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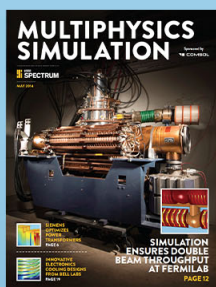
A compact chaotic laser device with a two-dimensional external cavity structure

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We propose a compact chaotic laser device, which consists of a semiconductor laser and a two-dimensional (2D) external cavity for delayed optical feedback. The overall size of the device is within $230\,\mu m \times 1\,mm$. A long time delay sufficient for chaos generation can be achieved with the small area by the multiple reflections at the 2D cavity boundary, and the feedback strength is controlled by the injection current to the external cavity. We experimentally demonstrate that a variety of output properties, including chaotic output, can be selectively generated by controlling the injection current to the external cavity. © 2014 AIP Publishing LLC. [http://dx.doi.org/10.1063/1.4883636]

Semiconductor lasers with delayed optical feedback exhibit numerous intriguing dynamical behaviors, one of which is high-dimensional chaos.[1–3] A purpose of the studies on such lasers is to create novel useful functionalities using the dynamical complexity. Up to now, the complex output properties induced by delayed feedback have been used for chaos communication encryption systems,[4] secure key distribution,[5] physical random number generation,[6,7] remote sensing,[8,9] rainbow refractometry,[10] and photonic information processing.[11]

An important trend in the above studies is to move toward monolithic photonic integration of the components needed for delayed feedback.[3] Such an integration can make it possible not only to stably control complex dynamics but also to realize the large-scale integration for achieving more complex functionalities. Argyris *et al.* have developed a photonic integrated circuit for chaos communications, where all the components needed for the delayed feedback control are monolithically integrated.[12] Photonic integrated devices for high-quality physical random number generation have been also developed.[13–15] However, in these devices, long one-dimensional waveguides over 1 cm that make up more than 90% of the device length have been used to generate delayed optical feedback. The use of such one-dimensional cavity structures would limit the flexibility of the device design and may make larger-scale integration difficult.

Meanwhile, various geometries of two-dimensional (2D) optical cavities have been recently realized by advanced semiconductor fabrication technologies, such as microdisk, deformed disk, ellipse, spiral, stadium, and quasi-stadium.[16,17] The main feature of a 2D cavity structure is its ability to confine the light field in a small area with low loss. A 2D cavity designed so that the light can be multi-reflected by the 2D boundary may be useful for optical delay.

In this Letter, we propose to use a 2D cavity as the external cavity for a semiconductor laser to generate delayed optical feedback. We experimentally demonstrate that the laser can be destabilized by the 2D external cavity, generating chaotic output.

Figure 1(a) shows a schematic of the proposed 2D external cavity, which consists of a flat end mirror of width W_1, one convex curved end mirror of radius R_1, and two straight side-wall mirrors of length L_s. The total length of the cavity is L_1. From the ray dynamical point of view, a self-retracing stable periodic ray trajectory exists if the cavity parameters satisfy the following conditions: $W_1 = L_1/10$, $L_s = 2L_1/5$, and $R_1 > L_1$. When a collimated laser beam is injected from the left-hand side of the cavity, as shown by the arrow in Fig. 1(b), it is reflected at the boundary points indicated by the
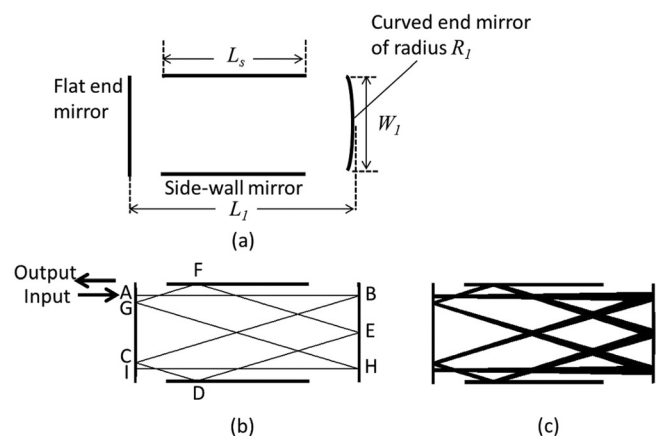

FIG. 1. (a) Schematic of the proposed 2D external cavity. (b) Stable periodic trajectory for $W_1/L_1 = 1/10$, $L_s/L_1 = 2/5$, and $R_1/L_1 = 1.1$. The letters from A to I indicate the reflection points at the cavity edge. A ray injected into the trajectory visits points in the following sequence: $A \rightarrow B \cdots H \rightarrow I \rightarrow H \cdots B \rightarrow A$. (c) Ray trajectories starting from slightly different initial conditions of incident position and angle.

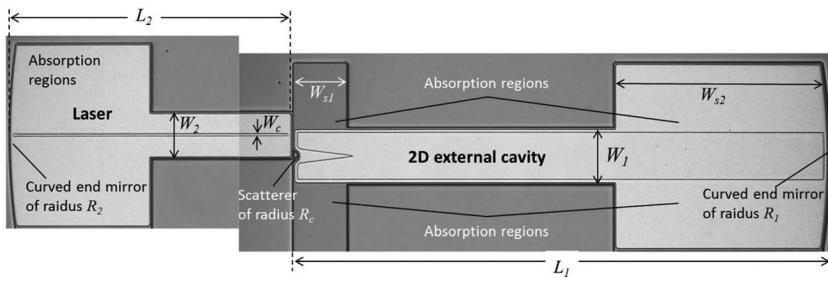a)Electronic mail: sunada@se.kanazawa-u.ac.jp

FIG. 2. Top-view photograph of the fabricated device which consists of the laser with a quasi-stadium shape (left-hand side) and the 2D external cavity (right-hand side). The overall size is within $230 \mu m \times 1$ mm.

letters from A to I along the following trajectory: $A \rightarrow B \cdots H \rightarrow I \rightarrow H \cdots B \rightarrow A$. As a result, the output beam of the external cavity emits from the point A in the direction opposite to the input beam. Because the trajectory is stable, even if there are slight deviations in the incident angle and position, the injected beams can propagate along the trajectory [see Fig. 1(c)].

The laser device integrated with the 2D external cavity was fabricated by applying a reactive-ion-etching technique to a graded index separate confinement heterostructure (GRIN-SCH) single quantum well GaAs/AlGaAs structure grown by metal organic chemical vapor deposition. The details of the layer structure and fabrication process are similar to those reported in Ref. 17. Figure 2 shows the top-view photograph of the fabricated device. The overall size of the device is within $230 \mu m \times 1$ mm. The left-hand side of the device is a laser with a quasi-stadium shape designed so that it can emit a collimated beam.[17,18] It consists of a flat end mirror of width $W_2 = 50 \mu m$ and a curved end mirror of radius $R_2 = 660 \mu m$. The cavity length $L_2 = 330 \mu m$ satisfies the half-symmetric confocal condition $L_2/R_2 = 1/2$; the cavity supports the axial modes, which propagate along the horizontal cavity axis.[17,18] The axial modes can be selectively excited with a narrow contact area of width $W_c = 2 \mu m$. The right-hand side cavity is the 2D external cavity designed to support the stable periodic trajectory shown in Fig. 1(b); the light output from the laser propagates along the trajectory and is fed back to the laser. The power loss of the feedback light is caused by the optical absorption inside the external cavity, the transmissions at the cavity edges, and the scattering at the air gap between the cavity and the laser. In particular, the transmission loss may be dominant because the reflectance at the cavity edges can be estimated to be approximately 28% according to the Fresnel's law. In order to compensate the power loss, the feedback light is amplified by applying the injection current to the external cavity. The air gap width between the external cavity and the laser is $1.5 \mu m$ and they are electrically isolated. To avoid the amplification of unwanted modes in the external cavity, a scatterer with radius $R_c = 6 \mu m$ and window regions working as absorption regions of width $W_{s1} = 60 \mu m$ and $W_{s2} = 240 \mu m$ were introduced. The other parameters of the 2D external cavity were set as follows: $L_1 = 600 \mu m$, $R_1 = 660 \mu m$, and $W_1 = 60 \mu m$. For these parameters, the round-trip optical path length is approximately $12 n_g L_1 (\approx 3 \text{ cm})$, where $n_g = 4.16$ is the group refractive index.[19]

In our experiment, the device was mounted on an AuSn metallized AlN heat sink with junction-up, and the substrate temperature was maintained at room temperature. The injection currents were controlled with an accuracy of ± 0.06 mA.

The output light from the left-hand side facet of the laser was collected by an anti-reflection coated lens and sent to a fast response photodetector with a bandwidth of 12.5 GHz via an optical isolator.

First, we evaluated the basic characteristics of the laser, when the injection current J_f into the 2D external cavity is 0 mA and the external cavity works as an absorption region, i.e., when there is no optical feedback. Figure 3(a) shows the characteristics of the light power as the injection current J_L is changed. The laser starts lasing at the threshold current $J_{th0} = 81$ mA and the light power increases almost linearly above the threshold. The detected power was approximately 4.2 mW for $J_L = 130$ mA. The lasing of the axial modes was confirmed by the optical spectrum [Fig. 3(b)]. The average longitudinal mode spacing is 0.28 nm, which is in close agreement with the theoretical value, 0.27 nm [$=\lambda^2/(2 n_g L_2)$], where the wavelength $\lambda = 860$ nm and $n_g = 4.16$ were used. In the spectrum, modes other than the longitudinal modes are also seen, e.g., the doublet peaks seen at approximately 862 nm. They indicate the existence of transverse axial modes. The average spacing (0.09 nm) of the doublets corresponds well to the theoretical values (0.07 nm) of the mode spacing between lowest-order and second-lowest-order transverse axial modes in the laser with the half-symmetric confocal condition.[20]

Next, we discuss the case when a current J_f is injected into the external cavity. We observed the reduction in the threshold current of the laser when J_f increases. The measured values of the threshold reduction, $(J_{th0} - J_{th,f})/J_{th0}$, range from less than 1% for $J_f = 110$ mA to 13.8% for $J_f = 165$ mA, where $J_{th,f}$ is the threshold current measured when $J_f \neq 0$.
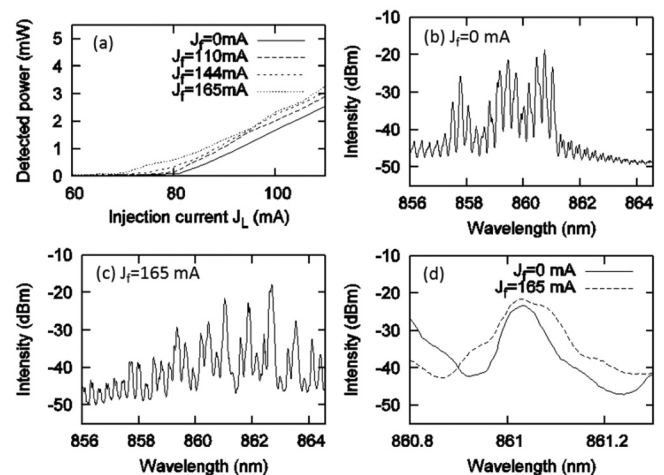

FIG. 3. (a) L-I curves of the laser for various values of J_f. Optical spectra of the laser for (b) $J_f = 0$ mA and (c) for $J_f = 165$ mA. J_L is fixed at 130 mA. The lasing wavelengths are red-shifted owing to the joule heating effect as J_f increases. (d) Enlarged view of optical spectra (b) and (c).
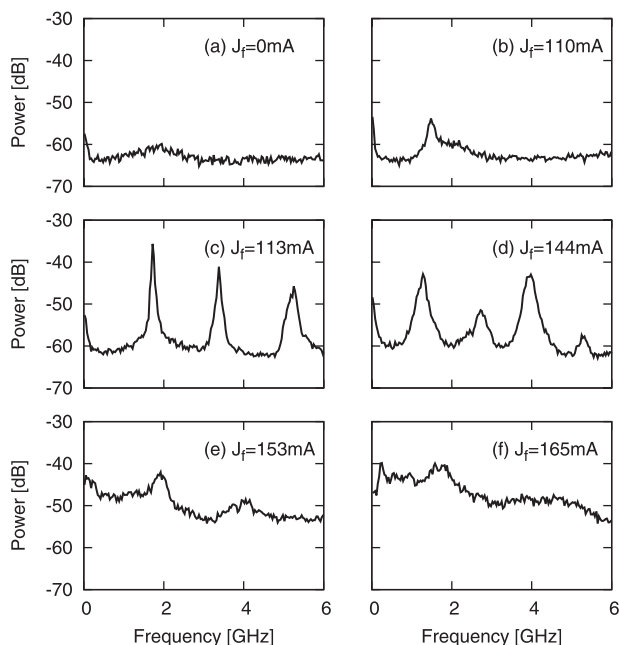
FIG. 4. RF spectra of the intensity fluctuations of the light output from the left-hand side of the laser. J_L was fixed at 130 mA.
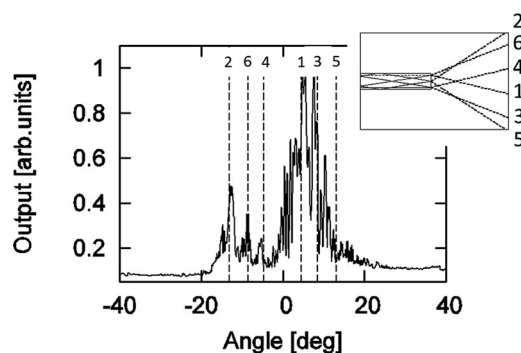

FIG. 5. Far-field emission pattern from the right-hand side of the 2D external cavity for $J_f = 165$ mA and $J_L = 130$ mA. The inset shows the direction of the output ray (dashed lines) from the curved end mirror of the external cavity (solid curve).

This reduction can be attributed to the feedback light amplified in the external cavity. At the same time, we observed that with increasing J_f, the intensity of the output laser light starts to fluctuate. Typical radio frequency (RF) spectra of the output intensity measured for various values of J_f are shown in Fig. 4, where J_L was fixed at 130 mA. For $J_f = 0$ mA [Fig. 4(a)], the output intensity is almost constant in time. The RF spectrum has a small broad peak corresponding to the relaxation oscillation frequency at approximately 2 GHz. For $J_f \approx 110$ mA [Fig. 4(b)], a sharp peak appears at approximately 1.5 GHz in the RF spectrum. As J_f increases slightly, the peak gains in amplitude and its higher harmonics also appear [Fig. 4(c)]. The peaks are slightly shifted with increasing J_f. The property of this oscillation state resembles the so-called pulse package, which is a typical phenomenon observed when the external cavity frequency f_{ex} is much larger than the relaxation oscillation frequency f_r.[21] In our device, f_{ex} is about 10 GHz, which is much larger than $f_r \approx 2$ GHz; the condition for the pulse packages is thus satisfied. When J_f increases further, the broad spectra were observed [Figs. 4(d) and 4(e)].

For $J_f = 165$ mA, we obtained the most broad spectrum [Fig. 4(f)]. The intensity is increased by more than about 20 dB compared to the case of $J_f = 0$ mA. We expect this large chaotic oscillation to be useful for chaos-based applications. In particular, it is our future plan to use this device for a compact random number generator.

The emergence of the chaotic oscillation can be understood as the effect of delayed feedback generated by the external cavity.[1,2] We found that the external cavity also changes the spectral characteristics. Figure 3(c) shows the optical spectrum of the chaotic state. We observed that owing to a random switching of the lasing modes, i.e., the mode-hopping phenomenon, the spectrum becomes broader compared to the case of $J_f = 0$ mA. In the spectrum, the spacing between neighboring peaks is no longer regular, because

the lowest-order and higher-order transverse axial modes are both excited. Moreover, as seen in Fig. 3(d), the linewidths of several peaks are increased.

Finally, we present evidence that the delayed feedback path is formed as we designed. For this purpose, we measured the far-field pattern of the laser beam emitted from the curved end mirror of the 2D cavity when the chaotic state was observed. The result is shown in Fig. 5. For comparison, we also show the theoretical values of the emission peak positions in the far field, which were obtained by the Snell's law. The peak numbers 1, 2, ..., 6 indicate, in order, the numbers of the reflections at the curved end mirror. We can see that the experimentally observed peak positions in the far-field pattern correspond to the theoretical prediction. Therefore, we conclude that the beams incident from the laser onto the external cavity certainly propagate inside the external cavity along the trajectory shown in Fig. 1(b). The decrease of the peak intensities is mainly due to the transmission loss at the end mirrors. Taking into account that the lowest-order and higher-order transverse modes were both excited, we consider that the deviation from the theoretical prediction may be due to the interference among these lasing modes.

In conclusion, we experimentally showed that broad-band chaotic output in the gigahertz regime can be observed in the laser device coupled with the 2D external cavity supporting a long periodic ray trajectory. The proposed device is much smaller than those reported in previous studies and could be useful for many chaos-based applications and large-scale integration. We note that the 2D external cavity can be improved by designing the shape to have a long-path stable periodic ray trajectory confined by total internal reflection. This enables the further downsizing of the device. We think the ideas presented here are useful not only for generating delayed optical feedback but also for realizing wide-wavelength range optical delay line and a narrow-linewidth laser. The work along these lines will be reported elsewhere.

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