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Communication

Experimental Investigation on the Mode Characteristics of an Excited-State Quantum Dot Laser under Concave Mirror Optical Feedback

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Abstract: In this paper, we experimentally investigated the mode configuration of an excited-state quantum dot laser (ESQDL) under concave mirror optical feedback, and the influences of the feedback strength on the mode characteristics were analyzed. The results showed that after introducing concave mirror optical feedback, some longitudinal modes of the excited-state (ES) existing in a free-running ESQDL could be suppressed. When the feedback strength increased to a certain extent, the ground-state (GS) emission occurred and co-existed with the ES emission. By further increasing the feedback strength, all the longitudinal modes of the ES emission were suppressed, and only the longitudinal modes of the GS emission could be observed. As a result, the emission-state switching from the ES to GS emission was realized. When the ESQDL was biased at a larger current, the feedback strength required to achieve emission-state switching was stronger.

Keywords: excited-state quantum dot laser (ESQDL); emission-state switching; concave mirror optical feedback; longitudinal mode

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1. Introduction

After introducing one or multiple external perturbations such as optical injection, optical feedback, and optoelectronic feedback, semiconductor lasers (SLs) can exhibit rich nonlinear dynamics [1–3], which can be applied in secure communication [4], random number generation [5], optical memory [6], all-optical logic gates [7], and so on.

Quantum dot lasers (QDLs) are self-assembled nanostructured SLs, in which nanoscale quantum dots are introduced into the active layer of the SLs. Due to the strong three-dimensional quantum confinement of carriers in the active region, QDLs possess a discrete energy level structure [8–10] and can lase in the ground-state (GS) and the excited-state (ES) emission individually or simultaneously [11]. Compared with conventional quantum well lasers (QWLs), QDLs have some unique advantages such as low threshold current density [12], low chirp [13], high-temperature stability [14,15], large modulation bandwidth [16], and insensitivity to optical feedback [17,18]; therefore, QDLs are excellent candidate light sources for optical communications [19], optical interconnects [20], silicon photonic-integrated circuits [21], and photonic microwave generation [22,23], etc. Related studies demonstrated that, due to the discrete energy levels of quantum dots and the limited in-band relaxation time, QDLs can be divided into three types: namely, two-state quantum dot lasers (TSQDLs), ground-state quantum dot lasers (GSQDLs), and excited-state quantum dot lasers (ESQDLs), respectively, where the different types of QDLs can exhibit different performances. For TSQDLs, there are two threshold currents. When the bias current arrives at the first threshold, TSQDLs operate at the GS emission. However, with the further increase in the bias current, the carrier number of the ES increases rapidly. Once the bias current reaches the second threshold, both the GS and ES emission can simultaneously oscillate in the TSQDLs [24,25]. Through adopting some techniques, only the GS emission or ES emission exists in the QDLs, and corresponding QDLs are named as GSQDLs or ESQDLs. Due to relatively low energy levels and strong damping of the relaxation oscillations, GSQDLs possess a low threshold current and low sensitivity to optical feedback [26–28]. Compared with GSQDLs, ESQDLs have a faster carrier capture rate [29,30] and possess a larger modulation bandwidth. For ESQDLs under external perturbation, richer nonlinear dynamics could be observed [31,32].

In recent years, the emission-state switching and hysteresis of QDLs under external perturbations have received considerable attention. In 2013, Virte et al. theoretically investigated the effect of optical feedback on the ES and GS emission in TSQDLs. The results showed that, depending on the feedback intensity and the injection current, the introduction of optical feedback can choose a lasing state or cause bistable switching between different emission states [12]. In 2014, Virte et al. experimentally studied the switching between the GS and ES emission in a TSQDL subject to optical feedback, and the results showed that recurrent but incomplete switching between the two emission states of the TSQDL could be observed by changing the external cavity length in a sub-micrometer scale [33]. Under such a small scale variation of feedback length, the influence of optical feedback mainly originated from the variation of the feedback phase. In 2014, Tykalewicz et al. experimentally studied the switching mechanism between the different emission states in a TSQDL subject to optical injection, where the relative state suppression above 40 dB and the switching time of several hundred picoseconds could be achieved [34]. In 2016, Virte et al. experimentally and theoretically investigated the multi-mode dynamics of a TSQDL subject to time-delayed optical feedback. The results demonstrated that the energy exchange between the longitudinal modes of the ES emission could be triggered by varying the feedback phase, and meanwhile the mode competition between the longitudinal modes appears independently within the GS and ES emission [35]. In 2016, Tykalewicz et al. experimentally studied the influence of optical injection at frequencies close to the GS when a free-running TSQDL operates at the ES emission. The results showed that there exist the injection-induced bistability between the GS-dominated emission and the ES-dominated emission [36]. In 2017, Kelleher et al. experimentally studied the burst oscillation of an optical-injected TSQDL, and the results showed that the laser periodically switches between two distinct operating states with distinct optical frequencies [37]. In 2017, Meinecke et al. theoretically investigated the dynamical stability of a TSQDL under external optical injection, and the results showed that the dynamical instabilities in the TSQDL could be strongly suppressed [25]. In 2019, Dillane et al. experimentally and theoretically studied the phase locking of a TSQDL with optical injection, and the results showed that the GS emission could be activated and the phase locked to the master laser via optical injection while the ES emission was completely suppressed [38]. Based on above reports, we have noticed that most of related investigations focus on the TSQDLs and relevant researches on the ESQDLs are relatively lacking.

In this work, we experimentally studied the mode characteristics of an ESQDL under external optical feedback, and the effects of the feedback strength and the bias current are analyzed. Taking a concave mirror as the reflector, we constructed an experimental system for the ESQDL under concave mirror optical feedback, and the evolution of longitudinal mode in the ES and GS emission state with the feedback strength was investigated for the laser biased at different currents. The results demonstrated that, for a given bias current, the optical spectrum structure could be adjusted by changing the feedback strength. Moreover, if the feedback strength was strong enough, the ES longitudinal mode could be completely suppressed, and then the state switching occurred.

2. Experimental Setup

The schematic diagram of the experimental setup for an ESQDL under concave mirror optical feedback is shown in Figure 1, in which the red and yellow lines represent the spatial and fiber optical path, respectively. The ESQDL used in this experiment is InAs/GaAs QD grown on a Si-doped GaAs (100) substrate by molecular beam epitaxy, and the laser is a p-doped QD Fabry−Perot (F-P) cavity structure with a length of 350.00 µm [11]. The bias current of the ESQDL is adjusted by a current source (ILX-Lightware LDX-3620, Newport Corporation, Irvine, CA, USA), and the operation temperature of the laser is controlled by a temperature controller (ILX-Lightware LDT-5412, Newport Corporation). During the experiment, the value of the thermistor built in the laser is stabilized at 15,227.87 Ω, and the corresponding temperature is 15.5 °C. The light emitted from the ESQDL is divided into two parts by a 40/60 beam splitter (BS) after passing through an aspheric lens (AL) with a focal length of 2.50 mm. The 60% emitted light is reflected by a concave mirror (CM, GMH13-025-200-AG, Anjun Technology Co., Ltd., Taoyuan, Taiwan) with a focal length of 200 mm, after passing through a neutral density filter (NDF), and then fed back into the laser. The NDF is utilized to adjust the feedback strength characterized by $\kappa = P_{pm}/P_{tot}$ (P_{tot} is the total output power of the free-running ESQDL and P_{pm} is the feedback optical power detected at Point B in Figure 1). The power is monitored by a power meter (PM, Thorlabs PM100D, Thorlabs, Newton, NJ, USA). The 40% emission light of the ESQDL is sent to an optical spectrum analyzer (OSA, Ando AQ6317C, Ando Electric Co., Ltd., Kawasaki, Japan) with a resolution of 0.01 nm for monitoring the spectrum distribution after passing through an output coupler (OC).

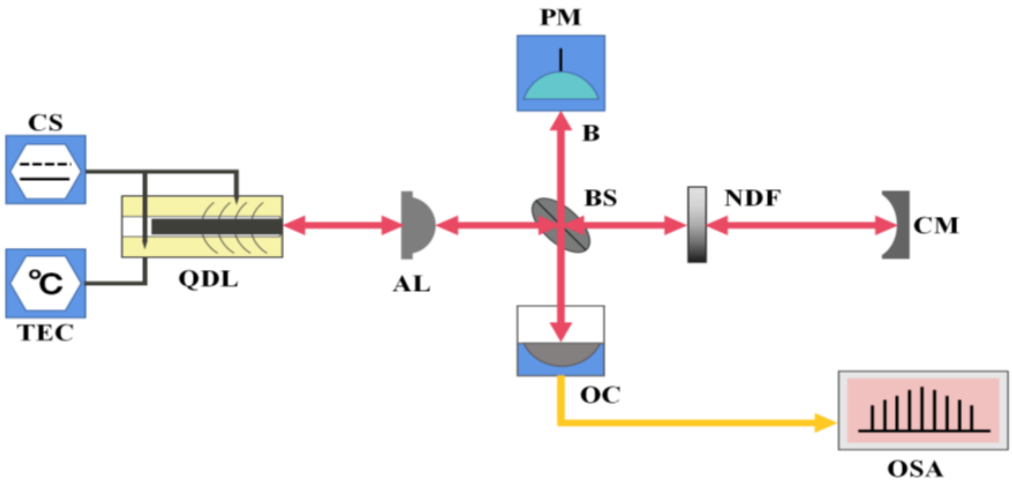

Figure 1. Experimental setup for an ESQDL under concave mirror optical feedback. ESQDL: quantum dot laser; CS: current source; TEC: temperature controller; AL: aspheric lens; BS: beam splitting; PM: power meter; NDF: neutral density filter; CM: concave mirror; OC: output coupler; OSA: optical spectrum analyzer.

3. Results and Discussion

Figure 2 shows the power-current ($P - I$) curve of the free-running ESQDL and corresponding optical spectra for the ESQDL biased at 66.00 mA, 80.00 mA, and 90.00 mA, respectively. From Figure 2a, it can be seen that the threshold current I_{th} of the ESQDL is about 63.00 mA. As shown in Figure 2(b1–b3), with the increase in the bias current, the number of longitudinal modes increases, and meanwhile the central wavelength of the ESQDL is red-shifted. Only the ES emission could be observed due to the property of ESQDLs.

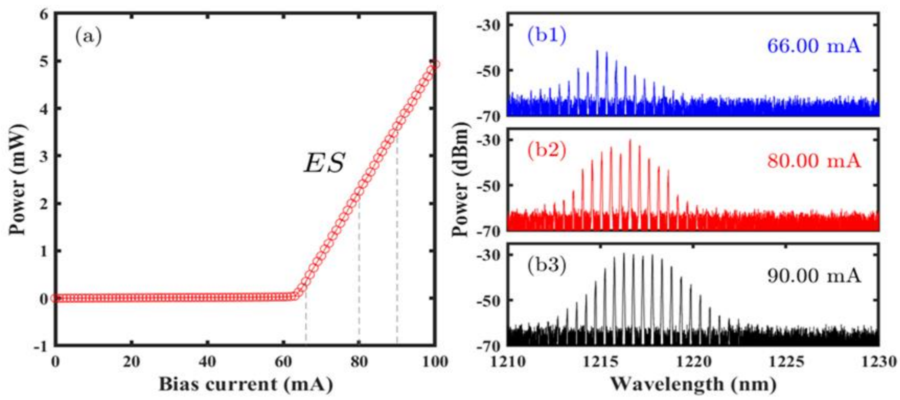

Figure 2. (**a**) Power-current ($P - I$) curve of free-running ESQDL and optical spectra for the ESQDL biased at (**b1**) 66.00 mA, (**b2**) 80.00 mA and (**b3**) 90.00 mA, respectively.

Next, we investigated the mode characteristics of the ESQDL subject to concave mirror optical feedback and revealed the influence of the feedback strength on the evolution of longitudinal mode. Figure 3 displays the optical spectra of the ESQDL under concave mirror optical feedback with different feedback strength. To better judge whether a mode is suppressed or not, we drew a blue dotted line parallel to the X-axis at 30 dB below the maximum value in each optical spectrum as a criterion. Under this condition, the modes below the blue dotted line were determined to be suppressed. Here, the bias current was set at 70.40 mA. As shown in Figure 3a, without optical feedback ($\kappa = 0.00$), the emission state of the laser belongs to the ES emission including multiple longitudinal modes with a mode interval of $\Delta\lambda_E = 0.51$ nm. When the feedback was introduced and the feedback ratio was $\kappa = 0.15$ (Figure 3b), some longitudinal modes were suppressed while some of the retained longitudinal modes were enhanced, obviously due to the mode competition. Under this condition, apart from the original mode interval, an extra mode interval $2\Delta\lambda_E$ could be observed. When the feedback strength increased to $\kappa = 0.19$ (Figure 3c), more longitudinal modes in the ES emission were suppressed, and only three longitudinal modes with a mode interval of $3\Delta\lambda_E$ could be observed. At the same time, two longitudinal modes in the GS emission emerged in the optical spectrum, and the mode interval was $7\Delta\lambda_G$, where $\Delta\lambda_G = 0.56$ nm. When the feedback strength increased to $\kappa = 0.23$ (Figure 3d), there were only two longitudinal modes with a mode interval of $3\Delta\lambda_E$ maintained in ES emission, and meanwhile a new longitudinal mode in the GS emission was excited and located between the two longitudinal modes of the GS emission compared with the case of $\kappa = 0.19$. As a result, two possible mode intervals of $3\Delta\lambda_G$ and $4\Delta\lambda_G$ were observed in the GS emission. When the feedback strength increased to $\kappa = 0.26$ (Figure 3e), only one longitudinal mode with a wavelength λ_1 of about 1218.48 nm remained in the ES emission. For the GS emission, it could be seen that the intensity of the longitudinal mode located between two longitudinal modes increased, and two possible longitudinal mode intervals of $4\Delta\lambda_G$ and $3\Delta\lambda_G$ could still be observed in the GS emission. Further increasing the feedback strength to $\kappa = 0.28$ (Figure 3f), the ES emission was suppressed completely while the longitudinal modes of the GS emission were enhanced. Several new longitudinal modes appeared, and the longitudinal mode intervals may be $\Delta\lambda_G$, $2\Delta\lambda_G$ and $3\Delta\lambda_G$. As a result, through continuously increasing the feedback strength, the emission-state switching could be achieved. In Ref. [12], via the energy level structure, the underlying physics mechanism for the emission-state switching resulted by varying the optical feedback strength, which can also be adopted to analyze and explain the results presented in Figure 3. As pointed out in Ref. [12], the optical feedback favors the GS emission; therefore, an increase in the feedback strength will generally lead to an increase in the gain of the GS emission. When the feedback strength is strong enough, the gain of the GS emission is much higher than that of the ES emission, and then the GS emission becomes the dominant mode while the ES emission is suppressed. However, in contrast to the QDL operating at a single mode adopted in [12], the laser utilized in this experiment operated at multi-longitudinal-mode originating from the F-P cavity structure. As a result, apart from the competition between the ES and GS emission, there also exists the competition among multiple longitudinal modes due to the sharing of carriers. Therefore, with the increase in the feedback strength, the evolution of the optical spectrum is much more complicated for the multi-longitudinal-mode QDL.

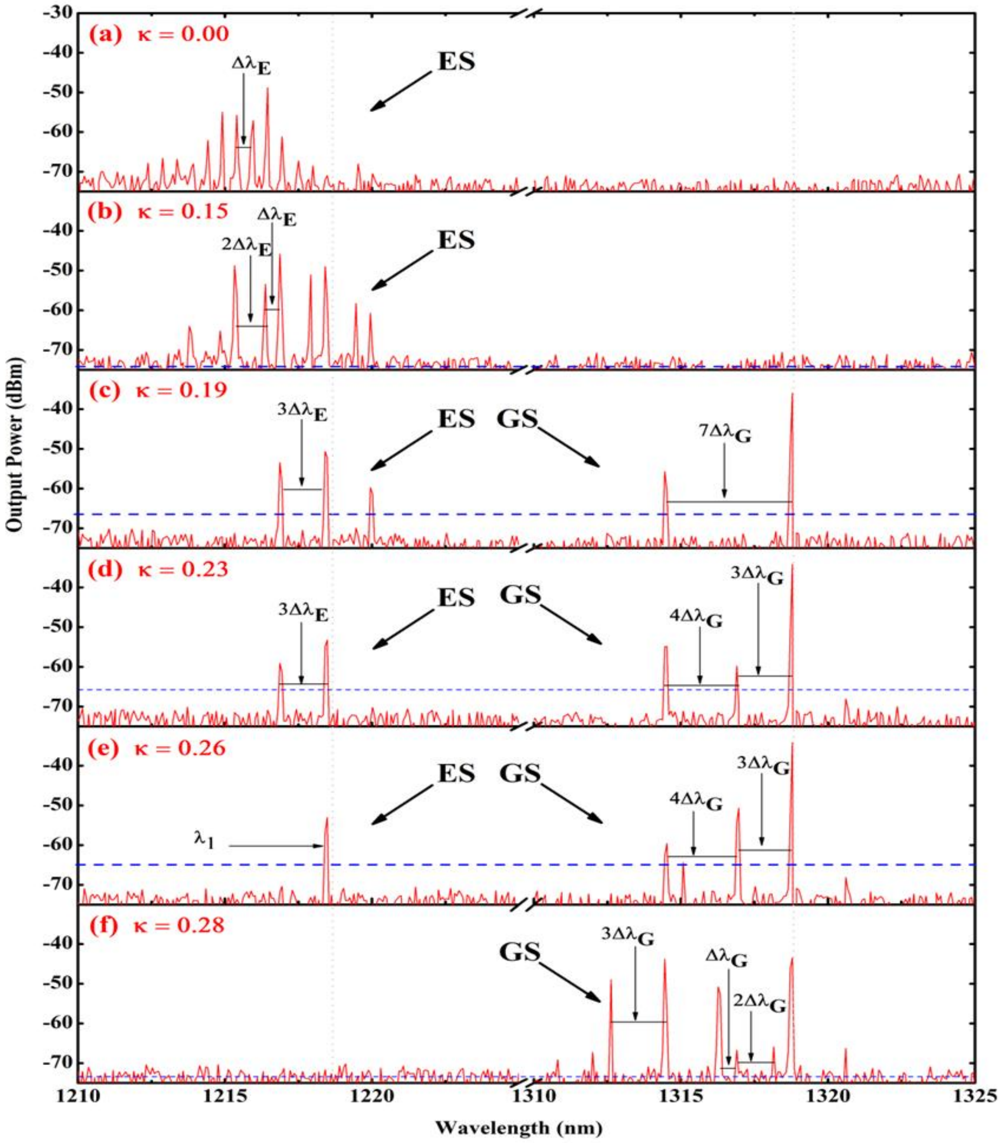

Figure 3. Optical spectra of ESQDL biased at 70.40 mA under concave mirror optical feedback with different feedback strength.

For the ESQDL biased at other currents, similar evolutions can also be observed. Figure 4 presents the corresponding results when the bias current is set at 80.00 mA. In order to better judge whether a mode is suppressed or not, we drew a blue dotted line parallel to *X*-axis at 40 dB below the maximum value in each optical spectrum as a criterion. As shown in Figure 4a, without optical feedback ($\kappa = 0.00$), multi-longitudinal modes with a mode interval of about $\Delta\lambda_E = 0.51$ nm appeared only in the ES emission, which is similar to that for the biased current being set at 70.40 mA. After introducing the feedback of $\kappa = 0.21$ (Figure 4b), some longitudinal modes of the ES emission were suppressed due to the mode competition and inter-mode energy exchange, and some retained modes were improved obviously. Since two adjacent longitudinal modes were simultaneously suppressed, the interval of the longitudinal mode becomes $3\Delta\lambda_E$. At the same time, multiple longitudinal modes originating from the GS emission could be observed, and the mode intervals formed between the two longitudinal modes may be $\Delta\lambda_G$, $2\Delta\lambda_G$ and $3\Delta\lambda_G$, where $\Delta\lambda_G = 0.61$ nm. When the feedback strength increased to $\kappa = 0.25$ (Figure 4c), some longitudinal modes in the ES emission were further suppressed, and only three longitudinal modes with a mode interval of $3\Delta\lambda_E$ could be observed. At the same time, when some longitudinal modes in the GS emission increased, a new longitudinal mode located at $\lambda_2 = 1315.30$ nm in the GS emission was excited, and the possible mode intervals in the GS emission were $\Delta\lambda_G$, $2\Delta\lambda_G$ and $3\Delta\lambda_G$. When the feedback strength increased to $\kappa = 0.28$ (Figure 4d), only one longitudinal mode located at the wavelength λ_1 of about 1218.59 nm remained in the ES emission, and two possible longitudinal mode intervals of $\Delta\lambda_G$ and $2\Delta\lambda_G$ were observed in the GS emission. Further increasing the feedback strength to $\kappa = 0.31$ (Figure 4e), the ES emission was suppressed completely while the GS emission was enhanced.

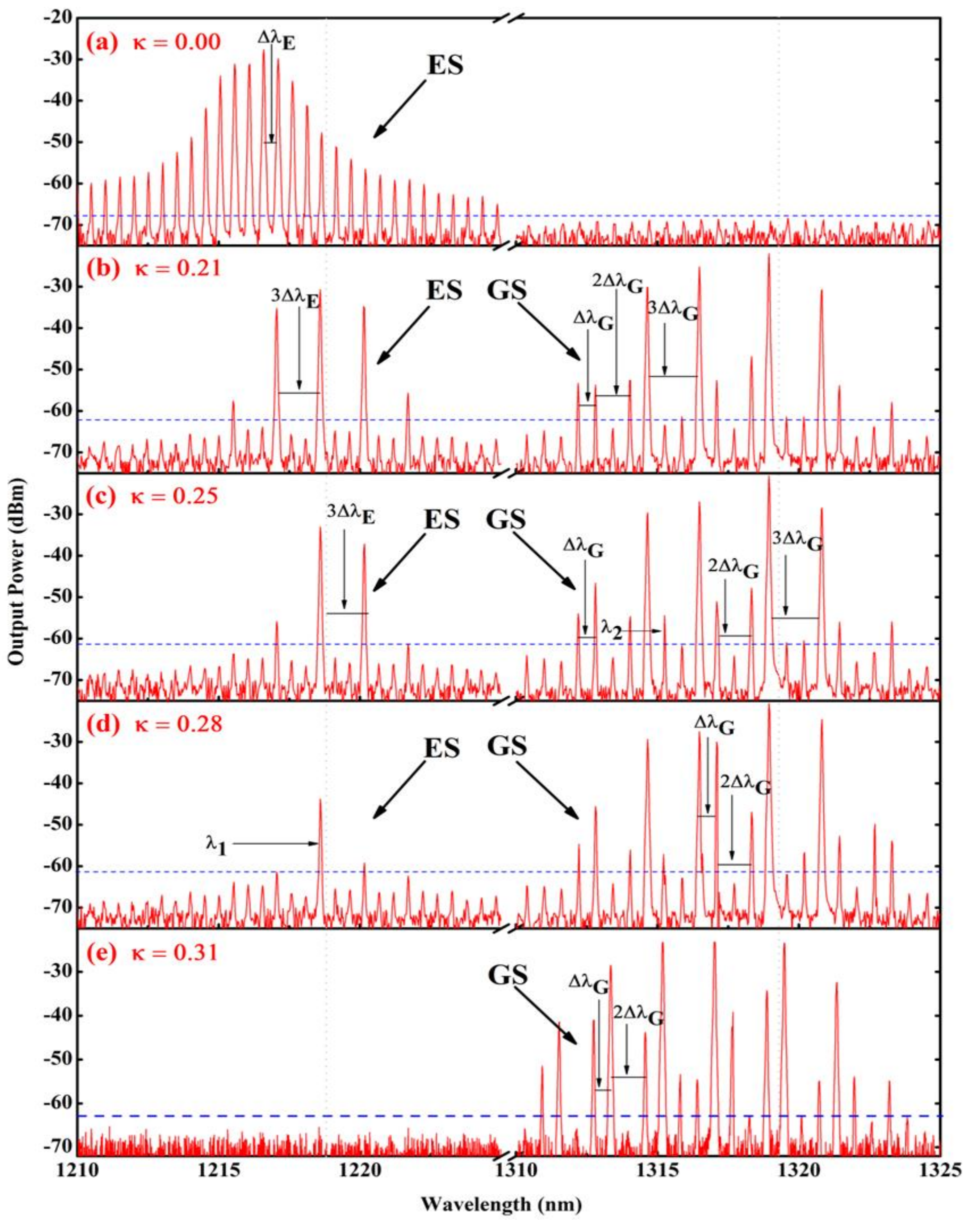

Figure 4. Optical spectra of the ESQDL under the biased current of 80.00 mA, where the longitudinal mode switching from the ES emission to the GS emission could be observed by varying the magnitude of the feedback ratio (**a**–**e**).

The above experimental results demonstrated that the GS emission could be activated for the ESQDL under concave mirror optical feedback with suitable feedback strength. When the feedback strength is large enough, the ES longitudinal mode could be completely suppressed, and then the emission-state switching occurs. Due to the large wavelength difference (about 100 nm) between the two emission states, some application prospects in the terahertz field could be anticipated. Additionally, we also experimentally investigated the case of the optical feedback being provided by a plane mirror, and the results were roughly similar. However, compared with the use of a plane mirror, adopting a concave mirror is helpful for obtaining more abundant spectrum structures while varying the feedback strength. The difference between the two feedback schemes may be due to different diffraction effects and optical path alterations resulting from the two different mirrors.

4. Conclusions

In summary, the evolution of the longitudinal mode construction in an ESQDL under concave mirror optical feedback was investigated experimentally. The results showed that, after introducing concave mirror optical feedback, the longitudinal mode construction of the ESQDL biased at 70.4 mA ($1.12I_{th}$) could be varied by adjusting the feedback strength, and the emission state switching from the ES emission to the GS emission could be realized. With the increase in the feedback ratio, some longitudinal modes in the ES emission were suppressed, resulting in different mode intervals. When the feedback strength was strong enough, the longitudinal modes in the GS emission could be activated. Further increasing the feedback strength, the number of the longitudinal modes in the GS emission increased and several mode intervals appeared. Once the feedback strength increased to a certain value, the ES emission was completely suppressed, and only the GS emission could be observed. As a result, the emission-state switching from the ES emission to the GS emission was realized. For the ESQDL biased at 80.00 mA ($1.27I_{th}$), the evolution process of the mode construction was similar. However, a larger feedback ratio was required for realizing the emission-state switching. The underlying physical mechanism may be qualitatively attributed to the combined effect of the concave mirror optical feedback and the mode competition. This research shows that the ESQDL has potential applications in the fields such as multiple wavelength transmission, optical switching, optical storage, and optical logic gate.

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