High quality factor two dimensional GaN photonic crystal cavity membranes grown on silicon substrate

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We report on the achievement of freestanding GaN photonic crystal L7 nanocavities with embedded InGaN/GaN quantum wells grown by metal organic vapor phase epitaxy on Si (111). GaN was patterned by e-beam lithography, using a SiO$_2$ layer as a hard mask, and usual dry etching techniques. The membrane was released by underetching the Si (111) substrate. Micro-photoluminescence measurements performed at low temperature exhibit a quality factor as high as 5200 at ~420 nm, a value suitable to expand cavity quantum electrodynamics to the near UV and the visible range and to develop nanophotonic platforms for biofluorescence spectroscopy.

Beyond their impact on solid state lighting, GaN and related alloys are promising semiconducting materials for both devices (e.g., gas sensors or on-chip biophotonic devices) and fundamental research. Their high oscillator strength (CES) and fundamental research. Their high oscillator strength (CES) and efficient light emission properties from the UV to the green wavelength range make them particularly suitable for the achievement of freestanding GaN photonic crystal L7 nanocavities with embedded InGaN/GaN quantum wells grown by metal organic vapor phase epitaxy on Si (111). GaN was patterned by e-beam lithography, using a SiO$_2$ layer as a hard mask, and usual dry etching techniques. The membrane was released by underetching the Si (111) substrate. Micro-photoluminescence measurements performed at low temperature exhibit a quality factor as high as 5200 at ~420 nm, a value suitable to expand cavity quantum electrodynamics to the near UV and the visible range and to develop nanophotonic platforms for biofluorescence spectroscopy.

reactive ion etching (RIE) and the resist was removed. Then GaN etching using chlorine-based inductively coupled plasma was carried out. Finally, the GaN membrane was released through dry RIE underetch of the Si (111) substrate. An airgap of the order of 1 μm was achieved, which is large enough to minimize interactions with the substrate and related light losses. The SiO₂ mask was finally dissolved in a hydrofluorhydric acid solution.

Despite the processing complexity, two-dimensional (2D) GaN L7 PhC cavity slabs of high structural quality were obtained as shown in the scanning-electron-microscope (SEM) top and side views displayed in Figs. 2(a) and 2(b).

We point out that the use of a SiO₂ hard mask seems to be determinant to ensure a low degradation of the pattern after completion of the whole process. The close-up view of one of the holes (inset of Fig. 2(a)) reveals a clear tendency toward a hexagonal shape due to the crystal structure, as already observed in similar AlN PhCs. It is worth noticing that our cavities were not tuned by displacing adjacent cavity holes, which is a widely used approach to further increase the Q factor. The large airgap achieved through substrate underetching is shown in Fig. 2(b). A hole cross-section is displayed in the inset exhibiting a vertical and smooth profile with a diameter ~100 nm.

Structures were characterized at LT by microphotoluminescence (μPL) spectroscopy using a continuous wave (cw) frequency-doubled Ar⁺ laser (λ = 244 nm) focused down to a 2 μm diameter at an excitation power density of 2 kW/cm². The signal was then sent to a liquid-nitrogen cooled UV-enhanced charge-coupled device monochromator combination providing a spectral resolution of up to ~100 μeV. A typical μPL spectrum is shown in Fig. 3(a).
Six main peaks are distinguished at 2.932, 2.938, 2.942, 2.952, 2.980, and 3.02 eV. The narrowest one, emitting at 2.938 eV, has a linewidth of 570 μeV corresponding to a Q factor as high as 5150.

To analyze the experimental spectra, we use the 2D plane wave expansion method for the calculation of the photonic crystal dispersion and cavity modes. The L7 PhC cavity induces multiple states inside the bandgap. Similar L7 multimode cavities were already studied in GaN membranes. In addition, owing to the thickness of our waveguide, three orders of transverse electric (TE) and transverse magnetic (TM) modes are supported among which only the first two TE modes provide a bandgap in the PhC. At this stage, one should point out that to properly determine the mode eigenfrequencies the refractive index dispersion of GaN (Ref. 23) has to be accounted for. Only the AlN and GaN contributions were included for the estimation of the effective refractive index (n_eff) used in 2D calculations. The InGaN refractive index was disregarded due to the relative imperfections absorption has also to be taken into account.

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High-finesse disk microcavity based on a circular Bragg reflector

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We made disk-shaped microcavities of approximately 10 μm² in area in a GaAs/AlGaAs waveguide structure by etching deep vertical concentric trenches. The trenches form a circular Bragg-like reflector that confines light in the remaining two lateral dimensions. We demonstrate from photoluminescence excited in the waveguide the confinement of discrete disk modes whose wave vector is mainly radial, in contrast with whispering gallery modes. Their quality factors up to 9 = 650 indicate in-plane reflectivities approaching 90%. In the near infrared, this represents a demonstration of wavelength-scale light confinement based on photonic crystal effects in two dimensions. © 1998 American Institute of Physics. [S0003-6951(98)00336-2]

Light confinement at wavelength scale in semiconductor microcavities has been productive in controlling optical processes along the “vertical” growth axis of the semiconductor heterostructure.1 Lateral light confinement at a similar scale is also desirable to control in-plane spontaneous emission.2 Because in many devices this emission couples into the guided mode(s) of the heterostructure, adding lateral confinement in the two “horizontal” dimensions results in a resonator with discrete photon modes which are confined in three dimensions. Flat circular disks defined in a waveguide are the simplest realization of such resonators: Since the vertical k component is dictated by the waveguide, in-plane propagation may simply be accounted for by the use of an effective index n_eff.3,4 Using, for simplicity, the crude zero-field boundary condition, the eigenmodes for a disk of radius R have the reduced vacuum wavelength (λ_R/R) = 2πn_eff(λ_R/R)x_R, where m and n are the azimuthal and radial quantum numbers, respectively, and x_R is the n-th zero of the m-th Bessel function J_m(x), whose first-order approximation is x_R ≈ (2n + m - 1/2)π/2 = β_{2n+1} for m ≪ n.5 Two noticeable kinds of modes are quasiradial modes [QRMs, Fig. 1(a), m ≫ n] and whispering-gallery modes [WGMs, Fig. 1(b), m ≫ n].3,4 WGMs correspond to rays at almost grazing incidence that sample only the periphery of the disk. Their wave vector k is essentially tangential, k_x ≈ k. Conversely, rays of QRMs impinge close to normal incidence (k_x ≪ k). Because QRMs do sample the entire disk, controlling them is a key to improving the light–matter interaction in actual devices.

At present, there have been numerous successful realizations of microdisks sustaining high finesse WGMs,4 on account of the good properties of total internal reflection (TIR) at grazing incidence. In contrast, reflectors that confine QRMs on a wavelength scale have not, to our knowledge, been demonstrated as yet. The shallow circular concentric gratings employed to define DBR-type (distributed Bragg reflector) round laser resonators offer surface emission capabilities,6 but with useful modes of diameter ≈ 100 μm. Conversely, at the wavelength scale, in-plane reflecting action of deep-etched straight trenches was demonstrated to provide lateral confinement in one dimension in micron-sized cavities around λ = 900 nm.7,8 In this letter, we combine these two approaches and study disk-shaped microcavities bounded by reflectors made of circular concentric deep-etched trenches (“leaks,” Fig. 2(a)) in order to achieve more control of lateral spontaneous emission. The photonic bandgap approach inspired this photonic structure as well as that of Ref. 8. Here, we included emitters in the cavity that consist of self-organized InAs quantum dots (QDs).9 Using their photoluminescence (PL), we demonstrate that our reflectors of inner diameter ≈ 3 μm strongly confine the QRMs with low m values (m ≲ 9).

A micrograph of a disk is shown in Fig. 2(b). The basic planar structure is a 0.24-μm-thick GaAs waveguide core...
embedding three layers of self-organized InAs dots. A 0.34-
µm-thick layer forms the top cladding. The circular trenches are deeply etched down to a depth \( \sim 0.8 \) µm in order to thoroughly cross the waveguide. The nanometer-scale e-beam lithography and etching methods are detailed in Refs. 10 and 11. The inner diameter of the disks is \( 2R = 2.9 - 3.2 \) µm, the concentric gratings consist of eight trenches of typical widths \( t = 70 \) nm and pitches \( \Delta = 580 - 640 \) nm. These in-plane mirrors operate at the fourth Bragg order around \( \lambda = 1 \) µm (\( \Lambda = 4 \times [\lambda/2n_{\text{eff}}] \) for \( \lambda \sim 1 \) µm), given that \( n_{\text{eff}}(\lambda) \approx 3.36 - 8 \times 10^{-7}[\lambda(\text{nm}) - 1000] \). The value of \( t \) is a compromise that ensures guided light reflection within a short length while minimizing out-of-plane scattering.7,8

Inside these resonators, we excite the QD photoluminescence in order for the guided spontaneous emission to probe the disk resonances. The dots offer the advantage of trapping the radiating electron-hole pairs, thereby reducing carrier diffusion towards etched interfaces and ensuring a large PL signal inside the disks. Furthermore, the deliberate broad distribution in dot size translates into a broad PL spectrum from 920 nm to well beyond our present 1040 nm detection limit. Photoexcitation is provided by a 678 nm laser diode beam focused to a \( \sim 2 \) µm spot with a \( \times 50 \), NA=0.50 objective also used for PL collection. Next, a fiber located in the image plane of the objective feeds the collected signal to a spectrometer so as to perform localized PL (µ-PL) with a resolution \( d \approx 1 \) µm.12

Excited cavity modes are primarily outcoupled in the guided mode outside the disk, forming a beam awkward to collect [Fig. 2(a)]. The grating, however, provides backreflection through its fourth Bragg order (8\( \pi \) phase difference on a round trip between trenches), so successive rays diffracted towards the vertical axis have a 4\( \pi \) phase difference and, similarly to the surface emission mechanism of second-order DBRs,6 guided light may be coherently outcoupled towards substrate and air [Fig. 2(a)]. Out of the two guided wave polarizations, TE and TM, only the first gives rise to a noticeable air emission because (i) at the source, the QD emit quite more in TE waves; (ii) in the grating, the TM diffraction efficiency vanishes around the vertical direction since in the regime \( t \ll \lambda \), each trench acts as a punctual secondary source of radiation, akin to a vertical oscillating dipole in the TM case that does not radiate vertically. Even in the TE case, we estimate that not more than a few percents of the guided power is diffracted outside the guide per trench. Eventually, with the µ-PL setup collecting selectively light from the grating area, we do detect the horizontal TE disk resonances, with provisions detailed below. This ability to probe disk modes along the vertical axis greatly eases the test of a large number of disks. But conversely, from the resonator viewpoint, this diffraction represents a loss that reduces the grating reflectivity and/or its in-plane transmission.

On the same wafer, we etched a series of homothetic structures with pitches \( \Lambda = 580, 600, 620, \) and 640 nm and inner diameters \( 2R = 5 \) \( \Lambda \). Our main observation is that many sharp peaks of width \( \Delta \lambda = 1.5 - 5 \) nm (hence quality factors up to \( Q = 650 \) ) show up on spectra collected from the grating area (Fig. 3), while light collected in the center exhibits no new features, or at most a minute remnant of the peaks. Peaks appear in clusters of one to four, but these clusters disappear at long wavelengths for \( \Lambda = 580 \) nm and short wavelengths for \( \Lambda = 640 \) nm. They are separated by a free spectral range (FSR) of 27–33 nm typical of the disk diameter. As a crosscheck, we collected the stray light from the edge of an isolated disk without reflector (\( 2R = 3 \) µm) and found only broad modal features (inset of Fig. 3).

We, thus, attribute unambiguously these peaks to QRM resonances radiating in air through grating diffraction,13 each cluster corresponding to a given value of \( 2n + m \), with successive odd and even clusters. Modes with higher \( m \) (from \( m \sim 10 \) up to WGMs) do not radiate in the grating region towards the objective or do not even radiate in air because of \( k \) conservation in Snell’s law.14

These conclusions are first supported by the simple idea that one has to lie in the grating reflectivity stop band to build up sharp resonances. We calculated the position of these stop bands, using, for simplicity, a one-dimensional multilayer model in the case of normal incidence: we take a refractive index of unity for the thin trenches and the value \( n_{\text{eff}}(\lambda) \) for the semiconductor ridges. The resulting stop bands are shown as black bars under each of the four curves in Fig. 3. The sharpest multiple clusters are located in the stop bands, while there are almost no marked features outside them. In detail, the long wavelength side of the stop band

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**FIG. 2.** (a) Schematic of the microcavity with circular trenches and measurement of resonances through localized detection of air-diffracted PL; (b) micrograph of a typical disk.

**FIG. 3.** Raw spectra of light collected selectively on the grating area of disks with pitches \( \Lambda = 580, 600, 620, \) and 640 nm, and diameters \( 2R = 5 \) \( \Lambda \), with a vertical shift for clarity; stop bands of the grating are represented as dark bars below each curve. Inset: spectrum of stray light from an isolated disk of diameter \( 2R = 3 \) µm showing only smooth features.
seems the worse, an effect which might stem from the over-
simplified normal incidence assumption: it is well known
that at oblique incidence, hence here for higher \( m \) values of
QRMs, stop bands tend to shift to lower wavelengths.

Whereas a one-dimensional approach takes the effects of
the grating periodicity into account, we shall neglect them in
two dimensions in using a “perfect disk” model that focuses
on those features that are specific to the round shape of the
resonator: this model simply assumes a zero field at an ef-
factive diameter \( 2R' > 2R \), in order to account for the field
penetration depth into the circular grating. Resonant wave-
lengths of such a perfect disk are
\[
\lambda_{m,n} \approx \frac{2 \pi R_{n,eff}}{\beta_{2n+m}} \left[ 1 + \frac{4 m^2 - 1}{2 \beta_{2n+m}^2} \right]^{-1}
\]
for which we have the following expansion:

\[
0 \leq R_{n,eff} < \beta_{2n+m}
\]
The first factor accounts for the succession of clusters asso-
ciated to odd and even \( m \) number. Then, the fine structure
within each cluster, given by \( m^2 \), is akin to the series
\((0,4,16,36,\ldots)\) for even \( m \) but to the different series
\((1,9,25,\ldots)\) for odd \( m \). Next, the resonance widths result from
the imperfect wall reflectivity, translating into a finite reso-

nator finesse \( F \), that we use as an estimate of the grating
power reflectivity \( R_0 \) according to \( F \approx 2 \pi (1 - R_0) \). Finally,
as \( m \) increases, light collection in air is impeded and is
expected to vanish for \( m \to 10 \). We account for this effect
through an \textit{ad hoc} visibility factor \( g(m) = \cos^2(\pi/2 \times (m/10)) \)
for \( m \leq 10 \), and \( g(m) = 0 \) beyond, that does not
modify the peak width. We hence calculate the intensity in
this model as a sum of weighted Lorentzians \( g(m) \times [1 + (\lambda - \lambda_{m,n})^2/\Delta \lambda^2]^{-1} \), with a finesse \( F = (\text{FSR}/\Delta \lambda) \).

To fit the data of the 3 \( \mu \)m disk (\( \lambda = 600 \) nm), we use a
finesse \( F \approx 65 \) (between clusters of same \( m \) parity and differ-
ent \( n \), i.e., with \( -60 \) nm FSR) and an effective diameter
\( 2R' = 3.70 \mu \)m. We obtain the simulated spectrum of Fig. 4.

The peak widths \( \Delta \lambda \) are fairly well reproduced, as well as the
typical alternate patterns from an even cluster (separations of about
1–3–5 nm, the two first peaks merging) to the next odd cluster (separations of about 2–4 nm). The strength of each peak within a cluster does not decrease as a function of
\( m \) as it does in the simulation. The intrinsic or extrinsic
(based on the measurement principle) nature of this discrep-
ancy is still unclear to us. From the finesse, one concludes
that the reflectivity at normal incidence is close to 90%.

In summary, by considering stop-bands and a simple
disk model, we show clear evidence that the observed peaks
stem from the quasiradial modes of the disk. Since confine-
ment of QRMs cannot be achieved with TIR, our results
clearly demonstrate the efficiency of the novel circular re-

flectors.

In conclusion, we demonstrate quasiradial microcavity
modes in disks of diameter \( 3 \) \( \mu \)m bound in two dimen-
sions by a short circular grating and confined in a planar
GaAs waveguide in the third dimension. These quasiradial
modes are confined by the circular grating whose reflectivity
may be as high as 90%, leading to a quality factor \( Q \approx 650 \).

This grating is a novel solution for lateral light confinement
and spontaneous emission control, going beyond the limita-
tion of total internal reflection that confines only whispering-
gallery modes and represents to our knowledge the first dem-
onstration of photonic crystal effects in two dimensions of a
microcavity.

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13 The dispersion of this grating is not a severe impairment. For normal
incidence on the grating, the air beam angle \( \theta_0 \) is given, by \( \sin \theta = n_{eff} \)
\( (\lambda - \lambda_0) \lambda_0 \), where \( \lambda_0 \) is the wavelength emerging at
\( \theta = 0 \). In our data (\( \lambda - \lambda_0 \))/\( \lambda_0 = 0.1 \), so that \( \sin \theta \) remains in the 0.5 collected aperture.
14 The field of disk modes \((m,n)\) contains \( \exp(\text{geom}) \) factors. Upon circulating
\( L = 2 \pi r \) onto a loop of radius \( r \), by matching \( \exp(\text{geom}) \) to the plane-
wave form \( \exp(ik_z) \), one finds \( k_x = m/r \); as a first-order estimate, Snell’s
law dictates the outside angle of incidence \( \theta_r \) of rays diffracted in air in
the azimuthal direction according to \( \sin \theta_r = k_x / \lambda \), where \( \lambda \) is the
value of \( \lambda \) for which \( 2.5 \mu \)m of detection in the grating area,
the air beam is allowed (\( \sin \theta = 1 \)) up to \( m \sim 16 \), while light collection
(\( \sin \theta \approx 0.5 \)) holds only up to \( m \sim 9 \). Note that for WGMs, \( m \) is of the
order of \( 50 (m \lambda \sim 2 \pi R_{n,eff}) \).
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Photonic crystal nanolaser monolithically integrated with passive waveguide for effective light extraction

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We recently reported room-temperature continuous-wave operation in a GaInAsP photonic crystal slab nanolaser. In this letter, we demonstrate effective light extraction from the nanolaser monolithically integrated with a passive waveguide by using a GaInAsP butt-joint regrowth technique. Theoretically, the extraction efficiency through the waveguide was calculated to be 80% for the optimum design of the coupling system of the nanolaser and the waveguide. In the experiment, we evaluated a differential quantum efficiency of 4%, which was degraded mainly due to the detection loss of the output light. © 2008 American Institute of Physics. [DOI: 10.1063/1.2831916]

Photonic crystal (PC) point defect nanolasers1–3 with ultrasmall modal volumes $V_m$ are anticipated to be used as local light sources in high-density photonic integrated circuits. We recently fabricated a point-shift PC nanolaser consisting of a shift of only two lattice points in a PC slab containing a GaInAsP quantum well active layer (called the $H_0$ nanolaser), and we succeeded in demonstrating room-temperature (RT) continuous-wave (cw) operation. 4 The fitting of theoretical results to experimental values indicated that the laser mode has one primary antinode at the cavity center, with $V_m$=0.019 $\mu$m$^3$, which is close to the smallest limit for optical cavities. 5 However, although it has never been quantitatively evaluated, people expect the output power and the efficiency of such nanolasers to be far below practical levels because of their small size and because their output light is strongly diffracted. Other groups have described candidate device configurations for light extraction, such as the coupling of the nanolaser with a PC line defect waveguide,6,7 vertical beaming of the laser light by structural tuning,8 and evanescent coupling of the laser mode with a tapered optical fiber.9,10 The latter two are effective for light extraction to external systems. However, integration with the PC waveguide is more advantageous in the case of potential photonic integrated circuits based on a PC slab. It should be noted that when the waveguide is formed in the active region, efficient light extraction and low loss optical wiring are not expected due to the strong interband absorption. To avoid this, we developed an active-passive-integrated PC slab, wherein a GaInAsP quantum well slab was connected with a wide bandgap quaternary bulk slab by using a butt-joint metal-organic chemical vapor deposition (MOCVD) regrowth technique. We previously demonstrated the coupling system of a line defect laser and passive line defect waveguide, and evaluated a differential quantum efficiency of 8% in laser operation.11 In this letter, we demonstrate the monolithic integration of the $H_0$ nanolaser and passive line defect waveguide, as well as the effective extraction of laser light from the waveguide.

First, we calculated the light coupling between the nanolaser and the waveguide using the three-dimensional finite-difference time-domain (FDTD) method. Figure 1(a) shows the schematic of the $H_0$ nanocavity and the line defect waveguide in a triangular lattice PC slab. We assumed a slab index $n$ of 3.4, a lattice constant $a$ of 480 nm, a normalized airhole diameter $2r/a$ of 0.54, a normalized slab thickness $d/a$ of 0.42, and a normalized airhole shift $s/a$ of 0.17. Under these conditions, the $H_0$ nanocavity maintains the mono-

FIG. 1. (Color online) FDTD calculation results for the coupling system of the $H_0$ nanocavity and the PC line defect waveguide. (a) Top view of the device model. (b) Field ($H_z$) distribution. (c) Dependence of cavity $Q$ factors on separation $N$. (d) Dependence of light extraction efficiency $\eta_{ex}$ on separation $N$.
pole mode with $V_m = 0.019 \mu m^3 = 0.15(\lambda/n)^3$, where $\lambda$ is the modal wavelength in vacuum. In the coupling system, the line defect waveguide is placed toward the direction that the monopole mode strongly penetrates. If the waveguide width $W$ was the same as the width $W_0$ of the simple line defect waveguide, the lasing mode takes several coupling points with an even and odd waveguide modes in the leaky region. Therefore, $W$ was moderately reduced to obtain a unique coupling condition with the even mode in the guiding region. In order to balance the high cavity $Q$ and extraction efficiency, the separation $N$ denoting the number of airholes between the cavity and the waveguide in $\Gamma$-X direction was also changed. Figure 1(b) shows the modal field distribution in the coupling system for $N=5$ and $W=0.8W_0$ when the nanocavity was excited at the monopole mode frequency. The cavity mode is clearly coupled to the waveguide. Figure 1(c) shows the calculation results for the $Q$ factor with separation $N$. Here, $Q_{\text{ver}}$, $Q_{\text{in}}$, and $Q_{\text{par}}$ are determined, respectively, by the out-of-plane radiation loss in the vertical direction, in-plane coupling to the waveguide, and parasitic losses caused by the free carrier absorption and the scattering loss due to the imperfection of the device. We set $Q_{\text{par}} = 20,000$, which was experimentally evaluated under the RT cw operation condition. As shown in Fig. 1(c), $Q_{\text{in}}$ exponentially decreases as $N$ decreases. $Q_{\text{ver}}$ also decreased when $N$ was less than five, because the out-of-plane radiation loss is sensitive to the field profile penetrating from the cavity to the PC. However, the total cavity $Q$, given as $Q_{\text{total}} = (Q_{\text{ver}} + Q_{\text{in}}^{-1} + Q_{\text{par}}^{-1})^{-1}$, is mainly limited by $Q_{\text{in}}$ when $N<5$. Figure 1(d) shows the light extraction efficiency from the nanocavity, $\eta_{\text{ex}} = Q_{\text{total}}/Q_{\text{in}}$, where $Q_{\text{par}}$ is an unknown variable. $\eta_{\text{ex}}$ increased with decreasing $N$ and increasing $Q_{\text{par}}$ because the parasitic losses were reduced relatively. For $N=3$ and $Q_{\text{par}} = 20,000$, $\eta_{\text{ex}}$ is expected to be 80% with $Q_{\text{total}}$ being maintained to be nearly 10$^5$.

In the experiment, we prepared a GaInAsP active-passive-integrated wafer formed by the MOCVD butt-joint regrowth process, the details of which are described in Ref. 11. The slab layer consisted of an active region with six PC airholes formed by e-beam lithography and H/I/Xe-inductively coupled plasma etching, and the airbridge structure was formed by selective HCl wet etching. The nanolaser and the waveguide were clearly formed with a smooth etching profile, as shown in Fig. 2(a).

In the measurement, the nanolaser was photopumped at RT by 0.98 $\mu m$ wavelength pulsed laser light with a duty ratio of 0.075% and a focused spot diameter of 2.5 $\mu m$. The light emitted from the facet of the waveguide was directly detected by an as-cleaved multimode fiber GI-50 and observed using an optical spectral analyzer. Figures 2(b) and 2(c) show the laser characteristics for a sample with $N=3$ and $W=0.8W_0$. The effective pump power $P_{\text{eff}}$ was evaluated from the absorption efficiency of the pump light in the slab (we estimated it to be 30%) (Ref. 14) and the overlap efficiency of the pump spot with the cavity area (we estimated this to be 10% when the cavity area is assumed to be an ellipse attaching the innermost airholes). The maximum output power $P_{\text{max}}$, threshold pump power $P_{\text{th}}$, and differential quantum efficiency $\eta_d$ were estimated to be 1.8 $\mu W$, 22 $\mu W$, and 4%, respectively. $\eta_d$ is not a real value of the device but dominantly includes the coupling loss between the waveguide and the detection fiber. If such a coupling loss is reduced by using a lensed fiber, this value will be improved to $\sim 30\%$. Although such measurement was not realized in this study because of the degradation of the device, more than a sevenfold improvement in $\eta_d$ has been confirmed for PC line defect lasers. However, this is still 2.7 times lower than the calculated light extraction efficiency $\eta_{\text{ex}}$. This difference cannot be due to the propagation loss in the waveguide since the waveguide length was shorter than 10 $\mu m$. One reason for this must be an internal quantum efficiency lower than 100%. Other reasons considered include a lower $\eta_{\text{ex}}$ of the fabricated device and the reflection and/or wide-angle diffraction of light at the waveguide facet. A small fabrication error in the structural parameters affects the depth and orientation of the field penetration from the cavity to the waveguide, resulting in lower $\eta_{\text{ex}}$. Also, the reflection and diffraction are sensitive to the position of the cleaved facet of the waveguide with respect to the airhole pattern of the PC, which could further degrade the detection efficiency.

Figure 3(a) compares the laser characteristics for some samples with different $N$ ranging from 3 to 7. Obviously, the maximum output power and $\eta_d$ increase as $N$ decreases. Figure 3(b) summarizes the dependence of $P_{\text{th}}$ and $\eta_d$ on $N$. $P_{\text{th}}$ also increases as $N$ decreases because of the decrease in $Q_{\text{in}}$; $P_{\text{th}}$ is 6 $\mu W$ without the waveguide and $\sim 20 $ $\mu W$ for $N=3$. The behavior of $\eta_d$ is very similar to that of $\eta_{\text{ex}}$ in Fig. 1(d) for $Q_{\text{in}} = 1000 - 5000$. Some fluctuations in the experimental plots observed even for the same $N$ may be due to fabrication error, as mentioned above. By reducing the fabrication error and optimizing the waveguide facet, further improvement and stable evaluation of $\eta_d$ can be expected. A $\eta_d$ of 80% with a low threshold of a few tens of microwatts is
theoretically obtainable for $N=3$ and $Q \sim 10^3$. In the case of using an active material such as a single quantum well or a quantum dot having a lower modal gain, a higher $Q_{\text{total}}$ of $10^4$ order for $N \geq 5$ is preferable to obtain a lower threshold of microwatt order while maintaining $\eta_d > 50\%$.

In conclusion, we demonstrated an ultrasmall $H_0$ nanolaser integrated with a passive waveguide in an active-passive-integrated GaInAsP slab for effective light extraction. Theoretical calculations showed that the light extraction efficiency from the laser to the waveguide can be $80\%$ by careful design of the coupling system. Experimentally, we fabricated the device and observed RT lasing operation by photopumping. The differential quantum efficiency of the laser light was evaluated to be $4\%$. However, the effective value without detection loss was considered to be $\sim 30\%$, and this value can be further improved by the optimization of the structure and the fabrication process. This is a promising result for future dense photonic integration of nanolasers, waveguides, and other functional photonic devices.

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