1.3 µm lasing of circular defect cavity photonic crystal laser with an AlO$_x$ cladding layer

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Abstract: We fabricated a photonic crystal (PC) laser having a circular defect cavity and a line defect output waveguide based on a heterostructure consisting of a slab layer with quantum dots and an AlO$_x$ cladding layer. The photonic crystal laser was excited by a 785 nm laser diode. Samples with different parameters have similar threshold values of about 25 µm. Room-temperature continuous-wave lasing operation at 1.3 µm range is confirmed by observing the spectrum of output light from the line defect waveguide. The wavelengths of the lasing modes show the dependence on the radius of circular resonator and the radius of air holes, which indicate that the lasing mode is the whispering-gallery mode. These results show the feasibility of realizing PC lasers using AlO$_x$ cladding layers.

Keywords: photonic crystal laser, circular defect cavity, line defect waveguide, 1.3 µm lasing

Classification: Integrated optoelectronics

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1 Introduction

Optical interconnects provide high bandwidth and low power operation compared to traditional electrical interconnects. It is promising that the optical interconnects should replace the electrical links in short reach applications, such as data centers, inter-chips, and intra-chip communications. Currently, Silicon photonics is considered as the best candidate to popularize inter-chips optical communications by reaching its highest bandwidth density at about 10 Tbps/cm² [1]. However, intra-chip communications require much higher bandwidth density of about 10 Pbps/cm² because higher level of integration is demanded [2]. It means a very stringent...
requirement for the footprint of the optical devices. Photonic crystal (PC) cavities can strongly confine photons in a very small volume with a high quality factor (Q factor) [3, 4]. Therefore, PC cavity lasers are considered one of the best candidates for small footprint and ultra-low threshold lasers which can be applied to intra-chip optical interconnections. In our study, we have proposed a PC cavity laser structure having the circular cavity [5]. We call it as CirD laser for abbreviation of circular defect cavity laser which is fabricated in a 2-dimensional PhC structure. The lasing mechanism of CirD laser is very similar with the microdisk laser [6] due to the analogous circular resonator. The 2 dimensional PC slab layer sandwiched by AlOx can be treated in the same way as a microdisk laser with air cladding layers. Whispering-gallery mode (WGM) can also be expected in the circular resonators for CirD lasers as shown in Fig. 1. Furthermore, when circular resonators with different lasing wavelengths are placed alongside with an output waveguide as shown in Fig. 2, wavelength division multiplexing (WDM) can be realized without a conventional optical multiplexer. Each laser can operate at a speed of above 50 Gbps, hopefully 100 Gbps due to small cavity volume [7]. So WDM with 10–20 channels results in bandwidth of 1 Tbps. Since the footprint of our integrated device is expected to be 100×100µm, the bandwidth density of 10 Pbps/cm² can be realized. This value is 1000 times higher than what Silicon photonics can achieve.

Fig. 1. A typical distribution of magnetic field ($H_z$) of WGM in the circular cavity calculated by 3-dimensional finite-difference time-domain (3D FDTD) method. There are 18 antinodes where is the highest amplitude for the standing wave of the WGM, because there are 18 air holes on the peripheral of the circular cavity.

There have been a few reports on electrically driven PC lasers operating at room temperature (RT) until now. Park et al. [8] used a post which is placed under the PC slab to inject holes into the defect cavity. However, this device can only operate under pulse conditions due to large electrical resistance and thermal resistance. Matsuo et al. achieved continues-wave (CW) lasing by developing so called LEAP laser which used a lateral current injection structure [9]. LEAP laser has a small threshold current of 7.8 µA but a low output power of about 10 µW. Crosnier et al. used one dimensional (1D) nanorib PC cavity to realize both current injection and light confinement [10]. Relatively high output power of 80 µW can be achieved from the 1D cavity, but high threshold of 100 µA and large footprint are
weak points. These PC lasers are still not ideal light source for intra-chip optical interconnections. Our proposed PC laser has three unique points which are important in realizing WDM light source shown in Fig. 2. First of all, the wavelength tuning can be easily realized by changing the radius of the circular cavity [11]. This feature enables to achieve WDM by using a simple structure as shown in Fig. 2. The second point is that it is possible to realize vertical current injection by using a special heterostructure which has been introduced in Refs. [5, 12]. The vertical current injection design reduces the footprint of the PC laser to the area of the cavity, so that the bandwidth density will be much higher than the one using LEAP laser or 1D cavity. Thirdly, the AlGaAs funnel area was used for current injection structure which is different from the post design [8]. Therefore, higher output power can be expected on our proposed structure due to smaller electrical resistance and thermal resistance.

In this study we investigated the optical properties of the circular defect PC cavity laser under optical pump conditions. The spectrum of edge emitting light shows CW lasing operation at 1.3 µm at RT. The results implies that the PC laser with circular defect cavities is promising for WDM laser sources for intra-chip optical interconnections.

2 Fabrication and measurement

Fig. 3 shows the schematic diagram of the sample structure in this study. The sample was fabricated using an epi-wafer consisting of a slab layer and an AlGaAs layer which were grown on a GaAs substrate. The slab layer is a 220-nm-thick GaAs layer with multiple InAs quantum dot (QD) layers. The AlGaAs layer is 500 nm which is used as the bottom cladding layer for the slab layer when AlGaAs is oxidized to AlOx. The photoluminescence (PL) peak of the core layer was at 1290 nm which is measured at RT. The fabrication process are as follows. The electron beam (EB) resist was spincoated on the epi-wafer firstly. Secondly, the PC pattern with a circular defect and a line defect was drawn on the resist by using the
EB lithography process. Thirdly, the sample was etched by inductively coupled plasma etching process [12] to form the air holes which penetrate the core layer. Then, the sample was emerged in the remover to take away the resist. Finally, the bottom AlGaAs was oxidized to AlO$_x$ through the air holes by using selective wet oxidation process [13].

The parameters of the PC structure and the circular resonator should be well designed, in order to insure that the Q factor of the circular resonator is high enough for lasing. The variable parameters of our samples are lattice constant of the PC structure $a$, the radius of the air holes $r$, and the radius of the circular cavity $R$. According to the calculated curves of the threshold current density as a function of Q factor for a PC cavity laser [9, 15], the Q factor of the cavity with a line defect waveguide should be higher than 4000, so that the threshold current density is small enough for RT-CW lasing. We calculated the Q factor of WGM by using 3-dimensional finite-difference time-domain (3D FDTD) method because only WGM had large Q factor in the cavity. Fig. 4 shows the calculated Q factor of the structure consisting of a circular defect cavity and a line defect waveguide with various $R$ and $r$ when $a$ is 360 nm. It shows that Q factor is larger than 4000 when $2.75a \leq R \leq 2.77a$ and $0.29a \leq r \leq 0.33a$. The circular resonators within these
parameters are expected to have small threshold and lasing operation. Considering the errors of simulations and avoiding the fabrication differences caused by EB lithography and dry etching process, the lattice constant $a$ was set as 340 nm, 350 nm, 360 nm, and 370 nm; the radii of the circular cavity $R$ was set as 2.75$a$, 2.76$a$, and 2.77$a$; and the air holes $r$ was set in the range of 0.24$a$ to 0.31$a$ in the EB lithography process.

Optical characterizations were performed with a micro-photoluminescence (µ-PL) system. The sample was mounted on a horizontal stage and the circular defect cavity was optically pumped from the upper side at an angle normal to the sample surface as shown in Fig. 3. The pump source used in the experiment was a 785 nm laser diode, and the beam spot was 4 µm diameter at the cavity surface through a 50× objective lens (numerical aperture = 0.55). The light generated in the circular defect cavity coupled to the line defect waveguide. A spherical lensed fiber (SLF) which is horizontally placed next to the facet of the line defect waveguide was used to collect the output light. Furthermore, the light vertically emitted from the surface of the cavity was also observed using the same 50× objective lens in the same way as Ref. 16. An optical spectrum analyzer (OSA) was used to measure the spectrum and linewidth of the lasing mode. The measurements were performed under RT-CW conditions.

3 Experimental results and discussion

Fig. 5 shows the excitation power versus output power curves for typical 3 samples with various parameters. The parameters of samples are summarized in the inset of each graph. All curves shown in Fig. 5 have a bending turn around the threshold part. By extrapolating the dot lines to zero output power, the threshold excitation power of about 25 µW was obtained for all three samples. CirD laser using an AlO$_x$ cladding also an ultra-small threshold as other PhC lasers with membrane structures [16, 17]. The output intensity increases with the increasing of excitation power up to about 1 mW without saturation, which should be attributed to the good thermal conductivity of AlO$_x$ cladding layer [18, 19]. The threshold current of the PC laser with circular defect $I_{th}$ can be estimated by

$$P_{th} \times k = I_{th} \times \frac{hc}{\epsilon \lambda},$$

where $P_{th}$ is the threshold excitation power of 25 µW. $k$ is the ratio of the pump power absorbed by the slab layer. Due to the similar heterostructure of slab layer and µ-PL measurement system described in Ref. 16, the same value of 0.15 for $k$ can be used in this equation. $\lambda$ is the wavelength of the lasing mode which is about 1.3 µm. Thus, $I_{th}$ is estimated to be 4 µA, which is close to that of LEAP laser [9, 17]. It means that the electrical driven PC lasers with circular defect cavities could have a reasonable and small threshold current.

Fig. 6 shows the spectrum of Sample b when the excitation power was 0.92 mW. A sharp peak at wavelength of 1296.8 nm with linewidth $\Delta \lambda$ of 0.07 nm was observed. Measured $\Delta \lambda$ is the same as the resolution limit of OSA, which means that the real linewidth might be smaller than 0.07 nm. The linewidth of the circular cavity is about 0.23 nm if the the calculated Q factor of 5600 was
used for estimation. The experimental value is much smaller than the estimated value. Therefore, the detected mode is coherent light and lasing operation of the PC lasers with the circular cavity is confirmed.

Fig. 5. Output intensity as a function of excitation power for three samples with various parameters which are shown in the insets.

Another series of samples with the parameters of $2.75a \leq R \leq 2.78a$, $0.23a \leq r \leq 0.27a$ and $a = 360\,\text{nm}$ was fabricated. The wavelength of the lasing mode for

Fig. 6. The measured spectrum of Sample b.

Another series of samples with the parameters of $2.75a \leq R \leq 2.78a$, $0.23a \leq r \leq 0.27a$ and $a = 360\,\text{nm}$ was fabricated. The wavelength of the lasing mode for
the samples were summarized. Fig. 7 shows the graphs which compared the simulation and experimental results for the wavelength of the lasing mode dependent on $R$ and $r$. The wavelengths of the lasing modes increases when $R$ is larger and decreases when is $r$ larger. It is corresponding to the trend of the simulated wavelength of the WGM in the circular cavity. WGM is a type of wave that can travel around concave part which is the periphery of the circular resonator in the fabricated samples [20]. Because the circular resonator was formed by 18 shifted air holes, the standing wave of the WGM in the circular resonator has 9 waves [21]. When $R$ is larger or $r$ is smaller, the periphery of the circular resonator becomes larger. Thus, wavelength of the WGM increases for keeping fitting the resonator perfectly. The matching of the experimental results and simulations implies that the lasing modes are the WGM in the circular resonators.

4 Summary

We have demonstrated the lasing action in a PC laser from the output waveguide by using a circular defect cavity. The fabricated circular defect cavity performed a threshold excitation power of about 25 µW. The wavelength of the lasing mode depending on the $R$ and $r$ means that the lasing mode is the WGM in the circular resonator. The optical properties of the circular defect cavity show feasibility of realizing electrical driven PC lasers using AlO$_x$ cladding layers.

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