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Simulation of Mode-Locking by Nonlinear Polarization Rotation in a Semiconductor Optical Amplifier

Z. Li, X. Yang, E. Tangdionga, H. Ju, G.-D. Khoe, *Fellow, IEEE*, H. J. S. Dorren, and D. Lenstra

Abstract—We present a theoretical investigation of a mode locked laser that has a semiconductor optical amplifier (SOA) in its ring cavity. A mode-locked train of narrow pulses is obtained by combining nonlinear polarization rotation in the SOA and a polarization filter whose polarization axis is set such that the tail of optical pulses is removed in each cavity round-trip. The pulse narrowing process is demonstrated numerically and good qualitative agreement with experiments in our previous work is achieved. The pulse performance is largely determined by the ultrafast SOA gain dynamics and the cavity dispersion. Our simulation shows that the laser can produce a pulse train of subpicosecond pulsewidth at a repetition rate of 28 GHz for a moderate SOA current level. We observe that the laser can switch itself on or off depending on the initial pulse.

Index Terms—Fiber ring laser, mode-locked ring laser, polarization switching, self-induced nonlinear polarization rotation, semiconductor optical amplifier (SOA).

I. INTRODUCTION

LIGHT sources capable of producing short optical pulses play a key role in optical communication systems [1]. Apart from applications in transmission systems, well-shaped optical pulses as short as several hundred femtoseconds may be needed for creating ultrashort switching windows in optical switches. Mode-locking is a widely used technique to generate short pulses [2]. Among the many available mode-locking schemes, nonlinear polarization rotation in optical fiber nonlinearities is often employed. Pulses as short as 42 fs have been generated by a passively mode-locked fiber ring laser based on nonlinear polarization rotation [3]. A clear disadvantage of employing fiber nonlinearities for mode-locking is the large

amount of pulse energies (~ 50 pJ for a 500-fs pulse) which are necessary in the optical fiber in order to utilize the weak nonlinearity in the optical fiber [3]. The long optical fiber cavity, as well as the high peak power of the optical pulses, limits the system to operate only at low repetition rates.

Nonlinear polarization rotation in a semiconductor optical amplifier (SOA) for optical signal processing has been investigated theoretically by [4]–[6], and experimentally in the context of wavelength conversion [7]–[9], all-optical switching [10]–[12], and an optical flip-flop memory [13]. These experiments were performed in the continuous-wave regime [9], [13] as well as in the pulsed regime [7], [8], [11]. Self-polarization rotation, i.e., nonlinear polarization rotation caused by the pulse itself, has also been utilized for all-optical signal processing [14]–[16].

Recently, we have demonstrated mode-locked pulses in a passively mode-locked ring laser, by using nonlinear self-polarization rotation in a SOA [17]. The pulses had duration of 800 fs. Although mode-locking using self-induced nonlinear polarization rotation in an SOA was already discussed in [18], to the best of our knowledge, the work in [17] was the first demonstration of this scheme. In [18], pulse narrowing and mode-locking due to self-polarization rotation has been investigated numerically. The pulse narrowing observed in their study was not counteracted by a broadening mechanism, such as group-velocity dispersion and ultrafast carrier dynamics. This gave the model in [18] only limited validity.

In this paper, using a consistent model with ultrafast gain dynamics [6], we will describe in detail how an initially broad pulse can be shortened using nonlinear polarization rotation in the SOA and what the condition is for the pulse to acquire enough round-trip gain to build up. The value of the linewidth enhancement factor of the SOA is found to be of crucial importance in the pulse built-up process. We will show simulations of the pulse evolution process, including the evolution of the spectrum. The final pulsewidth is found to be limited by ultrafast gain dynamics in the SOA combined with the dispersion effects in the laser cavity. We will also show that the highest possible repetition rate of the output pulses can be increased by increasing the injection current, but beyond a certain current unstable pulse patterns emerge.

II. PRINCIPLE OF OPERATION

The system setup is given in Fig. 1. The ring laser is composed of an SOA, followed by a polarization controller (PC), an optical isolator, an optical filter, an optical asymmetric output coupler,

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Fig. 1. System setup of the SOA-based fiber ring laser. SOA: semiconductor optical amplifier; PC: polarization controller. The linear polarizer has its transmitted polarization under 45° with respect to the TE and TM axes of the SOA.

and a polarizer. The isolator is introduced in the cavity to keep the signal to propagate in one direction. The coupler is used to monitor the signal in the ring cavity. When the input optical intensity (point A in Fig. 1) is sufficiently low, the SOA operates in the linear regime. The polarization state at point A in Fig. 1 is linear and is set to 45° to the transverse electric (TE) and transverse magnetic (TM) axes of the SOA. The two orthogonal polarization components in the amplifier collect different phases and gains. This causes intensity-independent polarization conversion at the SOA output. Note, in passing by, that in this context one often uses the word polarization rotation. However, this may not be a correct description because in general the TE and TM components will collect different phase shifts while propagating. Therefore an initial linear polarization state will not only rotate, but in general also assume a certain degree of ellipticity.

Now suppose the input optical intensity becomes high enough to saturate the amplifier. Then, TE and TM component collect different intensity-dependent phases and amplitudes. This implies that different parts of the output pulse assume different polarization states and this property makes it possible to cut away the pulse part that has the same polarization as in the low input intensity case. To realize this, one uses a combination of the PC and the polarizer, which are adjusted properly to achieve the required functionality: the PC is adjusted in such a way that for small signal case the polarization of the pulse (point C in Fig. 1) is orthogonal to the axis of the polarizer, while the latter has been oriented at 45° to the TE and TM axes of the SOA. By doing so, a low-intensity input signal to the SOA will be removed from the ring, preventing the signal from building up. On the other hand, for a sufficiently strong input pulse, the self-induced nonlinear polarization rotation of the high-intensity part of the pulse will create a nonzero but shortened pulse behind the polarizer. If the SOA has enough gain, a net round-trip gain for pulses can be established. In fact, the nonlinear polarization rotation, combined with the PC and the polarizer, has the same functionality as a saturable absorber. This provides the basic mechanism for our mode-locking system.

In agreement with the above description, we found that the system is by itself bistable in the sense that either an output train of short strong pulses or no output at all occurs in the system

depending on the initial conditions. Therefore, this mode-locked ring laser could act as a basic element for a flip-flop memory system, and may find its application in optical signal processing systems.

In the experiment in [17], one usually starts in the nonoptimized setting with a quasi-continuous oscillation in the laser. Then during the adjustment of PC, the system is disturbed to generate optical pulses randomly in the cavity. Some pulses happen to satisfy the conditions that are set by the PC and the polarizer such that they can pass through the polarizer and reach the SOA again after one round-trip in the cavity. After each round-trip those pulses become narrower and converge toward a stable pulse train.

III. MODEL

The nonlinear optical pulse propagation in the SOA is simulated using the model developed in [6]. This model is based on the decomposition of the polarized optical field into TE and TM components that interact via the gain saturation. The extensive description given in [6] will not be repeated here. It accounts for the influences of two-photon absorption, free-carrier absorption, self- and cross-phase modulation, carrier heating, and spectral and spatial hole burning. SOAs with unstrained bulk active material have much larger TE amplification than TM, which is due to the different confinement factors. Therefore, the SOAs active material is often strained in order to enhance the gain of TM with respect to TE, making the SOA less polarization dependent. In our model the strain-induced gain anisotropy is taken into account by introducing the separate hole populations for TE and TM and corresponding valence subband structures for the TE and TM transitions [19]. According to the pulse phase evolution equations given in [6], TE and TM components experience exactly the same phase due to two-photon absorption. Within that approximation two-photon absorption has no direct influence on the evolution of the pulse polarization.

The PC and polarizer are modeled according to [20]. By representing the electrical field as the Jones vector, the functions of the PC and the polarizer can be written in 2×2 matrices which act on the electrical field vector.

Suppose at point A in Fig. 1, a weak electric field is present with normalized polarization vector given by

$$\frac{1}{\sqrt{2}} \begin{bmatrix} 1 \\ 1 \end{bmatrix}. \quad (1)$$

Equation (1) represents linearly polarized light under 45° with respect to the TE and TM axes of the SOA. After propagation through the SOA, the TE and TM components acquire different amplitudes and phases. Hence, we can write the field at B as

$$\frac{1}{\sqrt{2}} \begin{bmatrix} \tau_0^{\text{TE}} e^{i\phi_0^{\text{TE}}} \\ \tau_0^{\text{TM}} e^{i\phi_0^{\text{TM}}} \end{bmatrix} \quad (2)$$

where τ_0^{TE} and τ_0^{TM} are the linear amplifications and ϕ_0^{TE} , ϕ_0^{TM} the linear phase shifts. Now, the PC is adjusted in such a way that the polarization state at C is orthogonal to that at A

$$\frac{1}{\sqrt{2}} \beta \begin{bmatrix} 1 \\ -1 \end{bmatrix} \quad (3)$$

where by assuming lossless propagation from B to C, β can be written as

$$\beta = \frac{1}{\sqrt{2}} \sqrt{(\tau_0^{\text{TE}})^2 + (\tau_0^{\text{TM}})^2}. \quad (4)$$

The unitary matrix U , representing the PC, can be written as

$$U = \frac{1}{\sqrt{2((\tau_0^{\text{TE}})^2 + (\tau_0^{\text{TM}})^2)}} \times \begin{bmatrix} (\tau_0^{\text{TE}} + \tau_0^{\text{TM}}) e^{-i\phi_0^{\text{TE}}} & (\tau_0^{\text{TM}} - \tau_0^{\text{TE}}) e^{-i\phi_0^{\text{TM}}} \\ (\tau_0^{\text{TM}} - \tau_0^{\text{TE}}) e^{-i\phi_0^{\text{TE}}} & -(\tau_0^{\text{TE}} + \tau_0^{\text{TM}}) e^{-i\phi_0^{\text{TM}}} \end{bmatrix} \quad (5)$$

which can be easily checked from the requirement

$$U \begin{bmatrix} \tau_0^{\text{TE}} e^{i\phi_0^{\text{TE}}} \\ \tau_0^{\text{TM}} e^{i\phi_0^{\text{TM}}} \end{bmatrix} = \frac{1}{\sqrt{2}} \sqrt{(\tau_0^{\text{TE}})^2 + (\tau_0^{\text{TM}})^2} \begin{bmatrix} 1 \\ -1 \end{bmatrix}. \quad (6)$$

It should be noted in (5) that U is calculated from simulations in the linear amplification regime. The polarizer is adjusted such that the field component along (1, 1) will be passed through and that along (1, -1) will be blocked.

Now suppose that the input intensity to the SOA increases to values that are large enough to induce polarization-dependent nonlinear gain saturation. Then, after the PC some field component will be generated along (1, 1), which can be expressed as

$$\frac{1}{2} \begin{bmatrix} 1 & 1 \\ 1 & 1 \end{bmatrix} U \begin{bmatrix} \gamma^{\text{TE}} \\ \gamma^{\text{TM}} \end{bmatrix} \quad (7)$$

where $(\gamma^{\text{TE}}, \gamma^{\text{TM}})$ represents the field at B. The field, represented by (7), will enter the SOA again.

A spectral filter is included in the simulations in order to account for dispersion effects in the experiment. This filter also accounts partly for the gain dispersion. The filter in the system is modeled as a Lorentzian filter with a full-width at half-maximum (FWHM) of $2D$. The transfer function of the filter is

$$f(\omega) = \frac{D}{D - i(\omega - \omega_0)} \quad (8)$$

where ω_0 is the central angular frequency of the filter. The filter is implemented in the frequency domain using a fast Fourier transform (FFT) algorithm while an eventual filter-induced change of the pulse polarization is included in the unitary matrix U .

IV. SIMULATION RESULTS AND DISCUSSION

The SOA has a strained bulk active region of $250 \mu\text{m}$ and active volume of $50 \mu\text{m}^3$ [6]. Other parameters are listed in Table I. All calculations were performed for 160-mA injection current except stated otherwise. The parameter values of the SOA were chosen in such a way that stable mode locking occurs. This is

TABLE I
SOA PARAMETER DEFINITIONS AND THEIR VALUES

Parameter	Value	units
Active volume	$250 \times 2 \times 0.1$	μm^3
Confinement factor TE/TM/TPA	0.18/0.13/0.5	
Linewidth enhancement factor TE/TM/TPA	4/4/-1	
FCA coefficient in conduction band	3×10^{-9}	μm^2
FCA coefficient in valence band	0	μm^2
Electron-hole pair lifetime	300	ps
Gain coefficient TE/TM	1.4×10^{-5}	$\mu\text{m}^3/\text{ps}$
Group velocity	100	$\mu\text{m}/\text{ps}$
Internal loss	0.00175	μm^{-1}
Optical transition energies(conduction band)	0.05, 1.12	eV
Optical transition energies(valence band)	0.005, 0.11	eV
Carrier-carrier scattering time in conduction band	0.1	ps
Carrier-carrier scattering time in valence band	0.05	ps
Carrier-phonon relaxation time in conduction band	0.7	ps
Carrier-phonon relaxation time in valence band	0.25	ps
TPA coefficient	2×10^{-9}	μm^2
Optical transition state density	3.6×10^6	μm^{-3}
TPA: Two photon absorption		
FCA: Free carrier absorption		

not an easy task because the region in the parameter space that yields stable mode-locking appears to be quite small. For these values, the small-signal gain for TE and TM components are 16.8 and 14.8 dB, respectively.

Since the polarization rotation necessary for pulse narrowing is mainly due to nonlinear phase shifts, it is obvious that the linewidth enhancement factor α plays an important role. In our simulation, we use $\alpha = \alpha^{\text{TE}} = \alpha^{\text{TM}}$. The net pulse round-trip gain will increase with higher values of α . Therefore, for a given injection current, α should be larger than some threshold value to cause the ring to build up optical pulse and to converge to a stable pulse train. The threshold is determined by the SOA parameters and the round-trip losses. If α is smaller than the threshold value, the pulse will be attenuated, irrespective of the intensity value of the initial pulse. This follows from the computation of the round-trip gain, which is taken as the ratio between the current optical intensity at point A in Fig. 1 and its previous intensity, shown in (9) at the bottom of the page, where $\tau_0^{\text{TE}}, \tau_0^{\text{TM}}, \varphi_0^{\text{TE}}$, and φ_0^{TM} are the single-pass transmission and the phase of the pulse for TE and TM components in the low-input intensity case while $\tau^{\text{TE}}, \tau^{\text{TM}}, \varphi^{\text{TE}}$, and φ^{TM} are the time-dependent single-pass transmission and phase of the pulse for TE and TM components in the nonlinear regime at point B in Fig. 1. The t -dependence in (9) originates from the fact that different parts of the pulse have different phase and intensity. The round-trip gain should be larger than 0 dB for the pulse to build up.

In Fig. 2, the gain at the pulse peak in the first round-trip is shown as a function of the initial pulse energy for different α for the injection current of 160 mA. Throughout the paper “initial pulse” means the pulse in the zeroth round-trip, referring to the

$$G(t) = \frac{(\tau_0^{\text{TM}} \tau^{\text{TE}}(t))^2 + (\tau_0^{\text{TE}} \tau^{\text{TM}}(t))^2 - 2\tau_0^{\text{TE}} \tau_0^{\text{TM}} \tau^{\text{TE}}(t) \tau^{\text{TM}}(t) \cos\{(\varphi^{\text{TM}}(t) - \varphi^{\text{TE}}(t)) - (\varphi_0^{\text{TM}} - \varphi_0^{\text{TE}})\}}{2((\tau_0^{\text{TE}})^2 + (\tau_0^{\text{TM}})^2)} \quad (9)$$

Fig. 2. Round-trip gain at the pulse peak versus the initial pulse energy for different linewidth enhancement factors α in the first round-trip. (Initial pulse shape is chirp-free Gaussian with 2-ps rms width).

Fig. 3. Net round-trip gain at the pulse peak versus the initial pulse energy for different injection current in the first round-trip. (Linewidth enhancement factor α is 4, other parameters as in Fig. 2).

initial values set in the computer code. One readily observes that the linewidth enhancement factor α plays a crucial role in the pulse built-up process. For the pulse to be amplified and narrowed, α should be larger than 4. For a given α , the loop gain can be increased by pumping larger current into the active region. That is shown in Fig. 3 for $\alpha = 4$. However, for very small α it may become impossible to obtain $G > 0$ dB because of gain saturation at higher currents. In Figs. 2 and 3, initial pulses were taken to be Gaussian pulse with a root mean square (rms) width of 2 ps.

The simulations show that initial pulses with insufficient intensity cannot induce large enough phase shifts between TE and TM components for the pulse to acquire positive round-trip gain. This is shown in Fig. 4, where a 2-ps 0.22-pJ Gaussian initial pulse is seen to decrease after each round-trip. When the initial pulse intensity is increased beyond a threshold value, the pulse is amplified and narrowed in every loop. After several tens of round-trips the pulse has evolved into a stable shape. This is shown in Fig. 5 for an unchirped Gaussian shaped initial pulse of

Fig. 4. Initial pulse has insufficient energy for a net positive round-trip gain, even though the parameter values are within the mode-locking regime. Therefore, the pulse is attenuated after each round-trip. Note that narrowing takes place. The initial Gaussian pulse has a width of 2 ps, is unchirped and has energy of 0.22 pJ. After a few round-trips, the pulse has disappeared. The injection current is 160 mA and the linewidth enhancement factor is 4.

Fig. 5. Numerical simulation of the pulse built-up for the same laser as in Fig. 4. Initially the pulse has duration of 2 ps and its energy is 0.66 pJ. After 3 round-trips, the pulse duration has decreased to 815 fs and the pulse energy has decreased to 0.45 pJ. After 25 round-trips, the pulse has been shortened further to the ultimate width of 537 fs and energy 2.33 pJ. The filter bandwidth is 3.2 THz. The injection current is 160 mA and the linewidth enhancement factor is 4.

2-ps duration and 0.66-pJ energy. A filter of 3.2 THz (FWHM) was used. The dispersion in the laser cavity, simulated by the filter, is estimated to be 0.235 ps/nm. One can observe in Fig. 5 that after about 25 round-trips the stable state is achieved, which is characterized by 537-fs (rms) duration output pulse train. The energy of each pulse is 2.33 pJ.

The evolutions of the pulse peak power and the pulse rms width are presented in Fig. 6, in which the solid line corresponds to the above mentioned case of Fig. 5 and the dotted line corresponds to an initial pulse of 4 ps, unchirped Gaussian pulse with the energy of 1.33 pJ. Two other cases are also shown in Fig. 6, i.e., the dot-dashed line, which corresponds to a super Gaussian pulse [21] (order $m = 3$) with white intensity noise, and the dashed line, which corresponds to a pulse with non-Gaussian shape. Fig. 6 illustrates that the system with different initial pulses evolves into the same final state, i.e., a stable identical pulse train. In Fig. 7, the pulse evolution is shown for the case of the noisy super-Gaussian initial pulse.

Fig. 6. Evolution of the width and the peak power in the pulse built-up process. The solid line corresponds to a 2-ps Gaussian initial pulse; the dot-dashed line corresponds to a super-Gaussian pulse (order $m = 3$) with white intensity noise; the dotted line corresponds to a 4-ps Gaussian initial pulse, and the dashed line corresponds to an arbitrary non-Gaussian pulse. The peak power in all the cases is the same, except for the super-Gaussian case due to the contribution of noise. The filter bandwidth is 3.2 THz.

Fig. 7. Pulse evolution in the 20 round-trips during the built-up process for a super-Gaussian pulse (order $m = 3$) with white intensity noise. The initial pulse energy is 0.54 pJ and the pulsewidth is 1.27 ps. The filter bandwidth is 3.2 THz.

In Fig. 8, the optical spectra corresponding to the pulses shown in Fig. 5 are presented. The spectrum steadily broadens after each round-trip and finally the pulses achieve their stable spectrum. The initial Gaussian pulse is unchirped, and its product of the rms pulse temporal width and the rms spectral width is $\Delta t \Delta \nu \approx 0.08$ [22]. The stable output pulse has a rms temporal width of 537 fs and a rms frequency width of 0.56 THz, hence, their time-bandwidth product $\Delta t \Delta \nu = 0.3$. The relatively large value is mainly caused by the pulse shape in which the leading edge is much steeper than the trailing edge. By comparing this value with the time-bandwidth product of the same pulse but without chirp, which is 0.19, we conclude that the output pulse is moderately chirped. It is also seen from Fig. 8 that the main frequency components of the pulse are red-shifted.

According to the system principle, the polarizer blocks the pedestal in the leading edge of the pulse and this causes the

Fig. 8. Optical spectra corresponding to Fig. 5. Initially the spectral width is 40 GHz. After five round-trips, the spectral width has increased to 0.18 THz, and after 25 round-trips, the spectral width has stabilized at 0.56 THz. The origin in frequency axis is the initial pulse center frequency.

Fig. 9. Time-dependent nonlinear phase difference between the TE and TM components after the first round-trip, where the initial pulse is a 2-ps unchirped Gaussian pulse with different initial pulse energies, as indicated.

leading edge to be very steep (see Fig. 5). On the other hand, the trailing edge of the output pulse has a long tail, which is caused by the incomplete recovery of SOA gain and phase difference between TE and TM components. This is shown in Fig. 9, where the phase difference between the TE and TM components in one pulse after one round-trip for different initial pulse energies is presented. The corresponding asymmetry of the pulse shape is the reason why we choose rms width as a measure for the pulsewidth instead of FWHM, similarly for the pulse spectrum. We note here that the nonlinear phase difference between TE and TM components evolves in a similar way as the corresponding gains, which explains the importance of gain dynamics in the pulse evolution process. In Fig. 10, the polarization states are shown during the first, third, and 50th round-trips, in terms of azimuth and ellipticity angles. The intensity-dependent polarization states within the pulse duration can be clearly seen. We also observe from Fig. 10 the large residual effect in the trailing edge of the final output pulse.

Fig. 10. (a) Azimuth angle and (b) ellipticity of the pulse at the exit of the SOA after various round-trips as indicated. The initial pulse is a 2-ps, unchirped Gaussian pulse with 0.66-pJ energy.

The output pulsewidth was found to depend on the width of the filter that is added in the model in order to account for the effect of dispersive effects. The stable pulsewidth decreased for the increased filter bandwidth, as expected. The question arises as to what determines the ultimate pulsewidth. As shown in Table II, the pulsewidth decreased to 350 fs when the carrier-phonon scattering time in the conduction band was decreased to 500 fs. The pulsewidth increased to 645 fs when the carrier-phonon scattering time was increased to 1 ps. The pulsewidth is also found to be injection current dependent. As shown in Fig. 11, the final pulsewidth increases from 0.15 to 0.82 ps when the injection current is increased from 152 to 175 mA. In the simulations, the carrier phonon relaxation time is kept as 700 fs and the FWHM of the filter bandwidth is 3.2 THz. When the injection current is below 152 mA, the system cannot build up pulses anymore because the net round-trip gain falls below 0 dB. On the other hand, when the injection current is further increased to higher than 180 mA, instabilities instead of mode-locking occur. To understand this current dependence, one should realize that the long-lived tail in Fig. 9 (or Fig. 10) also depends upon the current. In fact, for high currents the

TABLE II
PULSE rms WIDTH VERSUS CARRIER PHONON RELAXATION TIME AT 160 mA

Carrier-phonon relaxation time (ps)	0.5	0.7	1
Final pulse RMS width (ps)	0.35	0.455	0.645

Fig. 11. Stable pulse rms width under different injection currents. The carrier-phonon relaxation time is 700 fs. The filter bandwidth is 3.2 THz.

Fig. 12. Pulse rms width evolution with time when there is no filter in the cavity under different currents (160 and 152 mA). Initially, the pulse has duration of 2 ps and its energy is 0.66 pJ.

long-lived tail in the nonlinear phase shifts between TE and TM components is further away from the initial value than for low currents. This makes the pulse compression for the high currents less efficient than for the low currents.

When the filter is removed from the cavity (corresponding to the ideal dispersion-free operation), the pulsewidth decreases continuously in time, as shown in Fig. 12. Here we observe a rapid initial drop in pulsewidth, followed by a much more gradual and ultimately even linear decrease to zero. In the first 20 round-trips, the pulse peak power evolves in the same way as described in Fig. 6 while the pulse energy increases to its maximum value after its initial drop in the first several round-trips. After about 20 round-trips, the pulse peak power remains approximately constant and decreases dramatically after 110 round-trips for 152 mA and 280 round-trips for 160 mA. The pulsewidth decreased so much that the pulse energy cannot maintain the required gain saturation anymore: the pulses fade away. Note that all these behaviors refer to a situation without

TABLE III
(a) ACHIEVABLE BIT RATE VERSUS CARRIER LIFETIME AT 160 mA.
(b) ACHIEVABLE BIT RATE VERSUS INJECTION CURRENT (CARRIER LIFETIME IS 300 ps)

Carrier lifetime (ps)	200	300	500
Achievable bit rate @ 160 mA (GHz)	20	5	2.5

(a)

Injection current (mA)	160	170	200
Achievable bit rate (GHz)	5	8	28

(b)

any dispersion. Clearly, the effect of dispersion is to stabilize the pulsewidth as is shown in Fig. 6. Looking again at Fig. 12, the values of the pulsewidth directly after the initial drops are close to the corresponding values in Fig. 11. Hence, the current dependence in Fig. 12 is fully consistent with Fig. 11.

The pulse repetition rate in the experiments was 14 MHz [16]. In our simulations so far, the SOA fully recovered during one round-trip, i.e., the cavity length was assumed to be long enough for such recovery, leading to upper bounds on the repetition rate. We also investigated the effect of partial SOA recovery during one round-trip. In a series of simulation experiments we found that the achievable pulse repetition rate is constrained by the carrier recovery time. If the repetition rate increases, the intensity of the pulses decreases due to gain depletion, until the pulse round-trip gain falls below 0 dB and the laser switches off. Once switched off, the system cannot start mode-locking again due to the bistable behavior. As presented in Table III(a), the pulse repetition rate is limited up to 5 GHz when the carrier lifetime is assumed to be 300 ps. The pulse repetition rate is increased to 20 GHz when the carrier lifetime is assumed to be 200 ps. The pulse repetition rate decreased to about 2.5 GHz when the carrier lifetime is assumed to be 500 ps. At the same time, the pulse repetition rate can be improved by injecting larger current. In Table III(b), the achievable repetition rates at different injection currents are presented. As clearly seen, the repetition rate can be increased when the injection current is higher. However, after a critical current, 200 mA in our case, instabilities instead of mode-locking occur.

V. SUMMARY AND CONCLUSION

In conclusion, the pulse narrowing process in a passive mode-locking system based on nonlinear polarization rotation in a SOA was modeled and simulated. The SOA model is based on the fact that TE and TM modes interact with each other via carriers. The model includes two-photon absorption, free-carrier absorption, self- and cross- phase modulation, carrier heating, and spectral hole burning. The PC and the polarizer were modeled as transmission matrices, which is an efficient way to model polarization-dependent effects.

We presented and discussed simulation results for the pulse built-up and narrowing as well as the pulse decay, depending on whether or not the initial pulse intensity is sufficiently high. The pulse narrowing mechanism is the self-induced nonlinear phase difference change between the TE and TM field components, which was found to be more than 1 radian when the

input pulse energy is 1 pJ (2-ps Gaussian pulse). The pulse built-up condition was investigated. By increasing the linewidth enhancement factor or the injection current, the required energy for the initial pulse to acquire net round-trip gain is decreased, which indicates that it is easier for the system to evolve into a stable mode-locking state. In the unrealistic case of dispersion-free operation, there is no fundamental limit to the pulse narrowing. However, in practice, the achievable pulsewidth is limited by both the cavity dispersion and the ultrafast gain dynamics, which is current dependent. For currents beyond a critical value, instabilities destroy the mode locking. The highest possible pulse repetition rate is increased by increasing the injection current while finally limited by the carrier lifetime. We obtained highest possible repetition rate of 28 GHz at 200 mA. In the experiment of [17], the pulsewidth (FWHM) and the spectral width (FWHM) are measured to be 800 fs and 0.62 THz, respectively. In our simulation of the experiment, those values are 960 fs and 0.53 THz, respectively. In terms of time-bandwidth product, the simulation value (0.51) is close to the experiment value (0.49). Therefore, we conclude that the simulation is in agreement with the experiment.

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