Modeling and analysis of distributed feedback quantum dot passively mode-locked lasers

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Received 15 March 2016; revised 18 May 2016; accepted 19 May 2016; posted 20 May 2016 (Doc. ID 261060); published 23 June 2016

In this paper, we investigate numerically two proposed monolithic distributed feedback quantum dot passively mode-locked lasers (DFB-QDMLLs) with and without gratings in the saturable absorber (SA) section in order to enhance two important performances of QDMLLs for ultrahigh-bit-rate and single-mode applications. We find out that depending on the length of the grating, optical pulses with durations of about 3–8 ps at approximately 2nd and 4th harmonics of cavity round-trip frequencies can be generated by the proposed structures. We also compare the temporal and spectral behaviors of these structures under specified bias conditions and SA lengths. It is shown that DFB-QDMLLs have the ability to generate optical pulses with more peak power than grating-embedded saturable absorber (GESA-DFB-QDMLL) structures which generate shorter pulses with narrower spectral bandwidths. We also show that DFB-QDMLLs operate in a larger range of absorber voltages while the other structure is very sensitive to absorber voltage and operates well for middle ranges of this parameter. © 2016 Optical Society of America

OCIS codes: (140.3490) Lasers, distributed-feedback; (140.4050) Mode-locked lasers; (250.0250) Optoelectronics.

http://dx.doi.org/10.1364/AO.55.005102

1. INTRODUCTION

Optical short pulses with multigigahertz repetition rates generated by monolithic semiconductor mode-locked lasers (MLLs) attract considerable attention in optoelectronic applications, such as ultrahigh-bit-rate optical communications, ultrafast data processing, electro-optic sampling, soliton transition systems, and optical A–D conversion for examining biological or chemical processes [1–8]. Semiconductor lasers based on self-assembled quantum dots (QDs) are particularly interesting for the mode-locked (ML) regime, including the features of low threshold current densities, insensitivity to temperature, broad optical gain spectra due to the inhomogeneous broadening, ultrafast carrier dynamics, and low linewidth enhancement factors [8–10]. So far, there have been many advances in improving the time-domain performance of short optical pulses generated by semiconductor lasers such as peak power, pulse width [11,12], temporal stability, and time jitter reduction [13–15]. On the other hand, for single-mode applications, such as wavelength-division-multiplexed optical communications, a narrow spectrum is needed [7]. In order to achieve this goal, manipulation of multisection mode-locked distributed Bragg reflector (DBR) semiconductor lasers and mode-locked distributed feedback (DFB) lasers has been studied both in experiments and simulations. According to the literature, by using these structures, optical short pulses not only with narrower spectra but also with higher repetition rates can be generated [13,16–20].

Numerical analysis of MLL is discussed in many papers [13,21,22]. Among them there are two models which are widely used by researchers. Models based on finite difference traveling waves (FDTWs) and delay differential equations (DDEs) demonstrate powerful methods to study and analyze ML regimes [23–26]. With these two methods, one can consider spatial distributions of carriers and electric field amplitudes in order to study MLL. The DDE model assumes unidirectional operation like in a ring laser [21,27], so it reduces the computational cost in comparison to the FDTW model which is based on the direct solution via the finite difference method for solving counterpropagating optical fields circulating in the laser cavity. However, the FDTW approach is more appropriate because of the high accuracy and the possibility of considering real effects like spontaneous emission noise [28,29].

In this paper, we unveil how to exploit the monolithic DFB configuration in quantum dot mode-locked lasers (QDMLLs). Our aim is to design MLLs capable of generating optical short pulses with higher repetition rates and improved optical spectra in terms of having narrow spectral widths and larger free...
spectral ranges (FSRs). In this regard, we use the FDTW model to study a monolithic two-section DFB-QD-MLL with and without gratings in saturable absorber (SA). In order to do this, we consider two sets of rate equations for gain and absorber sections with appropriate terms of the electric field circulating in the laser cavity. The structure of the paper is as follows. We present the proposed structures in Section 2, and then the theoretical model is discussed in Section 3. In Section 4, we discuss the results of the simulations, and our conclusion is given in Section 5.

2. STRUCTURE

The proposed structures of the two-section DFB-QD-MLLs are illustrated in Fig. 1, which consist of a reverse-biased SA and a forward-biased gain section. We consider a two-section DFB-QD-MLL in which the absorber section has no grating [Fig. 1(a)] and the other similar structure with a grating-embedded saturable absorber (GESA) section [Fig. 1(b)]. The active region of both structures is composed of fifteen stacks of self-assembled QD InAs layers, and the details of the epitaxial layers can be found in [28].

3. THEORETICAL MODEL

In this section, the one-dimensional first-order wave equations governing the optical field evolution inside the laser cavity as well as the carrier rate equations are presented.

A. Field Equations

With some proper approximations, the propagation of the electromagnetic field inside the laser cavity can be described by a slowly varying envelop (SWE) of a counterpropagating electric field with complex amplitudes, \( E^+(z, t) \) and \( E^-(z, t) \), which satisfy the traveling wave (TW) equations [6,29]

\[
\left( \frac{1}{v_g} \frac{\partial}{\partial t} + \frac{\partial}{\partial z} \right) E^+ = -i\beta E^+ - i\kappa_{E^+} E^+ + F_{sp}^+ \tag{1a}
\]

\[
\left( \frac{1}{v_g} \frac{\partial}{\partial t} - \frac{\partial}{\partial z} \right) E^- = -i\beta E^- - i\kappa_{E^-} E^- + F_{sp}^- \tag{1b}
\]

where \( t \) indicates time, and \( Z [0, L] \) is the longitudinal direction along the laser cavity. To solve these equations, we use reflection boundary conditions at \( Z = 0 \) and \( Z = L \) for two laser facets as follow [28]:

\[
E^+(0, t) = r_0 E^+(0, t), \quad E^-(L, t) = r_L E^+(L, t),
\]

where \( v_g = c_0 / n_g \) is the group velocity (\( c_0 \) is the speed of light in vacuum, and \( n_g \) is the group refractive index), \( r_0 \) and \( r_L \) describe reflection coefficient of the laser facets, \( \kappa_{E^+} \) and \( \kappa_{E^-} \) (\( \kappa_{E^+} = \kappa_{E^-} = \kappa_i \), \( i \in \{a, b\} \)) are the coupling coefficients between forward and backward waves due to the grating, and \( F_{sp}^+ \) and \( F_{sp}^- \) denote spontaneous emission noise [29,30]. By considering only ground-state (GS) lasing, the propagation factor entering Eq. (1) can be described as [28]

\[
\beta = \beta(n_{GS}(z, t), z) = \delta - i\frac{\alpha}{2} + \frac{(i - \alpha_H)}{2} g' (2n_{GS} - 1)
\]

where \( \alpha \), \( \alpha_H \), \( g' \), and \( \delta \) denote the internal absorption, the linewidth enhancement factor, the effective differential gain (including the transverse confinement factor), and the static detuning factor, respectively. Moreover, \( n_{GS} \) is the ground-state carrier probability that will be described later. In this study, we neglect the inhomogeneous broadening due to the nonuniform distribution of quantum dots and we use a single-Lorentzian gain spectrum profile in simulations [28,31–33].

B. Carrier Rate Equations

In this section, we describe two sets of rate equations in order to properly take into account the carrier dynamics between the carrier reservoir (CR), excited state (ES), and ground state (GS) of the quantum dots in a reverse-biased SA and a forward-biased gain section. In this regard, the carrier dynamics in the gain section [as in Fig. 2(a)] are defined by following coupled rate equations [28,34]:

\[
\frac{d}{dt} n_{CR}(z, t) = \frac{I(z)}{e\tau_{CR}} - \frac{n_{CR}}{\tau_{CR}} + \frac{n_{CR}(1 - n_{ES})}{\tau_{CR} \rightarrow ES} + \frac{n_{ES}}{\tau_{ES} \rightarrow CR} \tag{4a}
\]

Fig. 1. Proposed structures of DFB-QD-MLLs. (a) DFB-QD-MLL without a grating in the absorber section. (b) DFB-QD-MLL with a grating-embedded saturable absorber section (GESA-DFB-QD-MLL).

Fig. 2. Energy band structure of QD. (a) Gain section. (b) Saturable absorber section.
\[ \frac{d}{dt} n_{ES}(z, t) = -\frac{n_{ES}}{\tau_{ES}} - \frac{n_{ES}(1 - n_{GS})}{\tau_{ES-GS}} + \frac{n_{GS}(1 - n_{ES})}{2\tau_{GS-ES}} \]
\[ + \frac{n_{CR}(1 - n_{ES})}{4\tau_{CR-ES}} - \frac{n_{ES}}{\tau_{ES-CR}}, \quad (4b) \]
\[ \frac{d}{dt} n_{GS}(z, t) = -\frac{n_{GS}}{\tau_{GS}} + 2\frac{n_{ES}(1 - n_{GS})}{\tau_{ES-GS}} - \frac{n_{GS}(1 - n_{ES})}{\tau_{ES-GS}} \]
\[ - R_s(n_{GS} E), \quad (4c) \]

where \( R_s \) is a term of stimulated recombination given by [28]
\[ R_s(n_{GS} E) = \frac{1}{\theta_e} \sum_{n_{GS} = \pm 1} E^{n_{GS}}(g' (2n_{GS} - 1)) E^e \quad (5) \]

for the reverse-biased absorber section [see Fig. 2(b)]. We use a simplified carrier rate equation model according to [28,35]
\[ \frac{d}{dt} n_{GS}(z, t) = -\frac{n_{GS}}{\tau_{GS}} + 2\frac{n_{ES}(1 - n_{GS})}{\tau_{ES-GS}} - \frac{n_{GS}(1 - n_{ES})}{\tau_{ES-GS}} \]
\[ - R_s(n_{GS} E), \quad (6a) \]
\[ \frac{d}{dt} n_{ES}(z, t) = -\frac{n_{ES}}{\tau_{ES-CR}} - \frac{n_{ES}(1 - n_{GS})}{\tau_{ES-GS}} + \frac{n_{GS}(1 - n_{ES})}{2\tau_{GS-ES}}, \quad (6b) \]

where \( e \) is the electron charge, \( \theta_e \) and \( \theta_i \) are scaling factors, and \( I(z) \) is the injection current which is equal to zero at the absorber section. In rate Eqs. (45)–(6), \( \tau_{GS}^{-1} \) and \( \tau_{ES-m}^{-1} \), \( n, m \in \{GS, ES, CR\} \), represent spontaneous relaxation and transition times between GS, ES, and CR, respectively, and \( |E|^2 \) is equal to \( |E^+|^2 + |E^-|^2 \) which is the optical normalized intensity that denotes optical output power. Other parameters used in the simulation are given in Table 1 [28].

### Table 1. Parameters Used in the Simulation [28]

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Quantity</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>( \lambda_0 )</td>
<td>Central wavelength</td>
<td>1.3 μm</td>
</tr>
<tr>
<td>( n_g )</td>
<td>Group refractive index</td>
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</tr>
<tr>
<td>( L )</td>
<td>Total length</td>
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</tr>
<tr>
<td>( \delta )</td>
<td>Static detuning</td>
<td>0 cm(^{-1})</td>
</tr>
<tr>
<td>( \alpha )</td>
<td>Internal absorption</td>
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</tr>
<tr>
<td>( \alpha_h )</td>
<td>Henry factor</td>
<td>2</td>
</tr>
<tr>
<td>( g' )</td>
<td>Effective differential gain/absorption</td>
<td>40/200 cm(^{-1})</td>
</tr>
<tr>
<td>( \tau_{GS} )</td>
<td>GS relaxation rate</td>
<td>1 ns</td>
</tr>
<tr>
<td>( \tau_{ES} )</td>
<td>ES relaxation rate</td>
<td>1 ns</td>
</tr>
<tr>
<td>( \tau_{CR} )</td>
<td>CR relaxation rate</td>
<td>1 ns</td>
</tr>
<tr>
<td>( \tau_{ES-GS} )</td>
<td>ES to GS transition time</td>
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</tr>
<tr>
<td>( \tau_{GS-ES} )</td>
<td>GS to ES transition time</td>
<td>5 ps</td>
</tr>
<tr>
<td>( \tau_{CR-ES} )</td>
<td>CR to ES transition time (SA)</td>
<td>0</td>
</tr>
<tr>
<td>( \tau_{CR-GS} )</td>
<td>CR to ES transition time (G)</td>
<td>5 ps</td>
</tr>
<tr>
<td>( \tau_{ES-CR} )</td>
<td>ES to CR transition rate (SA)</td>
<td>18(^{\circ}/\text{V}) ps</td>
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<td>( \tau_{ES-GS} )</td>
<td>ES to CR transition rate (G)</td>
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<tr>
<td>( \theta_i )</td>
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<tr>
<td>( \theta_e )</td>
<td>Field scaling factor</td>
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<td>( \Gamma )</td>
<td>Transversal confinement factor</td>
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<td>SA section facet reflectivity</td>
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<tr>
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</tr>
<tr>
<td>( \tau_0 )</td>
<td>Gain section facet reflectivity</td>
<td>0</td>
</tr>
</tbody>
</table>

### 4. SIMULATIONS AND RESULTS

A rigorous way to analyze the monolithic photonic integrated circuits (PICs) is by using finite difference methods in order to solve the counterpropagating traveling waves with coupled rate equations. For this, first we consider an appropriate discretization of the time axis with a step unit of \( \Delta t \) and then take the step length \( \Delta x \) in the longitudinal direction (z-axis) to be related by \( \Delta t \cdot v_g = \Delta x \). The field and rate equations of quantum dots will then be solved in each time step for all of the longitudinal sections using FDTW and Runge–Kutta methods, respectively [36]. In the following, we will discuss the results of our simulations with the mentioned approach for the structures given in Fig. 1.

### A. Temporal Behaviors of the Proposed Structures

Figure 3 shows the output power of the DFB-QD-MLL as a function of time. The gain injection current is 120 mA, and the SA with a length of 100 μm is biased at various voltages. The coupling coefficient between forward and backward waves in the first structure (\( \kappa_1 \)) is equal to 15 cm\(^{-1}\). For very small and large values of the \( \kappa_1 \), factor in this structure, we have no pulse in the output and the laser usually operates in the continuous wave (CW) regime. Within the coupling coefficient ranges of \( 15 \text{ cm}^{-1} < \kappa_1 < 20 \text{ cm}^{-1} \) our simulations show a stable ML regime. As can be seen in this figure, the output of the laser is harmonically mode locked and we have stable pulses at a repetition rate of about 70 GHz with a duration of 6–8 ps, depending on the absorber voltage. According to this figure, the laser reaches the stable ML regime faster as the absorber voltage increases. However, the turn-on delay time of the laser is almost invariant with the variation of the absorber reverse voltage.

In order to see the behavior of the device in terms of negative voltage applied to the absorber, Fig. 4 shows the steady-state pulses for different absorber voltages. According to this figure, it is seen that the output of the laser is a CW when the absorber is grounded. By increasing the reverse-bias voltage from \( U = 0 \text{ V} \) to \( U = -7 \text{ V} \), which leads to an increase in the
Saturation absorption in SA, the full width of the pulse at its half-maximum (FWHM) decreases and the shape of the optical pulse becomes more asymmetric due to the manifestation of an additional extreme.

As can be observed in Fig. 5, the output powers of the GESA-DFB-QDMLL [Fig. 1(b)] for the injection current of 120 mA and different absorber voltages are plotted. The value of the coupling coefficient for this structure ($\kappa_b$) is 20 cm$^{-1}$, where in comparison to the first structure the range of the coupling coefficient having stable ML pulses is even less ($19 \text{ cm}^{-1} < \kappa_b < 21 \text{ cm}^{-1}$). This structure is very sensitive to laser parameters such as absorber voltage, gain current, and the coupling coefficient. In the absorber length of 100 $\mu$m the device shows a stable ML regime. In contrast to the DFB-QDMLL, this structure operates in smaller range of reverse voltage, as shown in Fig. 5. As we can see, there is no pulse in the output of the laser for large and small values of reverse voltages [see Figs. 5(a), 5(c), and 5(d)]. However, for middle ranges of the absorber voltages, we have stable harmonic mode locking.

In Fig. 6, we show stable harmonic ML pulses at a repetition rate of about 88 GHz with an estimated pulse width of 5 ps for $I = 120$ mA and $U = -3$ V. By analyzing the results of Figs. 5 and 6, we see that the effect of the variation of the absorber reverse voltage on the output of the laser is totally different from that in the DFB-QDMLL. One can explain this behavior of the GESA-DFB-QDMLL by the spectrum-filtering property of the grating and also the AR facets used in this structure.

So far, we have only observed approximately the second harmonic of ML pulses with two different structures presented in Fig. 1, and we have not observed the fundamental ML regime because of the length of the grating used in these structures. As discussed before, the DFB-QDMLL is well behaved against the variation of the parameter $\kappa_a$, and it operates in the ML regime for middle values of $\kappa_a$. However, the GESA-DFB-QDMLL behaves in a way that is only related to the spectral behavior of the grating structure and its selectivity of longitudinal modes. This structure shows harmonic mode locking other than in the middle range of $\kappa_b$.

To elaborate more on issues discussed so far, we plot the output optical power of the GESA-DFB-QDMLL for the various absorber section lengths in Fig. 7. This figure depicts the dependency relationship between the absorber length and device operation regime at $\kappa_bL = 6$, where the total fixed length of the laser is 1 mm. When the absorber length is too short, mode locking does not occur due to insufficient saturable absorption. By increasing the SA length, optical pulses with strong backgrounds are produced. With a further increase in absorption.

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**Fig. 4.** Output power of the DFB-QDMLL for ML pulsation parameters $I = 120$ mA and different values of saturable absorber voltage in the steady state.

**Fig. 5.** Output power of the DFB-QDMLL for ML pulsation parameters $I = 120$ mA and (a) $U = 0$ V, (b) $U = -2.5$ V, (c) $U = -5$ V, and (d) $U = -7$ V.

**Fig. 6.** Output power of the GESA-DFB-QDMLL for ML pulsation parameters $I = 120$ mA and $U = -3$ V.

**Fig. 7.** Peak power of the GESA-DFB-QDMLL for different absorber lengths in $\kappa = 60$ cm$^{-1}$. The ML pulsation parameters are $I = 120$ mA and $U = -5$ V.
absorber length \(120 \leq l_A \leq 180\), stable harmonic mode locking is observed at the output of the device. When \(l_A\) becomes longer than 180 \(\mu\)m, the output pulses again experience some background due to the increase of the absorber loss. Finally, for very larger \(A\) lengths the lasing is not achieved due to the strong loss of the \(A\) section and insufficient gain.

Figure 8 shows the output power of the GESA-DFB-QDMLL for ML pulsation parameters \(I = 120\) mA and different values of saturable absorber voltage with \(\kappa_A = 60\) cm\(^{-1}\).

![Fig. 8. Output power of the GESA-DFB-QDMLL for ML pulsation parameters \(I = 120\) mA and different values of saturable absorber voltage with \(\kappa_A = 60\) cm\(^{-1}\).](image)

In Figs. 9, the output optical power of the DFB-QDMLL is plotted against the gain injection current for \(U = -3\) V, and \(\kappa_A = 15\) cm\(^{-1}\). This figure also depicts the typical sequence of operation regimes with increasing injection current. As shown in this figure, the laser is off for low values of gain currents \((U \leq I_a \approx 16\) mA\), which is shown by zero intensity in the figure. By increasing the injection current \((I_a < I \leq 68\) mA\), the laser operates in a \(Q\)-switching regime with relatively high output power. After this region, we have an incomplete ML with almost low power for a large range of injection currents \((68\) mA \(< I \leq 86\) mA\). At higher injection currents \((86\) mA \(< I \leq 128\) mA\), a stable harmonic ML is observed at a repetition rate of 70 GHz. It is seen that with increasing current in this region, the pulse power increases in contrast to the results represented in [28]. The occurrence of the observed behavior can be explained by the selectivity property of the DFB structure which can reduce the effect of the other groups of locked modes. This means that with increasing gain current, the power is not consumed by the other groups of locked phase because they are suppressed by the spectral filtering of the DFB structure. Last, with more increase in the gain current, the output will be a CW, as shown in the last part of Fig. 9.

![Fig. 9. Typical sequence of the operation regime versus injection current in the DFB-QDMLL for \(U = -3\) V.](image)

The typical sequence of the operation regime with increasing injection current for a GESA structure is also depicted in Fig. 10. This laser behaves approximately similar to the former one, except for few differences. First, we see the reduction of threshold current down to about 10 mA that can be explained by increasing the \(\kappa_A L\) factor in the second proposed structure. Another difference between the two figures is observed in the second region where we have no \(Q\)-switching regime in the GESA structure and the output is a CW with low power. The behavior of the output power in other ranges of the injection current is almost the same.

**B. Spectral Behaviors of the Proposed Structures**

The data presented and discussed thus far reveal the temporal behavior of the mentioned devices. Figure 11 shows the optical spectrum of fundamental mode-locked pulses of a conventional QD-MLL with \(I = 120\) mA and \(U = -3\) V presented in [28]. It can be seen that the longitudinal modes separated by 40 GHz correspond to the laser repetition rate given in [28]. Figure 12 shows the optical spectrum of the 8 ps pulses shown in Fig. 3(b). As we can see, the free spectral range of the laser is about 70 GHz, which is the repetition rate of the DFB-QDMLL shown in Fig. 1(a) under the bias condition mentioned in Fig. 3(b).

In Figs. 13 and 14, the corresponding optical spectra of Figs. 6 and 8 are plotted, respectively. These two spectra show the spectral behavior of the GESA-DFB-QDMLL shown in Fig. 1(b) under the specified bias condition and laser parameters. As can observed in Fig. 13, the free spectral range of the laser modes is about 88 GHz which is almost the 2nd harmonic

![Fig. 10. Typical sequence of the operation regime versus injection current in the GESA-DFB-QDMLL for \(U = -3\) V.](image)
of the cavity round-trip frequency. Because of the length of the grating and also using AR facets in the GESA-DFB-QDMLL, the free spectral range of the longitudinal modes is increased in comparison to the first structure. It can also be seen from Fig. 14 that the 4th harmonic of the ML pulses is generated and the spectrum has good purity so that only longitudinal modes separated by 170 GHz are enhanced and the other modes are strongly suppressed.

As can be seen in Figs. 13 and 14, both spectra have the central frequency in their spectral response. However, in conventional uniform DFBs with AR facets, the central frequency is stopped due to the spatial-hole burning and thus two side modes will oscillate instead. In our case, the scenario is totally different; however, both facets are AR and the structure has uniform grating. One can explain the complex spectral behavior of the GESA-QD-MLL by Fig. 15 and Eq. (3). In Fig. 15, the ground-state carrier probability is plotted both in gain \( n_{GS}(G) \) and absorber \( n_{GS}(SA) \) sections [37]. It is obvious that the value of GS occupation probability \( n_{GS} \) in the absorber section is always less than a specific threshold value (\( n_{GS} = 0.5 \)) which determines the absorption or amplification performance.
of the MLL sections. Indeed, this behavior of the carrier density in the absorber is a prerequisite for a reverse-biased absorber to act as a SA. The opposite behavior happens in the gain section, which causes the GS occupation probability to be above the threshold value. This difference between the pattern of the carrier probability in the amplification and absorption sections affects the propagation factor by applying the mentioned mechanism in the last term of Eq. (3), which consequently injects different phases to the traveling waves circulating in both sections and removes grating uniformity.

5. CONCLUSION

We have investigated a DFB-QD-MLL with and without a grating in the absorber section. Our simulations reveal that the SA section in the two discussed structures plays an important role. In the first structure in this study (without a grating in the SA), there is no mandatory situation where the device operates in a single longitudinal mode. However, for the second structure, again we observe several longitudinal modes because in this structure the SA acts as a passive section for the grating and itself induces additional modes, thus removing grating uniformity. As a result, we cannot assume these structures like a conventional DFB construction that favors single-mode operation. It has also been shown that based on the grating length and laser parameters, we only have approximately 2nd and 4th harmonics of the cavity round-trip frequencies in our model and we have not seen the fundamental ML. Simulations show that the output pulses are very sensitive to device parameters such as gain injection current, SA reverse voltage, and the coupling coefficient. Furthermore, we have presented optical spectra of output pulses and discuss the differences between the proposed structures with conventional mode-locked and DFB lasers. We have studied the performances of the proposed structures in improving the spectral response and increasing the free spectral range of the optical spectrum from 40 (conventional QD-MLL) to 170 GHz.

REFERENCES


