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Citation for published version (APA):

Gordon, C. D., Cumbajin, M., Carpintero, G., Bente, E., & Javaloyes, J. (2018). Absorber length optimization of on-chip colliding pulse mode-locked semiconductor laser. *IEEE Journal of Selected Topics in Quantum Electronics*, 24(1), [8063953]. <https://doi.org/10.1109/JSTQE.2017.2759263>

DOI:

[10.1109/JSTQE.2017.2759263](https://doi.org/10.1109/JSTQE.2017.2759263)

Document status and date:

Published: 01/01/2018

Document Version:

Publisher's PDF, also known as Version of Record (includes final page, issue and volume numbers)

Please check the document version of this publication:

- A submitted manuscript is the version of the article upon submission and before peer-review. There can be important differences between the submitted version and the official published version of record. People interested in the research are advised to contact the author for the final version of the publication, or visit the DOI to the publisher's website.
- The final author version and the galley proof are versions of the publication after peer review.
- The final published version features the final layout of the paper including the volume, issue and page numbers.

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Absorber Length Optimization of On-Chip Colliding Pulse Mode-Locked Semiconductor Laser

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Abstract—We present theoretical and experimental results regarding the saturable absorber length optimization for the generation of stable mode-locked regimes of a novel on-chip colliding pulse mode-locked semiconductor laser structure. We have been able to apply the design criteria acquired from previous theoretical and experimental reports to define a suitable gain section length for a given saturable absorber section length. The latter is independent from the cavity length and allows obtaining stable mode-locked regimes with the required repetition rate and pulse width in the range of picoseconds for different applications. We have developed four on-chip colliding pulse mode-locked laser structures with saturable absorber lengths ranging from 20 to 50 μm in steps of 10 μm with fundamental repetition rate at 25 GHz and twice this frequency at 50 GHz when operated in the colliding pulse mode-locked regime. The theoretical study was carried out by using the simulation tool called FreeTWM which is a free travelling wave model software designed for the study of the dynamics of multi-section semiconductor lasers, while the experimental analysis was executed on the samples fabricated on a generic InP photonic integrated technology through a multi-project-wafer run.

Index Terms—Laser mode locking, optical pulse generation, semiconductor lasers, quantum well lasers, semiconductor device modeling.

I. INTRODUCTION

INTENSE theoretical and experimental research has been carried out for the generation of ultrafast and ultrashort optical pulses using the colliding pulse mode-locked (CPM) technique applied to semiconductor lasers [1], due to the fact that

such kind of pulses are required for a wide range of applications among them telecommunications, metrology, medicine and so on [2]. On the one hand, the theoretical study of the dynamics of colliding pulse mode-locked semiconductor lasers is still a challenge and it has been carried out by using different approaches. The first approach is the Haus' master equation, which is based on the time domain and is capable to provide only some very qualitative predictions due to the many simplifying hypothesis involved [3]. The second approach focuses on subwavelength finite difference time domain description of the electromagnetic field, which allows satisfactorily describing the ultrafast dynamics, at the expense of requiring an enormous computational power in order to compute long time series for assessing timing jitter or pulse fluctuations [4]. An alternative approach with the intention to circumvent the limitation of both previous approaches has been reported, which consists in a travelling-wave model (TWM) for resolving the propagation of the electromagnetic waves under the slowly varying approximation [5]. On the other hand, the successful experimental study of the dynamics of mode-locked semiconductor lasers has been executed not only thanks to the samples developed using different kind of configurations such as self-colliding [6], colliding [7], anti-colliding [8], or multiple colliding [9], but also thanks to different kind of semiconductor structure such as quantum well [10], quantum well intermixing [11], quantum dot [12], bulk material [13] and so on.

The potential scheme for the generation of ultrafast and ultrashort optical pulses with excellent characteristics is the CPM semiconductor laser assembly [14], which has been discussed theoretically in detail [15] and experimentally demonstrated for the first time, many years ago [16]. The structure of the CPM lasers comprises a saturable absorber (SA) section located in the middle of the resonator cavity between two semiconductor optical amplifier (SOA) sections. The distribution of the SOA and SA within the Fabry-Perot cavity allows the collision of two counter-propagating pulses which leads to a more effective saturation of the absorber, an increased stability [10], a doubling of the repetition rate [14], [15] and to additional pulse shortening [17]. Also, the DC forward bias current of the SOA sections and the DC reverse bias voltage applied to the SA section allow reaching passive colliding pulse mode-locked regimes at high speed avoiding the limitations imposed by electronic sources when ultrafast direct modulation is required as in active mode-locking [18]. Moreover, Fourier-transform-limited pulses with pulse duration less than 1 ps [17] and pulse repetition rates

Manuscript received April 2, 2017; revised September 21, 2017; accepted September 29, 2017. Date of publication October 10, 2017; date of current version October 24, 2017. This work was supported in part by Spanish Ministerio de Economía y Competitividad DiDACTIC project (TEC2013-47753-C3-3-R), in part by Consejería de Educación, Juventud y Deporte of Comunidad de Madrid DIFRAGEOS project (P2013/ICE-3004), in part by project COMBINA (TEC2015-65212-C3-3-P AEI/FEDER UE), and in part by Ramón y Cajal fellowship. (*Corresponding author: Carlos Gordón.*)

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Digital Object Identifier 10.1109/JSTQE.2017.2759263

ranging from 10 GHz [19] to 480 GHz [20] are routinely achieved by CPM lasers.

A variety of monolithic semiconductor mode-locked laser structures have been reported, among them we have the realization of mode-locked lasers with an all-active semiconductor structure [21] and recent successful experimental demonstrations with extended cavity mode-locked laser structures. Unfortunately, the former structures increase: the intensity modulation in the range of relaxation oscillation [22], quantum noise [23], self-phase modulation [24], timing jitter, thus leading to pulse broadening [11]. All these drawbacks reveal that active waveguides are not the optimum medium to propagate short optical pulses. The latter structures use the active-passive integration, which allow including passive waveguide sections in order to avoid the disadvantages of all-active semiconductor mode-locked laser structures. As a result, extended cavity mode-locked lasers, which include passive waveguide sections, demonstrated improved stability of the mode-locked regimes, reduced phase noise and timing jitter, as a consequence of the reduction of the ratio of the active sections with respect to the passive ones [25], [26].

The simplest structure of the CPM which only includes SOA and SA sections allows the implementation on a photonic integrated circuit (PIC) [26]. The PICs which use active-passive integration, enable increased functionality and circuit reliability, while reducing their size, power, and cost [27], [28]. Also, the active-passive integration allows to set the length of the gain sections and adjust the length of the resonator cavity by changing the length of the passive sections in order to meet the specification of the required repetition rate for a particular application, independent from the ratio between the lengths of the gain and absorber sections [14]. As an added value, the previous theoretical and experimental reports provide the knowledge background and allow establishing the design rules which recommend the suitable lengths for the gain and absorber sections independently from the cavity length in order to achieve stable mode-locked regimes [29], [30]. Moreover, the use of the novel on-chip mirrors like the multimode interference reflectors allows the on-chip integration of the mode-locked laser, obtaining such state-of-the-art structures. The advantages of the on-chip mode-locked laser structures have been reported which provide the control of the amount of power at the output due to the relative position of the gain and absorber sections within the cavity using anti-colliding structures [31], or even the pulse shortening and beating linewidth reduction using complex mode-locked assemblies with distributed Bragg reflectors [32]. Also, on chip mode-locked lasers have been demonstrated to generate millimeter waves around 100 GHz thanks to the multiple colliding pulse mode-locking structure [33].

The main purpose of this work is to report the theoretical and experimental achievements of the absorber length optimization for the generation of stable mode-locked regimes of the newly designed on-chip colliding pulse mode-locked semiconductor laser (oc-CPM) structure. The theoretical achievement was carried out by using the simulation tool called FreeTWM which is a free travelling wave model software designed for the study of the dynamics of multi-section semiconductor lasers [34] while

Fig. 1. Structure of on-chip colliding pulse mode-locked laser.

the experimental study was executed on the samples fabricated by SMART Photonics on a generic InP photonic integrated technology through a multi-project wafer (MPW) run [35]. Also, the intention of this work is to provide the design criteria to define a suitable gain section length for a given saturable absorber section length that is independent from the cavity length. Thus, we are able to develop mode-locked laser structures capable to generate stable mode-locked regimes with the required repetition rate and pulse width for a particular application. The parameter considered to estimate the stability of the oc-CPM is the time bandwidth product (TBP) which is the figure of merit for the assessment of pulse quality of the extended cavity mode-locked laser structure [36].

II. DEVICE DESCRIPTION

We have developed four on-chip colliding pulse mode-locked quantum well semiconductor lasers with an extended cavity configuration. The structure of the oc-CPM is sketched in Fig. 1, which mainly comprises a SA and two SOAs. The SA is easily located at the center of the cavity, designing the resonator to be symmetrical on both sides of the SA. Thus, the precision with which the SA is located at the center depends on the lithographic process tolerances, down to the nanometer range. On each side of the SA, two SOAs of equal length are placed. The SOA is then followed by an active-passive transition and a passive waveguide. The passive waveguides not only are necessary to connect the SOA to the multimode interference reflectors (MIR) and set resonator cavity on-chip [37], but also allow us to control the resonator cavity length, and therefore, the repetition rate. On both sides, two ports 50% MIR reflectors define the resonator cavity and provide optical output. The optical output was 7° angled with respect to the cleaved and AR-coated facet in order to minimize back reflections from the edges of the chip. Considering that symmetry in colliding pulse mode-locked lasers ensures the best quality for the generated optical pulses [14], the same type of MIR reflectors on both ends was used.

The oc-CPMs with extended cavity linear laser configuration are capable to generate the fundamental repetition at 25 GHz, while the colliding pulse mode-locked regime is increased up to 50 GHz. The lengths of the total gain section and the cavity are the same while changing the length of the saturable absorber in order to carry out the optimization of the saturable absorber length. The selected absorber lengths for the study were 50 μm , 40 μm , 30 μm and 20 μm which are typical lengths stated in theoretical and experimental reports of colliding pulse mode-locked lasers [14], [29], [30]. Likewise, the microscope photograph of the fabricated oc-CPMs is shown in Fig. 2, where

Fig. 2. Microscope photograph of the oc-CPMs, with different saturable absorber length.

TABLE I
COMPONENTS LENGTH

Devices	MIR	SOA	SA	ISO	PW	L_{CAV}
Dev_SA50	90.3	455	50	20	451.4	1632
Dev_SA40	90.3	460	40	20	451.4	1632
Dev_SA30	90.3	465	30	20	451.4	1632
Dev_SA20	90.3	470	20	20	451.4	1632

Features of oc-CPMs fabricated for the saturable absorber length optimization.

the SA contacts are visible at the center of the cavity with their respective length. The different elements in the resonator are clearly visible, showing the symmetry around the SA. The four on-chip colliding pulse mode-locked laser structures were designed with the same cavity length which is $L_{CAV} = 1632 \mu\text{m}$. All of them have the same active region length, fixed to $1000 \mu\text{m}$. The lengths of the two SOAs add up to 930, 940, 950, $960 \mu\text{m}$, separated by the 50, 40, 30, $20 \mu\text{m}$ SA at the center respectively. In each case, two $20 \mu\text{m}$ isolators at both sides of the SA are located. Table I summarizes the features of all devices developed in the MPW run, with the component lengths, fundamental frequency (FF) which is the repetition rate and second harmonic frequency (SHF), which is the expected twice of the FF due to the colliding pulse mode locked repetition rate.

The four on-chip colliding pulse mode-locked laser structures were designed considering the rules provided by previous reports [14], [29], [30]. The design rules offer the design criteria for the optimized design of mode locked semiconductor lasers which meet the pulse source requirements for communications systems [38]. The essential rules are related to the length of the saturable absorber to the total cavity length and the relation between the gain and absorber section lengths.

Rule 1: the length of the saturable absorber related to the total cavity length (L_{SA}/L_{CAV}) ranging from 1% to 5% provides stable mode locked regimes [14], [30].

Rule 2: the relation between the gain and absorber section lengths (L_{SOA}/L_{SA}) from 10 to 20 times allows reaching stable mode locked regimes [14], [29].

A recent experimental study demonstrated a mode-locked laser diode with an extremely long ring cavity capable to generate 2.5 GHz repetition rate [39]. The design rule 1 was not

satisfied because of the $50 \mu\text{m}$ saturable absorber length used in the device provided a relation $L_{SA}/L_{CAV} < 1\%$ due to the long cavity length configuration, while the design rule 2 is satisfied with the relation $L_{SOA}/L_{SA} \approx 15$ times. This recommends that the most critical rule that needs to be satisfied is the design rule 2, in order to obtain stable mode-locked regimes. As a result, we can fix both rules independently due to the fact that length of the cavity is not related to the length of the SOA. Table II shows the design rules and the result of its application in the design stage of the four samples.

III. SIMULATION TOOL

The simulation of the oc-CPM was carried out by using the FreeTWM (travelling wave model) software. The FreeTWM is free software designed for the study of the dynamics of multi-section semiconductor lasers based on the traveling wave approach of Maxwell Bloch equations [34]. Active-passive coupled sections can be modeled by using this free software. The program is implemented as an ensemble of functions to be used from within Octave or Matlab. The FreeTWM software allows reproducing the dynamics of semiconductor lasers, which we will use to fit our experimental results qualitatively.

There are several key parameters that affect the dynamics and the mode-locked properties of semiconductor Fabry–Perot lasers with intracavity saturable absorber such as the influence of the saturable absorber length, recovery time of the saturable absorber, intraband relaxation time, and gain/absorber relative frequency shift, which have been theoretically studied with the FreeTWM software [30]. In the present work, we have studied as key parameter, the influence of the saturable absorber length section in the generation of stable mode-locked regime.

The structure of mode-locked laser is composed of different sections within the mode locked laser cavity such as gain, absorber, and passive sections. Fig. 3 depicts the different sections considered in the FreeTWM.

Also, it is necessary to set the material parameters for each section. The waveguide parameters are well known for semiconductor InP waveguides with the emission wavelength at $1.55 \mu\text{m}$. The facet reflectivity is 50% provided by the two ports MIR reflectors and the single trip time in the cavity is 12.5 ps which correspond to 25 GHz fundamental repetition rate linear cavity mode-locked laser.

The parameters for the gain section such as the internal losses, saturated gain factor, polarization decay rate, and the transparency carrier density have been confirmed by gain measurements of a InGaAsP/InP quantum well based gain section. While, the recombination coefficients A, B, C correspond to the InGaAsP/InP material [40] and the rest of parameters have been obtained from previous theoretical studies [30].

The absorber section works in the regime of slow saturation, so the absorber recovery time of the saturable absorber must be taken longer than the pulse duration and shorter than the round trip time [41]. The absorber recovery time used in the simulation has 10 ps and the bandgap offset is 5 THz. Also, the parameters for the passive section are set to zero (0) due to the fact that there are no gain factor, nor radiative, spontaneous and Auger

TABLE II
DESIGN RULES

Design criteria	Dev_SA50	Dev_SA40	Dev_SA30	Dev_SA20
Rule 1: L_{SA}/L_{CAV} 1% to 5%	50/1632 $\approx$ 3%	40/1632 $\approx$ 2.45%	30/1632 $\approx$ 1.84%	20/1632 $\approx$ 1.23%
Rule 2: L_{SOA}/L_{SA} 10 to 20	455/50 $\approx$ 10	460/40 $\approx$ 12	465/30 $\approx$ 16	470/20 $\approx$ 24
Result	The design meets the criteria	The design meets the criteria	The design meets the criteria	Outside the upper limit of Rule 2.

Design rules and the result of its application. We designed the Dev_SA20 outside the upper limit of Rule 2, with the intention to study the mode-locked regimes under this feature.

Fig. 3. Structure of the oc-CPM used by FreeTWM.

TABLE III
MATERIAL PARAMETERS

Meaning	Symbol	Value	Units
Waveguide Parameters			
Emission wavelength	λ_o	1.55	μm
Group refractive index	n_g	3.57	
Transparency Carrier Density	N_t	1×10^{18}	cm^{-3}
Group Velocity	$v_g = \frac{c}{n_g}$	0.84×10^8	m/s
Left facet reflectivity	R_r	50%	—
Right facet reflectivity	R_l	50%	—
Single trip time in the cavity	τ_g	12.5	ps
Gain Section Parameters			
Internal losses	$2\alpha_i$	14.4	cm^{-1}
Saturated gain factor	$2\chi_0$	424	cm^{-1}
Intraband relaxation time	τ_k	125	fs
Bandgap offset	Ω_g	0	THz
Empty band contribution	Ω_t	90	THz
Transparency current	J_t	8.1×10^8	$\text{cm}^3 \cdot \text{s}^{-1}$
Non radiative recombination	A	1×10^8	s^{-1}
Spontaneous recombination	B	7×10^{-10}	$\text{cm}^3 \cdot \text{s}^{-1}$
Auger recombination	C	1×10^{-29}	$\text{cm}^6 \cdot \text{s}^{-1}$
Ambipolar diffusion coefficient	$\mathcal{D}$	12	$\text{cm}^2 \cdot \text{s}^{-1}$
Noise variance	β	3×10^{-3}	—
Absorber Section Parameters			
Bandgap offset	Ω_g	5	THz
Non radiative recombination	A	$1/10 \times 10^{-12}$	s^{-1}
Absorber recovery time	τ_{SA}	10	ps

Parameters used by FreeTWM [40].

recombinations. All the parameters required by the FreeTWM software for the different sections are summarized in Table III.

The FreeTWM software provides the profiles for the optical power, electric field intensity and carriers concentration against a discretized length, obtained after 500 single trips in the cavity. The discretized length is directly related to the cavity length in micrometers, so 1632 μm in the cavity length correspond to 1632 points in the discretization. The blue and red lines in Fig. 4(a) represent the forward and the backward waves, respectively. We clearly observe the intensities and fields of the two optical pulses coexisting within the cavity which are depicted in

Fig. 4. Profiles of Dev_SA50, delivered by FreeTWM. (a) Optical power, (b) electrical field intensity, and (c) carriers concentration.

Fig. 5. Experimental setup. I: Current source, -V: reverse bias voltage, TE cooler: thermoelectric cooler, OI: optical isolator, PM: power meter, EDFA: erbium doped fiber amplifier, PC: polarization controller, AC: autocorrelator, OSA: optical spectrum analyzer.

Fig. 4(a) and (b). Also, it is clearly observable the amount of carriers concentrated in SOA sections which are depicted in Fig. 4(c).

IV. EXPERIMENTAL SETUP

The setup that we have used to characterize the chip is sketched in Fig. 5. The device is mounted on a copper chuck that was temperature stabilized to 16 $^{\circ}\text{C}$. The electrical access was provided through DC needle probes. The current into the two SOA sections was supplied from a Thorlabs PRO 8000 laser diode controller, while the reverse bias into the SA was provided by an Agilent E3631A voltage source. The optical output from the angled facet of the oc-CPM was collected using anti-reflection coated lensed fibers, including an optical isolator (OI). This element was followed by a 90/10 splitter which divided the light in two branches. The 10% branch is connected to a Newport 842-PE power meter (PM), providing the measurement of the generated optical power all the time. The other

Fig. 6. Simulated optical spectrum. (a) Dev_SA50. (b) Dev_SA40. (c) Dev_SA30. (d) Dev_SA20.

branch, with 90% split, is used to characterize the device using different instruments. The optical characterization includes a Yokogawa AQ6370B optical spectrum analyzer (OSA), to observe the optical spectrum. Also, after being amplified on a Nor-tel FA14UFAC telecom erbium doped fiber amplifier (EDFA), an APE pulse-check auto-correlator (AC) estimates the pulse autocorrelation.

V. CHARACTERIZATION RESULTS

The characterization in detail of the colliding pulse mode-locked regime was carried out at a bias setting which exhibits a colliding pulse mode-locked regime. For the sake of comparison between theoretical and experimental achievements of the absorber length optimization, the similar amount of power around 1 mW at the output was considered. In the experimental results, the gain section was forward bias at $I_{SOA} = 64$ mA which is double of the threshold current and SA reverse biased $V_{SA} = -2.2$ V. Similarly, for the simulation results the bias setting was at injected carrier rate $J_{-(ZJ)SOA} = 120.68 \text{ s}^{-1}$, which is also double of the threshold current rate obtained from the FreeTWM, and the absorber section works in the regime of slow saturation so the absorber recovery time is $\tau_{SA} = 10$ ps. We will refer to these bias settings as colliding pulse mode-locked bias settings for all the samples developed in the saturable absorber length optimization. Once, the simulation and experimental processes have been carried out, we present the results for each laser with different length of the SA.

A. Optical Power Characteristics

The simulated optical spectrum of the samples with SA section lengths of $50 \mu\text{m}$, $40 \mu\text{m}$, $30 \mu\text{m}$ and $20 \mu\text{m}$ simulated at the colliding pulse bias settings are shown in Fig. 6(a), (b), (c), and (d), respectively. The simulation results, confirms the colliding pulse mode locked regimes at different length of the SA section. We observe in the insets the fundamental repetition rate at 25 GHz and twice this frequency 50 GHz due to the colliding pulse mode-locked regime for all the samples. The main

Fig. 7. Experimental optical spectrum. (a) Dev_SA50. (b) Dev_SA40. (c) Dev_SA30. (d) Dev_SA20.

parameter which catches our attention is the side mode suppression reduction when the length of the SA section decreases. For the samples with SA section lengths of $50 \mu\text{m}$, $40 \mu\text{m}$, $30 \mu\text{m}$ and $20 \mu\text{m}$, the side mode suppression is 40 dB, 19 dB, 12 dB, and 8 dB, respectively. Also, the estimated spectral width obtained from the Gaussian fitting is 370 GHz, 350 GHz, 360 GHz, and 375 GHz, which correspond to the devices with SA section length $50 \mu\text{m}$, $40 \mu\text{m}$, $30 \mu\text{m}$ and $20 \mu\text{m}$, respectively.

Fig. 7(a), (b), (c), and (d) sketch the measured optical spectrum for the oc-CPM with SA section length of $50 \mu\text{m}$, $40 \mu\text{m}$, $30 \mu\text{m}$ and $20 \mu\text{m}$, respectively. We also observe the colliding pulse mode-locked regimes at different lengths of the SA sections. The insets in all figures show the fundamental repetition rate at 25 GHz and twice this frequency 50 GHz due to the colliding pulse mode-locked regime for all the samples. The side mode suppression reduces gradually when the length of the SA section decreases. For the samples with SA section lengths of $50 \mu\text{m}$, $40 \mu\text{m}$, $30 \mu\text{m}$ and $20 \mu\text{m}$, the side mode suppression is 35 dB, 20 dB, 15 dB, and 8 dB, respectively. Also, the estimated spectral width obtained from the Gaussian fitting is 325 GHz, 360 GHz, 410 GHz, and 450 GHz, which correspond to the devices with SA section length $50 \mu\text{m}$, $40 \mu\text{m}$, $30 \mu\text{m}$ and $20 \mu\text{m}$, respectively.

B. Pulse Characterization

The pulse width obtained from the simulation is depicted in Fig. 8(a), (b), (c), and (d) related to the devices with SA section length of $50 \mu\text{m}$, $40 \mu\text{m}$, $30 \mu\text{m}$ and $20 \mu\text{m}$, respectively. For Dev_SA50, a Gaussian pulse shape fitting was used in order to estimate the pulse width $\Delta\tau_{S-50} = 1.30$ ps and the corresponding time bandwidth product obtained was $\text{TBP}_{S-50} = 0.48$. For Dev_SA40, the pulse width of $\Delta\tau_{S-40} = 1.20$ ps was estimated from hyperbolic secant pulse shape fitting and the corresponding time bandwidth product obtained was $\text{TBP}_{S-40} = 0.42$. In the same way, for Dev_SA30, a Lorentzian pulse shape fitting was used in order to estimate the pulse width $\Delta\tau_{S-30} = 1.10$ ps and the corresponding time bandwidth

Fig. 8. Simulated pulse width. (a) Dev_SA50. (b) Dev_SA40. (c) Dev_SA30. (d) Dev_SA20.

Fig. 9. Experimental pulse width. (a) Dev_SA50. (b) Dev_SA40. (c) Dev_SA30. (d) Dev_SA20.

product obtained was $TBP_{S-30} = 0.40$. For Dev_SA20, the pulse width of $\Delta\tau_{S-20} = 1.0$ ps was estimated from Lorentzian pulse shape fitting and the corresponding time bandwidth product obtained was $TBP_{S-20} = 0.37$. It is important to highlight that for all devices the pulse width obtained was close to the Fourier transform limit for the corresponding devices.

The experimental autocorrelation traces for all samples are depicted in Fig. 9(a), (b), (c), and (d) for Dev_SA50, Dev_SA40, Dev_SA30, and Dev_SA20, respectively. The pulse width from the deconvolution of the autocorrelation trace was estimated using the corresponding pulse shape fitting previously mentioned in the simulation stage. So, the pulse width and the TBP for the samples of SA section length of 50 μm , 40 μm , 30 μm and 20 μm are $\Delta\tau_{SA50} = 1.50$ ps, $TBP_{SA50} = 0.49$, $\Delta\tau_{SA40} = 1.22$ ps, $TBP_{SA40} = 0.44$, $\Delta\tau_{SA30} = 0.95$ ps, $TBP_{SA30} = 0.39$, $\Delta\tau_{SA20} = 0.85$ ps, and $TBP_{SA20} = 0.38$, respectively. Also, the experimental results reveal that all samples allow achieving time bandwidth products close to the transform limit.

Also, the optical pulse train of the oc-CPM simulated by the FreeTWM software is sketched in Fig. 10(a), (b), (c), and (d)

Fig. 10. Simulated pulse train. (a) Dev_SA50. (b) Dev_SA40. (c) Dev_SA30. (d) Dev_SA20.

Fig. 11. Experimental pulse train. (a) Dev_SA50. (b) Dev_SA40. (c) Dev_SA30. (d) Dev_SA20.

for Dev_SA50, Dev_SA40, Dev_SA30, and Dev_SA20, respectively. While, the experimental results of the oc-CPM recorded by the APE Pulse-Check autocorrelator are depicted in Fig. 11(a), (b), (c), and (d) for Dev_SA50, Dev_SA40, Dev_SA30, and Dev_SA20, respectively. All results were recorded at the colliding pulse bias settings in a period of 50 ps. Three pulses with a time between pulses of 20 ps which correspond to 50 GHz frequency, is observed in all cases. The repetition rate frequency of 50 GHz confirms that the oc-CPM laser works at the colliding pulse mode-locked regime.

C. Analysis of the Saturable Absorber Length Influence

From the comparison of the simulation an experimental results of oc-CPM with different saturable length, we confirm the design rules provided by previous reports [14], [29], [30] for our colliding laser structures. The evaluation among all the samples with different saturable absorber length allows assessing the mode-locking regimes and estimating the tendency of the pulse width, time bandwidth product, and side mode suppression ratio

TABLE IV
MODE-LOCKING REGIMES AND DESIGN RULES

Design criteria	Dev_SA50	Dev_SA40	Dev_SA30	Dev_SA20
Rule 1: L_{SA}/L_{CAV} 1% to 5%	Yes	Yes	Yes	Yes
Rule 2: L_{SOA}/L_{SA} 10 to 20	Yes (Close to the lower limit)	Yes (Within the limits)	Yes (Close to the upper limit)	No (Outside the upper limit)
Mode-locked Regime	Stable	Stable	Stable	Stable

while the length of the SA changes from 20 μm to 50 μm in steps of 10 μm .

For Dev_SA50, Dev_SA40 and Dev_SA30, which meet the design criteria, the relations of the absorber section length to cavity length are $L_{SA-50}/L_{CAV} \approx 3\%$, $L_{SA-40}/L_{CAV} \approx 2.45\%$, and $L_{SA-30}/L_{CAV} \approx 1.84\%$, respectively. Regarding the gain to absorber, the ratios are $L_{SOA-50}/L_{SA-50} \approx 10$ times, $L_{SOA-40}/L_{SA-40} \approx 12$ times, and $L_{SOA-30}/L_{SA} \approx 16$ times. Finally, regarding the evaluation of the mode-locking regimes and considering Table IV, these devices Dev_SA50, Dev_SA40 and Dev_SA30 deliver stable pulse train.

Moreover, stable mode-locked regimes were achieved by Dev_SA20 in spite of both design rules are not met simultaneously. For Dev_SA20 the relations are $L_{SA-20}/L_{CAV} \approx 1.23\%$ and $L_{SOA-20}/L_{SA-20} \approx 24$ times so the gain section is larger than the design rule recommendation. The Dev_SA20 works in mode-locking regime, but we have to consider that the larger gain sections should be avoided due to the fact that an active waveguide is not the optimum medium in which to propagate short pulses because the pulses are broadened by the group velocity dispersion induced by the gain dispersion, such that the broadening depends on the active section length. Finally, Table IV summarizes the rules and the mode-locked regimes.

From the comparison between simulation and experimental results, we conclude that the saturable absorber length variation affects the pulse width, time bandwidth product, and side mode suppression ratio. We confirm a direct relation among pulse width, time bandwidth product and side mode suppression ratio against saturable absorber length [14]. When reducing the length of the saturable absorber from 50 μm to 20 μm we observe the following behavior in the simulation and experimental results. First, the pulse width reduces from 1.30 ps to 1.0 ps in the simulation results, while reduces from 1.50 to 0.85 ps in the experimental results. The pulse shape also changes while the pulse width reduces, starting with Gaussian pulse shape, passing through hyperbolic secant pulse shape, and finishing with Lorentzian pulse shape in the simulation and experimental results simultaneously. Second, time bandwidth product also reduces from 0.48 to 0.37 in the simulation or from 0.49 to 0.38 in the experimental results. And finally, the side mode suppression ratio reduces around 8 dB·m for each 10 μm length reduction of the saturable absorber, from 40 dB·m to 8 dB·m in the simulation or from 35 dB·m to 10 dB·m in the experimental results. Moreover, it is important to highlight that while the reduction of the pulse width, TBP and SMSR occur, the repetition rate does not change in any device and remain at 50 GHz (time between pulses of 20 ps). So, we are able to confirm that the repetition rate frequency is not affected by the saturable absorber length reduction.

Fig. 12. Saturable absorber length influence. (a) Pulse width, (b) TBP, and (c) SMSR vs. saturable absorber length.

Fig. 12(a)–(c) show the simulation and experimental results of pulse width, time bandwidth product and side mode suppression ratio tendency while the saturable absorber length changes. In order to demonstrate that the variability of experimental results are within the tolerances of the results obtained from the FreeTWM software, 20% error bars were included in the pulse width results while 10% error bars were used in the time bandwidth product and side mode suppression ratio results in order to consider that the measurement is within the estimated tolerances.

VI. CONCLUSION

In summary, we have presented the theoretical and experimental achievements of absorber length optimization for the generation of stable mode-locked regimes of an on-chip colliding pulse mode-locked semiconductor laser structure. We have been able to apply the design criteria to define a suitable gain section length for a given saturable absorber section length independent from the cavity length in order to obtain stable mode-locked regimes.

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