Abstract—Theoretical results on the extinction ratio (ER) improvement in ultralong semiconductor optical amplifiers (UL-SOAs) are presented indicating a Bogatov-like effect in the saturated section. Starting from general nonlinear gain equations, an analytic description of the Bogatov-like effect is derived in terms of gain coefficients. These equations are used to explain the results of fully numerical simulations. The data signal’s ER improves because of a two-step process. First, the data signal cross-gain modulates the additionally injected CW signal. Second, due to this inverse modulation, the data signal’s states are differently amplified via the Bogatov-like effect. Since the ER improvement is caused by the fast intraband effects, this simple scheme has the potential for high-speed regeneration.

Index Terms—All-optical, Bogatov effect, extinction ratio improvement, ultralong semiconductor optical amplifiers (UL-SOAs).

I. INTRODUCTION

WITH increasing data rates in optical wavelength-division multiplexed transmission systems, all-optical regeneration of data signals will become more and more important. In contrast to regeneration concepts with highly nonlinear fibers, most semiconductor optical amplifier (SOA) schemes can be integrated. Typical SOA solutions are based on interferometer structures [1], [2]. Regarding data rates and wavelengths, they are phase-sensitive and inherently narrowband due to the two interferometer paths. To overcome these problems, single-path techniques were invented. In [3], the nonlinearity of a combined device, consisting of an SOA and an VCSEL, has been used to amplify the signal states differently. Another single-path technique only using the nonlinear gain characteristic of an SOA is presented in [4]. Since these schemes are dependent on the slow interband effects, the transmission speed is limited due to the carrier lifetime (several hundred ps).

A novel single-path extinction ratio (ER) regeneration concept using the nonlinear gain of ultralong SOAs (UL-SOAs) was presented in [5]. This regenerator concept is based on the fast intraband effects. For this reason, the speed limitation should be in excess of several hundred Gb/s. The nonlinear transfer function is obtained due to an additionally injected CW signal. In [6], simulations as well as measurements for sine modulated signals of this regeneration scheme were presented. In addition, a first attempt for an analytic description of the ER improvement, which is based on four-wave mixing (FWM), is given.

In a previous publication, we investigated a basic set of the UL-SOA’s driving conditions for the ER improvement [7]. First indications were observed that a Bogatov-like effect in the UL-SOA’s saturated section could be the reason for the ER improvement. In addition, it has been proven that the regeneration scheme is a stable and simple regenerative process with the potential for 2R regeneration.

In this paper, a theoretical explanation for the ER improvement in UL-SOAs will be presented. The paper will be structured as follows. First, the basic properties of UL-SOAs are discussed in order to get the preconditions for the analytic description of the Bogatov-like effect. In Section III, the analytic description of the Bogatov-like effect in the UL-SOA’s saturated section is derived in terms of gain coefficients that are dependent on the power and the detuning of the additionally injected CW signal. In Section IV, the UL-SOA’s driving conditions that indicate the Bogatov-like effect as a reason for the ER improvement are briefly presented. Finally, with the help of further numerical simulations and the analytic description of the Bogatov-like effect, the ER improvement in UL-SOAs will be explained in Section V. Furthermore, the results of Section IV are discussed with this new insight.

II. PROPERTIES OF UL-SOAS

The purpose of UL-SOAs is to benefit from the semiconductor’s fast nonlinear intraband effects. The influence of the slow interband effects should be suppressed as far as possible, in order to avoid pattern effects.

Unlike short SOAs, UL-SOAs are saturated after a certain length by the amplified signals and by the amplified spontaneous emission (ASE) noise. For this reason, UL-SOAs can be regarded as being divided into an amplifying section and a saturated section. For typically dimensioned bulk SOAs, the transition between these sections takes place after approximately 1 mm of propagation (Fig. 1). The amplifying section has the same properties as a short SOA while the saturated section can be regarded as another device with different properties. In the amplifying section, the carrier density cannot follow high-speed modulated signals because of the long carrier lifetime. As long as the signal changes are fast enough, the carrier density experiences the average signal power and no pattern effects occur. In the saturated section, the carrier density is clamped to the net transparency level because of the high optical power after the
amplifying section. In this part, only the fast nonlinear effects like carrier heating (CH), spectral hole burning (SHB), free carrier absorption (FCA), and two-photon absorption (TPA) influence the signals. These nonlinear effects are in the gain regime and are mainly dependent on the photon density. Compared with the slow carrier density pulsation (CDP), their response time is about 1000 times shorter.

III. BOGATOV-LIKE EFFECT IN THE UL-SOA'S SATURATED SECTION

Here, an analytic description of the Bogatov-like effect in the UL-SOA's saturated section is derived. With the help of these equations, the full numerical results in Section V will be explained.

Bogatov described the interaction of two signals that propagate in a semiconductor media [8]. The beating of the two input signals creates a dynamic gain and index grating which, in turn, results in a parametric amplification of the signals. While the effect described by Bogatov is based on the slow interband effects, the Bogatov-like effect described in this section is created by the fast intraband effects.

To simplify the derivation of this effect, which will be done in the style of [9] and [10], both input signals are assumed to be copolarized CW signals. Because of the wavelength detuning, they create a beating of the field amplitudes $E$, given by

$$S \equiv \frac{1}{K} \left( E_{\text{pump}} \exp(\imath \omega_{\text{pump}} t) + E_{\text{probe}} \exp(\imath \omega_{\text{probe}} t) \right)^2$$

where $\omega_{\text{pump}} = \omega_{\text{pump}} - \omega_{\text{probe}}$ is the difference frequency of the CW signals and $K = \hbar \omega_0 (d/\Gamma) (\epsilon_1/\epsilon_0) G$ is the conversion factor from photon density to the optical power.

The fluctuation of the nonlinear gain results in a nonlinear index change due to the $\alpha$-factor of each nonlinear gain mechanism. Fig. 2 shows these dynamic gratings. Because of the short time constants of the nonlinear gain, even pulsation frequencies of several terahertz can be observed.

The propagation of an optical field inside the SOA cavity is governed by the wave equation where $n$ is the refractive index and $c$ is the velocity of light as follows:

$$\nabla^2 E - \frac{n^2}{c^2} \frac{\partial^2 E}{\partial t^2} = \frac{1}{\epsilon_0 n^2} \frac{\partial^2}{\partial t^2} F_{\text{NL}}.$$  \hspace{1cm} (2)

The equation describes how the electrical field and the electrical nonlinear polarization $F_{\text{NL}}$ interact. In nonlinear media, the optical field and the electrical polarization are coupled through the medium’s susceptibility $\chi_{\text{NL}}$. Due to the short polarization dephasing time ($\sim 25$ fs), the electrical field change of the slowly varying envelope is negligible and the polarization’s steady-state approximation can be used ($\epsilon = \text{CDP, SHB, CH, and FCA}$):

$$F_{\text{NL}} = \varepsilon_0 \chi_{\text{NL}} E \chi_{\text{NL}} = \frac{c n}{\omega} \sum_{\text{FCA}} (\varepsilon - \alpha_\text{F}) \Delta E.$$  \hspace{1cm} (3)

The term for the TPA gain suppression can be neglected because the Bogatov-like effect for TPA only contributes to FWM products. In the UL-SOA’s saturated section, only the nonlinear gain varies due to long carrier lifetime, while the linear gain can
be assumed to be constant. The nonlinear gain in SOAs can be characterized with a set of rate equations [11]. Each rate equation can be ascribed to a gain suppression mechanism

\[
\frac{\partial g_{\text{SHB}}}{\partial t} = -\frac{g_{\text{SHB}}}{\tau_{\text{SHB}}} + \frac{g_S}{\tau_{\text{SHB}}} - \left( \frac{\partial g_{\text{CH}}}{\partial t} + \frac{\partial g_{\text{FC}}}{\partial t} + \frac{\partial g_{\text{DP}}}{\partial t} \right) \quad (4a)
\]

\[
\frac{\partial g_{\text{CH}}}{\partial t} = -\frac{g_{\text{CH}}}{\tau_{\text{CH}}} - \frac{g_S}{\tau_{\text{CH}}} \quad (4b)
\]

\[
\frac{\partial g_{\text{FC}}}{\partial t} = -\frac{g_{\text{FC}}}{\tau_{\text{CH}}} - \frac{g_{\text{FC}}}{\tau_{\text{CH}}} \frac{dg}{dN} N_{\text{S}} \quad (4c)
\]

To figure out how the two CW-signals interact, the electrical polarization has to be calculated. For this reason, the rate equations for the nonlinear gain have to be solved. In the saturated section, the overall modal gain \( g \) just compensates for the internal losses, so that the net gain equals zero. The linear gain \( g_{\text{DP}} \) is only dependent on the carrier density \( N \). Since the carrier density in the UL-SOAs saturated section is fixed to the net transparency level \( N_{\text{sat}} \) and the amount of the linear gain is much bigger than the contribution due to the NL gain [Fig. 2(a)], the following approximation is made for solving the rate equations:

\[
g = g_{\text{sat}} \approx g_{\text{DP,sat}} = \frac{dg}{dN} (N_{\text{sat}} - N_{\text{tr}}) = \frac{\alpha_{\text{sat}}}{\Gamma} \quad (5)
\]

In addition, the last term of (4a) has to be neglected in order to solve the differential equation. This assumption can be made because the gain derivatives on the right-hand side are negligible compared with the SHB’s derivative due to bigger time constants.

Since the electrical field beating is the reason for the Bogatov-like effect, only the dynamic term of (1) is of interest:

\[
\chi_{\text{NL}} = \chi_{\text{NL,0}} + \Delta \chi_{\text{NL}}(\Omega) \quad \text{static} + \Delta \chi_{\text{NL}}(\Omega) \quad \text{dynamic}
\]

\[
P_{\text{NL}} = P_{\text{NL,0}} + \Delta P_{\text{NL}}(\Omega) \quad \text{static} + \Delta P_{\text{NL}}(\Omega) \quad \text{dynamic}
\]

The approach for solving the differential equations in (4) is

\[
\Delta g_{\text{CH}} \approx 0
\]

\[
\Delta g_{\text{SHB}} = g_{\text{SHB}} \exp(i\Omega t) + c.c. \quad (7a)
\]

\[
\Delta g_{\text{FC}} = g_{\text{FC}} \exp(i\Omega t) + c.c. \quad (7b)
\]

Inserting (1), (5), and (7) into (4) leads to the following solutions of the rate equations for the nonlinear gain due to the photon density pulsation:

\[
\Delta g_{\text{SHB}} = \frac{g_{\text{sat}} \epsilon_{\text{SHB}}}{\kappa(i\tau_{\text{SHB}} \Omega + 1)} \exp(i\Omega t) + c.c. \quad (8a)
\]

\[
\Delta g_{\text{CH}} = \frac{g_{\text{sat}} \epsilon_{\text{CH}}}{\kappa(i\tau_{\text{CH}} \Omega + 1)} \exp(i\Omega t) + c.c. \quad (8b)
\]

\[
\Delta g_{\text{FC}} = \frac{g_{\text{sat}} \epsilon_{\text{FC}}}{\kappa(i\tau_{\text{CH}} \Omega + 1)} \frac{dg}{dN} N_{\text{sat}} \exp(i\Omega t) + c.c. \quad (8c)
\]

With these solutions, the dynamic part of the susceptibility \( \chi_{\text{NL}} \) in (3) can be obtained. For the electrical field in (3), the superposition of the two signals has to be taken \( (E = E_{\text{pump}} \exp(i\omega_{\text{pump}} t) + E_{\text{probe}} \exp(i\omega_{\text{probe}} t)) \). When expanding the equation and only retaining terms which are either proportional to \( \exp(\pm i\omega_{\text{pump}} t) \) or \( \exp(\pm i\omega_{\text{probe}} t) \), one obtains the dynamic electrical polarization \( \Delta P_{\text{NL}} \) due to the nonlinear gain and index pulsation given in

\[
\Delta P_{\text{NL}} = \varepsilon_0 \frac{c_{\text{NG}}}{\omega} \times \left\{ \begin{array}{c}
\left[ \frac{i - \alpha_{\text{SHB}} \epsilon_{\text{sat}} \epsilon_{\text{SHB}}}{1 - i\tau_{\text{SHB}} \Omega} + \frac{i - \alpha_{\text{CH}} \epsilon_{\text{sat}} \epsilon_{\text{CH}}}{1 - i\tau_{\text{CH}} \Omega} \\
+ \frac{i - \alpha_{\text{FC}} \epsilon_{\text{sat}} \epsilon_{\text{FC}} N_{\text{sat}}}{1 - i\tau_{\text{CH}} \Omega} \right] \\
\frac{|E_{\text{pump}}|^2}{\kappa} E_{\text{pump}} \exp(i\omega_{\text{pump}} t) \\
- \left[ \frac{i - \alpha_{\text{SHB}} \epsilon_{\text{sat}} \epsilon_{\text{SHB}}}{1 - i\tau_{\text{SHB}} \Omega + 1} + \frac{i - \alpha_{\text{CH}} \epsilon_{\text{sat}} \epsilon_{\text{CH}}}{i\tau_{\text{CH}} \Omega + 1} \\
+ \frac{i - \alpha_{\text{FC}} \epsilon_{\text{sat}} \epsilon_{\text{FC}} N_{\text{sat}}}{i\tau_{\text{CH}} \Omega + 1} \right] \\
\times \frac{|E_{\text{pump}}|^2}{\kappa} E_{\text{pump}} \exp(i\omega_{\text{pump}} t) \right\} + c.c.
\end{array} \right. \quad (9)
\]
The effective probe gain due to the nonlinear polarization is

\[ \Delta g_{\text{probe}} = \frac{\omega}{c h} \text{Im} \left( \Delta \chi_{\text{NL}}^{\text{probe}} \right) = \Delta g_{\text{SHB}}^{\text{probe}} + \Delta g_{\text{CH}}^{\text{probe}} + \Delta g_{\text{FCA}}^{\text{probe}} \]  

where \( \text{Im} \) denotes the imaginary part. Using (10) and \( \Delta \chi_{\text{NL}}^{\text{pump}} \) as defined in (9), the probe signal’s gain coefficients that occur due to the various nonlinear gain and index gratings can be obtained:

\[ \Delta g_{\text{SHB}}^{\text{probe}}(\Omega) = g_{\text{sat}} e^{\text{SHB}} \left| E_{\text{pump}} \right|^2 \frac{\alpha_{\text{SHB}} e^{\text{SHB}} \Omega - 1}{(7 \text{SHB} \Omega)^2 + 1} \]  \hspace{1cm} (11a)

\[ \Delta g_{\text{CH}}^{\text{probe}}(\Omega) = g_{\text{sat}} e^{\text{CH}} \left| E_{\text{pump}} \right|^2 \frac{\alpha_{\text{CH}} e^{\text{CH}}\Omega - 1}{(7 \text{CH} \Omega)^2 + 1} \]  \hspace{1cm} (11b)

\[ \Delta g_{\text{FCA}}^{\text{probe}}(\Omega) = \frac{dg}{dN} e^{\text{FCA}} N_{\text{sat}} \left| E_{\text{pump}} \right|^2 \frac{\alpha_{\text{FCA}} e^{\text{FCA}}\Omega - 1}{(7 \text{CH} \Omega)^2 + 1} \]  \hspace{1cm} (11c)

This is the main result of this section. Equation (11) shows that, due to the dynamic nonlinear gain and index gratings in the UL-SOA’s saturated section, the probe signal experiences a gain asymmetry except TPA. Similar results for the nonlinear effects in short SOAs were already presented in [12].

Since the \( \alpha \)-factors in (11a)–(c) only contribute to the numerator’s linear polynomial terms, they have a major influence on the asymmetry of the probe signal’s amplification. For example, the gain suppressions with a very low \( \alpha \)-factor (SHB and FCA) result in a nearly symmetric gain profile around the axis of \( \Omega = 0 \) [Fig. 3(a)]. In general the \( \alpha \)-factors in SOAs are positive, so that due to the dynamic nonlinear gain, the probe signal will be amplified for a positive frequency detuning and attenuated for a negative frequency detuning [Fig. 3(b)].

Opposite to the original Bogatov effect, the amplification asymmetry can be observed over several nanometers. The reason for this are the short time constants of the nonlinear effects. With an increasing detuning, the effect decreases and becomes zero for an infinite detuning. For a certain detuning, a maximum gain asymmetry is observed.

IV. NUMERICAL ER IMPROVEMENT RESULTS

In [7], a set of the UL-SOAs’s driving conditions for the ER improvement has been investigated being confirmed by measurements. Some of the driving conditions indicate that the Bogatov-like effect from the previous section is the reason for the ER improvement. Here, these driving conditions for the ER improvement will be briefly presented.

The simulations were done with a fully numerical UL-SOA model. As a simulation tool an improved time-domain SOA model based on [13] and [14] is used. In the original model the wavelength dependence of the gain is implemented with the help of a FIR filter, fitted to a parabolic gain model. In order to apply the model on UL-SOAs, the FIR filter coefficients are adaptively fitted to a cubic gain model [15]. Moreover, further nonlinear effects like FCA and TPA were implemented because even these weak effects influence the signal over such a long device length. The effects of FCA and TPA are governed by the equations in [11] and [16], respectively. For the simulation, typical parameters for a bulk SOA have been taken from literature as listed in Table I [6], [11], [13], [15]. In [7], a very good qualitative match between measurements and results from this simulation model was demonstrated.

Fig. 4 shows a conceptual setup for the investigations. To keep the influence of the bandpass filter after the UL-SOA on the ER improvement as small as possible, an 80-GHz sine-modulated signal was used as a data signal. The optical bandpass filter is a second-order Gaussian filter with a 3-dB bandwidth of 240 GHz. The investigated device was a 4-mm-long bulk SOA. The driving current was set to 250 mA/mm, which is a typical value for nonlinear bulk SOAs. The parameter of the input signals are \( \bar{P}(\lambda_{\text{data}}) = -3 \) dBm, \( \text{ER} = 6 \) dB. Throughout this study, 1557 and 1562 nm are used as input wavelengths while the alignment of the pump and probe swaps.

Since the ER improvement is sensitive to the input signals’ power ratio, it is useful to plot the ER improvement over the

\[ Fig. 3. \] Probe signal’s amplification asymmetry due to the dynamic part of the gain suppressions in the UL-SOA’s saturated section (\( \left| E_{\text{pump}} \right|^2 \approx P_{\text{sat}} \)); for comparison, the original Bogatov asymmetry for a hypothetical carrier density pulsation in the UL-SOA’s saturated section is plotted.

\[ Fig. 4. \] A conceptual setup for the investigations. To keep the influence of the bandpass filter on the ER improvement as small as possible, an 80-GHz sine-modulated signal was used as a data signal. The optical bandpass filter is a second-order Gaussian filter with a 3-dB bandwidth of 240 GHz. The investigated device was a 4-mm-long bulk SOA.
power ratio (Fig. 5). For certain power ratios, the ER increases, while the signal propagates through the device. The impact of the signal’s relative wavelength alignment on the ER improvement is also shown in Fig. 5. Having the CW signal located on the shorter wavelength side, the ER decreases. In order to achieve an ER improvement, the CW signal has to be located on the longer wavelength side. For this reason, the regeneration scheme is not symmetric. An asymmetric dependence on the wavelength detuning was also presented in Section III.

Similar to the degenerating wavelength detuning, the ER improvement vanishes if the two signals are not parallelly polarized. If the signals are orthogonally polarized, there is no dynamic gain and index grating, which are necessary for the Bogatov-like effect. For this reason, the input signals need to be parallelly polarized in order to obtain an ER improvement.

Finally, the dependence of the \( \alpha \)-factors (\( \alpha = \text{CDP, SHB, CH, FCA, and TPA} \)) on the ER improvement is investigated (Fig. 6). Even for a device without any \( \alpha \)-factors, an ER improvement can be observed. A detailed explanation for this fact will be given in Section V-C.

V. ER DEVELOPMENT INSIDE THE UL-SOA

Here, numerical results from the ER development inside the UL-SOA are presented and explained with the help of the equations for the Bogatov-like effect derived in Section III. As shown in Fig. 5, the ER development is dependent on the wavelength alignment of the data and the CW signal. Therefore, first the case for the ER enhancement will be discussed (\( \lambda_{\text{Data}} < \lambda_{\text{CW}} \)). Later, the same line of arguments will be applied to the degenerating case (\( \lambda_{\text{Data}} > \lambda_{\text{CW}} \)). Furthermore, with the new insight, some additional explanations on the results from Section IV will be given.

Since the influence of the Bogatov-like effect can be easier explained for CW signals than for modulated signals, the development of the signal’s levels inside the UL-SOA will be treated separately in two different simulations with each two CW as input signals (static simulation). In addition, the extinction ratio is the power ratio between the data signal’s “1”-level and “0”-level (\( \text{ER} = P_1 / P_0 \)). For this reason only the cases for a data signal’s “1”-level (\( P_1 = \max (P_{\text{Data}}) \)) and “0”-level (\( P_0 = \min (P_{\text{Data}}) \)) have to be considered.

A. Explanation of the ER Improvement (\( \lambda_{\text{Data}} < \lambda_{\text{CW}} \))

Fig. 7 shows the ER development inside the UL-SOA for different input power ratios. On the first 1.5 mm of the device, the ER decreases. As mentioned in Section II, the UL-SOA behaves in this part like a short SOA where the “1”-level is less amplified than the “0”-level due to the saturation of the device. However, after these 1.5 mm, the signals’ power is large enough in order to fully saturate the UL-SOA and the regenerative effect influences the signals.

As an example, the ER development will be explained for the optimized input power ratio of 3 dB (Fig. 8). Following the notation in Section III, we will now refer to the CW signal as the pump and to the data signal as the probe. This convention is verified by Fig. 8(a) showing that the CW signal is always the stronger signal.

When regarding Fig. 8(a), it becomes noticeable that the ER improvement in the saturated section is a two-step process. First, the pump signal is cross-gain modulated by the probe signal (\( \text{ER} \approx 1.5 \text{ dB} \)). This inverse modulation results in two different pump power levels for the “0” and the “1” state of the probe signal. As shown in (11) in Section III, the gain coefficients related to the Bogatov-like effect are dependent on the pump power. For a probe signal’s “0”-level the power of the pump is maximal, resulting in a stronger attenuation due to the Bogatov-like effect than for a probe signal’s “1”-level. As a result, the ER increases.

Moreover, the reason why the ER mainly increases on the last 1.5 mm of the device, can also be explained with the dependence of the Bogatov-like effect on the pump signal’s power. Between 1.5 and 2.5 mm, the pump signal is still amplified by 1.5 dB. This corresponds to a 40% increased gain coefficient in (11).
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Due to the exponential dependence of the probe power on the gain coefficients, the effect is boosted and the ER improvement is more pronounced on the last 1.5 mm.

Since the Bogatov-like effect can be easily applied to CW signals, the ER improvement inside the UL-SOA’s saturated section has been explained by regarding the “0”-level and “1”-level separately (static simulation). This approach is truly justified, can be seen if the static simulation is compared with a simulation of a sine modulated data signal (dynamic simulation). A very good match between both simulations is shown in Fig. 9. For this reason, the ER improvement can be truly ascribed to the Bogatov-like effect and not to any further unknown dynamic effect.

B. Explanation of the ER Degeneration ($\lambda_{\text{Data}} > \lambda_{\text{CW}}$)

For positive frequency detuning ($\lambda_{\text{Data}} > \lambda_{\text{CW}}$), the ER decreases more drastically in UL-SOAs than conventionally expected. The conventionally decreased ER can be obtained for orthogonally polarised input signals and simply occurs due to the saturation of the linear gain. The main additional degeneration takes place on the last 1.5 mm of the device (Fig. 8(b)) and can also be explained with the help of the Bogatov-like effect.

Since the wavelength alignment of the signals has changed the frequency detuning is now positive. For this reason the Bogatov-like effect results in an additional amplification. Again the pump signal is inversely modulated to the probe signal. As a result a probe signal’s “1”-level is less amplified than the “0”-level and the ER decreases. For this frequency

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Fig. 7. ER development in decibels inside the UL-SOA for different input power ratios (a) $\lambda_{\text{Data}} < \lambda_{\text{CW}}$ and (b) $\lambda_{\text{Data}} > \lambda_{\text{CW}}$; for both cases, the ER decreases on the first 1.5 mm of the device; after 1.5 mm the ER further decreases for $\lambda_{\text{Data}} > \lambda_{\text{CW}}$, and for $\lambda_{\text{Data}} < \lambda_{\text{CW}}$ the regenerative mechanism sets in; the results have been obtained from full numerical simulations.

Fig. 8. Development of the optical power inside the UL-SOA along the amplifier axis for an input power ratio of $P_{\text{CW}}/P_{\text{Data}} = 3$ dB (a) $\lambda_{\text{Data}} < \lambda_{\text{CW}}$ and (b) $\lambda_{\text{Data}} > \lambda_{\text{CW}}$; for $\lambda_{\text{Data}} < \lambda_{\text{CW}}$, the major part of the regenerative effect takes place in the last 1.5 mm of the device; the results have been obtained from full numerical simulations.

Fig. 9. Development of the optical power inside the UL-SOA according to Fig. 8(a) (solid lines—dynamic simulation, dashed lines—static simulation).
detuning, the pump power is smaller than for the negative frequency detuning ($|P_{pump}|^2 < P_{sat}$), resulting in a decreased efficiency of the Bogatov-like effect.

C. Discussion of the Numerical Results in Section IV

The ER improvement dependence on the input power ratio in Fig. 5 can be explained with the help of (11). From (11), it is known that the efficiency of the Bogatov-like effect increases with increasing power of the pump (CW signal). Therefore, it is advantageous to launch the CW with increased power (higher power ratio) into the UL-SOA, so that the efficiency of the Bogatov-like effect increases sooner. For this reason, the effective length in which the ER improvement mainly takes place will be increased for the same device with higher input power ratios.

In Fig. 6, even for $\alpha = 0$, an ER improvement could be observed, which at least compensates for the degeneration due to the saturation of the linear gain. The previous discussion has shown that, for the ER improvement, an unbalanced additional attenuation of the signal states is necessary. As shown in Fig. 10, this can also be achieved by the Bogatov-like effect without any $\alpha$-factors, although the effect is not as strong as for devices with $\alpha$-factors. For devices like highly nonlinear quantum dash SOAs with a decreased $\alpha$-factor, the ER improvement might also be observable, since the fast nonlinear intraband effects are more pronounced than in bulk devices. First investigations of these devices have shown similar Bogatov-like effects [17].

VI. CONCLUSION AND OUTLOOK

Investigations of the UL-SOA’s driving condition have indicated that a Bogatov-like effect is the reason for the ER improvement in UL-SOAs. Due to simulations, preconditions for the analytic description of the Bogatov-like effect in the UL-SOA’s saturated section could be obtained. With the help of an analytic model and further simulations, the mechanism of the ER improvement could be revealed. Due to the cross-gain-modulated pump signal and the dependence of the Bogatov-like effect’s intensity on the pump signal (CW), the data signal’s levels are differently amplified. As a result, the ER increases for $\lambda_{Data} < \lambda_{CW}$ and decreases for $\lambda_{Data} > \lambda_{CW}$.

In the UL-SOA’s saturated section, the carrier density is fixed to the net transparency level and only the fast intraband effects influence the signals. For this reason, the effects can be applied to high-speed optical communication signals. For high-speed signals fairly above the carrier lifetime’s resonance frequency, the carrier density is also fixed in the amplifying section and pattern effects due to the slow interband effects are prevented. Since the Bogatov-like effect is caused by the fast intraband effects, the ER improvement should be observable for data signals up to several hundred Gb/s. As a proof of concept, simulation results for 100 Gb/s OOK-RZ50% PRBS signals are shown in Fig. 11. In order to obtain a better SNR, the device had to be optimized for the simulation of the PRBS signal: $\Gamma = 0.45$ and $\alpha_{int} = 3000 \text{ m}^{-1}$. After the UL-SOA, the data signal’s ER has been increased by 9 dB and the “+1”-level has been amplified by 11 dB. For this reason, the presented scheme has the potential for 2R regeneration.

A speed limitation of this regenerator scheme might not result from the fast intraband effects but due to an overlap of the signal’s spectrum and its FWM products. A remedy for this problem could be different highly nonlinear device structures like MQW or QD. In such devices, faster intraband effects like SHB dominate so that the detuning can be further increased. In addition, different material compositions with faster recombination times could solve the problem when reaching this limitation.

REFERENCES

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