Numerical Analysis of Gain Saturation, Noise Figure, and Carrier Distribution for Quantum-Dot Semiconductor-Optical Amplifiers

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Abstract—The gain saturation behaviors and noise figure are numerically analyzed for quantum-dot semiconductor optical amplifiers (QD-SOAs). The carrier and photon distributions in the longitudinal direction as well as the photon energy dependent facet reflectivity are accounted in the rate equations, which are solved with output amplified spontaneous emission spectrum as iterative variables. The longitudinal distributions of the occupation probabilities and spectral-hole burning are presented for electrons in the excited and ground states of quantum dots. The saturation output power 19.7 dBm and device gain 20.6 dB are obtained for a QD-SOA with the cavity length of 6 mm at the bias current of 500 mA. The influences of the electron intradot relaxation time and the QD capture time on the gain spectrum are simulated with the relaxation time of 1, 30, and 60 ps and capture time of 1, 5, and 10 ps. The noise figure as low as 3.5 dB is expected due to the strong polarization sensitive spontaneous emission. The characteristics of gain saturation and noise figure versus input signal power for QD-SOAs are similar to that of semiconductor linear optical amplifiers with gain clamping by vertical laser fields.

Index Terms—Gain, noise, quantum dots (QDs), semiconductor-optical amplifiers (SOAs).

I. INTRODUCTION

RECENTLY, quantum-dot semiconductor-optical amplifiers (QD-SOAs) have attracted great attention due to their promising features that could provide breakthrough improvement of SOAs performance in the future optical networks. Compared with bulk and quantum-well SOAs, a lot of unique properties have been demonstrated in GaAs-based and InP-based QD-SOAs. The linewidth enhancement factor less than one was obtained [1]–[4] due to the atom-like density of states giving rise to a symmetric gain spectrum, and symmetrical four-wave mixing properties were demonstrated experimentally because of the small linewidth enhancement factor [5], [6]. Ultrafast gain recovery times of subpicosecond to picosecond were measured [7], [8], and fast signal processing and pattern free amplification up to 40 Gb/s were realized [9]. With respect to their application as linear amplifiers, QD-SOAs can exhibit high saturation output power, low noise figure, and large gain bandwidth at the same time [10].

Rate equation method is a powerful tool for simulating the characteristics of QD-SOAs [11]–[15], where gain model and electron capture and relaxation lifetimes are crucial factors. The intradot relaxation lifetime from excited state (ES) to ground state (GS) of QDs is an important parameter in determining the steady and dynamical behaviors [16], [17], which is taken from subpicosecond to tens of picoseconds dependent on carrier occupation [13], [17]–[20]. In addition, charge neutrality assumption in each quantum dot [16], [21] and equilibrium distribution of holes over whole structure with a common quasi-Fermi level of the valence band [13] were assumed respectively for accounting the distribution of holes. Numerical results indicated that QD-SOAs can offer higher output power and lower noise figure than bulk and quantum well amplifiers, and a small modal gain requires a long cavity length to realize high signal gain [13]. Longitudinal carrier spatial distribution and carrier spectral-hole burning due to the finite relaxation lifetime are important factors affecting the device characteristics of the QD-SOAs.

In this article, gain saturation, noise figure, and electron spatial and spectral distributions are investigated for QD-SOAs by the numerical simulation of rate equations, especially in the case with high input signal power. A practical power reflectivity spectrum is considered, and the QDs are divided as groups with energy interval much smaller than homogeneous broadening. So electron spectral hole-burning and influence of a relative high reflectivity at ES resonant wavelength can be accounted in our model. The gain model for QDs is given in Section II, and the rate equations are introduced in Section III, which include the carrier distributions in wetting layer (WL), the ES and GS of QDs and traveling-wave equations for signal field and spontaneous emission intensity. The numerical results of carrier distribution, gain and saturation output power are presented in Section IV under different bias currents and input signals; amplified spontaneous emission spectrum and noise figure are discussed in Section V; and finally a summary is given in Section VI.

II. GAIN MODEL FOR QDS

QDs grown by the Stranski–Krastanow mode have slightly different properties induced by fluctuations in size, shape, strain, etc., which lead to the variation of resonant energy and the inhomogeneous broadening of the ensemble properties. Dividing the QD ensemble into $2M + 1$ groups of identical QDs with an
energy interval of $\Delta E$, we can express the linear optical gains of the $m$th group QDs at frequency $v$ as [21], [22]

$$g_{i,m}(z,t,v) = \frac{e^2 N_m}{\epsilon_0c_0m_0^2 V E_{i,m}} \frac{2e_i}{V E_{i,m}} |M_b|^2 |M_{en}|^2 \times [f_{i,m}(z,t) - f_{i,m}^N(z,t)] \times \text{Lorentz}(E_{i,m}, hv).$$

where $z$ is the longitudinal position in the QD-SOAs, $t$ is the time, $e$ is electron charge, $h$ is Planck’s constant, $c$ is speed of light in vacuum, $n_r$ is the refractive index, $\epsilon_0$ is permittivity of vacuum, $m_0$ is electron mass, $V$ is the active region volume, $\epsilon_{GS}$ and $\epsilon_{ES}$ are the degeneracy (not including spin) of the GS and ES, respectively, $M_b$ is the bulk matrix element, $M_{en}$ is the overlap integral between the envelope functions of an electron and a hole, and $f_{GS,m}$ and $f_{ES,m}$ are the electron occupation probabilities of GS and ES states in the $m$th group QDs, respectively. The charge neutrality in each quantum dot is assumed with valence band electron occupation probability $\gamma_m(v)$. The GS and ES resonant energies $E_{GS,m}$ and $E_{ES,m}$ of the $m$th group QDs can be expressed as

$$E_{i,m} = E_{i,0} - (M - m)\Delta E$$

where $i = \text{GS, ES}$, $m = 0, 1, 2, \ldots, 2M$, and $E_{i,0}$ is the resonant energy of the most probable size of QDs. The QD number in the $m$th group $N_m$ is related to the total number of QDs $N_{QD}$ as

$$N_m = N_{QD} \text{Gauss}(E_{GS,m}, E_{GS,0}) \Delta E$$

where $N_{QD} = n_l n_{QD} LW$ with QD layer number $n_l$, surface density $n_{QD}$, device length $L$, and stripe width $W$. The homogeneous broadening of the QDs is described by a Gaussian distribution as

$$\text{Gauss}(E', E) = \frac{1}{\sqrt{2\pi}\sigma} \exp \left[ -\frac{1}{2\sigma^2}(E' - E)^2 \right]$$

with the full-width at half-maximum (FWHM) of $2.35\sigma$. The dephase of polarization and Coulomb effects between electrons and holes are assumed to be a Lorentzian homogeneous broadening with the FWHM of $2\Gamma_{\text{in}}$

$$\text{Lorentz}(E, hv) = \frac{\eta \Gamma_{\text{in}}}{\pi (hv - E)^2 + (\eta \Gamma_{\text{in}})^2}.$$

Accounting the contribution of all groups of QDs, the linear optical gain $g$ at frequency $v$ is obtained by summing all the individual contribution of ES and GS carriers over all QDs

$$g(z,t,v) = \sum_{i=\text{ES, GS}} \sum_{m=0}^{2M} g_{i,m}(z,t,v).$$

### III. RATE EQUATIONS

#### A. Traveling-Wave Equations for Signal Field and Spontaneous Emission Intensity

Coupling a transverse-electric (TE)-mode continuous wave signal with optical frequency $\nu_s$ and power $P_s$ into the QD-SOA at the facet $z = 0$, we can have two complex traveling-waves $E_s^+$ and $E_s^-$ for the signal fields propagating in the positive and negative $z$ directions, which satisfy the following traveling-wave equations:

$$\frac{c}{n_r} \frac{\partial E_s^\pm(z,t,v_s)}{\partial t} = \pm \frac{\partial E_s^\pm(z,t,v_s)}{\partial z} \left\{ \mp j \beta \pm \frac{1}{2} \left[ \Gamma(g(z,t,v_s) - \alpha_{\text{in}}) \right] E_s^\mp(z,t,v_s) \right\}$$

where $j = \sqrt{-1}$, $\beta = 2\pi n_r v_s / c$ is the propagation constant of the signal, $\alpha_{\text{in}}$ is the loss coefficient, and $\Gamma$ is optical confinement factor. The superscript “$\pm$” denotes the signal propagating in the forward and backward directions. The boundary conditions are given by [23]

$$E_s^+(0,t,v_s) = \sqrt{1 - R_1} \sqrt{\frac{P_s}{hv_s}} + \sqrt{R_1} E_s^-(0,t,v_s),$$

$$E_s^-(L,t,v_s) = \sqrt{R_2} E_s^+(L,t,v_s)$$

where $R_1$ and $R_2$ are power reflectivity at the input and output facets, respectively. The square modulus of the traveling-wave amplitude is taken to be the signal photon rate (in units of photons/second)

$$S_s^\pm = |E_s^\pm|^2.$$

Because the spontaneous emission spectrum and gain spectrum are strong polarization sensitive in QDs, we ignore the spontaneous emission of transverse-magnetic (TM) polarization which is much smaller than that of TE polarization. The spontaneous emission photon rates $S_{sp}^\pm$ (in units of photons/second), with TE polarization in a frequency interval $\Delta \nu = \Delta E / h$, centered at frequency $v_{sp}$ traveling in the positive and negative $z$-directions, obey the following equations:

$$\frac{c}{n_r} \frac{\partial S_{sp}^\pm(z,t,v_{sp})}{\partial t} = \pm \frac{\partial S_{sp}^\pm(z,t,v_{sp})}{\partial z} \left\{ \Gamma(g(z,t,v_{sp}) - \alpha_{\text{in}}) S_{sp}^\pm(z,t,v_{sp}) + R_{sp}(z,t,v_{sp}) \right\}.$$

The spontaneous emission term $R_{sp}$ obtained by comparing the noise output of an ideal amplifier obtained from (11) with the quantum mechanical expression is [23]

$$R_{sp} = S_{sp}^\pm \Delta \nu$$

$$g' = \sum_{i=\text{ES, GS}} \sum_{m=0}^{2M} g_{i,m}(z,t,v_s) \frac{f_{i,m}(1 - f_{i,m}^N)}{f_{i,m}^N - f_{i,m}^N}.$$
The boundary conditions of the spontaneous emission photon rates are given by

\begin{align}
S_{sp}^L(0, t, v_{sp}) &= R_1 S_{sp}^L(0, t, v_{sp}) \\
S_{sp}^R(L, t, v_{sp}) &= R_2 S_{sp}^R(L, t, v_{sp}),
\end{align}

where $R_1$ and $R_2$ are the reflection coefficients at the left and right boundaries, respectively.

### B. Carrier Rate Equation

To account the longitudinal distribution of the carrier density, we split the QD-SOAs into $K$ sections ($k = 1$ to $K$) of equal length in longitudinal direction, and assume a uniform carrier density and averaged photon density in each section. Although the WL is widely adopted as a reservoir of QDs carriers [8], [12], [15], [24], [25], carrier capture directly from WL into the GS is neglected due to the large energy separation between the GS and the WL bandedge and fast intradot carrier relaxation [12]. Therefore, QD ES instead of WL acts as a reservoir of carriers for the GS. The carrier rate equations as in [16] and [21] are considered for the position dependent occupation probabilities in the WL, ES, and GS. The following rate (16) for WL carrier occupation probability is related to the injection current, the WL spontaneous emission, the WL carrier captured by QDs ES, and escaping from QDs ES to the WL. The terms from left to right in the ES carrier (17) are: the WL carriers acting as a reservoir captured by the ES, carriers escaping from ES to WL, intradot carrier excitation from GS to ES, carrier relaxing from ES to GS, GS spontaneous emission, and stimulated emission, respectively. The terms on the right-hand side of the GS carrier (18) represent the ES carrier relaxation to GS, intradot carrier excitation from GS to ES, GS spontaneous emission, and stimulated emission (including signal photon and amplified spontaneous emission (ASE) photon)

\begin{align}
\frac{df_{WL}}{dt} &= \frac{\eta L}{e^\varepsilon_{WL,k}} - \frac{f_{WL}}{\tau_{sp}} - \frac{f_{WL}}{\tau_{w,E}} + \sum_{m=0}^{M} \frac{2\varepsilon_{GS,N_m} f_{ES,m}}{\rho_{WL,k} \tau_{EW}} \tag{16}
\end{align}

\begin{align}
\frac{df_{ES,m}}{dt} &= \frac{N_m}{N_{QD,k} 2\varepsilon_{GS,N_m} \tau_{GW}} - \frac{f_{ES,m}}{\tau_{EW}} - \frac{f_{ES,m}}{\tau_{G,E}} - \frac{f_{ES,m}}{\tau_{r}} - P_{ES,m} \tag{17}
\end{align}

\begin{align}
\frac{df_{GS,m}}{dt} &= \frac{2\varepsilon_{ES,N_m} f_{ES,m}}{\tau_{G,E}} - \frac{f_{GS,m}}{\tau_{G,E}} - \frac{f_{GS,m}}{\tau_{r}} - P_{GS,m} \tag{18}
\end{align}

where $\eta$ is the injection efficiency of bias current. A uniform bias current is assumed across the QD-SOA, i.e., $I_k = I/K$, here $I$ denotes the total bias current. The effect of nonuniform current injection due to longitudinally varying Fermi level is beyond our model and numerical simulation power. The stimulated emission recombination terms at (17) and (18) can be expressed as

\begin{align}
P_{ES,m} &= \frac{\Gamma}{2\varepsilon_{i,N_m}} \Delta z \cdot g_{ES,m}(z, t, v_{sp}) \{ S_{sp}^+ (z) + S_{sp}^- (z) \\
&+ \frac{\Gamma}{2\varepsilon_{i,N_m}} \Delta z \sum_{sp} \{ g_{ES,m}(z, t, v_{sp}) \{ S_{sp}^+ (z) + S_{sp}^- (z) \} \}
\end{align}

with $\Delta z = L/K$ is the section length of the QD-SOA and $i = \text{GS}$ and ES. Taking into account the “Pauli blocking” effect, carrier capture lifetime $\tau_{W,E}$, carrier escape lifetime $\tau_{E,W}$, intradot relaxation lifetime $\tau_{E,G}$, and intradot excitation lifetime $\tau_{G,E}$ in the $k$th section are affected by the occupation probabilities of terminal state energy levels in each section

\begin{align}
\frac{1}{\tau_{W,E}} &= \frac{1}{\tau_{ES,m}} \tag{20}
\end{align}

\begin{align}
\frac{1}{\tau_{E,W}} &= \frac{1}{\tau_{W,E}} \tag{21}
\end{align}

\begin{align}
\frac{1}{\tau_{E,G}} &= \frac{1}{\tau_{E,W}} \tag{22}
\end{align}

\begin{align}
\frac{1}{\tau_{G,E}} &= \frac{1}{\tau_{E,G}} \tag{23}
\end{align}

\begin{align}
\frac{1}{\tau_{G,E}} &= \sum_{m=0}^{M} \frac{1}{\tau_{W,E} N_{QD}} \tag{24}
\end{align}

\[ \tau_{W,E}, \tau_{E,W}, \tau_{E,G}, \tau_{G,E} \] are the corresponding characteristic times in the absence of the related occupations. Simple fixed time constants were used in [11], [16], and [21], and the time constants were expressed as the functions of the edge occupation probability of WL accounting Auger process [13]. In our model, the spectral hole-burning results in a great computing burden due to a strong correlation between all carriers, ASE, and the signal. To avoid the increase of computing burden, we choose fixed time constants in the numerical simulation. Furthermore, detail balance relationship between the relaxation and emission rates of carriers is adopted as

\begin{align}
\tau_{E,W,0} &= \tau_{W,E,0} \exp \left( \frac{E_{WL} - E_{ES,m}}{k_B T} \right) \tag{25}
\end{align}

\begin{align}
\tau_{G,E,0} &= \tau_{E,G,0} \exp \left( \frac{E_{ES,0} - E_{GS,0}}{k_B T} \right) \tag{26}
\end{align}

where $E_{WL}$ is the energy level of the WL and $k_B$ is the Boltzmann constant, $T$ is the absolute temperature. Finally, the WL degeneracy $\rho_{WL,k}$ in each section is expressed as [16]

\begin{align}
\rho_{WL,k} &= \frac{m^*}{\pi \hbar^2 k_B T} A_{WL,k} \tag{27}
\end{align}

where $m^*$ is the electron effective mass of WL, and $A_{WL,k}$ is the WL area of the $k$th section. It should be noted that the number of section $k$ is omitted in QD index numbers, occupation probabilities, and lifetimes in (16)–(24) to simplify.

### IV. NUMERICAL RESULTS OF STEADY CARRIER DISTRIBUTION AND GAIN SATURATION

#### A. Steady-State Algorithm and Parameter

We solve steady state solutions for rate (16)–(18) by two-step process. Firstly, giving the value of the injection current in each section, we calculate $f_{WL}(z)$ from (16) with given values of $f_{ES,m}(z)$ (the staring values are zero). Secondly, submitting the...
to (17), we solve (17) and (18) by photon it-
ips, we have the diffu-
Then we ex-
and the capture
as iterative variables [28], and ob-
obtained from two
s obtained from Einstein relation
was simply taken as the value of
cm,
Vs at room temperature [29]
cm-directional distributions of ASE spectrum
THz corresponding to the GS resonant
values of the other parameters are listed in Table I.
The values of the other parameters are listed in Table I.

### B. Steady Carrier Distribution

Fig. 2 shows the longitudinal occupation probability of WL
carrier at bias currents of 100, 200, 300, 400 mA without input
optical signal. The ratio of the occupation probability in the mid-
point to that at the input and output facets increases from 5.5 to
32 as the injection current increases from 100 to 400 mA, due
to the strong amplified spontaneous emission near the facets.
The spatial variations of carriers will result in the carrier dif-
fusion, which can be considered by adding the diffusion term
$D \cdot \nabla^2 f_{WL}$ to the right side of (16). Taking WL carrier diffusion
coefficient $D = 870 \text{cm}^2/\text{s}$ obtained from Einstein relation
with mobility $\mu = 34000 \text{cm}^2/\text{Vs}$ at room temperature [29]
and the WL carrier lifetime $\tau_{W,E,0} = 3 \text{ps}$, we have the diffusion
length of 0.51 $\mu$m for the WL carriers. With such diffusion
length, we get the maximum diffusion term at the bias current
of 400 mA on the order of $10^5/\text{s}$, which is three orders smaller
than the magnitude of the injection current term. In fact, the lon-
gitudinal carrier variation is over a rather long cavity length, so
the diffusion term is negligible for WL carriers.

The longitudinal position and carrier resonant energy depen-
dences of the carrier occupation probabilities in the GS and ES
are plotted in Fig. 3(a) and (b), respectively, for the QD-SOA
with the bias current of 400 mA and the input signal power of
1.7 dBm. The corresponding values at the QD-SOA input and
output facets are presented in Fig. 4(a) and (b) for clearly shown.
The GS carrier occupation probability is nearly unity at the input
facet due to the high injection current and fast carrier relaxation
from ES to GS. A distinct sink around the input signal photon
energy at the input facet and output facet can be observed due
to the strong stimulated emission. At the input signal photon
energy, the GS occupation probability is 0.9964 and 0.6706 at
bias currents of 100, 200, 300, and 400 mA and without input signal.

![Fig. 1. Power reflectivity of an antireflection mirror for the QD-SOA.](image1)

![Fig. 2. Longitudinal distribution of WL carrier occupation probability at bias current of 100, 200, 300, and 400 mA and without input signal.](image2)

### Table I: Parameter Values of QD- SOAs

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Value</th>
<th>Symbol</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\sigma$</td>
<td>20 meV</td>
<td>$\alpha_0$</td>
<td>2 cm$^{-1}$</td>
</tr>
<tr>
<td>$2\hbar n_0^0$</td>
<td>12 meV</td>
<td>$\tau_0$</td>
<td>1 ns</td>
</tr>
<tr>
<td>$E_{W,G}$</td>
<td>0.97 eV</td>
<td>$\tau_{\text{eq}}$</td>
<td>1 ns</td>
</tr>
<tr>
<td>$f_{WL}^0$</td>
<td>1.04 eV</td>
<td>$\Delta$</td>
<td>6 mm</td>
</tr>
<tr>
<td>$W$</td>
<td>1.14 eV</td>
<td>$\Delta E$</td>
<td>10 nm</td>
</tr>
<tr>
<td>$\Delta E$</td>
<td>1.5 meV</td>
<td>$\Delta \tau$</td>
<td>500 K</td>
</tr>
<tr>
<td>$\Delta \tau$</td>
<td>0.363 THz</td>
<td>$\Delta n$</td>
<td>1 nm</td>
</tr>
<tr>
<td>$n_{\text{WL}}$</td>
<td>3</td>
<td>$\eta$</td>
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</tr>
<tr>
<td>$n_{\text{ES}}$</td>
<td>3</td>
<td>$n_0$</td>
<td>3.5</td>
</tr>
<tr>
<td>$\Gamma$</td>
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<td>$\mu$</td>
<td>0.024 meV$^{-1}$</td>
</tr>
<tr>
<td>$\phi_{ES}$</td>
<td>2</td>
<td>$M$</td>
<td>40</td>
</tr>
<tr>
<td>$\phi_{GS}$</td>
<td>11</td>
<td>$K$</td>
<td>30</td>
</tr>
</tbody>
</table>
Fig. 3. Longitudinal position and energy dependences of the carrier occupation probabilities for (a) GS and (b) ES of the QDs at the bias current of 400 mA. The input signal frequency is 234.7 THz corresponding to the GS gain peak and the input power is 1.7 dBm.

Fig. 4. Carrier resonant energy dependences of occupation probabilities for (a) GS and (b) ES at the input and output facets.

Fig. 5. Device gain versus output signal power at the bias current of 40, 60, 100, and 500 mA.

Fig. 6. Device gain spectra of small input signal at the bias current of 30, 40, 50, 60, 70, 100, and 200 mA.

Fig. 7. Gain spectra at the bias current of 400 mA and input signal power of $P_s = -4.0, -0.4, 3.2, 8.5$, and $15.6$ dBm.

C. Device Gain and Saturation Output Power

The signal gain versus the signal output power curves are plotted in Fig. 5 at the bias currents of 40, 60, 100, 500 mA, where the maximum gain is 19.7 dB and the saturation output power is 20.6 dBm at the bias current of 500 mA. The saturation output power of the QD-SOA increases with the bias current as GS carriers quickly supplied by the carriers in the ES and WL. The small signal gain spectra at the bias currents of 30, 40, 50, 60, 70, 100, and 200 mA are plotted in Fig. 6, where the peak gains of the GS and ES saturate at the values of 19.5 and 26.4 dB at 1280.33 and 1197.49 nm limited by the GS and ES state density, respectively, at the bias currents of 70 and 100 mA.

Fig. 7 shows the gain spectra for the QD-SOA at the bias current of 400 mA and the input signal power $P_s = -4.0, -0.4, 3.2, 8.5$, and $15.6$ dBm. Both GS and ES gains decrease with the increase of the input signal power. However, GS gain maintains positive because the reduction of carriers in
GS are caused by the stimulated emission and ES gain becomes negative at large input signal power due to the depletion of ES carriers by the fast relaxation to the GS. ES carriers are consumed by the energetically lower GS transition, so the ES gain is significant reduction.

D. Influence of Relaxation Time and Capture Time

Taking the intradot relaxation time from ES to GS $\tau_{E-G,0} = 1$, 30, and 60 ps and the capture time $\tau_{W-E,0} = 3$ ps, we investigate the effect of QD relaxation time on gain spectrum. The obtained gain spectra without signal input are plotted in Fig. 8(a) at the bias current of 70 mA. The gain at wavelength $\lambda = 1278.35$ nm decreases from 19.5 to 17.8 dB with the relaxation time increasing from 1 to 60 ps, and that at $\lambda = 1194.03$ nm increases from 23.1 to 23.6 dB. A large relaxation time will greatly influence the magnitude of gain on the GS wavelength range. $\tau_{W-E,0} = 1$, 5, 10 ps and $\tau_{E-G,0} = 2$ ps are also taken to investigate the effect of capture time on the gain spectrum. As shown in Fig. 8(b), the gain at the wavelength $\lambda = 1278.35$ nm ($\lambda = 1194.03$ nm) decreases from 19.6 (23.6) to 19.3 (21.4) dB with the capture time increasing from 1 to 10 ps. The gain decreases with the increase of the capture time, but the variation at short wavelength of the ES transition is much pronounced due to the fast intradot relaxation time.

V. NOISE FIGURE

Finally, we consider the noise figure for the QD-SOA with the relaxation time $\tau_{E-G,0} = 2$ ps and the capture time $\tau_{W-E,0} = 3$ ps. The output ASE spectra of the QD-SOAs are plotted in Fig. 9 at the bias current of 400 mA and the input signal power of $P_s = \pm 4.0, \pm 0.4, 3.2, 8.5$, and 15.6 dBm, respectively. The device gain and the corresponding noise figure are obtained. The ASE spectra rapidly decrease with the increase of input signal power, especially around wavelength of 1190 nm, which is nearly lasing at low input signal and the variation of ASE spectral intensity is over seven orders of magnitude as the input signal increases from $\pm 4.0$ to 15.6 dBm. The threshold gain is 26 dB at the wavelength of 1190 nm with the reflectivity of 0.00248 as shown in Fig. 1. But the magnitude of the ASE spectral intensity around 1280 nm only decreases about one order because the ES carriers work as a reservoir to the GS carriers.

Based on the output ASE spectrum, we can obtain the noise figure of the QD-SOA by [30]

$$F_{\text{ASE}} = 1 + \frac{\text{ASE noise power in bandwidth } B_s}{G_D h \nu B_s}$$

(28)

where $G_D$ is the device gain and $B_s$ is the bandwidth of ASE filter in front of the detector, which is taken to be $B_s = 1$ nm. The device gain and the corresponding noise figure at the wavelength of 1278.35 nm are plotted in Fig. 10 as functions of input signal power for the QD-SOA at a bias current of 400 mA. The noise figure almost maintains a constant of 3.5 dB when the input signal power is less than 11 dBm. The gain saturation and noise figure curves are similar to the results of semiconductor linear optical amplifiers with gain clamping by vertical laser fields [23]. The ES carriers and ASE around the resonant wavelength of ES states in the QD-SOAs have similar functions as the vertical laser field in the linear optical amplifiers for regulating carriers.
The noise figure spectra at the input signal power $P_{in} = −4.0, −0.4, 3.2, 8.5,$ and $15.6$ dBm are plotted in Fig. 11 for the QD-SOA at the bias current of 400 mA. The noise figure first decreases with the increase of the input signal power from $−4.0$ to $8.5$ dBm, and then greatly increases as the input power reaches $15.6$ dBm. The output ASE decreases with the increase of input signal power as shown in Fig. 9, so the signal-ASE beating noise decreases with the increase of the input signal power. As the QD-SOA reaches strong gain saturation with the increase of the input power, the noise figure increases quickly. The noise figure of QD-SOAs at long wavelength side almost keeps a constant value over a large range of input signal power, while that at the short wavelength side varies drastically with the signal input power, which is mainly caused by the different inversions for the GS and ES carriers.

VI. CONCLUSION

We have simulated the characteristics for QD-SOAs based on a rate equation model. The wetting layer state and two bound states are considered for QDs and the inhomogeneous broadening of the QDs is described by a Gaussian distribution. The gain saturation behaviors and saturated output power are numerically investigated, and a low noise gain saturation and the noise figure keep nearly constant within a large range of input signal power at the ground state resonance energy. The gain saturation and the noise figure of the QD-SOAs have similar behaviors as those of semiconductor optical amplifiers with the gain saturated by integrated vertical-cavity surface-emitting lasers.

REFERENCES


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