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Square Wave Modulation in a Closed-Loop Semiconductor Laser with Optical Feedback

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ABSTRACT
We achieve chaotic behavior in the dynamics of a semiconductor laser with ac-coupled optical feedback by experimentally applying a new modulating waveform to the bias current other than a pure sine wave. The embedding technic of the attracter and the quantitative bifurcation diagram analyze the duty cycle and phase effect. The dynamics become chaotic with the increasing values of the duty cycle, and it is chaotic in all values of phase change. Furthermore, the applied square wave modulation gives additional parameters to be tuned, which enhances the security level provided by a closed-loop semiconductor laser with optical feedback.

Keywords:
chaos, duty cycle, optical feedback, modulating.

INTRODUCTION
Semiconductor laser induced by optical feedback is exciting not only from fundamental physics but also for practical application due to their ability to generate highly complicated signals used in optical communication, optical data storages, and optical measurements **[1-4]**. Nonlinear delay differential equations describe the irregular oscillations called chaos induced by laser dynamics **[5-9]**. Nonlinearity and three-fold dimensionality are the conditions of chaos in semiconductor lasers **[10-13]**. Once the laser's nonlinearity is not strong enough, it can be raised by a delayed feedback loop **[14]**. Semiconductor lasers with external cavities exhibit parameters, including feedback delay, feedback strength, pump current feedback type, and laser **[15-18]**. A high spiking rate in a closed-loop semiconductor laser with optical feedback gives a masking waveform that can hide a message **[19]**. Square wave oscillations are predicted in semiconductor lasers with delayed optical feedback in the past years **[20-24]**. The dynamical behavior of semiconductor laser with optical feedback was analyzed as a function of feedback strength, pumping current, and detuning frequency **[19, 25]**. Here instead, we apply a modulating square signal other than pure sinusoidal gives additional parameters to be tuned, which enriches the security level provided by a semiconductor laser.

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Experimental setup

From the experimental setup of our previous work, Fig. 1, A single-mode semiconductor laser (1550nm wavelength) with optical feedback using an optical fiber closed loop. The pigtailed laser output is connected to two 1x2 directional couplers (1x2 DC, 90%:10% and 1x2YC, 50%:50%). We realize the loop by combining the two output branches of the Y-coupler. The reflected light from the coupler is split into two parts; the first one is indicated as feedback to the semiconductor laser cavity, while the other is connected to a high-speed InGaAs photodetector with response time <1ns. The sampling digital storage scope (LeCroy 500MHz) is attached to the photodetector [19]. An external modulating signal 50MHz directly modulates the laser with an amplitude of 10mw, and the bias current is set at 19.5mA.

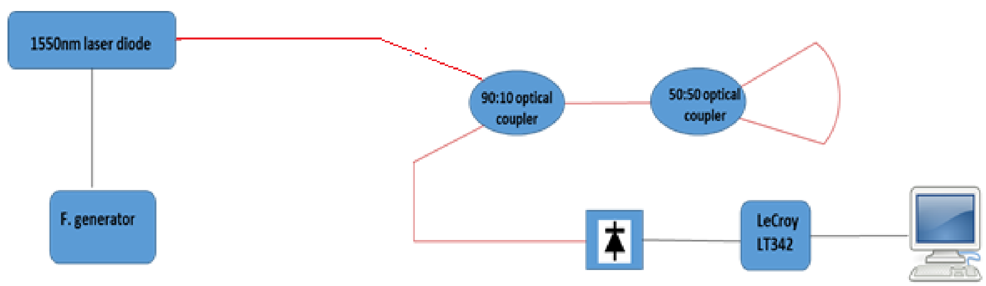

Fig.1.Experimental setup of a semiconductor laser with optical feedback systems using two 1x2 directional couplers [19].

- **Effect of duty cycle variation**

One new parameter that becomes accessible after changing the modulating signal to a square wave from a sine wave is the square wave's duty cycle. We modulate the laser directly in the source by an external function generator at bias current 19.5mA, amplitude 10mv, and frequency 50MHz.To infer the system's character and know what will happen in the future, we plot 2-dimension state variable space by making an embedding delay plot (Ruelle-Takens embedding technique). The output Time-series analyses and reconstruction of the phase portrait through the Ruelle-Takens embedding technique shown in Fig.2 (a) to (c) under the influence of the duty cycle from %1 to %5. Initially, the output is more regular as the duty cycle increased a transition to a chaotically spiking regime is observed gradually.

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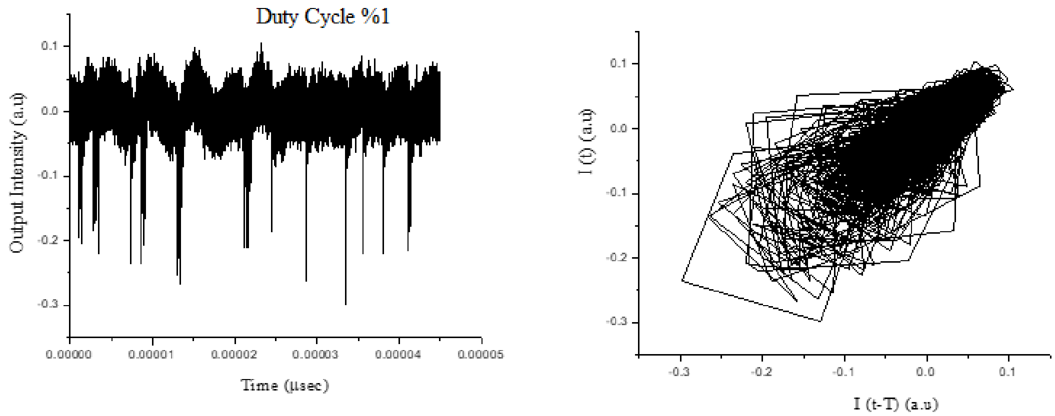
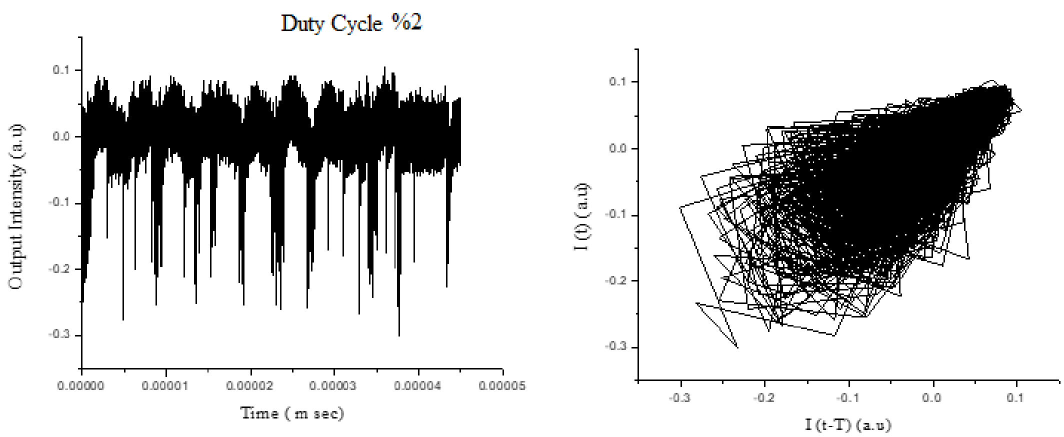
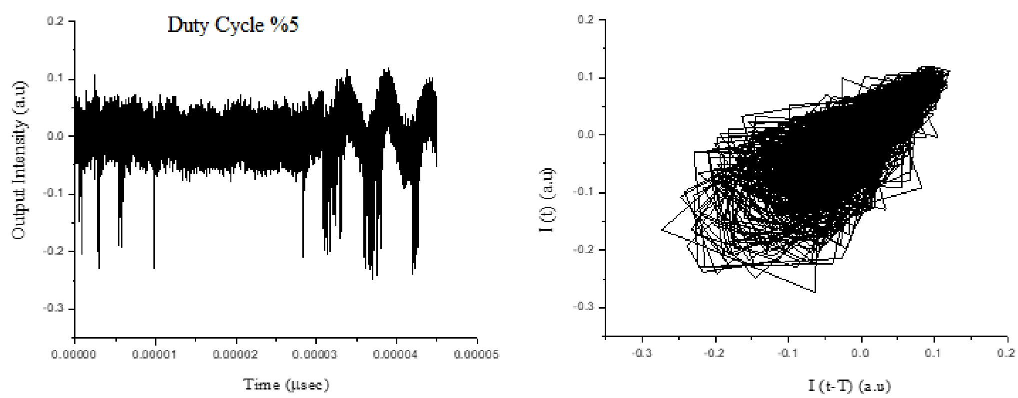


(a)



(b)

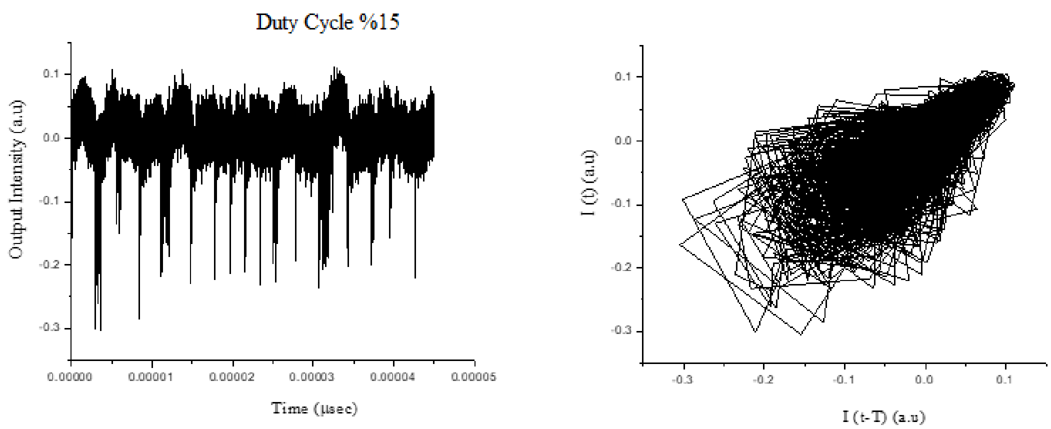


(c)

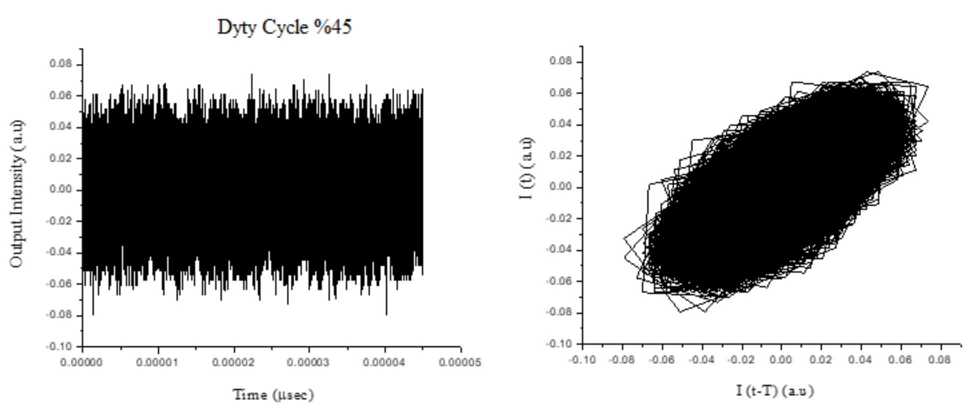
Fig. 2:Time series and reconstruction of the phase portrait through the Ruelle-Takens embedding technique for change in duty cycle (%) (a) %1 (b) %2 (c) %5

The duty cycle further increased from 10 to 99 percent, and the resulting output dynamical sequence shows in Fig.3 (a) to (c). We observe the transition to chaotic spiking as the duty cycle is increased. We follow a strange attractor from the embedding reconstruction, which implies that the dynamics are chaotic and consist of bounded periodic limit cycles. So the duty cycle is a new control parameter available if a square signal modulates the laser.

The degree of chaos generated by variation in the duty cycle can be quantified by drawing a bifurcation diagram obtained through plotting the peak to peak laser output intensity against the duty cycle Fig.4. For low values of the duty cycle, the dynamics of the oscillator is chaotic with higher amplitudes; for higher values, the dynamics remain chaotic but with constant amplitudes.



(a)



(b)

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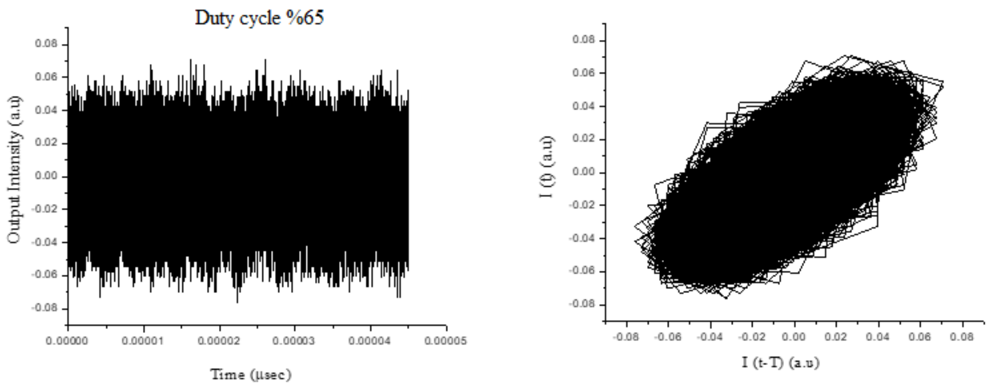
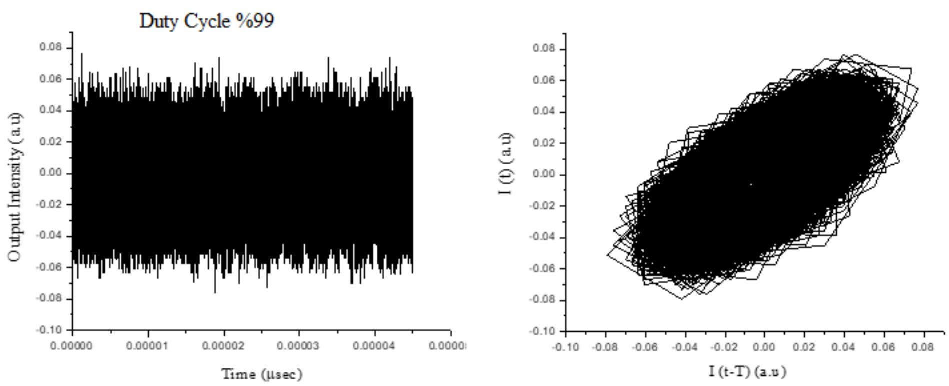


(c)



(d)

Fig.3 :Time series and reconstruction of the phase portrait through the Ruelle-Takens embedding technique for change in duty cycle (%) (a) %15 (b) %45 (c) %65 (d) %99

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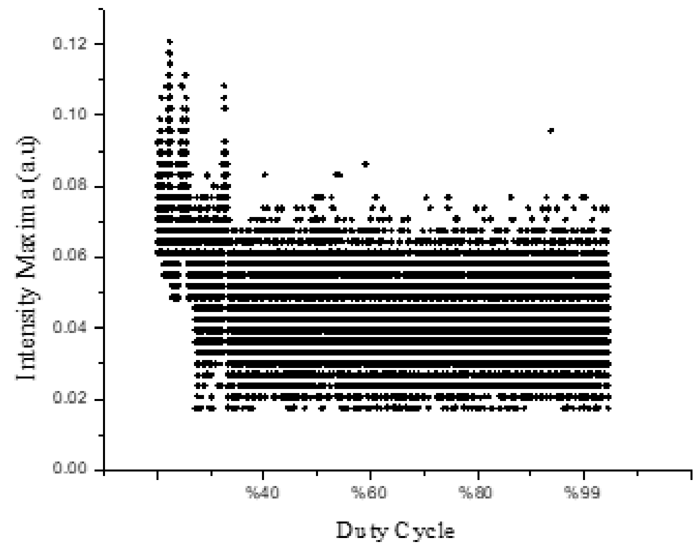
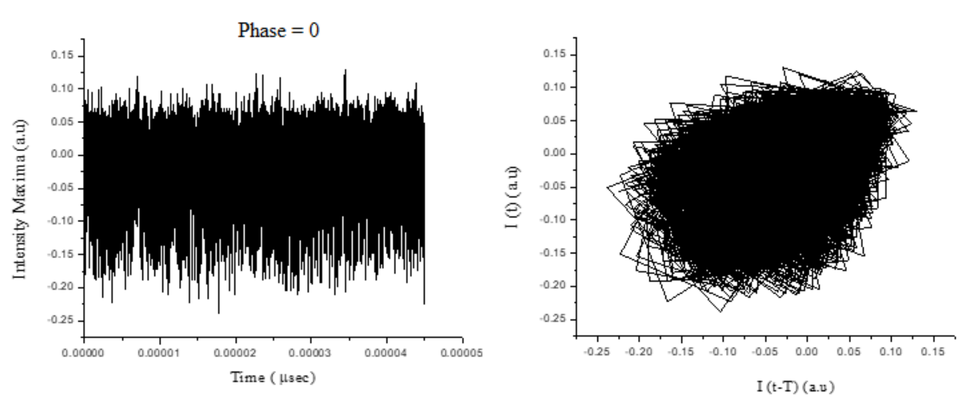


Fig.4: Bifurcation diagram of chaotic optical spiking as a function of the duty cycle.

- **Effect of phase variation**

The square wave phase is varied from 0 to 360 degrees. The results plots are in Fig.5 (a) to (d).while keeping all other parameters on the values given in the duty cycle effect. Thus, the dynamics are chaotic for all values of phase change and remain almost the same amplitude. Moreover, we observe a strange attractor from the two-dimension state variable space plot using the embedding delay technique. It implies that the dynamics are chaotic, consisting of bounded periodic limit cycles.

The qualitative structure (bifurcation diagram) of the flow for phase change shows in Fig.6. we observe chaotic dynamics in all values of phase change with almost the same amplitude.



(a)

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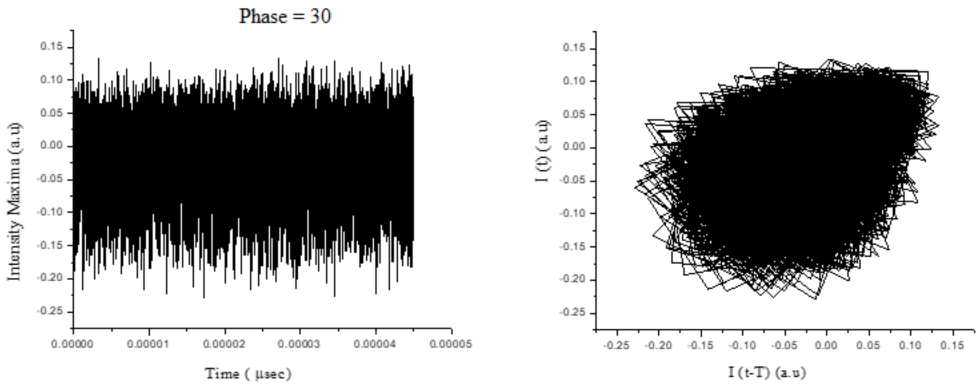
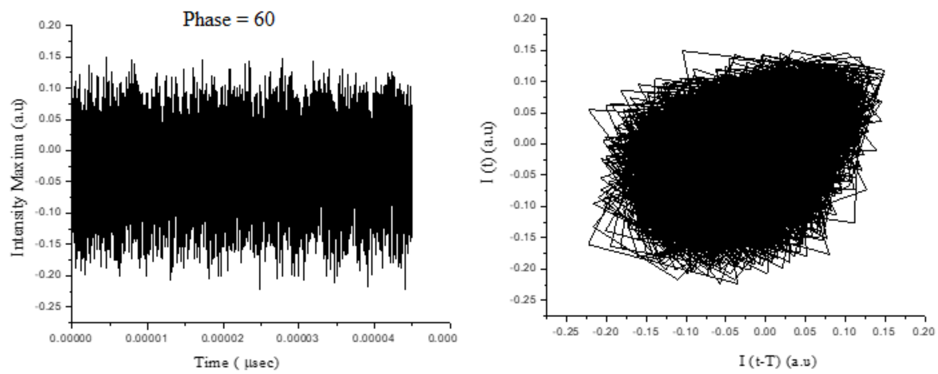
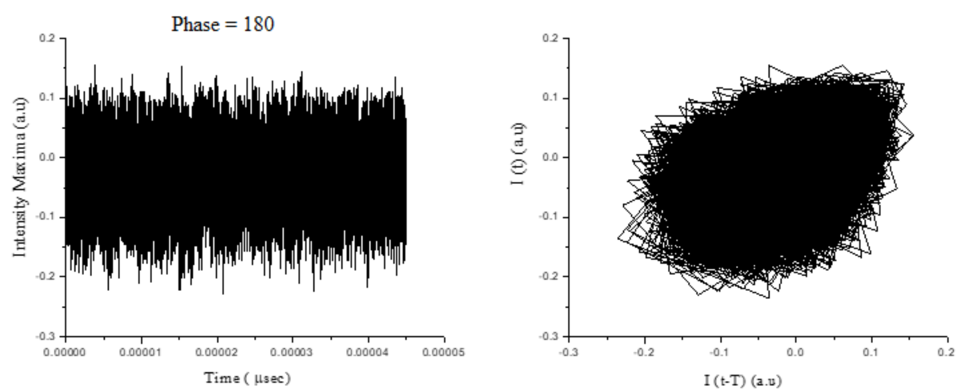


(b)



(c)



(d)

Fig. 5:Time series and reconstruction of the phase portrait through the Ruelle-Takens embedding technique for phase change in degree (a) 0 (b) 30 (c) 60 (d) 180

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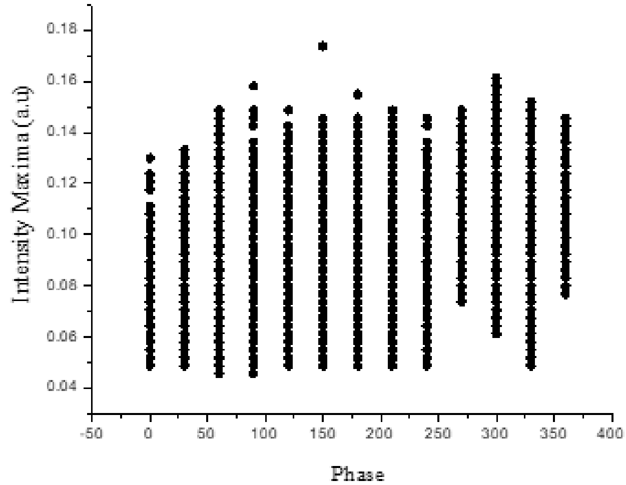

Fig.6: Bifurcation diagram of chaotic optical spiking as a function of phase change.

Results and Discussion

We investigated the effect of variation in parameters of the modulating signal on the degree of chaos. A square modulating signal is used instead of a sine modulating signal. The duty cycle of the square modulating signal identifies as a control parameter for chaotic behavior. The dynamics become chaotic with increasing values of the duty cycle with almost the same amplitude. The effect of phase change shows that the system is chaotic in all values of phase variation. The qualitative diagram of the bifurcation plot clarifies that the system is chaotic in all ranges of phase change. Therefore, the characteristics of the modulating signal provide additional control to generate new chaos. Thus the benefits of using a modulating signal as a control parameter in the system security due to addition in unknown parameters list.

Conflict of interests.

There are non-conflicts of interest.

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