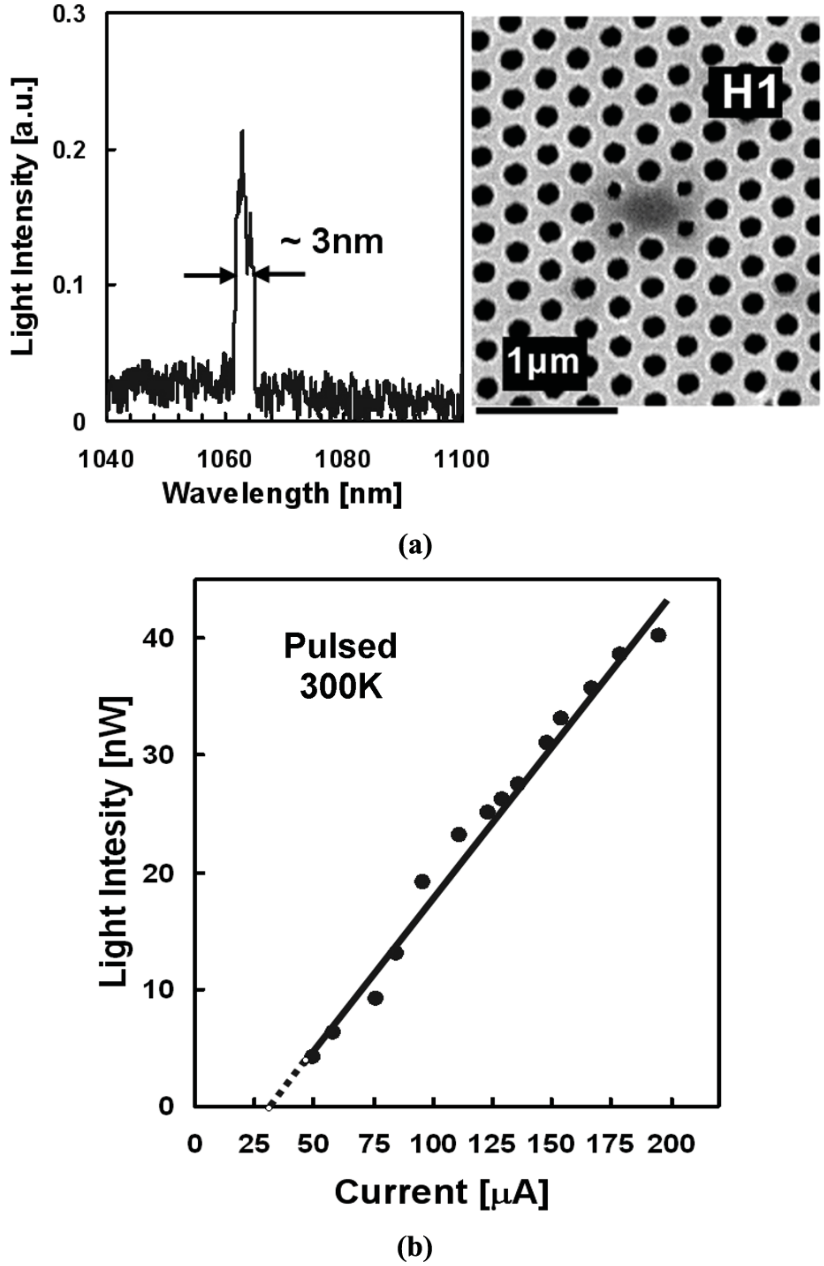


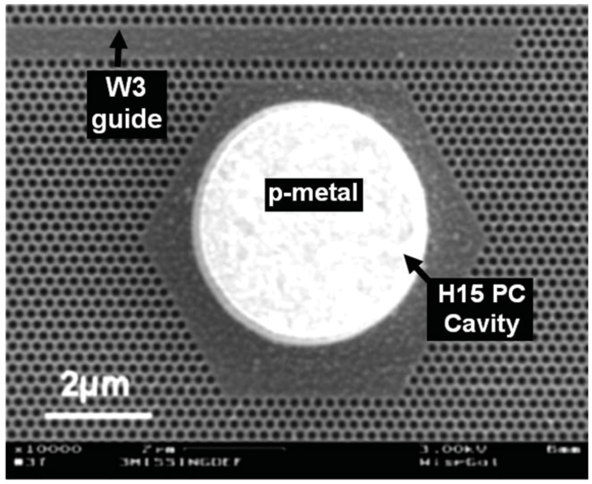
Fig. 9. (a) Emission spectra of a single missing defect cavity with a split dipole degeneracy showing a ∼3-nm-broad microcavity resonance at 1063 nm. (b) L–I characteristics of a modified H1 single-cell microcavity.

we observed 15-fold enhancement of spontaneous emission due to the Purcell factor. The emission spectra at different injection currents are shown in Fig. 4(b). Using a similar configuration, an InGaAsP/InP-based multiquantum well emitter was also fabricated and tested showing slightly lower light output (0.8 μW) [86]. The SEM micrographs of the fabricated device shown in Fig. 3(b). It is worthwhile to note that we obtained large values of spontaneous emission factors β corresponding to the fraction of spontaneous emission coupled to the microcavity resonant mode, namely, $\beta = .06$ for the GaAs-based microcavity device and $\beta \sim 0.01$ for the InP-based device. These values, though less than unity, are significantly larger than conventional semiconductor lasers ($\beta \sim 10^{-4} - 10^{-5}$).

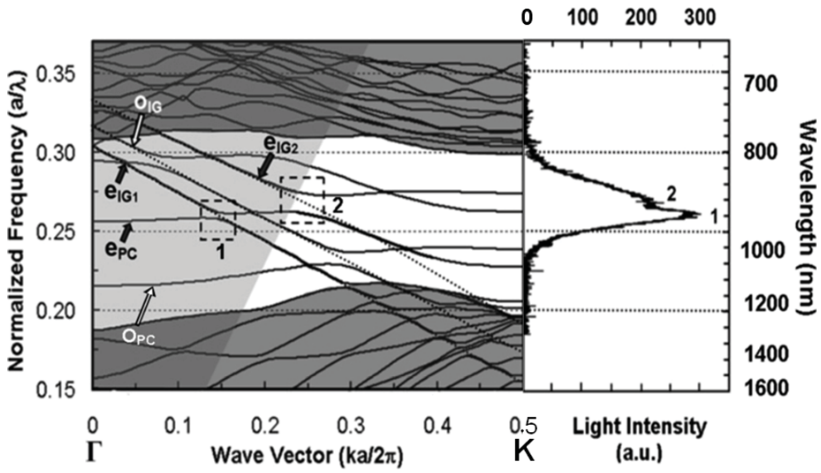
A significant experimental landmark in the pursuit of electrically injected optical microresonators has been reached recently by Park *et al.* [87]. The demonstrated device is based on an air-clad free-standing PC slab supported by a micropost that is used for carrier injection, heat dissipation, and mode selection. The laser exhibits many desirable properties of microcavity light sources such as single-mode operation, small modal volume with high Q ($\sim$ 2500), large spontaneous emission ($\beta \sim 0.25$) and Purcell factors (389), and low threshold current ($\sim$ 260 μA). The device represents a significant step toward electrically pumped PC microcavity lasers suitable for CQED studies.

B. QD Devices

We have attempted to incorporate QDs in the active region of electrically pumped PC optical microcavities [88]. The QD heterostructure used in this device is shown in Fig. 5(a),



(a)



(b)

Fig. 10. (a) SEM image of the fabricated PC 6 μm cavity device (H15) coupled to a three-missing defect waveguide. (b) Measured spectral characteristics showing spontaneous emission coupled to the waveguide.

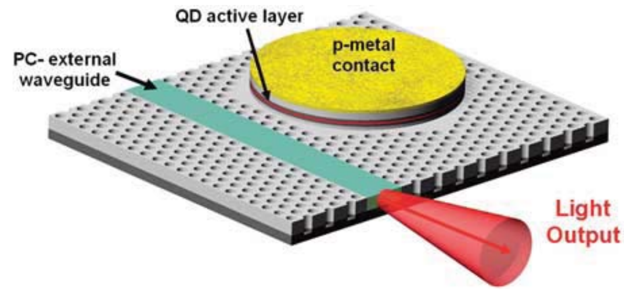
and the device schematic is similar to quantum well emitters discussed in Section V-A. The PBG in normalized frequency range a/λ is between 0.39 and 0.43. The normalized frequency at mid-gap $(a/\lambda = 0.41)$ is chosen for our design encompassing the peak emission of the QDs at $\lambda = 1.04\ \mu$m and fill factor $r/a = 0.35$. The final design values for the PC with a hexagonal unit cell are $a = 0.42\ \mu$m and $r = 0.15\ \mu$m. QDs offer a significantly lower gain when compared with quantum wells, which results in significantly lower output powers $(\sim 0.17\ \mu\mathrm{W})$ even from larger multicell cavities H2. It is estimated that there are ~500 dots in the PC microcavity. Due to extremely low output power from these devices, we were unable to study output spectral characteristics, but we did observe a consistent increase of light output as the cavity size decreases, which we attributed to improved output directionality due to microcavity effects. The L–I characteristics of H2 and H5 hexagonal microcavities are shown in Fig. 5(b). The near-field image of the output, shown in the inset, confirms photon emission from the PC microcavity and not the patterned area around it.

Placing the p-metal contact directly above the PC microcavity presents a promising way of improving the carrier injection efficiency of PC emitters. We have attempted to address this issue with a bottom emitting device with oxide clad active region and additional pairs of GaAs/$Al_{0.84}Ga_{0.16}As$ DBRs above and below the active region for improved vertical mode confinement is shown in the device schematic and QD heterostructure in Fig. 6(a) and (b), respectively. Although considerably degrading the Q factors of resonant modes, this method provides superior stability and thermal conductivity to the alternative free standing structures [87]. The oxide cladding that improves both carrier and optical mode confinement is created by selective wet oxidation of 85 nm $Al_{0.98}Ga_{0.02}As$ layers surrounding the active GaAs region with embedded QDs. The PC pattern defined by electron beam lithography was transferred on a silicon nitride mask that served as an etch mask for the deep GaAs electron cyclotron resonance (ECR) reactive ion etch. We have investigated microcavities of various sizes and geometries such as short linear cavities, single-cell cavities with split degeneracies, and larger hexagonal cavities. The top view of the PC microcavity before the silicon oxide passivation and interconnect deposition is shown in Fig. 7(a) and the device cross section in Fig. 7(b). The devices were characterized in pulsed mode (5% duty cycle) at room temperature, and the output light was observed through the polished semi-insulating substrate. The IR image of the biased device with a H3-microcavity illuminated with a white-light source obtained with a 100× lens (numerical aperture $= 1.25$) shows light emitted from the resonant cavity region surrounded by PC region [Fig. 8(a)]. Emission spectra of PC microcavities with different sizes and geometries clearly show narrow resonances corresponding to individual modes supported by microcavities. Figs. 8(b) and 9(a) show such resonances observed in a hexagonal H3 and a single-cell modified H1 microcavity, respectively. It is estimated that there are on average 50 QDs confined in the H1 microcavity. The linewidth of these microcavity resonances is dictated by the microcavity Q factor. For the case of H3 microcavity, we observed a single ~3-nm broad peak, and for a modified H1 cavity we observed ~1.5-nm multiple resonances at the QD electroluminescence peak, which corresponds to cavity cold Q factors of 350 and 700, respectively. It should be noted that these values are considerably smaller than those observed in free-standing electrically injected structures ($Q \sim 2500$) [87], which is due to low vertical Q of our low-index contrast structures. Due to the limited detector sensitivity, we do not observe any indication of a threshold in the L–I curve for the H1 device, shown in Fig. 9(b). Such behavior is characteristic of ideal single-mode microcavity devices [85]. If there is, however, a measurable threshold below the detection sensitivity of our germanium detector, it is considerably lower than any value in electrically pumped PC microcavity devices reported so far. The demonstrated H1 device is a near-perfect single-mode light emitter diode (or microcavity laser), and it represents a considerable improvement over our previous QD electrically injected microcavity devices with low-index contrast vertical confinement [88]. By further reducing the QD density and/or reducing the cavity size while preserving the high Q, it is conceivable that a single dot will be successfully embedded in an electrically injected high-Q PC nanocavity in the near future. Further improvements in vertical cavity Q factor are achievable through introducing more DBRs in the vertical direction. Currently available state-of-the-art chemically assisted ion beam etching (CAIBE) technology approaches the aspect ratios necessary to etch through such structures [89]. This could lead to efficient electrically injected PBG VCSELs with ultralow thresholds, exceptional mode confinement, and superior mechanical and thermal stability.

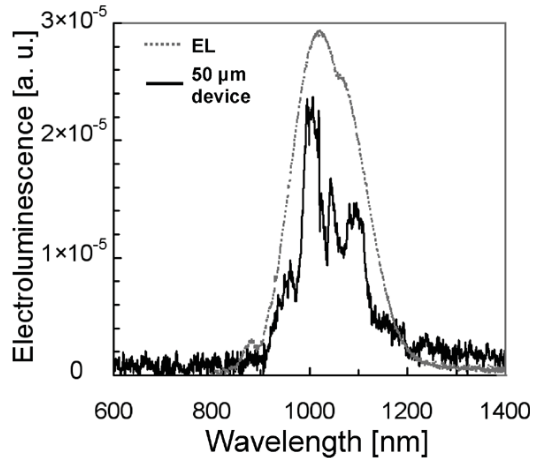
VI. Device Planar Integration

Various optoelectronic applications including small-scale sensors and optical communication systems require integration of PC-based microstructures. Significant progress has been done on design of unique PC coupled cavity waveguides [90] and on coupling of PC missing defect waveguides [91], [92] to PC resonant microcavities [93]. Ultrasmall microcavity resonant add/drop filters have been realized [13], and complex integration schemes have been demonstrated using cavity/waveguide and coupled cavity designs on active quantum well and QD PC slabs [94]. We have attempted to address the in-plane device integration issues and demonstrated electrically injected 2-D PC-based light sources coupled to PC-based waveguides [95]. The top view SEM of a fabricated PC resonant cavity to a three-missing defect waveguide (W3) is shown in Fig. 10(a). The observed spectra contain little evidence of coherent photon exchange between the resonant cavity and the waveguide as it mainly reflects the dispersion properties of the W3 PC waveguide [Fig. 10(b)].

It should be noted that reabsorption in the QD external waveguide layer increases the waveguide losses and considerably limits the size and complexity of the optical circuits. As an important step toward practical devices, we have explored multilayered waveguide structures that avoid light reabsorption in the waveguide region without applying MBE regrowth on patterned substrates [96]. The device shown schematically in Fig. 11(a) consists of an active cylindrical cavity for light oscillations and the external waveguide in



(a)



(b)

Fig. 11. (a) Schematic of a PC edge emitter based on a twin-guide heterostructure that avoids the reabsorption in the waveguide region. (b) Spectral characteristics of a 50-μm PC resonant cavity coupled to a three-missing defect waveguide and electroluminescence of an unpatterned sample. Individual cavity resonances can be distinguished in the spectra.

which the PC resonant cavity and waveguide are defined. The electroluminescence generated in the QD active region first couples vertically to the external guide layer, where it excites the PC hexagonal cavity resonant modes. These modes then transversely couple to the adjacent PC-based waveguide. The spectral measurements of devices with vertically separated active and guided region indicate significant spectral narrowing due to resonant cavity effects. Fig. 11(b) shows output spectra of a 50 μm PC resonant cavity coupled to a three-missing defect waveguide. With smaller mode volumes and higher quality factors, the energy exchange between the QD spontaneous emission, the stimulated emission mode within the cavity, and the waveguide mode can be significantly improved. The next step would involve on-chip integration of a high-efficiency QD PC laser source with PC waveguides and QD PC photodiodes, which will function as an ultracompact integrated photonic chip applicable to a wide range of applications from optical communication systems to sensors.

VII. Summary

We have given an overview of the advantages of PC-based microcavity optical resonators. Incorporating QDs into these devices has been attained with interesting results. With efficient PC-based electrically injected emitters, sensitive and highly selective photodiodes, and low loss-waveguides and passive guiding components, integrated optoelectronic circuits are easily envisioned. When the prospect of a single QD in a high-Q PC microcavity and even single-dot lasing at room temperature is achieved in the near future, it will open the way for several novel applications including single-photon sources for quantum information processing and provide an experimental framework for strong coupling CQED measurements in semiconductor systems.

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