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Experiment on decision making using chaotic multi-mode semiconductor laser with optical feedback and injection

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Abstract– Photonic decision making has been investigated for solving the multi-armed bandit problem, which is one of the important problems in reinforcement learning. Photonic decision making using controlling chaotic itinerancy in a multi-mode semiconductor laser has been reported in numerical simulations. In this study, we experimentally investigate photonic decision making using chaotic itinerancy in a multi-mode semiconductor laser with optical feedback and injection. We solve the two-armed bandit problem by controlling the optical injection strengths for the multi-mode semiconductor laser.

1. Introduction

Photonic accelerators have been widely studied, where optical technologies are used to accelerate information processing [1]. One of the photonic accelerators is photonic decision making, in which optical dynamics is used to solve the multi-armed bandit problem [2–6]. The multi-armed bandit problem is the problem to maximize the total reward in selecting among multiple slot machines with unknown hit probabilities [7, 8]. The multi-armed bandit problem well describes a dilemma between exploration and exploitation, which represents a challenge in reinforcement learning [8]. Here, exploration is the action of selecting a slot machine which has not been selected yet and looking for a slot machine which can provide many rewards. On the other hand, exploitation is the action of selecting slot machines which provides many rewards based on the knowledge obtained by exploration. Thus, decision making in selecting the slot machines is important to solve the multi-armed bandit problem because biases in exploration and exploitation reduce the total rewards.

Many studies on photonic decision making for solving the multi-armed bandit problem have been reported [2–6]. The two-armed bandit problem has been solved for two slot machines by comparing the chaotic temporal waveform of laser output with a threshold value [2] and mode switching in a ring-cavity laser [4], where each of the two states corresponds to selecting a slot machine as a fundamental of photonic decision making. Methods for more than two slot machines have been proposed by combining two choices in a hierarchical architecture [3], using lag synchronization of chaos in a laser network [5], and using digital-to-analog converted chaotic signals [6]. However, these methods highly depend on software processing for the selection of slot machines. Thus, there is a challenge for increasing the number of slot machines in hardware-based photonic decision making.

In single-mode semiconductor lasers with optical feedback, a chaotic itinerancy has been reported, where spontaneous transitions occur among multiple external cavity modes generated by optical feedback [9]. It is expected to explore slot machines spontaneously by using the spontaneous transitions caused by chaotic itinerancy. In addition, multiple longitudinal modes in a multi-mode semiconductor laser can be used to deal with the large number of slot machines. In a multi-mode semiconductor laser with optical feedback, chaotic mode-competition dynamics of the dominant mode occurs, which is the mode with the maximum intensity [10]. Recently, a scheme for decision making in more than two slot machines has been numerically proposed using chaotic mode-competition dynamics (chaotic itinerancy) in a multi-mode semiconductor laser with optical feedback, and chaotic itinerancy can be controlled to select a particular slot machine by optical injection [11]. In addition, high scalability can be achieved in this scheme by using the power concentration to one longitudinal mode. However, the experimental feasibility of this method has not been demonstrated yet.

In this study, we experimentally demonstrate decision-making scheme using chaotic multi-mode semiconductor laser with optical feedback and injection optical fiber components. We control mode-competition dynamics of the chaotic multi-mode laser by optical injection. We experimentally achieve decision making for solving the two-armed bandit problem using the chaotic multi-mode semiconductor laser.

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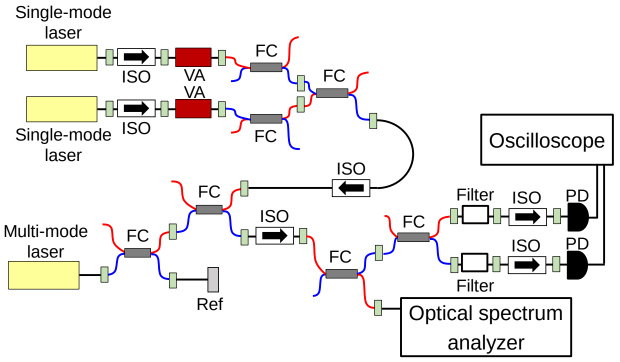

Fig. 1: Experimental setup of a multi-mode semiconductor laser with optical feedback and injection. ISO: isolator, VA: variable optical attenuator, FC: fiber coupler, Ref: reflector, Filter: wavelength filter, PD: photodetector.

2. Experimental setup and dynamics in multi-mode semiconductor laser with optical feedback and injection

Figure 1 shows our experimental setup for controlling two longitudinal modes in a multi-mode semiconductor laser with optical feedback. The light from the multi-mode semiconductor laser is reflected by a reflector and reinjected into the multi-mode laser as optical feedback. The two longitudinal modes in the multi-mode semiconductor laser are controlled by using optical injection from two single-mode semiconductor lasers. Here, the wavelength detuning of each single-mode semiconductor laser is set to 0.040 nm to the longitudinal mode to be controlled ($\lambda_{multi} - \lambda_{single} = -0.040$ nm, i.e., a negative wavelength detuning). The optical injection strengths from the single-mode lasers can be adjusted by variable optical attenuators whose transmittance can be controlled by voltage controllers. Here, the optical injection strength for mode m is normalized by the maximum injection power and expressed as $\kappa_{inj,m}$. On the other hand, two modes in a multi-mode semiconductor laser are extracted from the output of the multi-mode semiconductor laser using two wavelength filters, and the optical signals are converted to electric signals by photodetectors. The temporal dynamics of the modal intensities are observed by a digital oscilloscope. The optical spectra are also observed using an optical spectrum analyzer. Here, the longitudinal modes at 1547.241 and 1546.659 nm are defined as mode 1 and 2, respectively.

Figure 2 shows the modal intensities and optical spectra obtained by the experiment. Figure 2(a) shows the modal intensities of the two modes with small injection strengths $\kappa_{inj,1} = \kappa_{inj,2} = 0.05$. The two modes oscillate chaotically while the dominant mode is changing in time. Thus, the chaotic mode-competition dynamics with optical feedback can be confirmed under small optical injection. Figure 2(b) shows the corresponding optical spectra at $\kappa_{inj,1} = \kappa_{inj,2} = 0.05$. The small peaks in the long wavelength side of mode 1 and 2 appear due to the appearance of the injected light. However, mode 1 and 2 have similar power, which indicates that the modes are competing in power as

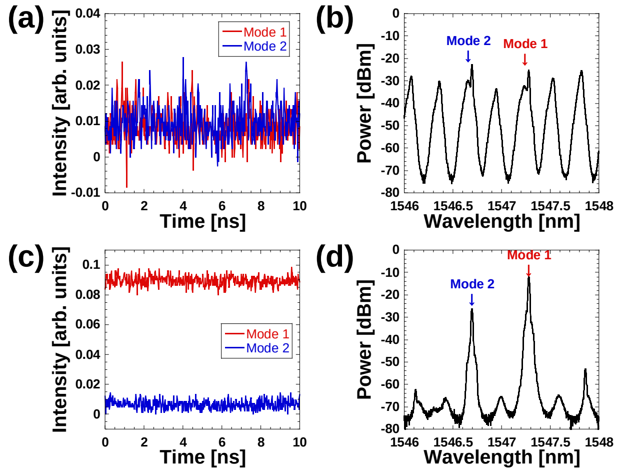

Fig. 2: (a), (c) Temporal waveforms of modal intensities in the multi-mode laser. (b), (d) Corresponding optical spectra. Optical injection strengths for two modes are set to (a), (b) $\kappa_{inj,1} = \kappa_{inj,2} = 0.05$ and (c), (d) $\kappa_{inj,1} = 1.0, \kappa_{inj,2} = 0.05$.

shown in Fig. 2(a). In addition, other longitudinal modes also have power, which suggests that mode-competition dynamics occur in multiple longitudinal modes.

Figure 2(c) shows the modal intensities of the two modes with strong optical injection strength to mode 1 ($\kappa_{inj,1} = 1.0, \kappa_{inj,2} = 0.05$). Mode 1 always oscillates with the maximum intensity and become the dominant mode, which means that chaotic mode-competition dynamics do not occur. In other words, the mode-competition dynamics is controlled by strong optical injection. Figure 2(d) shows the corresponding optical spectra at $\kappa_{inj,1} = 1.0, \kappa_{inj,2} = 0.05$. The modes are shifted to the wavelengths of the injected light, and injection locking is achieved [12]. In addition, the mode power except for mode 1 and 2 is suppressed, which indicates that the longitudinal modes have been controlled by optical injection. In particular, the power of mode 1 is 10-dB higher than that of mode 2, which indicates that the power is concentrated to mode 1. The power of other modes is suppressed by exciting the power of mode 1 via optical injection. Thus, mode 1 has been stabilized as the dominant mode as shown in Fig. 2(c).

We measure the dominant mode ratio [10, 11] to quantitatively confirm that the dominant mode can be controlled by optical injection. The dominant mode ratio DMR_m for mode m represents the probability of being the dominant mode and is defined as follows [10, 11],

$$DMR_m = \frac{1}{d}\sum_{l=1}^{d} D_m(l) \qquad (1)$$

where d represents the number of sampling points. The function $D_m(l)$ represents 1 if mode m is the dominant mode at the l-th sampling point, and 0 otherwise.

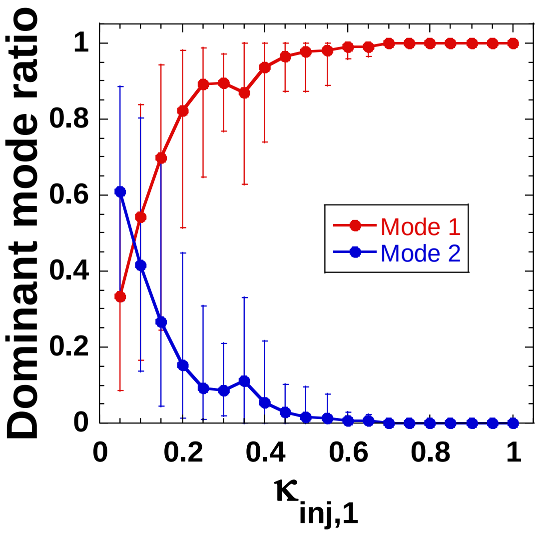

Fig. 3: Dominant mode ratio when the optical injection strength for mode 1 is increased and that for mode 2 is fixed at $\kappa_{inj,2} = 0.05$.

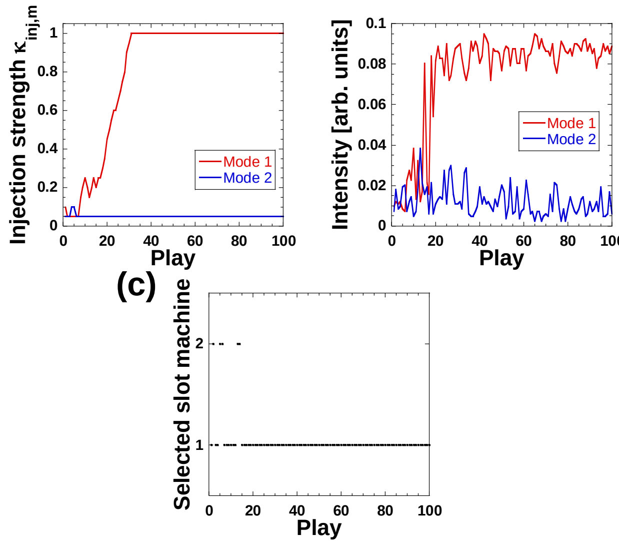

Fig. 4: Experimental results of decision making. (a) Optical injection strength, (b) modal intensities, and (c) selected slot machine as a function of the number of plays. The hit probability of slot machines 1 is set to 0.8 and that of slot machine 2 is set to 0.2.

Figure 3 shows the dominant mode ratio when the optical injection strength for mode 2 is fixed at $\kappa_{inj,2} = 0.05$ and that for mode 1 is increased. The dominant mode ratio is obtained from the temporal waveforms for 10 μs and repeated 10 times at each optical injection strength. The average value of the dominant mode ratios is represented by a dot, and the maximum and minimum values are represented by error bars. The dominant mode ratio of mode 1 increases gradually as the optical injection strength for mode 1 is increased, and the dominant mode ratio reaches 1. Therefore, we experimentally confirmed that the dominant mode can be controlled by increasing optical injection strength.

3. Decision making using a multi-mode semiconductor laser with optical feedback and injection

In the previous section, we experimentally confirmed that chaotic mode-competition dynamics can be controlled by optical injection. In this section we perform decision making in the multi-armed bandit problem by assigning the slot machines to the longitudinal modes and controlling the mode-competition dynamics based on the results of slot machine selection [11].

For decision making, we add the experimental setup in Fig. 1 to a personal computer and direct-current (DC) voltage controllers for changing the attenuation ratio of the variable optical attenuators. The personal computer, oscilloscope, and voltage controllers are connected by LAN cables. Two slot machines are emulated in the computer and each slot machine is assigned to longitudinal mode of the multi-mode laser. The temporal waveforms of the modal intensities of the two modes are measured by the oscilloscope, and a sampled point of the temporal waveforms is used to determine the dominant mode. The slot machine assigned to the dominant mode is selected, and the result of "hit" or "miss" is obtained in the computer. Then, the voltage of the variable optical attenuator is controlled according to the results of the slot machine selection using an algorithm called the tug-of-war method [11, 13]. For example, if slot machine 1 is selected and the result shows "hit", the optical injection strength for mode 1 is increased and that for mode 2 is decreased, so that mode 1 tends to become the dominant mode to promote the selection of slot machine 1. On the other hand, if slot machine 1 is selected and the result shows "miss", then the optical injection strength for mode 1 is decreased and that for mode 2 is increased, so that mode 1 tends to become the non-dominant mode, which suppresses the selection of slot machine 1. The same procedure is done when slot machine 2 is selected. Decision making is performed by repeating these processes.

Figure 4 shows the experimental results of decision making at each play when the hit probability of slot machine 1 is set to 0.8 and that of slot machine 2 is set to 0.2. Figure 4(a) shows the change in the optical injection strengths as a function of the number of plays. The optical injection strength for mode 1 increases as the number of plays increases. Figure 4(b) shows the change in modal intensities as a function of the number of plays. The two modes compete up to about 20 plays. After that, mode 1 is enhanced and becomes the dominant mode, because optical injection strength for mode 1 is increased as a result of the exploration. Figure 4(c) shows the selected slot machine. Slot machines 1 and 2 are randomly selected and searched up to 20 plays. Then, slot machine 1 is always selected when the number of plays increases, because mode 1 is enhanced as shown in Fig. 4(b). The mode-competition dynamics can be controlled for exploration and exploitation.

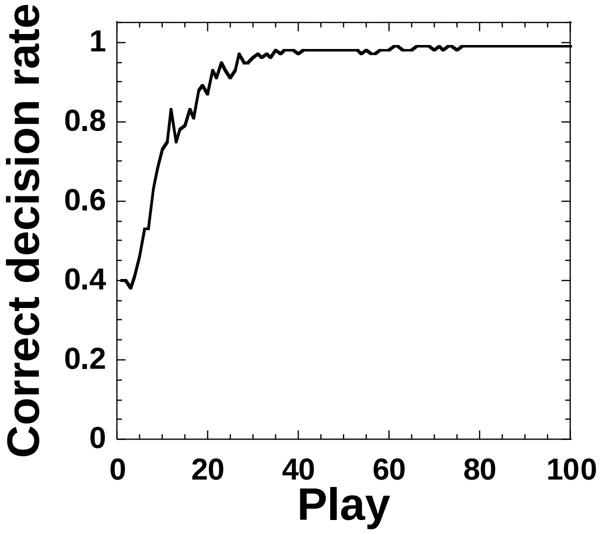

Fig. 5: Correct decision rate as a function of the number of plays. The he hit probability of slot machines 1 is set to 0.8 and that of slot machine 2 is set to 0.2.

We also conduct decision making for multiple cycles. The correct decision rate [2–6, 11] is used for evaluation. The correct decision rate represents the rate of selecting the slot machine with the highest hit probability at t-th play when decision making is performed for multiple cycles. Figure 5 shows the correct decision rate of decision making for 100 cycles and 100 plays when the hit probability of slot machine 1 is set to 0.8 and that of slot machine 2 is set to 0.2. The correct decision rate is low at the beginning because the slot machine is selected randomly when the number of plays is small. However, the correct decision rate increases and converges to 1 as the number of plays increases. This result indicates that correct decision making can be performed successfully. Therefore, we experimentally achieve decision making using chaotic multi-mode semiconductor laser with optical feedback and injection.

4. Conclusions

We experimentally demonstrated decision-making scheme using a chaotic multi-mode semiconductor laser with optical feedback and injection. We confirmed that chaotic mode-competition dynamics in the multi-mode semiconductor laser with optical feedback can be controlled by optical injection. We experimentally achieved decision making for two-armed bandit problem using mode-competition dynamics in a multi-mode semiconductor laser.

Acknowledgments

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