Analysis of vertical coupling between a 2D photonic crystal cavity and a hydrogenated-amorphous-silicon-wire waveguide

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Abstract

We present an efficient means of light extraction from two-dimensional photonic crystal (2D PC) cavities with SiO_2 cladding. We propose a vertically coupled system consisting of a 2D PC cavity and a hydrogenated-amorphous-silicon (a-Si:H)-wire waveguide, which we theoretically investigate using the 3D finite-difference time-domain method. Light can be extracted with an efficiency of greater than 95% to both output ports of the a-Si:H-wire waveguide or extracted with an efficiency of greater than 90% to a single output port of the a-Si:H-wire waveguide with a reflector.

Keywords photonic crystal, silicon photonics, cavity, waveguide

Research highlights

> We have investigated the extraction of light from 2D PC cavities with SiO_2 cladding.

> The extraction of light with an efficiency of greater than 90% can be achieved.

> The light is efficiently extracted from the cavity to a a-Si:H-wire waveguide.

> Although SiO_2 cladding is used (not air), the attractive system can be achieved.

Abbreviations for "Research highlights"

two-dimensional photonic crystal (2D PC)

hydrogenated-amorphous-silicon (a-Si:H)

1. Introduction

Two-dimensional photonic crystal (2D PC) cavities have the ability to simultaneously enhance and suppress the emission of light [1]. The enhancement of light emission into the resonant modes occurs via the Purcell effect [2], and the suppression of light emission into the non-resonant modes takes place by means of the photonic band gap (PBG) effect [3]. The potential applications of 2D PC cavities include single-photon sources for quantum cryptography [1] and ultra-low-threshold lasers for optical interconnections [4]. A number of recent investigations have focused on 2D PC cavities with cladding comprised of a low-refractive-index (low-*n*) material [5-8]. These have higher mechanical strength and better passivation than air-bridge cavities, and also allow heterogeneous integration and vertical stacking. Furthermore, they are compatible with both silicon photonics based on silicon wire/rib waveguides [9-12] and silicon electronics. Although the characteristics of low-*n*-material-clad 2D PC cavities themselves have already been investigated, the extraction of light from such cavities has not yet been studied.

Here we focus on the extraction of light from low-*n*-material-clad 2D PC cavities. There are two important approaches using in-plane or vertical coupling. The extraction of light from an active air-bridge 2D PC cavity to a passive 2D PC waveguide has been demonstrated using in-plane coupling [13,14]. This type of system requires a special active-passive integrated wafer formed by a regrowth process, because the waveguide must be transmissive to the light generated in the cavity. This component can be formed using an InP wafer, and the in-plane coupling system is thus suitable for large-scale InP photonic integrated circuits. On the other hand, the extraction of light from an active 2D PC waveguide and an active 1D PC cavity, both with air upper cladding, to a passive silicon-wire waveguide has been demonstrated using vertical coupling [15,16]. This type of system is fabricated using a wafer bonding process, and the active compound semiconductor thin film can be selectively and efficiently integrated on a silicon wafer. The vertically coupled system is suitable for the heterogeneous integration of compound semiconductor light emitters and large-scale silicon photonic integrated circuits [17].

Note that there are two disadvantages in the in-plane coupling system, which employs the 2D PC cavity and waveguide. First, the distance between the 2D PC cavity and waveguide cannot be continuously adjusted due to the limit of the lattice constant, and the coupling strength cannot be continuously adjusted. Second, highly efficient coupling between 2D PC waveguides and optical fibers is typically more difficult than that between silicon-wire waveguides and optical fibers.

In this paper, we focus on the vertically coupled system, and propose an efficient means of light extraction using a hydrogenated-amorphous-silicon (a-Si:H)-wire waveguide [18,19]. The unique properties of a-Si:H, which include a large optical band gap and ultrafast response [19], have attracted a great deal of attention. a-Si:H with a large optical band gap of ~1.7 eV allows shorter wavelength light than crystalline silicon (c-Si) with a band gap of 1.1 eV, and the wavelength of signal light (and pump light) can be selected over a wide wavelength range in the a-Si:H-wire waveguide. 2D PC cavity light emitters with various emission wavelengths have been demonstrated [1,4,20]. Ultrafast response of a-Si:H is important when a high-speed optical modulator (or switch) based on carrier injection and/or depletion [10,21] in the a-Si:H waveguide is required for quantum cryptography or optical interconnections. Furthermore, a-Si:H can be formed by a low-temperature deposition process and can be vertically integrated on silicon electronic integrated circuits. Vertically coupled systems comprised of a compound semiconductor 2D PC cavity and a a-Si:H-wire waveguide can be fabricated through wafer bonding and deposition processes, and they can be vertically integrated on large-scale silicon electronic integrated circuits.

The operation of an electrically pumped 2D PC cavity light emitter has recently been demonstrated using a laterally doped p-i-n junction [22,23]. This type of light emitter is promising for the construction of ultra-compact and ultrafast directly modulated lasers for off-chip and on-chip optical interconnections [24,25]. The vertically coupled system comprised of a 2D PC cavity and a a-Si:H-wire waveguide is potentially a key element of large-scale opto-electronic integrated circuits. Moreover, it may play an important role in future large-scale quantum cryptography systems.

In the following sections, we theoretically investigate the extraction of light from a 2D PC cavity to a a-Si:H-wire waveguide using the 3D finite-difference time-domain (FDTD) method [26], where both the cavity and waveguide are covered with low-*n*-material cladding. We believe that the enhanced passivation by low-*n*-material cladding is essential for commercialization. Our results demonstrate the great potential of this type of vertically coupled system; the extraction of light to either both output ports or to a single output port of the a-Si:H-wire waveguide can be achieved with an efficiency of greater than 90%, satisfying the conditions of a high quality (Q) factor and an ultra-small modal volume. The efficient extraction of light is important in order to meet the energy targets of future innovative opto-electronic integrated circuits [24] and to realize quantum cryptography systems using single photon communication.

2. Calculation model and method

Figure 1 shows the vertically stacked structure considered here, which is comprised of a compound semiconductor 2D PC cavity and a a-Si:H-wire waveguide on a silicon wafer. The cavity can be integrated through a wafer bonding process [5,27,28]; here we assume that divinylsiloxane-bis(benzocyclobutene) (DVS-BCB) bonding is used. The a-Si:H-wire waveguide can be integrated through a deposition process [18,19]. The refractive indices of a-Si:H, SiO_2, and compound semiconductors such as GaAs and InP are assumed to be 3.5, 1.445, and 3.4, respectively. The slab thickness of the 2D PC is 0.7*a* and the hole radius is 0.31*a*, where *a* is the lattice constant. In our calculations, the air above the SiO_2 cladding is neglected, and the DVS-BCB layer and the silicon substrate below the SiO_2 cladding are also neglected. Therefore, the cavity and waveguide are surrounded only by the SiO_2 cladding. It is permissible to neglect these components when the SiO_2 cladding is thick enough. We employ the 3D FDTD method with Berenger's perfectly matched layer boundary condition [29,30] in order to directly solve Maxwell's equations. The 3D FDTD mesh is comprised of 14 cells per lattice constant *a* and 12 cells per ($\sqrt{3}/2$)*a* in the in-plane directions, and 14 cells per 0.98*a* in the vertical direction.

3. Results and discussion

3.1 Fine tuning of 2D PC L7 cavity with SiO_2 cladding

First, we designed a high-*Q* 2D PC cavity with SiO_2 cladding. In order to realize highly efficient light extraction using the evanescent coupling between the cavity and waveguide, a high-*Q* cavity ($Q > 10^5$) is desirable [31]. For this purpose we fine-tuned a so-called L7 cavity, which is formed by omitting a row of seven holes as shown in Fig. 2(a). The tuning was carried out by adjusting the positions of the holes at both ends of the cavity [32-34]. Although the fine adjustment of an L3 cavity with low-*n*-material cladding has already been reported, the resulting *Q* factor was less than 10^5 [6]. The fine adjustment of an L7 cavity with low-*n*-material cladding has not yet been studied.

When the two holes at position A (the nearest-neighbor holes) were shifted inward, the Q factor increased from its initial value of 2.43×10^4 to a maximum of 6.30×10^4 when the shift, r_A, was $-0.64a$. When the two holes at position A were shifted outward, the Q factor greatly increased and reached a maximum of 1.21×10^5 for $r_A = 0.25a$. Next, with r_A fixed at $0.25a$, the two holes at position B (the second-nearest-neighbor holes) were shifted both inward and outward, but no increase in the Q factor was obtained. On setting $r_A = 0.25a$ and $r_B = 0$, the two holes at position C (the third-nearest-neighbor holes) were then shifted both inward and outward. The Q factor increased to 1.45×10^5 for an outward shift of $r_C = 0.18a$. Finally, setting $r_A = 0.25a$, $r_B = 0$, and $r_C = 0.18a$, the two holes at position D (the fourth-nearest-neighbor holes) were shifted in similar fashion, resulting in an increase of the Q factor to 1.48×10^5 for an outward shift of $r_D = 0.18a$. The modal volume (V) [1] of this cavity is $1.52(\lambda/n)^3$, Q/V is $0.974 \times 10^5 (n/\lambda)^3$, and the Purcell factor (F_P) [1,2] is 7.40×10^3, where λ is the wavelength of the light in air and n is the refractive index of the 2D PC core. The calculated electric field distribution (E_y) in the fine-tuned L7 cavity, across the middle of the 2D PC slab, is shown in Fig. 2(b). The dependence of the Q factor on the shifts of the holes at positions A, B, C and D is shown in Fig. 2(c).

In summary, although SiO_2 cladding is used instead of air, a high Q factor of greater than 10^5 can be achieved for the L7 cavity by fine tuning of the positions of the holes.

3.2 Light extraction from fine-tuned 2D PC L7 cavity to a-Si:H-wire waveguide

We next investigated the extraction of light from the fine-tuned L7 cavity to the a-Si:H-wire waveguide. The width and height of the waveguide used in our calculations were $w = 1.02a$ and $h = 0.51a$, respectively. If the resonant wavelength of the fine-tuned L7 cavity is assumed to be 1550 nm, the corresponding values of a, w, and h are 392 nm, 400 nm, and 200 nm, respectively. Figure 3(a) shows the calculated electric field distribution (E_y) in a vertically stacked structure characterized by these parameters, where the center-to-center distance between the fine-tuned L7 cavity and the a-Si:H-wire waveguide is 1.54a (604 nm). Here, the in-plane size of the 2D PC is $37a\times29a_y$, where a_y is $(\sqrt{3}/2)a$. It is apparent from Fig. 3(a) that light is successfully extracted from the fine-tuned L7 cavity to both output ports of the waveguide. The modal symmetry of the fundamental resonant mode in this cavity is B_{2u} (the point group is D_{2h}) [5,7], and the light couples to the transverse electric (TE)-like ground mode in the waveguide. The overall light extraction efficiency (η) is 96.0% (48.0% for each output port), with a Q factor of 5.82×10^3. The values of V, Q/V, and F_P are $1.53(\lambda/n)^3$, $3.80\times10^3(n/\lambda)^3$, and 2.89×10^2, respectively. The value of η is defined as the ratio of the energy flow that passes through the output ports to the total energy flow around the cavity:

$$\eta = \frac{\frac{1}{T}\int_T\left[\int_{S_{\text{port}}}\mathbf{S}(\mathbf{r},t)\cdot\mathbf{n}da\right]dt}{\frac{1}{T}\int_T\left[\int_{S_{\text{c}}}\mathbf{S}(\mathbf{r},t)\cdot\mathbf{n}da\right]dt} = \frac{\int_T\left[\int_{S_{\text{port}}}\mathbf{S}(\mathbf{r},t)\cdot\mathbf{n}da\right]dt}{\int_T\left[\int_{S_{\text{c}}}\mathbf{S}(\mathbf{r},t)\cdot\mathbf{n}da\right]dt}, \quad (1)$$

where $\mathbf{S}(\mathbf{r},t)$ is the Poynting vector, $\mathbf{n}da$ is the surface vector element, S_{port} is the surface of the output ports, S_c is the closed surface that surrounds the cavity, and T is the integration time. In our calculations, T is set as m/f, where m is an integer ~65 and f is the resonant frequency, and S_{port} is the surface of dimensions $4.17a_y\times3.50a$ (1.41×1.37 μm^2). In the calculations shown in Fig. 3, S_c is the closed surface of a rectangular parallelepiped of dimensions $57a\times33a_y\times16.66a$ ($22.34\times11.20\times6.53$ μm^3), and the distance in the x direction between S_{port} and the center of the cavity is 28.5a. Thus, light extraction from the 2D PC cavity to the two output ports of the a-Si:H-wire waveguide can be achieved with an efficiency of greater than 95% and a Q factor of greater than 5.0×10^3.

The value of η can be expressed as

$$\eta = \frac{1/Q_{\text{port}}}{1/Q_{\text{port}} + 1/Q_{\text{nonport}}} = 1 - Q_{\text{T}}/Q_{\text{nonport}} , \quad (2)$$

where

$$1/Q_{\text{T}} = 1/Q_{\text{port}} + 1/Q_{\text{nonport}} . \quad (3)$$

Here, Q_{T} is the total Q factor of the coupled system, Q_{port} is the Q factor corresponding to the light extracted to the output ports, and Q_{nonport} is the Q factor corresponding to the light that is not extracted to the output ports [31]. In the above case where η = 96.0% and Q_{T} = 5.82×10^3, the values of Q_{port} and Q_{nonport} are 6.06×10^3 and 1.455×10^5, respectively. Note that the waveguide perturbs the resonant mode, and parasitic losses such as additional radiation loss and TE to transverse magnetic (TM) coupling loss are typically induced in these vertically coupled systems.

Under ideal conditions with no parasitic loss, η is generally expressed as

$$\eta = 1 - Q_{\text{T}}/Q_{\text{cav}} , \quad (4)$$

where Q_{cav} is the intrinsic Q factor of the cavity in the absence of a waveguide (in our case, Q_{cav} = 1.48×10^5) [31]. The value of Q_{nonport} is almost equal to Q_{cav}, and thus there is very little degradation due to parasitic losses in this structure. The ideal value of η is defined by Eq. (4) and is estimated to be 96.1% when Q_{T} = 5.82×10^3. Therefore, the actual value of η is almost equal to the ideal value. The vertically coupled system that we consider here has a SiO_2 layer between the cavity and waveguide, and is based on evanescent coupling. Therefore, undesired decrease of the intrinsic Q factor, which is induced by the perturbation of the resonant mode, is avoided ($Q_{\text{nonport}} \approx Q_{\text{cav}}$). In addition, the use of a a-Si:H-wire waveguide, which strongly confines the light, minimizes undesired scattering loss via the 2D PC slab. Consequently, our vertically stacked structure exhibits almost ideal light extraction from the 2D PC cavity to the two output ports of the a-Si:H-wire waveguide.

We also investigated the extraction of light to a single output port, which is particularly important in the operation of single-photon sources. Figure 3(b) shows the electric field distribution (E_y) in a vertically stacked structure with one output port, in which the left-hand a-Si:H-wire waveguide has been removed. Here, the center-to-center distance between the cavity and waveguide is 1.54a (604 nm). The values of η and Q_T are 60.3% and 1.50×10^4, respectively. The values of V, Q_T/V, and F_P are 1.53$(\lambda/n)^3$, 9.80×10$^3(n/\lambda)^3$, and 7.45×10^2, respectively. In this case, the value of $Q_{nonport}$ is 3.78×10^4 and there is thus significant degradation due to parasitic losses. The ideal value of η is estimated to be 89.9% when Q_T is 1.50×10^4, which is 29.6% greater than the actual value of η. Although the TE-TM coupling loss is very small, the undesired radiation loss occurs on the left-hand side of this structure where the waveguide is absent; the end of a a-Si:H-wire waveguide thus gives rise to parasitic losses.

3.3 Light extraction from fine-tuned 2D PC L7 cavity to a-Si:H-wire waveguide with reflector

In order to improve the efficiency of light extraction to a single output port, we introduced a distribution Bragg reflector (DBR) into our vertically stacked structure with two output ports, shown schematically in Figs. 4(a) and 4(b). The DBR consists of the a-Si:H-wire waveguide and an additional a-Si:H-wire grating. The width, height, and period of the grating used in our calculations were 0.43a, 0.28a, and 0.86a (corresponding to 168 nm, 110 nm, and 336 nm), respectively. The center-to-center distance between the waveguide and grating was 0.49a (192 nm). Figure 4(c) shows the 1D photonic band structure of the TE-like ground mode in the DBR. The 1D PBG is found in the region from 0.2462c/a to 0.2562c/a (1530 nm to 1592 nm), where the resonant frequency of the fine-tuned L7 cavity is 0.25288c/a (1550 nm).

Figure 5(a) shows the electric field distribution (E_y) in the vertically coupled system incorporating the DBR. Here, the center-to-center distance between the cavity and waveguide is 1.54a (604 nm), and the center-to-center distance in the x direction between the cavity and the nearest rod of the grating is 11.43a (4480 nm). The grating consists of 31 rods. It is apparent from Fig. 5(a) that light is successfully reflected by the DBR and extracted to one output port of the waveguide. The values of η and Q_T for this system are 94.1% and 3.04×10^3, respectively. The values of V, Q_T/V, and F_P are $1.56(\lambda/n)^3$, $1.95\times10^3(n/\lambda)^3$, and 1.48×10^2, respectively. In the calculations shown in Fig. 5, S_c is the closed surface of a rectangular parallelepiped of dimensions $73a\times33a_y\times16.66a$. The distances in the x direction between S_c and the center of the cavity are $-44.5a$ and $28.5a$, respectively, and the distance in the x direction between S_{port} and the center of the cavity is $28.5a$. Thus, light extraction from the 2D PC cavity to the single output port of the a-Si:H-wire waveguide with the DBR can be achieved with an efficiency of greater than 90% and a Q factor of greater than 3.0×10^3.

We also investigated this system using coupled-mode theory in time [35,36]. Assuming a perfect reflector, the values of η and Q_T can be obtained by substituting

$$Q_{port} = Q_{1port}^{system} = Q_{2ports} / (1+\cos\theta) \tag{5}$$

into Eqs. (2) and (3):

$$\eta = \frac{1}{1+\dfrac{Q_{2ports}}{Q_{nonport}}\dfrac{1}{1+\cos\theta}}, \tag{6}$$

$$Q_T = \frac{Q_{2ports}}{1+\cos\theta+\dfrac{Q_{2ports}}{Q_{nonport}}}, \tag{7}$$

where Q_{1port}^{system} is the Q factor corresponding to light extracted to the single output port, and Q_{2ports} is the Q factor corresponding to light extracted to the two output ports when the reflector is absent. The parameter θ is defined as $2kl+\Delta$, where k is the wavenumber of the waveguide mode, l is the distance between the cavity and reflector, and Δ is the phase shift induced by the reflection. Equations (6) and (7) show that η and Q_T vary periodically with respect to the shift of the reflector. The maximum value of η and the minimum value of Q_T are obtained when $\theta = 2m\pi$ (m is an integer). Conversely, the minimum value of η and the maximum value of Q_T are obtained when $\theta = (2m+1)\pi$ (m is an integer).

Figure 5(b) shows the dependence of η and Q_T on the position of the DBR in the x direction, calculated using the 3D FDTD method. The periodicity of η and Q_T is ~0.9a. The wavenumber and wavelength of the TE-like ground mode in the a-Si:H-wire waveguide is 0.554(2π/a) and 1.81a, respectively, where the dispersion curve was calculated using the 3D FDTD method. The periodicity of η and Q_T corresponds to half of the wavelength of the waveguide mode. The value of η reaches a maximum of 94.1% when the center-to-center distance in the x direction between the cavity and the nearest rod is 11.43a. The minimum value of η (2.5%) is obtained when this distance is 11.00a. Figure 5(c) shows the dependence of η and Q_T on the phase θ, calculated using the coupled-mode theory in time (Eqs. (6) and (7)), where Q_{2ports} and $Q_{nonport}$ are 6.06×10^3 and 1.455×10^5, respectively. The 3D FDTD results agree with the coupled-mode theory results, and the slight difference is mainly due to the imperfection of the reflector. In the 3D FDTD calculations, small radiation loss occurs at the joint of the waveguide and reflector.

Highly efficient light extraction to a single output port is promising for the realization of single-photon sources. In the system shown in Fig. 5(a), the values of F_P and η are 1.48×10^2 and 94.1%, respectively. The spontaneous emission (SE) coupling factor into the resonant mode [1] is given by $\beta = F_P/(F_P + F_{PC}) > 0.993$. A 2D PC cavity can simultaneously enhance and suppress the SE by the Purcell and PBG effects, respectively. The term F_{PC} represents the SE into the nonresonant modes, and is typically smaller than one due to the PBG effect (for example, F_{PC} was ~0.2 in Ref. [1]). The total extraction efficiency of the SE is defined as $\beta\eta$ [31], corresponding to the rate at which the SE couples to the resonant mode and is extracted to the output port of the waveguide. The ideal extraction efficiency is $\beta\eta = 1$. We achieve $\beta\eta > 0.935$ in our system, which demonstrates that vertically coupled systems comprised of a 2D PC cavity and a a-Si:H-wire waveguide with a reflector are suitable for the realization of highly efficient single-photon sources.

We then discuss a potential way to perform pumping. There are three important potential ways in our system. First, the cavity can be optically pumped from above [16,37]. The system covered with low-*n*-material cladding allows additional vertical stacking. A microlens can be formed on the low-*n*-material cladding to focus a pump laser beam [38]. Second, the cavity can be optically pumped through the a-Si:H-wire waveguide [15,31]. Light with a frequency outside the 1D PBG passes through the DBR, and the optical pumping through the waveguide and the DBR is possible. a-Si:H has a larger optical band gap than c-Si. The a-Si:H-wire waveguides allow shorter wavelength light than the c-Si-wire waveguides. Third, the cavity can be electrically pumped using a vertical or lateral p-i-n junction [22,23,39,40]. Especially, 2D PC cavities are suitable for current injection using a lateral p-i-n junction. The compound semiconductor 2D PC region around the cavity can simultaneously work as an optical insulator and an electrical conductor. The in-plane compound semiconductor is typically removed in disk resonators and 1D PC cavities.

Finally, we discuss a potential way to perform tuning. Tuning of the resonant wavelength is important for commercialization of single-photon sources for quantum cryptography and lasers for wavelength-division multiplexing system. Especially, tuning for the spectral matching between the emitter and the resonant mode is essential for commercialization of single-photon sources. There are two important potential ways to tune the resonant wavelength in our system. First, the tuning can be achieved using a microheater. A microheater can be formed on the low-*n*-material cladding [41-43] or on the compound semiconductor slab near the cavity [44]. Second, the tuning can be achieved using electro-optic (EO) polymers [45], liquid crystals [46], or nanofluidics [47], which is introduced around the cavity instead of the SiO_2 cladding. Electrodes can be formed on the above material, the SiO_2 cladding, the compound semiconductor slab, and/or the silicon substrate. In addition, tuning of the emitter can be achieved by electrically controlling the emitter via the quadratic quantum confined Stark effect [48]. In our system, tuning of Q (and η) can also be achieved by dynamically controlling the phase $\theta = 2kl + \Delta$, where a phase modulator is introduced between the cavity and reflector and the length of a phase modulator should be large enough to perform desired tuning. Most of advanced technologies of c-Si based phase modulators can be applied to a-Si:H based phase modulators. Many kinds of phase modulators using a microheater [49], EO polymers [50], liquid crystals, p-i-n junction [21], or p-n junction [10] can be introduced in our system.

4. Conclusions

We have presented an efficient means of light extraction from 2D PC cavities with SiO_2 cladding. First, we fine-tuned a 2D PC L7 cavity with SiO_2 cladding and showed that a Q factor of greater than 10^5 can be achieved. We then investigated vertically coupled systems comprised of the fine-tuned 2D PC L7 cavity and a a-Si:H-wire waveguide, where both the cavity and waveguide are covered with SiO_2 cladding. The light extraction from the fine-tuned 2D PC L7 cavity to two output ports of the a-Si:H-wire waveguide can be achieved with an efficiency of greater than 95% and a Q factor of greater than 5.0×10^3. We then introduced the reflector into our vertically stacked structure, and the light extraction from the 2D PC cavity to a single output port of the a-Si:H-wire waveguide with the reflector can be achieved with an efficiency of greater than 90% and a Q factor of greater than 3.0×10^3. These results demonstrate the great potential of vertically coupled systems comprised of a compound semiconductor 2D PC cavity and a a-Si:H-wire waveguide covered with SiO_2 cladding.

The research and development of ultra-compact 2D PC cavity light emitters, and the efficient extraction of light from them, are of great importance in order to meet energy targets in future innovative opto-electronic integrated circuits and in order to realize quantum cryptography systems using single-photon communication. We believe that vertically coupled systems comprised of a 2D PC cavity and a a-Si:H-wire waveguide will play an important role in these future applications.

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Figure captions

Fig. 1. (Color on the Web only) Schematic picture of the vertically stacked structure comprised of a compound semiconductor 2D PC cavity and a a-Si:H-wire waveguide on a silicon wafer. The cavity and waveguide are enclosed by SiO_2 cladding.

Fig. 2. (Color on the Web only) (a) Schematic picture of the 2D PC L7 cavity, where the holes are filled with SiO_2 cladding. (b) Electric field distribution E_y of the fundamental resonant mode in the fine-tuned L7 cavity with SiO_2 cladding, across the middle of the 2D PC slab. (c) Q factor of the fundamental resonant mode in the L7 cavity with SiO_2 cladding as a function of the shifts of the holes at positions A, B, C and D. When the holes at position B were shifted, the shift of the holes at position A, r_A, was 0.25a. When the holes at position C were shifted, r_A and r_B were 0.25a and 0, respectively. When the holes at position D were shifted, r_A, r_B and r_C were 0.25a, 0 and 0.18a, respectively.

Fig. 3. (Color on the Web only) Electric field distributions E_y in vertically stacked structures with (a) two output ports and (b) one output port.

Fig. 4. (Color on the Web only) (a) Schematic representation and (b) side cross-sectional view of the DBR. (c) 1D photonic band structure of the TE-like ground mode in the DBR.

Fig. 5. (Color on the Web only) (a) Electric field distribution E_y in the vertically coupled system containing a DBR. (b) Dependence of the values of η and Q_T on the DBR position, which was calculated using the 3D FDTD method. (c) Dependence of the values of η and Q_T on the phase θ, which was calculated using the coupled-mode theory in time.

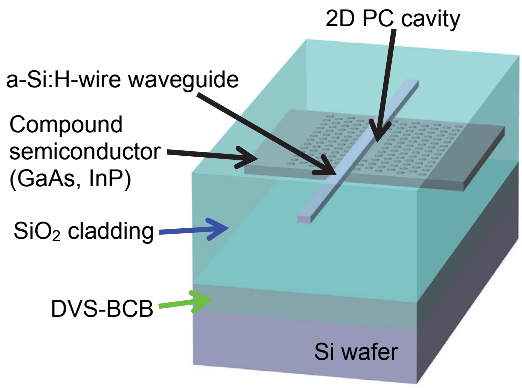
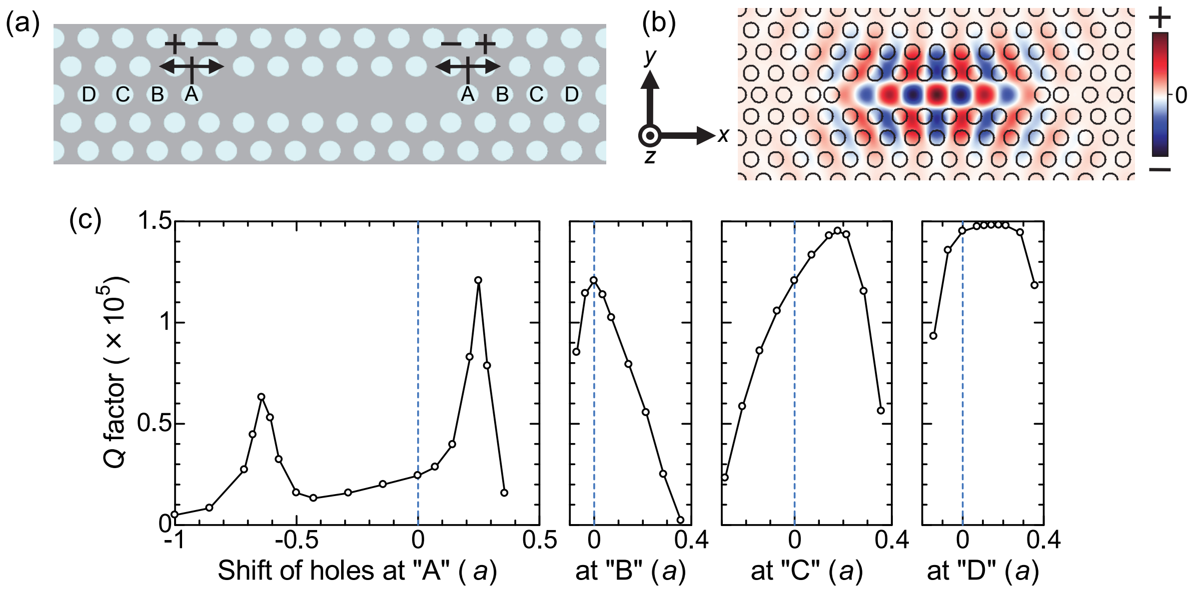


Fig. 1. (Color on the Web only)



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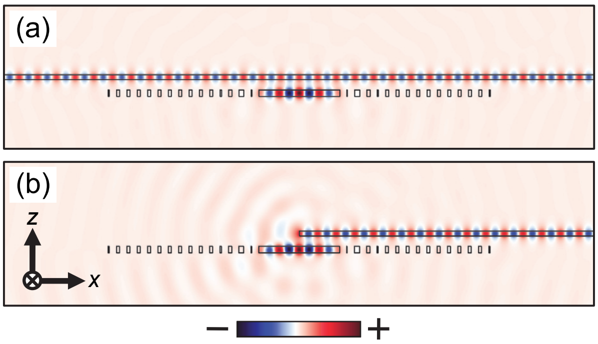

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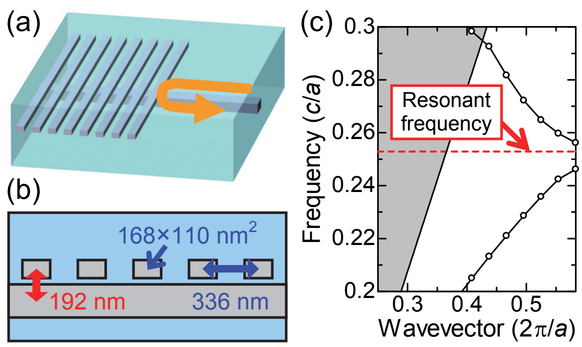

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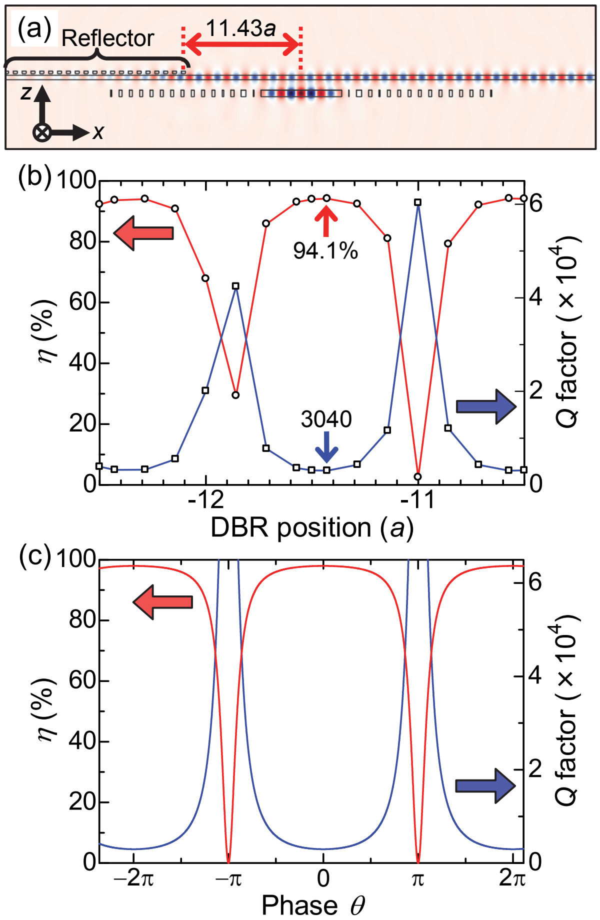

Fig. 5. (Color on the Web only)