Alternate oscillations in quasistadium laser diodes

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We found alternate oscillations in AlGaAs/GaAs single-quantum-well quasistadium laser diodes (QSLDs). Unlike the alternate oscillations in conventional ring lasers, which are explained by interaction between two counterpropagating modes, the alternate oscillations in QSLDs arise from two nearly degenerate cavity modes due to its geometric structure. The lasing signals in QSLDs are directly obtained from the emitted beams which spread over the space without the use of waveguides. We also showed that the alternate oscillation frequencies decrease linearly as the amplitudes of the two different cavity modes increase.

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The internal dynamics in ring laser systems has been intensively studied during several decades because theoretically it provides fundamental insight into nonlinear systems [1–4] and in practice it is closely related to the development of the optical ring laser gyroscope, optical memory, and optical logic devices [5–7]. In conventional ring laser systems, the two counterpropagating waves, counterclockwise (CCW) and clockwise (CW), can be the lasing modes. Thus, the coupling between the two modes caused by the backscattering arising from defects (e.g., surface roughness, atomic scattering) plays a central role in determining the dynamics of these systems. In particular, in certain pumping regimes the systems lose lasing stability due to the interaction of these two modes, and show alternate oscillatory time behavior, i.e., the amplitudes of the modes oscillate between their maximum and minimum values with π phase difference. This oscillatory behavior is called *alternate oscillation* (AO) in ring laser systems. It is of great interest to understand the origin of the oscillatory behavior from the theoretical point of view, as well as in experiments and applications. The AOs are connected to the fundamental restriction of optical ring laser gyroscopes, because they cause a natural beat note even when the system angular velocity is zero [8,9]. These AO phenomena have been reported in He-Ne ring laser [10] and dye ring laser systems [11,12] by several experimental and theoretical groups. AO was also observed in semiconductor ring lasers (SRLs) [13]. The results from the SRL experiment have attracted much more interest for industrial purposes than those of other laser systems, because a SRL can be easily achieved by a monolithic integration process.

Recently, by virtue of developments in fabrication technology, it has become possible to fabricate another type of laser diode having various geometric shapes, the two-dimensional (2D) cavity laser diode [14]. It enables one to utilize various lasing modes due to its characteristic geometric shapes. The schematic of the structure of the AlGaAs/GaAs single-quantum-well (SQW) quasistadium laser diode (QSLD) is shown in Fig. 1(a). The width of the cavity is 50 μm and the cavity length L is equal to the radius R of the curved end mirrors, designed to be 600 μm, so that the laser cavity's end mirrors satisfy the confocal resonator condition. The AlGaAs/GaAs SQW QSLD was fabricated using the dry-etching technique [14,15].

In our previous work in Fox-Li mode calculation for the QSLD, we found two kinds of resonator eigenmode of the QSLD that correspond to beam propagation along the cavity axis and along a closed ring trajectory [14]. Figure 2 shows the beam intensity patterns calculated for six low-loss axis modes and ring modes. As the mode number increases, the number of peaks in the transverse direction increases. It is also found that twin modes, which have almost the same beam intensity patterns but different parities with respect to the x axis, appear as modes 0 (even) and 1 (odd), 2 (even) and 3 (odd), etc. The Fox-Li mode calculation is a practical calculation method to obtain the cavity modes by using the differences of their lifetimes. We have failed to distinguish the modes with different parities with respect to the y axis since their lifetime differences are too small. Actually QSLDs have four kinds of similar parity modes and there is no degeneracy among them. This will be explained later.

In order to excite only ring modes, we used the 11-μm-wide diamond-shaped contact pattern shown in Fig. 1(b). The shape of the p contact roughly matches the ring patterns calculated for the lowest-loss ring modes. Through the p contact area, the pumping current is locally injected

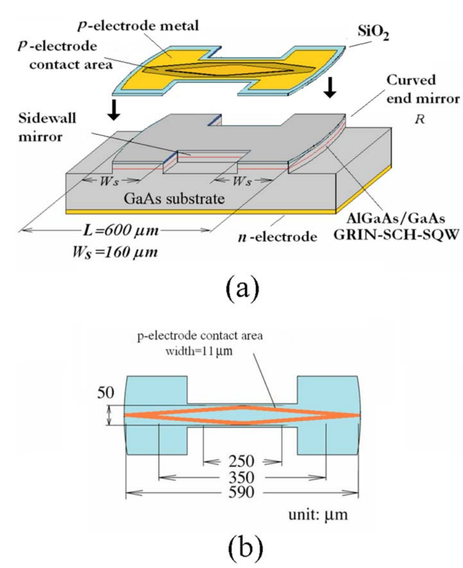

FIG. 1. (Color online) Schematic diagrams of quasistadium laser diode: (a) device structure and (b) p-electrode contact area pattern.

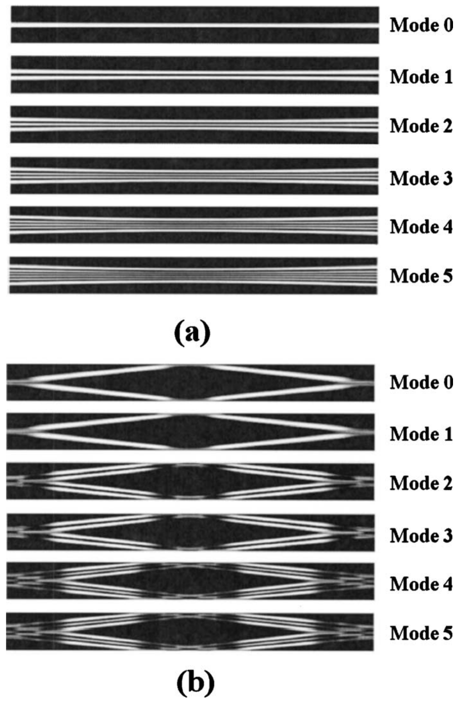

FIG. 2. Resonating eigenmodes in the confocal quasistadium resonator. Beam intensity patterns of (a) six low-loss axis modes and (b) six low-loss ring modes.

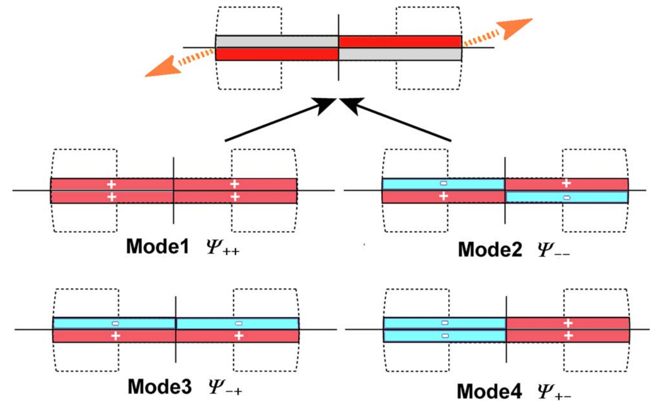

FIG. 3. (Color online) Schematic explanation of the locking of two resonance modes with different symmetries and different frequencies (the first sign is + if the wave function is even with respect to $x \to -x$, and − otherwise; correspondingly, the second refers to $y \to -y$).

into the QSLD. The QSLD has some analogy with conventional ring-laser systems in that the spatial distributions of the excited ring modes have closed ring shapes. However, it is distinguished from conventional ring-laser systems in that the shape of laser cavity does not have any ring structure.

In this paper, we report the observation of AOs in a AlGaAs/GaAs SQW QSLD, which results from the interaction of two-dimensional stationary cavity modes, instead of the backscattering of counterpropagating modes as in conventional ring lasers. The AO signals in the QSLD are directly obtained from the beams emitted in different directions without the aid of the waveguides, which are commonly used in conventional semiconductor ring lasers to couple lasing light to the outside. We also show that the alternate oscillation frequencies are inversely proportional to the amplitudes of the two nearly degenerate cavity modes. We explain the AOs in the QSLD by the locking phenomena of two nearly degenerate cavity modes due to the geometrical symmetry of the QSLD [17,18].

First, let us consider AO in a conventional ring laser briefly. In order to understand the dynamics of a conventional ring laser, it is important to take into account the presence of the two counterpropagating modes (CCW and CW modes) and their interactions. These two modes are coupled in two ways: indirectly, through the active medium cross-gain saturation coefficient, and directly, through backscattered fields caused by cavity sidewall roughness and imperfections. Previous works in ring lasers show that the appearance of the AO phenomenon depends on the complex coupling coefficient related to the backscattering. Thus, the notion of backscattering is a central element in understanding AOs [10,13,16].

On the other hand, AO in the QSLD is explained by adifferent mechanism, namely, *locking of two modes* [17,18]. If a laser cavity has reflection symmetries with respect to the x and y axes, like the stadium shape which belongs to the C_{2v} symmetric group, the resonance modes can be classified into four symmetry classes: $\psi_{ab}(-x,y)=a\psi_{ab}(x,y)$ and $\psi_{ab}(x,-y)=b\psi_{ab}(x,y)$, with the parities $a\in\{+,-\}$ and $b\in\{+,-\}$. These modes are generally not degenerate with each other: the C_{2v} symmetry group has only a one-dimensional irreducible representation (no degeneracy except for accidental ones). Therefore, in this system, CW and CCW modes cannot initially be eigenmodes for geometrical reasons. It is shown that in 2D stadium-shaped lasers, when two modes from different symmetry classes are locked by nonlinear interaction of the active medium, the spatial shape of the stationary lasing state becomes asymmetric [17,18]. Since QSLDs have the same kind of symmetry structure as stadiums, we can apply the theory of locking of two modes to the QSLD.

Figure 3 schematically explains the asymmetric stationary lasing of the quasistadium by the locking of two resonance modes with different symmetries. First, we take account of

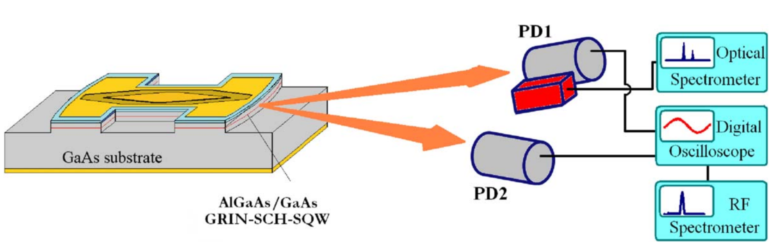

FIG. 4. (Color online) Experimental setup (see text).

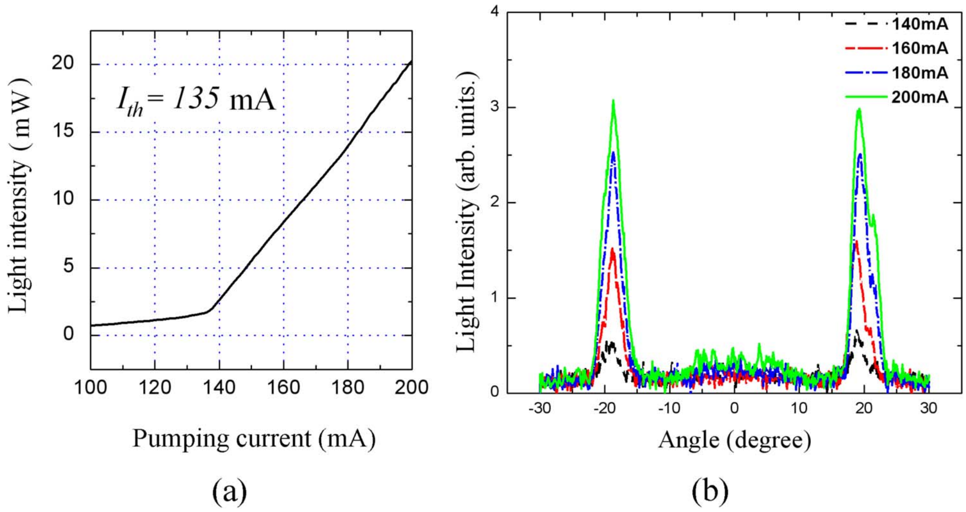

FIG. 5. (Color online) (a) *L-I* curves of the QSLD: We carried out continuous wave operation at 25 °C (room temperature). (b) Far-field patterns of QSLD with various pumping currents.

two nearly degenerate modes with different symmetries. As the energy gain increases, their frequencies come closer together because of the nonlinear interaction of the active medium, and finally the two lasing modes reach the perfectly locked state. Before reaching perfect locking, if the frequency difference is sufficiently small, one can see the AO in the radio-frequency (rf) range as a beat note between two modes. In this approach, the AO of the nearly degenerate resonance modes arises purely from the cavity geometry, not from the backscattering mechanism.

Figure 4 shows the experimental setup for AO measurement. The time traces of the optical signals of the QSLD are measured with two external photodetectors (PD1 and PD2) with rise time 12 ns (~80 MHz) located in the positions that give maximum intensities in the far-field patterns, and simultaneously the optical spectrum is also measured. The optical spectra were obtained with resolution 0.02 nm. We carried out continuous wave operation at 25 °C. By virtue of the novel design of the QSLD, all signals are directly obtained from the emitted beams spreading over the space.

Figure 5(a) shows *L-I* curves of the QSLD. In this measurement the threshold current was evaluated to be $I_{\text{th}} = 135$ mA. The full widths at half maximum (FWHMs) of lasing modes are measured to be about 0.04 nm: they are almost comparable with the resolution of the equipment. Figure 5(b) represents the experimental results for far-field intensity patterns of the QSLD with increasing pumping current. It shows that the lowest ring modes are successively excited. Figure 6(a) shows the typical optical spectra at the two main lobes of the far field. They perfectly correspond with each other because they come from the same stationary mode. The AO phenomena are observed with pumping current above 146 mA. Figure 6(b) shows typical time traces of AO in a QSLD, exhibiting antiphase oscillatory behaviors with a characteristic oscillation frequency. The signals are measured at two different positions (PD1 and PD2) at a pumping current of 156 mA.

Figures 7(a) and 7(b) show the current dependence of the optical and rf spectra of the laser outputs, respectively. At 141 mA, although the lasing has already begun, there is no peak in the rf spectrum. As the pumping current is increased, the AO is observed from the pumping current at 146 mA and its amplitude continuously increases until the pumping current reaches 158 mA. In contrast, above 158 mA, the AO amplitude decreases while the output power still increases. In order to understand these experimental results and the origin of the AO phenomena, let us make the following in-depth inspection of the optical spectra of the laser outputs.

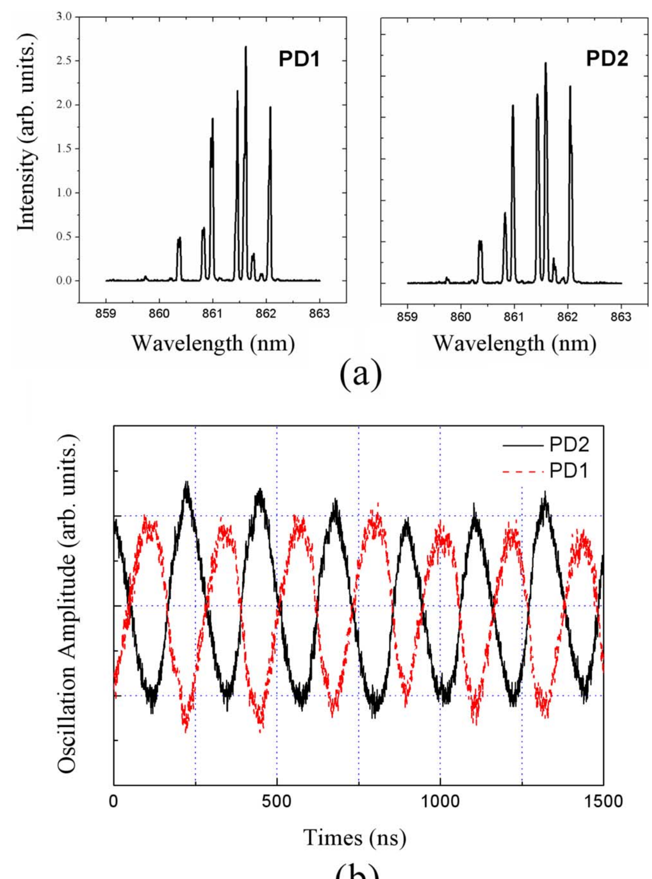

FIG. 6. (Color online) (a) Typical optical spectra at the two main lobes of the far field in the high-pumping regime. (b) Time traces of lasing beams measured at two external photodetectors PD1 and PD2 at current 156 mA. Dashed red line (PD2); solid black line (PD1).

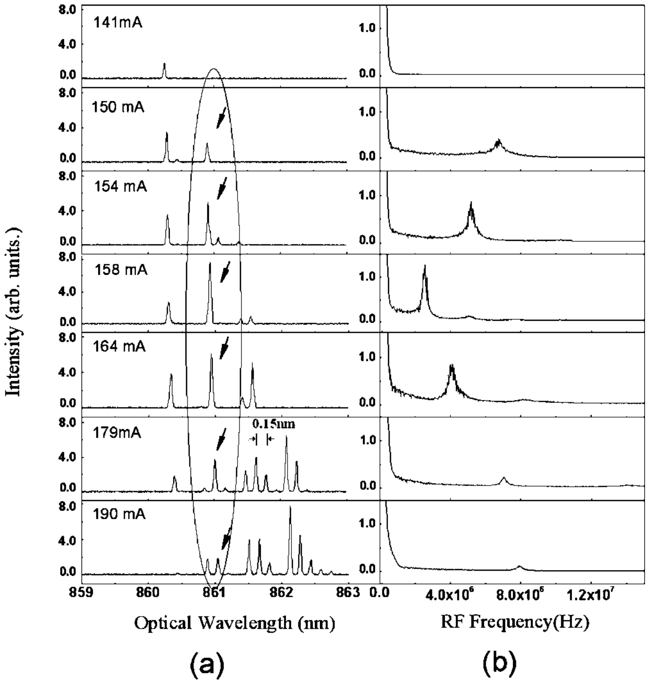

FIG. 7. Observed spectra: (a) Optical and (b) rf spectra of laser output due to an increase in pumping current; the mode spacings in the optical spectra measured about 0.15 nm.

From a close inspection of optical spectra, several important observations can be made. First, we note that the AO is not coming from the beating of high-order longitudinal modes, which correspond to the peaks with 0.15 nm regular mode spacing in the optical spectra, because the AO has several megahertz ($\sim$0.000 001 nm) oscillation frequencies which are very far from 0.15 nm (60 Ghz). Moreover, the slow gain competition between the cavity modes, which is another possible cause of AO, cannot explain the AO phenomena either. This can be seen by noting that the output intensities of the standing modes and their superposition are always symmetric, while the AO has asymmetric output intensity at each lobe at every moment (i.e., whenever the output intensity at one lobe reaches its maximum value, the output intensity at the other lobe reaches its minimum). From what has been discussed above, we can conclude that AO has no relation with an interaction or beating of the modes corresponding to regular distant peaks in the optical spectra, so that we can focus our attention only on one peak in the optical spectra to figure out the cause of the AO.

A second important observation is the fact that the AO is related only to a specific optical mode (arrow-tagged peak). As shown in Fig. 8(a), there is a linear correlation between the oscillation amplitude and the light intensity of the arrow-tagged peak in the optical spectrum. It gives us an important clue for clarifying the origin of AOs in QSMLs. From the above discussion, we have already excluded the interactions of the longitudinal modes as the cause of AO. Therefore, we can conclude that there exist two nearly degenerate modes in the arrow-tagged peak and the AO arises from their beating, even though the peak looks like a single mode owing to the resolution limit of the optical spectrometer.(i.e., our measurement is performed under the resolution 0.02 nm but the mode difference will be within 0.000 001 nm).

The other evidence to support the existence of two modes in the arrow-tagged peak is shown in Fig. 8(b). It shows that the oscillation frequency of the AO decreases as the amplitude of the arrowed peak increases. The experimental result looks like a mode pulling effect caused by nonlinear interaction in the active medium introduced by the locking of two modes [17,18]. Although perfect locking was not achieved due to the lack of pumping energy, the resonance frequencies become closer and closer to each other as the energy gain is increased. Here, to explain the frequency difference we can exclude the backscattering model for the following reasons. First, the rotational wave cannot be an eigenmode of this system. Second, if the oscillation were induced by the backscattering effect, it would be more reasonable for the oscillation amplitude to be proportional to the total intensity of the lasing output rather than that of the arrow-tagged modes, because all modes are under the same influence of the cavity

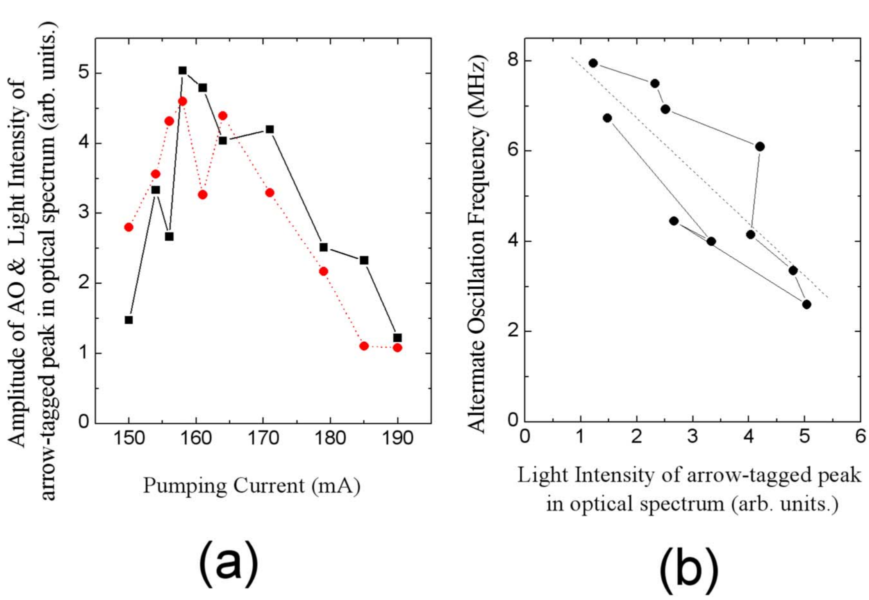

FIG. 8. (Color online) Relation between rf and optical spectra. (a) Amplitude of AO (red circles) and light intensities of arrow-tagged peaks in the optical spectra (black squares) versus an increase in pumping current. (b) Frequency of AO vs light intensity of arrow-tagged peak in the optical spectra.

environment, such as geometrical defects, surface roughness, atomic scattering, etc. This result, therefore, is an experimental demonstration showing the locking of two nearly degenerate stationary cavity modes.

Finally, let us explain why the frequency of AO does not decrease but increases above the pumping current 158 mA, although the pumping current still increases. This result comes from the fact that the energy band gap of the active layer shrinks as the temperature of the active layer produced by the pumping current increases. As a consequence, the center frequency of the gain moves to the longer-wavelength regime. As the gain center moves further away from the arrow-tagged peak, its intensity is further decreased although the pumping current is still increasing.

In summary, we have experimentally demonstrated AO in a QSLD. Unlike the AO in conventional ring lasers, explained by interactions between two counterpropagating modes, the AO in the QSLD arises from two nearly degenerate cavity modes due to its geometric structure. We have also explained the change of the AO frequency by the locking process between these two modes.

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