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Periodic dark pulse emission induced by delayed feedback in a quantum well semiconductor laser

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We report the experimental observation of periodic dark pulse emission in a quantum-well semiconductor laser with delayed optical feedback. We found that under appropriate operation conditions the laser can also emit a stable train of dark pulses. The repetition frequency of the dark pulse is determined by the external cavity length. Splitting of the dark pulse was also observed. We speculate that the observed dark pulse is a kind of temporal cavity soliton formed in the laser. *Copyright 2012 Author(s). This article is distributed under a Creative Commons Attribution 3.0 Unported License.* [<http://dx.doi.org/10.1063/1.4769089>]

Semiconductor lasers subject to optical feedback from an external mirror have been extensively investigated both theoretically¹⁻³ and experimentally.^{4,5} It has been shown that as a result of the delayed feedback, the lasers can exhibit a variety of interesting features, including the destabilization of relaxation oscillations,⁶⁻⁹ coherence collapse,¹⁰ and low-frequency fluctuations (LFF) or drop-outs.^{1,11} Physically, a nonlinear system with delayed feedback has infinite solutions, whose behaviors need to be explained in terms of the nonlinear dynamics. Theoretical studies on the semiconductor lasers with delayed feedback based on the Lang-Kobayashi (LK) equations² or their simplified form¹² have shown that multiple attractors can coexist in the system. Not only bifurcations to chaos but also collision between the coexisting attractors could have resulted in the complicated features of the lasers.

Theoretical studies further revealed the complicated bifurcation diagram of the laser system, including the existence of many Hopf-bifurcations.³ Using a local multiple time scale analysis Giacomelli and Politi have theoretically shown that near a Hopf-bifurcation, the dynamics of a delayed dynamical system is equivalent to that of the complex Ginzburg-Landau equation (CGLE).¹³ According to Giacomelli and Politi, the delayed feedback not only shifts the light from one to the successive delay unit, but also plays the role of “group velocity dispersion” in a dispersive medium. As apart from chaotic dynamics, under appropriate conditions, a CGLE also possesses stable localized solutions. One would expect that a semiconductor laser with delayed feedback could also emit stable temporal pulses.

We have experimentally investigated the operation of a semiconductor quantum-well laser with delayed feedback. It was found that in a certain optical feedback strength range, the laser could emit a stable train of dark pulses. The repetition rate of the dark pulses varied with the feedback delay time. Dark pulse splitting was also observed. We interpret the observed dark pulse as a kind of temporal cavity soliton formed in the laser.

The experimental setup is depicted in Fig. 1. A quantum-well laser diode module operating at a solitary wavelength of $\lambda = 770$ nm was used. One facet of the laser diode is high reflection

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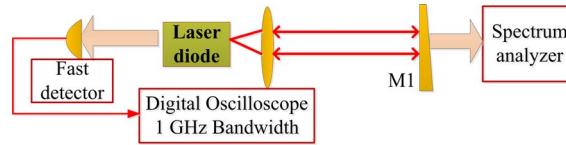


FIG. 1. Schematic of the experimental setup

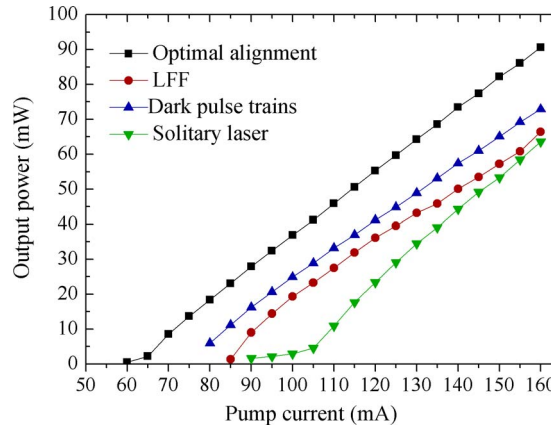


FIG. 2. Characteristics of output power versus pump current.

coated, and the other facet is anti-reflection coated. The laser diode was driven by an ultra-low noise current source (Sacher MLD-100) and mounted on a water-cooled copper block maintained at 17 °C. A wedge-shaped mirror M1 with a reflectivity of 30% was used as the external cavity mirror. To collimate the laser beam an antireflection-coated aspheric lens was inserted between the diode and the external cavity mirror. The laser output and its optical spectrum were simultaneously monitored by an optical spectrum analyzer with a resolution of 0.05 nm (Ando, AQ-6315B), and a 1 GHz bandwidth photo-detector (NewFocus, 1611-FC-AC) together with a fast digital oscilloscope of the same bandwidth (Tektronix, DP0714).

We first measured the operation of the laser diode under different injection currents with M1 removed. The results are shown in Fig. 2 and Fig. 3, respectively. The diode module started lasing as the injection current exceeded 90 mA. Its emission wavelength was at 770 nm. Under all the experimental accessible current range the diode module always emitted in CW mode. We then installed M1. It was found that under the delayed feedback, depending on the alignment of M1, the laser could exhibit different features. We changed the external cavity length from 40 cm to 170 cm. At different external cavity lengths, when M1 was optimally aligned, CW emission was again obtained. In Fig. 2, we show the CW operation of the laser for an external cavity length at 37.5 cm. Under existence of the delayed feedback the laser threshold decreased to 60 mA, and the CW emission wavelength shifted to 781 nm.

Under the optimized M1 alignment the feedback strength is also the strongest. Carefully misaligning M1, the laser then exhibited various emission features. Fig. 2 and Fig. 3 show the laser output performance and emission wavelength under two typical emission states, one is the well-known LFF emission, as shown in Fig. 4(a), and the other is a periodic dark pulse emission state which we will discuss in the following. Based on the laser oscillation wavelengths we deduce that the LFF state corresponds to a relatively weaker feedback. In a LFF emission state, due to the irregular laser intensity drop-outs, the spectral bandwidth of the laser emission obviously broadened. This effect has also been called coherence collapse.¹⁰ The center wavelength of the laser under LFF emission is 774 nm.

As the optical feedback strength was increased, the drop-out events in the LFF state became less frequent. At a certain feedback strength, segments of dark pulse train suddenly appeared in the laser emission, as shown in Fig. 4(b). Eventually the LFF drop-outs disappeared, and the laser

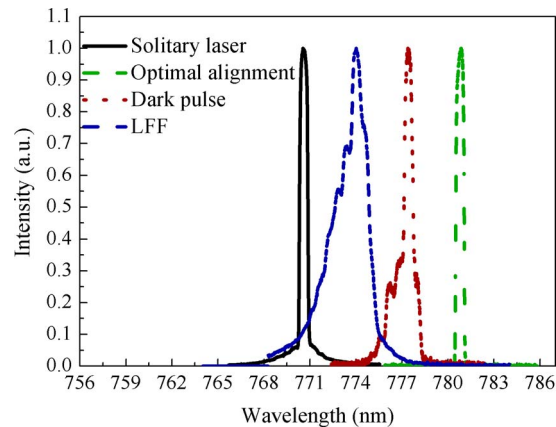
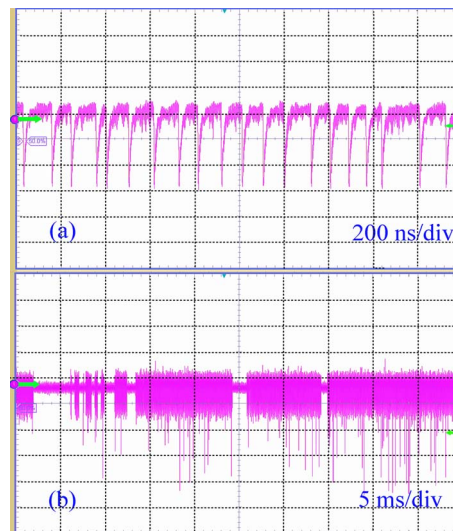


FIG. 3. Spectra of laser diode in different regimes

FIG. 4. Oscilloscope traces of the semiconductor laser emission under delayed feedback. $I = 120$ mA, $L_{\text{ext}} = 37.5$ cm. (a) a state of LFF emission (b) a state of transition from LFF to stable dark pulse emission.

emission evolved into a state of stable periodical dark pulse emission, as shown in Fig. 5(a). The optical spectrum of the laser under the dark pulse emission is shown in Fig. 3. Compared with the LFF emission, its spectrum is remarkably narrower. The output power of the laser under the dark pulse emission is depicted in Fig. 2. The threshold injection current is about 75 mA, which is higher than that of the CW laser emission. The center wavelength of the laser under dark pulse emission is 777 nm.

When the cavity length was 37.5 cm, the repetition rate of the dark pulses was about 400 MHz (Fig. 5(a)). While the cavity length was increased to 61 cm, the dark pulse repetition rate changed to 244 MHz (Fig. 6(a)). This result clearly shows that the dark pulse repetition rate was $c/2L$ and varied with the cavity length. In the states shown in Fig. 5(a) and 6(a), there was one dark pulse in the cavity. Depending on the details of the cavity alignment, multiple dark pulse emission was also observed. Fig. 6(b) shows a state of double pulse emission measured at the cavity length of 61 cm. In fact, multiple dark pulse emission was much easier to obtain than the single dark pulse emission. A tiny adjustment of M1 could switch a single dark pulse emission state to a double dark pulse or

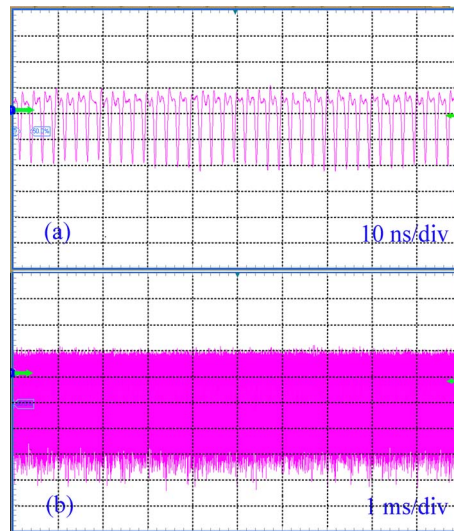


FIG. 5. Oscilloscope traces of the stable dark pulse emission of the laser. $I = 120$ mA, $L_{\text{ext}} = 37.5$ cm. (a) single dark pulse in cavity with a repetition rate of 400 MHz (b) The dark pulse train measured with a time scale of 1 ms/div.



FIG. 6. Oscilloscope traces of the dark pulse emission of the laser. $I = 120$ mA, $L_{\text{ext}} = 61$ cm. (a) single dark pulse in cavity with a repetition rate of 244 MHz. (b) Two dark pulses in cavity with a repetition rate of 488 MHz.

multiple dark pulse emission state. The dark pulse emission state was stable, as demonstrated in Fig. 5(b).

The photodetector used in our experiment has AC coupling. Hence the actual darkness of the pulses could not be detected. To check the darkness of the pulses, we further used a photodetector (NewFocus-1801-DC) with DC coupling and a bandwidth of 125 MHz to measure the ratio of the dark pulse to the CW level. Considering the limited bandwidth of the photodetector, we changed the length of the external cavity to 170 cm. The single dark pulse obtained in the external cavity length had a repetition rate of 88 MHz. It showed that the dark pulses had a darkness of about 35% compared to the CW level. Tested with a femto-second mode-locked laser source, we confirmed that our detection system (photodetector and oscilloscope) has a rise and fall time of ~ 400 ps, respectively. The measured FWHM width of the dark pulses was ~ 450 ps and they did not change with the experimental conditions, indicating that it is limited by our detection system. The actual dark pulse width should be narrower than 450 ps.

We note that stable dark pulse emission was also observed in a quantum dot (QD) semiconductor laser with a SESAM in cavity by Feng *et al.*¹⁴ However, in our laser cavity there is no saturable absorber or equivalent component. Carroll *et al.* also reported a kind of stable dark pulse emission from a QD laser induced by the optical feedback from a distant reflector.¹⁵ It was considered as a unique property of the QD semiconductor lasers. However, our experiment shows that with appropriate optical feedback, similar periodical dark pulses could also be obtained in a quantum-well semiconductor laser. We believe this could be attributed to two changes on the quantum-well lasers. First, thanks to the advance in semiconductor laser technology the stability of the laser diode has been significantly improved, therefore, the influence of noises is greatly reduced. Second, the anti-reflection coating of the laser diode facets can now reach 2% or even less, which reduced the multiple reflection effect in the cavity.

To understand why the laser could emit stable dark pulses, we note that recently Zhang *et al.* reported the experimental observation of stable dark pulse emission of an erbium-doped fiber laser.¹⁶ It was shown that dark pulse formation could be a general effect of a bistable nonlinear system subject to delayed feedback. The dark pulses reported by Zhang *et al.* are the temporal equivalent of the cavity solitons reported by Tanguy *et al.*¹⁷ Considering that near a Hopf-bifurcation point the dynamics of a semiconductor laser with delayed feedback is similar to that of the CGLE, as theoretically pointed out by Giacomelli and Politi,¹³ we speculate that the observed stable dark pulses could be a kind of the dark cavity solitons formed in the laser. The hypothesis is further supported by our experimental evidence that the multiple dark pulse formation as the feedback strength is increased. Multiple soliton formation is a typical feature of the cavity solitons.

In conclusion, we have observed stable dark pulse emission in a quantum-well semiconductor laser with delayed optical feedback. The repetition rate of the dark pulses is found to be determined by the external cavity length, and depending on the feedback strength, multiple dark pulse formation was also observed. We believe that the stable dark pulse emission could be another operation mode of the laser under relatively strong optical feedback. We attributed the stable dark pulses as a kind of temporal dark cavity soliton formed in the laser.

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