InGaAsP–InP Square Microlasers With a Vertex Output Waveguide
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Abstract—InGaAsP–InP square microlasers with a vertex output waveguide are fabricated by planar processes, and the etched sidewalls of the lasers are confined by insulating layer SiO$_2$ and p-electrode Ti–Au metals. For a square microlaser with a side length of 30 $\mu$m and a 2-$\mu$m-wide output waveguide, a continuous-wave threshold current is 26 mA at room temperature and output power is 0.72 mW at 86 mA. The mode interval of 21 and 7.4 nm is observed for the microlasers with the side length of 10 and 30 $\mu$m, respectively. Finite-difference time-domain (FDTD) simulations indicate that the lasing modes have incident angles of about 45° at the boundaries of the resonator. In addition, square resonators surrounded by air, SiO$_2$–Ti–Au, and SiO$_2$–Au are compared by FDTD simulations.

Index Terms—Finite-difference time-domain (FDTD) simulation, InGaAsP–InP, semiconductor microlasers, square resonator.

I. INTRODUCTION

Circular resonators with high-quality (Q) whispering-gallery modes (WGMs) and low mode volumes were received great attention for fabricating semiconductor microlasers [1], [2]. Directional emission microlasers were investigated based on chaotic resonators [3], spiral-shape micropillars [4], asymmetric resonators [5], and limaçon-shaped microcavity [6]–[8]. Furthermore, microdisk lasers vertically coupled with a bus waveguide were realized by wafer bonding technique [9], [10]. Recently, room-temperature continuous-wave (CW) electrically injected InGaAsP–InP triangle and square microlasers were fabricated with an output waveguide connected to the resonator [11], [12]. The triangle and square resonators are laterally confined by insulator SiO$_2$ and p-electrode metals on etched sidewalls, which greatly affect the mode $Q$ factor [13], [14], and up to six transverse modes are observed in a square microlaser with the side length of 20 $\mu$m [15].

In this letter, we report the lasing characteristics of square microlasers with a vertex output waveguide fabricated by planar processes. For a 30-$\mu$m side square microlaser, room-temperature CW lasing is realized with a threshold current of 26 mA and an output power of 0.72 mW at 86 mA. In addition, square microlasers with an output waveguide connected to a vertex or the middle of one side are compared, and the square resonators surrounded by air, SiO$_2$–Ti–Au, and SiO$_2$–Au are discussed, based on finite-difference time-domain (FDTD) simulations.

II. DEVICES CHARACTERISTICS

The InGaAsP–InP laser wafer with seven 7-nm compressively strained quantum wells is used for fabricating square microlasers as in [12]. The wafer is etched by the inductively coupled-plasma (ICP) etching technique with the depth of about 5.6 $\mu$m. Fig. 1(a) shows a scanning electron microscope image of a 10-$\mu$m side square resonator after the ICP and, Ti, and Au for the p-electrode metals on etched sidewalls, which greatly affect the mode $Q$ factor. In Fig. 1(a), we plot laser spectrum at 40 mA and output spectra measured at 280 K are plotted in Fig. 2 for a 10-$\mu$m side square microlaser with a 1-$\mu$m-wide vertex output waveguide. Five evident peaks at 1477.5, 1497.2, 1517.6, 1538.6, and 1560.4 nm are observed at the injection current of 7 mA, with the longitudinal mode intervals of 19.7, 20.4, 21.0, and 21.8 nm. The full-width at half-maximum (FWHM) of the peak 1517.6 nm is 0.565, 0.478, and 0.406 nm at the injection current of 5, 6, and 7 mA, respectively. In addition to the sharp peaks, evident wide peaks are observed with a wavelength interval about 10 nm.

In Fig. 3(a) and (b), we plot laser spectrum at 40 mA and output power versus the injection current at room temperature, for a 30-$\mu$m side square microlaser with a 2-$\mu$m-wide vertex output waveguide. The lasing spectrum shows longitudinal mode intervals from 7.2 to 7.5 nm, and two transverse modes with the wavelength interval of 1.0–1.1 nm appear for each longitudinal mode. The FWHzs of the peaks at 1537.7 and 1538.8 nm are 0.27 nm. Fig. 3(b) shows the threshold current
of 26 mA, and the output power is 0.72 mW at the current of 86 mA.

III. FDTD SIMULATION

In this section, mode characteristics are investigated by two-dimensional (2-D) FDTD simulation using Rsoft code, for the square resonator laterally confined by SiO$_2$–Ti–Au layers, as shown in Fig. 1 (b). The side length of the square is 10 $\mu$m, the width of output waveguide is 1 $\mu$m, and the effective refractive index of the laser wafer is 3.2. The thicknesses of SiO$_2$, Ti, and Au layers are 450, 50, and 200 nm, respectively, and the corresponding refractive indices are 1.45, 3.7 + 4.5i, and 0.18 + 10.2i [16]. The variations of one component of electromagnetic fields at one point inside the resonator are recorded as an FDTD output, and then the Padé approximation is used to transform a late FDTD output from the time domain to the frequency domain [17].

The obtained intensity spectra are plotted in Fig. 4(a) for transverse-electric (TE) modes as the thickness of Ti layer is 50 nm. The solid and the dashed lines are for the square resonator with a vertex output waveguide connected to the middle of one side [12], respectively. Fitting the resonance peak with a Lorentzian function, we obtain the mode $Q$-factors of $1.82 \times 10^4$, $3.82 \times 10^3$, $1.75 \times 10^4$, and $4.35 \times 10^3$ for the modes at 1470.66, 1494.47, 1519.73, and 1545.36 nm, respectively, from the solid line. The mode interval $\delta \lambda_{FP}$ 25.26 nm can be reduced to the experimental value of 20.4 nm if the group mode index is 3.96. Compared to the dashed line, we find that the square with the vertex output waveguide has fewer confined modes. From the lasing spectra, we observed more modes in the square microlasers with the output waveguide connected to the middle of a side [12], [15]. In Fig. 4(b), the intensity spectra are plotted as the solid and the dashed lines for the square resonator with the vertex output waveguide surrounded by SiO$_2$–Au and air, respectively. Much more high $Q$ modes exist in the resonator surrounded by SiO$_2$–Au without the Ti layer, and Fabry–Pérot-type modes also have high $Q$ factors with the mode interval $\delta \lambda_{FP}$ = 32.4 nm, due to the high reflectivity of the Au layer. Fewer high $Q$ modes are observed in the square resonator only surrounded by air. The results indicate that the lateral $p$-electrode plays an important role in mode confinement. The resonator surrounded by the SiO$_2$ and the Au layers can reduce the radiation loss [19], [20].

To further examine the high $Q$ modes, we simulate the mode field pattern for the main peak of the solid line in Fig. 4(a) under narrowband exciting source centered at the mode frequency. The obtained magnetic field patterns are plotted in Fig. 5(a) for modes TE$^{0}(28,30)$ and TE$^{0}(29,30)$ at the wavelengths of 1519.73 and 1494.47 nm. The mode numbers $p$ and $q$ of TE$^{p}(p,q)$ and TE$^{0}(p,q)$ are the numbers of wave nodes along the sides of the square [18], and the superscript “o” indicates odd
mode relative to the diagonal lines of the square, which has the highest $Q$ factor in the square surrounded by air [18]. The mode field distributions are greatly influenced by the vertex output waveguide, due to the weak field patterns along the diagonal lines. The high $Q$ modes at 1470.66- and 1545.36-nm peaks of the solid line in Fig. 4(a) are TE$^{(29,31)}$ and TE(28,29). The modes with $p \approx q$ have the incident angle about 45° for mode light rays at the boundaries of the square resonator.

The mode $Q$ factors versus the width $W$ of the vertex output waveguide are plotted in Fig. 5(b) for TE$^{(28,30)}$ and TE(29,30). The mode $Q$ factor of TE$^{(28,30)}$ decreases from $3.0 \times 10^4$ to $4.7 \times 10^3$, but that of TE(29,30) increases from $4.7 \times 10^3$ to $1.2 \times 10^4$ with a small oscillation, as $W$ increases from 0 to 2 μm. The increase of mode $Q$ factor for TE(29,30) can be explained by the modification of mode field pattern. The oscillation of mode $Q$ factors is corresponding to the appearance of new guided mode in the output waveguide, which influences the coupling between the confined mode in the square resonator and those in the output waveguide.

IV. CONCLUSION

Square microlasers with an output waveguide connected to one of the vertices are fabricated with the side lengths of 10 and 30 μm. The laser spectra and FDTD simulations indicate that fewer high $Q$ modes exist in the square resonator with the vertex output waveguide than that with the output waveguide connected to the middle of a side. For the square resonator with a vertex output waveguide, FDTD simulations indicate that the high $Q$ modes have the incident angles about 45° on the boundaries and the mode field patterns are greatly influenced by the output waveguide. The Ti and Au layers of the $p$-electrode surround the etched sidewalls of the square resonator play an important role in mode confinement.

REFERENCES