Bow-tie Mode Lasing in a Grooved Rectangular Semiconductor Microcavity

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Bow-tie modes were proposed in a grooved rectangular resonator and their lasing characteristics were investigated in semiconductor microcavities. The observed spacing between two adjacent lasing peaks from the grooved cavity was reduced compared to that of 4-bounce whispering gallery modes (WGMs) from the same-sized simple rectangular cavity due to increased round-trip path length of the bow-tie modes. The lasing spectra of bow-tie modes obtained from two adjacent corners showed highly correlated patterns while those of 4-bounce WGMs did not.

Keywords : Bow-tie mode, Grooved rectangle, Microcavity laser

OCIS codes : (140.3948) Microcavity devices; (140.3410) Laser resonators

I. INTRODUCTION

Whispering gallery modes (WGMs) in circular or polygonal cavities have attracted a great deal of interest due to the attainable high-Q values originating from total internal reflection of light at the boundaries [1-5]. Various applications of WGMs have been presented, such as add-drop passive filters in dense wavelength-division multiplex (DWDM) communication and low-threshold microcavity lasers [6-10]. In many applications of WGMs, external waveguides are adapted as coupling devices. Because the evanescent field of waveguide modes or WGMs decreases exponentially from the boundary, a very small gap distance between the cavity and the waveguide is essential for optimal coupling strength, particularly in the lateral coupling scheme using circular cavities. In order to enhance the coupling strength with reasonable gap distances, square or rectangular cavities were studied because they have a longer interaction length than circular cavities [12]. The entire flat boundary itself becomes the coupling region, which allows a relatively large gap distance for optimal coupling with external waveguides.

Figure 1 shows a schematic layout of the waveguide-coupled rectangular cavity add-drop filter [13, 14]. The resonance modes of a rectangular cavity (refractive index m , size of $a \times b$) can be understood by a simple ray optics picture. If the incident angle θ at the boundary is $\theta_{\text{clo}} = \tan^{-1}(\frac{b}{a})$, the rays form 4-bounce closed trajectories as

shown in Fig. 1. The optical path length L of the closed modes is approximately given by

$$L = ml = 2m \sqrt{a^2 + b^2} \quad (1)$$

where l is the round-trip length. The round-trip length of the open orbit modes whose trajectory does not close after one round-trip is defined as the length traveled by the wave front until it meets the starting wave front. The open trajectories have smaller round-trip lengths than the closed orbits, and the corresponding optical path length decreases

FIG. 1. Schematic layout of waveguide-coupled rectangular cavity add-drop filter. A closed trajectory corresponding to the 4-bounce WGMs is shown in the rectangular cavity.

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as θ deviates from θ_{clo} , resulting in multi-modes in a rectangular cavity [3].

In the previous add-drop filters using ring, square, or rectangular cavities, the input light on the add port should propagate opposite to that of the input port and the signal from the drop port also propagates in opposite direction to the input one. It is desirable to find a scheme using microcavities in which the drop and add port have same direction of propagation with the input port because it allows additional design choices in the arrangement of the waveguide array. In this work, we propose a grooved rectangular cavity satisfying the above requirement, and we investigate lasing properties in grooved rectangular semiconductor cavities. If this cavity is adapted in the add-drop filter, the add and drop port will have the same propagation direction to the input port as illustrated Fig. 2.

II. PROPOSED BOW-TIE MODES

The proposed rectangular cavity is shown in Fig. 2. A groove is made on the center of a long side of the rectangular cavity (refractive index m , size of $a \times b$, $b > a$) with the depth of $a/2$. In this cavity, previous 4-bounce WGMs could not be permitted as resonance modes because the deep groove blocks the 4-bounce trajectories shown in Fig. 1. The next possible trajectories selected by the deep groove are the 6-bounce orbit. In Fig. 2, the 6-bounce bow-tie shaped closed orbit is shown. The optical path length of the bow-tie modes can be approximately calculated as

$$L = 4m \sqrt{a^2 + (b/2)^2} \quad (2)$$

The 6-bounce open orbit modes are also similarly possible to the case of a rectangular cavity. The resonance wavelength λ of bow-tie modes can be determined from the resonance condition as

FIG. 2. Proposed grooved rectangular cavity and schematic layout of corresponding filter. A closed orbit corresponding to the 6-bounce bow-tie modes is shown in the cavity.

$$\frac{2\pi}{\lambda} L + 4\Psi(\theta) + 2\Psi(\pi/2 - \theta) = q(2\pi) \quad (3)$$

where q is an integer, and $\Psi(\theta)$ and $\Psi(\pi/2 - \theta)$ are the phase changes during total internal reflections at the side walls of the cavity.

III. EXPERIMENTS

The experimental setup for bow-tie mode lasing was similar to that used previously [15, 16]. InGaAsP/InGaAs multiple quantum wells (8 MQWs, $\lambda_g \sim 1.3 \mu\text{m}$) were surrounded by two confinement layers in the epistructure. The total thickness of the epistructure formed on an InP substrate was about $0.8 \mu\text{m}$. Various cavities were lithographically patterned and etched vertically by the RIE (Reactive Ion Etching) process. The total etching depth was controlled to be about $4 \mu\text{m}$. A pulsed Nd:YVO₄ laser (wavelength of $1.06 \mu\text{m}$, repetition rate of 10 kHz, pulse width of 150 ns) was loosely focused on a cavity using a lens and a beam splitter in order to optically pump MQWs. The illuminated cavity was monitored through the beam splitter using a CCD camera attached to a high-resolution microscope with a long working distance. A tapered fiber was approached to the cavity corner in order to collect the lasing signal. The lasing spectrum was measured using an optical spectrum analyzer (OSA).

IV. RESULTS & DISCUSSIONS

Lasing spectra were measured from various rectangular cavities fabricated on the same wafer. Because the signal level of spontaneous emission was very low, no apparent spectrum was observed with the OSA below the threshold of lasing. When the pump intensity increased, a single lasing peak was observed at slightly above threshold. As the pump intensity increased further, the number of lasing peaks increased and their widths became broad. Figure 3 shows typical lasing spectra at high above threshold from a square, a rectangle, and grooved rectangles. The lasing spectrum from a square with $a=b=40 \mu\text{m}$ appeared around 1245 nm with a spacing of 3.8 nm, as shown in Fig. 3(a). For the case of a rectangle with $a=40 \mu\text{m}$, $b=80 \mu\text{m}$ in Fig. 3(b), the center wavelength appeared around 1280 nm with a spacing of 2.5 nm. A multi-mode characteristic was seen in Fig. 3(a), which could be attributed to the simultaneous lasing of open orbit modes. The free spectral range $\Delta\lambda_{\text{FSR}}$ or mode spacing in the semiconductor laser can be approximately expressed as [15]

$$\Delta\lambda_{\text{FSR}} \cong \frac{\lambda^2}{\left[1 - \frac{\lambda}{m(\lambda)} \frac{dm}{d\lambda}\right] L} = \frac{\lambda^2}{M(\lambda)l} \quad (4)$$

where $M(\lambda)$ accounts for the dispersion in m of the semiconductor epiwafer and is a function of λ . From Eq. (1), the round-trip length l of the closed 4-bounce WGM is calculated to be about 179 μm . Hence, $M(\lambda)$ in Eq. (4) can be estimated as about 3.66 at around $\lambda=1280$ nm.

Figure 3(c) shows a lasing spectrum centered around 1275 nm~1280 nm, similarly to Fig. 3(b) from a grooved rectangle with $a=40$ μm , $b=80$ μm . The width and depth of the groove are 10 μm and 20 μm , respectively. Because the round-trip length of the bow-tie modes from the cavity in Fig. 3(c) is twice of that of 4-bounce WGMs from the cavity in Fig. 3(a), the measured $\Delta\lambda_{\text{FSR}}$ should be about half if the lasing modes were bow-tie modes. As a matter of fact, $\Delta\lambda_{\text{FSR}}$ was measured to be about 1.9 nm, which is half of that in Fig. 3(a), as expected. The round-trip length of bow-tie modes was calculated as about 226 μm from Eq. (2). By using the deduced $M(\lambda)=3.66$ at around $\lambda\sim 1280$ nm from Fig. 3(b), $\Delta\lambda_{\text{FSR}}$ of bow-tie modes is calculated to be 1.98 nm, which is also in agreement with the observed value of 1.9 nm within the experimental error. Hence, the lasing modes in Fig. 3(c) should be the proposed bow-tie modes. Figure 3(d) shows a lasing spectrum from a grooved rectangle having a larger b ($a=40$ μm , $b=$

100 μm). In this case, $\Delta\lambda_{\text{FSR}}$ was reduced to about 1.6 nm. From Eq. (2) and $\Delta\lambda_{\text{FSR}}\sim 1.9$ nm in Fig. 3(c), the expected $\Delta\lambda_{\text{FSR}}$ of bow-tie modes was calculated to be $\sqrt{40^2 + 40^2} / \sqrt{40^2 + 50^2} \times 1.9 \text{ nm} \cong 1.67 \text{ nm}$, which agreed well with the measured one. Therefore, the lasing modes in Fig. 3(d) should also be the bow-tie modes.

To confirm that the lasing modes from grooved rectangles are the proposed bow-tie modes, the lasing spectra were obtained from two adjacent corners (A and B) of the grooved cavity by changing the detection position of the fiber tip. The lasing spectra from a simple rectangle were also measured for comparison. Figure 4 shows two spectra of the 4-bounce WGMs from a rectangle with $a=30$ μm , $b=60$ μm . Multi-mode characteristics could be seen in the spectra with $\Delta\lambda_{\text{FSR}}$ of about 3.2 nm, which is expected from Eq. (1) describing the 4-bounce WGMs. It is notable that the peak's wavelengths obtained from A and B did not coincide with each other and the spectral envelopes were fairly different. This is attributable to the fact that the lasing light dominantly leaked out from A had a different orbit to that from B, which can be seen in the inset in Fig. 4. Because the corresponding orbits O_A and O_B shown in the inset are not spatially overlapped and the corresponding circulation directions are opposite, it is no wonder that the two spectra had no correlation with each other because both lasing modes might be different in polarization or different open orbit modes.

Figure 5 shows two lasing spectra from a grooved rectangle with $a=30$ μm , $b=60$ μm . Unlike the case of Fig. 4, the lasing peaks in the two spectra coincide with each other with the spacing of about 2.4 nm. The reduced $\Delta\lambda_{\text{FSR}}$ compared to Fig. 4 should be due to the lasing of the bow-tie modes having a larger round-trip length than the 4-bounce WGMs, as expected. On the whole, the two spectra showed highly correlated patterns. The envelopes of two spectra

FIG. 3. Typical lasing spectra from various shaped rectangular semiconductor cavities: (a) a square ($a=b=40$ μm), (b) a rectangle ($a=40$ μm , $b=80$ μm), (c) a grooved rectangle ($a=40$ μm , $b=80$ μm), (d) a grooved rectangle ($a=40$ μm , $b=$

FIG. 4. Lasing spectra measured from two adjacent corners of a rectangular cavity with $a=30$ μm and $b=60$ μm . The peak's positions and spectral envelopes appear different from each other.

FIG. 5. Lasing spectra measured from two adjacent corners of a grooved rectangular cavity with $a=30\ \mu\text{m}$ and $b=60\ \mu\text{m}$. The lasing spectra show highly correlated patterns.

were similar to each other even though the relative peak strengths were slightly different. The high correlation must be due to the fact that the lasing light from A and B leaked from the same bow-tie orbit shown in the inset in Fig. 5. Because the two coupling geometries (distance or location of fiber tip with the corner) of the fiber tip are slightly different, the relative strengths of each peak could be detected slightly differently as observed. The highly correlated pattern in Fig. 5 is further strong evidence of the proposed 6-bounce bow-tie modes in a grooved rectangular cavity in addition to the reduced mode spacing. The result in Fig. 5 suggests a waveguide-coupled microcavity laser in which the two waveguide outputs have the same propagation direction with a highly correlated spectral property. If the grooved rectangle in Fig. 2 has gain for lasing, the lights coupled through the parallel waveguides will have the same propagation direction because the two outputs originate from a bow-tie mode having a particular direction of circulation.

V. CONCLUSION

In conclusion, bow-tie mode lasing was demonstrated in a grooved rectangular semiconductor cavity. The mode spacing of lasing peaks was reduced due to the increased round-trip length of the 6-bounce bow-tie modes compared to the 4-bounce WGMs observed from a simple rectangular cavity having the same outer size. Two spectra obtained from two adjacent corners of the grooved rectangle were highly correlated because they originated from the same bow-tie modes, while those from a simple rectangle did not. The demonstrated grooved rectangular cavity could be applied to the waveguides-coupled microcavity laser having the same output direction and add-drop passive filter where add and drop ports have the same propagation direction to the input port.

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