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Theoretical and Experimental Investigation of Unidirectionality in an Integrated Semiconductor Ring Mode-Locked Laser with two Saturable Absorbers

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Abstract—The lack of integrated optical isolators in standard integrated semiconductor photonics platforms leaves integrated lasers vulnerable to back reflections. A hypothesis is that by making a ring laser operate unidirectionally, external reflections will couple back into the non-lasing direction, and the sensitivity towards reflections will be reduced. In this paper, unidirectionality is pursued by placing two saturable absorbers asymmetrically in a ring mode-locked laser. In the case of passive mode-locking, and for internal reflections below -75 dB, simulations, based on the Slowly Varying Envelope Approximation, show extinction ratios of up to 37 dB between the two propagation directions. For larger reflections the extinction ratio degrades linearly with reflection magnitude. The extinction ratio is shown to increase when the reverse bias of the saturable absorbers is modulated actively with a phase difference. Our simulations show that unidirectional operation reduces the amplitude noise in the frequency range 1 MHz to 10 GHz from around 0.022 % to 0.004 % when compared to bidirectional operation, whereas the timing jitter of the pulse train increases from around 172 fs to 412 fs. Experiments show that the extinction ratio of a realization of this mode-locked laser design is limited to around 3 dB. Simulations suggest that this is due to internal butt-joint reflections in the laser cavity.

Index Terms—Laser mode locking, semiconductor lasers, photonic integrated circuits, unidirectional laser, phase noise

I. INTRODUCTION

The interest in photonic integrated circuits (PICs) has increased during the recent years, for example due to their high speed performance in intra-datacenter interconnects. There are no indications that this trend will stop since the demands for high bandwidth just seem to grow [1]. Moreover, the fact that certain foundries have made PICs cheaper and more accessible, through standardized foundry processes and so-called multi project wafer runs, also points in the direction of a sustained interest [2]. However, certain limitations still need to be overcome in order to make the PIC technology more

robust and thereby more attractive. One of these limitations is the lack of integrated optical isolators, and thus there is a need for stable lasers which are not influenced by the back reflections originating from on-chip components.

One class of lasers is the mode-locked laser (MLL), i.e., a pulsed laser, which is made by phase locking the different longitudinal modes in the cavity of a multimode laser. The frequency of the pulse train is typically in the range of tens of gigahertz for integrated MLLs [3], turning them into important components of low noise microwave oscillators such as the coupled opto-electronic oscillator (COEO) [4]. Many applications rely on stable microwaves both in terms of timing jitter and amplitude noise. For example, the effective number of bits in an ADC relies on both parameters and is thus greatly influenced by the quality of the oscillator [5]. Optical ADCs also utilize the short pulses generated by MLLs in order to limit the aperture time [6]. Doppler radars [7], clock recovery circuits [8], clock distribution [9], optical communications [10] and optical frequency metrology [11] are also examples of applications that rely on stable microwave oscillators. Moreover, since the pulsed MLL output in the frequency domain corresponds to a comb of equally spaced frequencies, the MLL can be used as a comb source for Wavelength Division Multiplexing (WDM) [12].

In all these cases a stable pulse train is needed, but if unwanted feedback, i.e. external reflections, in subsequent parts of the PIC is introduced to a laser, it might cause an unstable output and/or increase the timing jitter of the pulse train [13], [14]. In bulk optics, isolators based on the Faraday rotation in magneto-optic materials are very effective and feasible, and are used to break the reciprocity of light propagation and achieve a loss difference between forward and backwards propagating light, thus isolating lasers from unwanted reflections. Isolation techniques based on magneto-optic effects have also been presented in integrated photonics, but they lack either small size or compatibility with existing foundry processes [15]–[17]. Other approaches without the use of magneto-optic materials have also been proposed. One way is to utilize phase modulators in Mach-Zehnder configurations. However, this approach relies on active modulation and thus access to control electronics [18], [19]. Also non-linear phenomena in active materials have been utilized to provide isolation of pulsed signals, but in this approach the isolation depends on

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Fig. 1. Overview of the asymmetric ring MLL design.

the magnitude of the signal, and additional noise in the form of amplified spontaneous emission (ASE) is introduced as well [20]. Thus, several issues prohibit existing approaches to be widely employed, even though they exhibit a certain degree of isolation, and thus lasers are still left unprotected from back reflections on PICs. A way to circumvent the lack of isolators is to make the lasers insensitive to back reflections by establishing a small loss difference between the counter clockwise (CCW) and clockwise (CW) directions in a ring laser, as hypothesized in [21], [22], and thus make it operate unidirectional. From this rationale the initial step in achieving a feedback insensitive laser is to make it operate unidirectional, which is the background for the work in this paper. The approach used for achieving unidirectionality should also, preferably, be compatible with existing standard semiconductor photonics foundry processes.

This paper treats, theoretically and experimentally, a semiconductor ring MLL with two asymmetrically placed saturable absorbers (SA), and examines whether unidirectionality is achieved in such a structure. The influence of internal butt-joint reflections and the performance in terms of phase and amplitude noise of the pulse train are also investigated theoretically. To show the compatibility with existing photonic foundries the PIC for the experiments is realized on the SMART Photonics InP platform [2].

The paper consists of five sections, beyond this Introduction. Section II presents the theoretical model, which is used for simulations throughout the paper. In section III the results from simulations on the proposed MLL structure are presented, and compared to similar simulations of a symmetric MLL. An experiment on two realized asymmetric MLLs is presented in section IV. In section V the results are discussed and a conclusion ends the paper in section VI. Some of the work presented in this paper has already been published in a conference paper [23].

II. THEORETICAL MODEL

A simulation tool was developed to facilitate simulations of the proposed MLL structure, which is schematically depicted in Fig. 1. The tool is based on a theoretical model, which describes the propagation of optical pulses in the case of slow envelope variations compared to the optical carrier frequency, the so-called Slowly Varying Envelope Approximation (SVEA). The gain dynamics of the SAs and the Semiconductor Optical Amplifier (SOA) are modelled by spatially distributed

differential equations which originate from a linearisation between gain and carrier density in the carrier rate equations.

The three differential equations describing the evolution of the system are given by the findings of Tang and Shore [24]:

$$\frac{\partial g}{\partial t} = \frac{g_0 - g}{\tau_s} - \frac{1}{E_{sat}} \frac{g - \epsilon_2 P^2}{1 + \epsilon_1 P} P + \Gamma_2 \beta_2' P^2 \quad (1)$$

$$\frac{\partial P}{\partial z} = \frac{g - \epsilon_2 P^2}{1 + \epsilon_1 P} P - 2\Gamma_2 \beta_2 \frac{1}{\sigma} P^2 - \alpha_{int} P \quad (2)$$

$$\frac{\partial \phi}{\partial z} = -\frac{1}{2} \left[\alpha_N \cdot g - \alpha_{Tc} \cdot \frac{\epsilon_1 g P + \epsilon_2 P^2}{1 + \epsilon_1 P} \right] - \Gamma_2' \frac{\omega_0}{c} n_2 \frac{1}{\sigma} P \quad (3)$$

In this g is the gain, P the optical power of the envelope and ϕ the phase of the envelope. The optical field envelope is related to the power and phase through $A(z, t) = \sqrt{P(z, t)} e^{i\phi(z, t)}$. The mode cross section is $\sigma = wd/\Gamma$ and the unsaturated gain g_0 is given by:

$$g_0 = \Gamma a_N N_{tr} \left(\frac{I_{SOA} \cdot \tau_s}{q \cdot w \cdot d \cdot L_{SOA} \cdot N_{tr}} - 1 \right) \quad (4)$$

The saturation energy E_{sat} depends on the differential gain a_N , i.e. the rate of change in gain per change in carrier density, and is explicitly given by $E_{sat} = \hbar\omega\sigma/a_N$. The other parameters are listed in Table I. The model treats Spectral Hole Burning (SHB), Carrier Heating (CH) and Two-Photon Absorption (TPA) as ultrafast instantaneous effects, which is a valid approximation for pulsewidths above ~ 1 ps.

Equations (1)-(3) can be solved numerically by slicing the one-dimensional space of the spatial variable z into discrete blocks of length Δz . The time resolution is found according to $\Delta t = \Delta z/v_g$, in which v_g is the group velocity around the optical carrier frequency. The spatial step size used in this paper is $\Delta z = 5 \mu\text{m}$, resulting in a temporal resolution of $\Delta t \approx 59$ fs.

Passive waveguides are modelled solely by (2) but only with passive losses and thus without the gain dynamics. The SOA and the SAs are described by all three equations. However, the injection current I_{SOA} is zero for SAs and a reverse bias V_{bias} which influences the carrier transparency density $N_{tr,SA}$ and the carrier lifetime τ_{SA} is included instead. The absorption characteristics of an SA changes with the reverse bias voltage and a simple linear equation is used for modelling this [25]. The carrier lifetime τ_{SA} reduces with an increase in reverse bias voltage due to the faster sweep out of carriers, and for this a simple exponential model is used [26]. It must be kept in mind, though, that this relationship is simplified, since it does not take into account space charge effects which will become important for high energy pulses [27]. A correct modelling of this would need differential equations for the carrier transport across the PIN structure, but this would make the model computationally inefficient. The equations describing the reverse bias voltage influence on the SAs are explicitly presented in Table I.

The gain medium has a limited bandwidth which is typically modelled by a Lorentzian lineshape as in the case of a two-level system. To model this numerically a first order Infinite Impulse Response (IIR) filter is implemented into each spatial

gain block [28] such that a cascading of all gain blocks results in a final 3 dB-bandwidth of $2\omega_L$.

Another important phenomenon occurring in the active elements is spontaneous emission, which is the radiation from random recombination of electron-hole pairs. A complex random generator with a normal distribution for both real and imaginary parts accounts for this effect in each spatial block [29]:

$$A_{sp} = \sqrt{\frac{P_{sp}}{2}}(x_1 + ix_2) \quad (5)$$

In this $P_{sp} = \Delta z \hbar \omega_0 \beta \sigma B N^2$, with B being the bimolecular recombination coefficient and N the carrier density.

Group Velocity Dispersion (GVD) is omitted in the model in order to speed up the numerical calculations. One must be aware, though, that GVD can either decrease or increase the pulse width, depending on the sign [30]. Nevertheless, this is expected to be negligible for the difference in gain experienced by the two counter propagating directions.

III. SIMULATION RESULTS

In this section the results from the simulations are presented. Intrinsic parameters for the different elements have been found in literature and they are shown in Table I. The structure of the section is as follows: initially a map of the different regions of operation is generated in order to identify the regions of mode-locking (ML). Afterwards the extinction ratio as a function of separation between the SAs is investigated in the ideal case of no internal reflections. Following this are the results of including internal butt-joint reflections. The section ends with a treatment of the phase and amplitude noise performance.

A. Mode Locking Map

Three different MLL structures were simulated regarding their ML map for the CCW direction: an asymmetric ring MLL with two SAs separated with $\Delta z_{SA} = 750 \mu\text{m}$, an asymmetric ring MLL with only one SA, i.e. $\Delta z_{SA} = 0$, and a completely symmetric ring MLL with a single SA placed in the middle of the SOA. The ML map for the CW direction was omitted, since the aim of this work is to achieve lasing in only the CCW direction. The total output power of the CW direction is of interest when determining the extinction ratio between the two directions, but the exact region of operation is not.

The resulting maps are presented in Fig. 2, and four regions can be identified. The dark grey region is operation below threshold; the light grey region is when the conditions for fundamental ML are not fulfilled, and the output is either unstable or consists of multiple pulses; the black region is where fundamental ML takes place, and the red region is when Q switched ML occurs. A clear difference in ML region is seen in the different plots. The widest region is found in the symmetric case, whereas the most narrow region is found in the asymmetric case with two separated SAs. A possible reason for this might be that gain saturation occurs only once when a single pulse circulates, whereas it occurs twice when two pulses circulate. Thus, the gain has less time to recover, and this supports the fact that the narrowing of the ML region is done mainly by displacing the leading edge

TABLE I
SIMULATION PARAMETER VALUES

Parameter	Symbol	Value	Reference
SOA			
Length	L_{SOA}	$750 \mu\text{m}$	[31]
Width of active region	w	$2.0 \mu\text{m}$	[25]
Depth of active region	d	$0.12 \mu\text{m}$	[25]
Linear confinement factor	Γ	0.285	[25]
Confinement factor for TPA	Γ_2	0.5	[25]
Confinement factor for UNR	Γ_2'	0.4	[25]
Differential gain	a_N	$3.5 \cdot 10^{-20} \text{ m}^2$	[25]
Carrier lifetime	τ_s	0.5 ns	[25]
Carrier density linewidth enhancement factor	α_N	5	[25]
Temperature linewidth enhancement factor	α_T	1	[25]
Coefficient for TPA	β_2	37 cm/GW	[25]
Non-linear gain refractive index	n_2	$-3.5 \cdot 10^{-16} \text{ m}^2/\text{W}$	[25]
Non-linear gain compression factor	ϵ_1	0.2 W^{-1}	[25]
Non-linear gain compression corresponding to TPA	ϵ_2	$200 \text{ W}^{-2} \text{ m}^{-1}$	[25]
Transparency carrier density	N_{tr}	$0.3 \cdot 10^{24} \text{ m}^{-3}$	[25]
Linear loss	α_{int}	$2.0 \cdot 10^3 \text{ m}^{-1}$	[25]
Spontaneous emission coupling	β_{sp}	10^{-5}	[32]
Bimolecular recombination rate	B	$2.602 \cdot 10^{-16} \text{ m}^3/\text{s}$	[32]
Lorentzian gain bandwidth	ω_L	$10 \cdot 10^{12} \text{ rad/s}$	[33]
SA			
Length SA1	L_{SA1}	$25 \mu\text{m}$	-
Length SA2	L_{SA2}	$25 \mu\text{m}$	-
Carrier density linewidth enhancement factor	α_{SA}	1	[25]
Differential gain	$a_{N,SA}$	$40 \cdot 10^{-20} \text{ m}^2$	[25]
Effective carrier lifetime	τ_{SA}	$85 \cdot e^{-(V_{bias}+1.5V)/1.8V} \text{ ps}$	[26]
Transparency carrier density	$N_{tr,SA}$	$(0.034 \cdot V_{bias} + 0.05) \cdot 10^{24} \text{ m}^{-3}$	[25]
Reverse bias voltage	V_{bias}	1 V – 4 V	-
CWG (Coupled waveguides)			
Length	L_{CWG}	$750 \mu\text{m}$	-
Coupling coefficient	κ	$\pi/(4 \cdot L_{CWG})$	-
Passive Waveguides			
Total length of passive waveguides	L_{pass}	$2660 \mu\text{m}$	-
Linear loss	α_{pass}	3 dB/cm	[34]
General parameters			
Group velocity	v_g	$8.43 \cdot 10^7 \text{ m/s}$	[24]
Group velocity dispersion	k''	0	-
Spatial step size	Δz	$5 \mu\text{m}$	-

Fig. 2. ML map for CCW direction. From top to bottom: symmetric design, asymmetric design w. $\Delta z_{SA} = 0 \mu\text{m}$, and asymmetric design w. $\Delta z_{SA} = 750 \mu\text{m}$.

Fig. 3. Calculated extinction ratio r_e versus separation distance Δz_{SA} for the asymmetric laser with two SAs. The operating point is $I_{SOA} = 50\text{mA}$ and $V_{bias} = 4\text{V}$.

stability boundary towards lower currents. The fact that only one pulse is circulating in the ML region of the asymmetric ring MLL with two SAs, i.e. it operates unidirectional, will be confirmed in section III-B.

B. Unidirectional Operation without Internal Reflections

In order to investigate the influence of the separation distance between the two SAs on the unidirectionality, simulations were carried out for different values of Δz_{SA} . The operating point was fixed at injection current $I_{SOA} = 50\text{mA}$ and reverse bias $V_{bias} = 4\text{V}$ while Δz_{SA} was swept in steps of $10\text{ }\mu\text{m}$.

The extinction ratio was monitored and the resulting plot is shown in Fig. 3. The plot can be divided into three regions: A region for $\Delta z_{SA} < 200\text{ }\mu\text{m}$ with a large increase in extinction ratio, a region for $200\text{ }\mu\text{m} < \Delta z_{SA} < 400\text{ }\mu\text{m}$ with a slow increase in extinction ratio, and a region $400\text{ }\mu\text{m} < \Delta z_{SA}$ with a slow decrease in extinction ratio. An explanation for the occurrence of these regions could be as follows. The initial sharp increase in extinction ratio comes from the reduced overlap in the SAs between the two counter propagating pulses. The following slow increase in extinction ratio is due to the recovery of SA1. Further separation of the SAs degrades the extinction ratio slowly, since SA1 has almost recovered and the SOA recovery rate starts to dominate.

C. Unidirectional Operation with Internal Reflections

During the fabrication process of integrated ring MLLs a certain amount of reflections is introduced inside the cavity due to process resolution and regrowth. This is seen in different regions of the structure. The most notable reflections are the ones seen at the discontinuities between active and passive regions, normally referred to as butt-joint reflections [35], and those in the output coupler [36]. In this investigation only butt-joint reflections are taken into account.

Fig. 4. Extinction ratio vs. reflection magnitude at different injection currents I_{SOA} . The separation distance Δz_{SA} between the two SAs is fixed at $400\text{ }\mu\text{m}$ which is the optimum from the operating point in Fig. 3.

The plot in Fig. 4 is the result of placing reflections at the locations depicted in Fig. 1 and varying the reflection magnitude. It is seen that a certain reflection cut-off is placed around -75 dB and above this value the extinction ratio decreases linearly. This trend can be found analytically by looking at the coupling of energy between CW and CCW direction. By assuming that the CCW pulse acts as an energy reservoir for small reflections, one finds, in accordance with the derivation in Appendix A, that the extinction ratio is given by:

$$r_e = 10 \log \left(\frac{1}{\tilde{N}} \frac{\alpha_R \tilde{N}}{R + \alpha_R \tilde{N}} \right) \quad (6)$$

In this, $\tilde{N}$ is the noise energy added per roundtrip, normalized to the CCW pulse energy and effective loss seen by the noise, and α_R is the effective loss per roundtrip seen in the CW direction for the reflection. The combined term $\alpha_R \tilde{N}$ determines the placement of the cut-off, whereas $\tilde{N}$ determines the vertical offset of the curve. This makes sense since the noise should dominate the extinction ratio for negligible reflections.

Equation 6 has been fitted to the simulated data and the results are shown alongside the data points in Fig. 4. From the fitted data it is seen that when increasing the injection current, the effective loss for the reflection increases, and the normalized noise contribution decreases. This makes sense since the pulse energy increases with increasing injection current, leading to an overall decrease in cavity losses due to the greater saturation of the SAs, which means greater saturation of the SOA. A greater saturation of the SOA will give an overall increased loss in the regions where the SAs are fully recovered. Moreover, a greater pulse energy will automatically lead to a decrease in the normalized noise contribution, since the pulse energy takes part in the normalization.

It is also seen that (6) enables an easy estimation of the loss which is effectively seen for the reflection. When the reflection R is much larger than the noise contribution $\alpha_R \tilde{N}$ one can see that the extinction ratio equals 0dB when R equals α_R .

Fig. 5. Extinction ratio vs. reflection magnitude at different peak-peak modulations ΔV_{bias} of the reverse bias. The separation distance Δz_{SA} between the two SAs is fixed at $1050\mu m$ which corresponds to $1/4$ of the roundtrip.

Thus, the effective loss for the reflection can be read from the intersect between the graph and the x-axis, and by looking at these points in the plot of Fig. 4 one immediately identifies a very weak effective loss around -40 dB for the reflections.

Active modulation of two SAs with a phase difference in a symmetric ring MLL has been shown to give a gain difference between CCW and CW direction [22]. In Fig. 5 this approach was pursued by applying an RF modulation to the bias voltage of each SA with a frequency corresponding to the pulse repetition rate of the MLL. SA1 and SA2 were separated by $1/4$ of the cavity length and the RF modulation for SA2 was delayed by 90° . This corresponds to the design proposed in [22], the only difference being the asymmetrical placement of the SAs. Alongside the data points, a fit of (6) is shown. Note how the effective loss for the reflections increases with the modulation depth, due to the synchronized modulation of the SAs in the CCW direction and unsynchronized modulation in the CW direction. The normalized noise contribution decreases slightly, which might be explained by an increase in CCW pulse energy. However, the decrease is not as pronounced as the increase in effective loss for the reflection, and therefore the active modulation seems to be beneficial for the extinction ratio mainly in the presence of internal reflections.

D. Amplitude and Phase Noise Performance

The performance of the symmetric bidirectional ring MLL and the asymmetric unidirectional MLL with two separated SAs is now investigated for passive ML, both with and without reflections present in the system. The operating points investigated are limited to the stable ML region of the asymmetric ring MLL with two separated SAs, shown in the bottom plot of Fig. 2. The pulse train from the CCW output port of the laser is characterized regarding its RF characteristics, being phase noise and amplitude noise. Phase noise is found from the time fluctuations in the gravity center of the pulse energy and amplitude noise is found from fluctuations in pulse energy

Fig. 6. (a) phase noise and (b) amplitude noise. In case of reflections the magnitude is $R = -40$ dB. Simulation results from asymmetric and symmetric design are both included. The operating point is: $I_{SOA} = 52.5$ mA and $V_{bias} = 4$ V.

[37], [38]. The amplitude fluctuations in this paper are defined to be the pulse energy fluctuations normalized to the average pulse energy and the amplitude spectral density is the discrete Fourier transform hereof. All plots in this section result from an average of 3 simulations.

In Fig. 6 the single side band phase noise $\mathcal{L}(f)$ and amplitude noise $S_{E^2}(f)$ for both the symmetric and asymmetric design are shown. The operating point was chosen at $I_{SOA} = 52.5$ mA and $V_{bias} = 4$ V. The characteristic $1/f^2$ dependency is seen for both the phase noise and the amplitude noise, but the amplitude noise flattens at low frequencies whereas the phase noise keeps on growing, which implies a random walk nature of the pulse position [38]. It is interesting to note that the symmetric design has lower phase noise over the entire frequency band shown, except at the relaxation oscillation peak around 1 GHz, whereas it is the exact opposite case when looking at low frequency amplitude noise. The same trend is seen with butt-joint reflections at -40 dB, however the difference in performance between the two designs has decreased.

In order to investigate how the operating point of the ring MLL influences the phase noise and amplitude noise, the integrated timing jitter σ_τ and integrated amplitude noise σ_E were computed. For this the lower limit of the integration was set to the resolution limit of the Fourier transform $1/(T_R N) = 1$ MHz and the upper limit was set to the Nyquist frequency $1/(2T_R) = 10$ GHz, and the results are shown in Fig. 7(a). It is seen that an increase in reverse bias decreases the timing jitter which is in agreement with the observations made in [38]. There is no real trend for the timing jitter and amplitude noise when increasing the injection current I_{SOA} , except for the abrupt increase in amplitude noise at 55 mA when the Q switched ML regime is entered. It is, however, seen that for all operating points the symmetric ring MLL outperforms the asymmetric ring MLL in terms of timing jitter whereas it is the other way around for amplitude noise. For the

Fig. 7. Blue: timing jitter and orange: amplitude noise, both integrated in the range 1 MHz $\rightarrow$ 10 GHz. The injection current is 52.5 mA in (b).

operating point used in Fig. 6, the amplitude noise is lowered from 0.022 % to 0.004 % when comparing the asymmetric design with the symmetric. The timing jitter is increased from 172 fs to 412 fs.

The integrated noise contributions were also computed when varying the reflection magnitude, and the results are shown in Fig. 7(b). The timing jitter increases on average as the reflections are increased, however there are local minima for both the symmetric and the asymmetric design. For the asymmetric design the amplitude noise is seen to be strictly increasing with the reflection magnitude, whereas it remains almost flat for the symmetric design.

IV. EXPERIMENTAL INVESTIGATION OF UNIDIRECTIONALITY

In order to verify the theoretical predictions of unidirectionality an asymmetric design was realized on an InP PIC. The PIC was fabricated using a butt-joint technology with a regrowth step which enables the simultaneous integration of both active and passive components. The fabrication was done in the SP20 Multi Project Wafer run at SMART Photonics. The design was made using the standard building blocks provided in the Process Design Kit (PDK) [39]. These standard building blocks use shallowly and deeply etched ridge waveguides that are 2.0 and 1.5 μm wide, respectively. The layer stack has a 500 nm thick InGaAsP waveguiding layer, with a bandgap corresponding to $\lambda = 1.25 \mu\text{m}$, and for the active regions a stack of four quantum wells is included.

Two devices were measured. A microscope image of one of them is shown at the bottom of Fig. 8 and the GDS layout is shown at the top. This design includes two SAs separated by $\Delta z_{SA} = 1020 \mu\text{m}$. The other device measured is similar, but with $\Delta z_{SA} = 0 \mu\text{m}$. In both devices light is coupled from the laser cavity to output waveguides through a 2x2 MMI coupler. Devices with SA lengths of 30 μm were chosen for the measurements, since these turned out to have better performance than devices with shorter SAs. This is

Fig. 8. GDS layout (top) and microscope image (bottom) of the realized asymmetric ring MLL with a separation between the SAs.

Fig. 9. Extinction ratio vs. injection current for the numerical model

5 μm longer than in the simulations. However, already there is a great uncertainty in using simulation parameters from literature, and therefore the exact length of the SA is not crucial, as long as ML is achieved. This also implies that the comparison between simulations and experiments should be made only in a qualitative way.

The aim of the measurements was two-fold, namely to determine the extinction ratio as a function of injection current, and to determine the regions of operation. The extinction ratio was found from measuring the CCW and CW output port simultaneously with optical power meters. By fixing the reverse bias voltage at 2 V and sweeping the injection current, the results in Fig. 10 were produced. For comparison reasons a similar plot was produced by the simulation tool and this is presented in Fig. 9.

The regions of operation were determined from individual measurements with an Electrical Spectrum Analyzer (ESA), an Optical Spectrum Analyzer (OSA) and an Autocorrelator (AC). ML was assumed when a peak of minimum 40 dB with respect to the noise floor was seen around the fundamental ML frequency on the ESA. Moreover, it was verified that frequency combs, i.e. a set of equally spaced optical frequencies, were visible on the OSA, and that pulses were detected on the AC in this region. Q-switched ML was assumed when low frequency modulations were present on the ESA, and continuous wave (CW) operation was assumed when only a single wavelength was visible on the OSA. The regions are indicated by the background colors in Fig. 10.

Note that the reflections in the experiment are not limited

Fig. 10. Extinction ratio vs. injection current for the experiment.

to the butt-joint reflections. Reflections might occur at both the 2x2 MMI splitter in the cavity as well as externally at the PIC output facets, and thus reduce the extinction ratio. Nevertheless, a sudden increase in extinction ratio at the transition to the ML region is seen both theoretically and experimentally. For the case of $\Delta z_{SA} = 1020 \mu\text{m}$ a change in the sign of the extinction ratio is also seen experimentally, meaning that the CCW direction becomes dominant at the output. This is in fact significant since the output is close to the point of minimum pulse energy for the CCW direction due to the given sequence of non-linear elements.

V. DISCUSSION

In this section two topics are discussed: the effects causing unidirectional operation, and the change in amplitude and phase noise performance due to this unidirectional operation.

A. The Origin of Unidirectional Operation

The unidirectional operation as seen in the simulations, and to some degree in the experiments, can be explained by two effects.

Firstly, a difference in gain is seen due to asymmetry. When Δz_{SA} is set to zero a simple asymmetric ring MLL appears with only one SA placed at the output of the SOA in the CCW direction. By assuming that the counter propagating pulses meet in the SA, because of the great reduction in loss by doing so, one observes that the CCW pulse will pass the SOA and saturate the gain before the CW pulse passes by. Thus the CCW pulse achieves a greater gain, which is in accordance to the observations made in [31], [32], [40].

Secondly, a difference in gain is seen due to the relative spatial displacement of the two SAs. When the SA is split into two parts, SA1 and SA2, the common low absorption window between the two pulse directions is closed and only one propagating direction survives, namely the CCW direction which holds the dominating pulse. This happens because the pulses are travelling in opposite directions and therefore are unable to saturate the SAs at the same time. Because of the

Fig. 11. Net gain in both CCW (solid lines) and CW (dashed lines) direction for different injection currents. A roundtrip linear loss of 2.6184 was measured for the cold cavity and this has been added to the absorption of the SAs before subtracting this from the gain of the SOA. The operating point is $V_{bias} = 4 \text{ V}$ and $\Delta z_{SA} = 750 \mu\text{m}$.

fast absorption recovery in the SA elements an increase in Δz_{SA} will decrease the saturation overlap between the two directions. In order to investigate this phenomenon, a gain monitoring algorithm was implemented in the simulation tool. This algorithm monitors the net gain window in a retarded time frame which follows the pulse, and the resulting plot for both CCW and CW direction is shown in Fig. 11. The gain window for the dominating CCW pulse has one large peak in net gain, created by the pulse itself. However, the CW direction has two weak peaks, which are located at the saturation of the SAs made by the CCW pulse. In fact, a small net gain is seen for the left most point, but the finite gain bandwidth in the SOA is not taken into account here and therefore this point will effectively experience a gain below zero, i.e. a loss. It is interesting to note that the weak peaks are located where butt-joint reflections occur, and this might be the reason for the large sensitivity towards reflections seen in Fig. 4 and the experiments.

B. Amplitude and Phase Noise in Unidirectional Operation

Fig. 7 reveals that timing jitter is increased when unidirectionality is achieved, even though the amplitude noise is reduced. Two hypotheses can be made to explain this.

Firstly, the bidirectional symmetric ring MLL might be viewed as two coupled oscillators: the CCW and CW oscillator. The mutual locking of these two oscillators might have a larger effect than having a single oscillator in the CCW direction with twice the pulse energy, which is the case for the unidirectional asymmetric ring MLL. Under certain approximations, such as no coupling between amplitude and phase noise, Chang et. al. have shown that by coupling N free running oscillators a $1/N$ reduction is seen in the phase noise as compared to a single uncoupled free running oscillator [41].

Secondly, the net gain window will look different when compared to a bidirectional MLL. When two pulses co-exist

in the cavity and travel in opposite directions, a sharpening of the leading edge will be seen in the gain window. This is due to the fact that the opposite travelling pulse drains the SOA, which is not the case for a single pulse in a unidirectional MLL. Effectively this will lead to an extra loss notch in front of the pulse, which will suppress the noise added in this region. This might have a reducing effect on the timing jitter of the pulse.

The reduction of amplitude noise in unidirectional operation might be explained by the fact that only a single lasing direction is present and thus the mode partition noise is lowered. The total energy in the MLL cavity should remain constant, but if two counter propagating modes are present, energy can fluctuate between these modes in an anticorrelated manner and still preserve the total energy [42].

VI. CONCLUSION

A numerical model based on the travelling wave approximation has been proposed for simulating the behaviour of a ring MLL with different configurations. The model predicts unidirectional operation when two SAs are placed asymmetrically in the cavity with an extinction ratio greater than 15 dB for internal butt joint reflections lower than -50 dB. Experiments show that the extinction ratio achievable in a practical passive MLL is quite limited, and the values reported in this paper are below 3 dB, which translate into internal reflections around -40 dB in the simulation. This value is realistic in real world active-passive integration schemes, and thus the limited extinction ratio could be explained by such reflections.

This implies, that unidirectional lasing cannot be achieved passively for the proposed asymmetric configuration on the experimentally investigated InP platform, since the level of butt-joint reflections seems too high. However, the simulations show that by modulating the SAs with a certain phase difference, one can increase the extinction ratio. This indicates that a passive ring MLL with a limited extinction ratio, due to internal reflections, can be made unidirectional only by applying a sufficiently large modulation to the SAs. The peak-peak modulation depth of the reverse bias voltage in this work was limited to 0.5 V. However, an isolation of -0.29 dB for a 6 V peak-peak modulation can be extrapolated from the data in [22], and this would correspond to a loss of $\alpha_R^{dB} \approx -12$ dB for the CW direction. When plugging this into (6), a 20 dB increase in extinction ratio is identified in the region dominated by reflections, as compared to that for the greatest modulation depth in Fig. 5. This would eventually result in an extinction ratio of around 28 dB at a reflection magnitude of -40 dB. Equation (6) was derived for internal reflections, but the derivation for external reflections would be similar, and therefore the influence from these is expected to be the same. So, one might hypothesize that immunity towards both internal and external reflections can be achieved up to a certain level, which depends on the SA modulation depth. One must remember that the quantitative results from the simulations should not be trusted blindly, since the simulation parameters were found in literature and thus not calibrated to any technology platform. Therefore, the extinction ratio might either be overestimated or underestimated.

A theoretical comparison of phase and amplitude noise performance for the different designs was made. The results of this comparison clearly show that the amplitude noise is reduced when unidirectionality is achieved, whereas the phase noise and timing jitter gets worse. The main trend of a lower timing jitter for the symmetric design and a lower amplitude noise for the asymmetric design was not altered by internal reflections. Therefore it cannot be concluded that unidirectionality reduces timing jitter, even not when internal reflections are present.

Altogether it is concluded that applications, which rely on a low phase noise microwave signal, will not necessarily be improved by turning a stand-alone ring MLL unidirectional, since the timing jitter is worsened by doing so. However, amplitude noise is reduced, and this might in fact decrease the phase noise when the MLL is a subcomponent of a low noise microwave oscillator, since coupling mechanisms between amplitude noise and phase noise might be present in such a system. Also, this work treats intra-cavity reflections only, and the scenario will be different for external reflections, which will have a much larger time scale. Therefore, robust unidirectional behaviour should still be pursued, still with the aim of making a feedback insensitive MLL. According to the results of this work, increasing the modulation depth of the SAs should be the next step towards a fully functional and realizable unidirectional MLL. In addition to increasing the SA modulation depth, one could also include other elements with a modulable gain/loss in the cavity to increase the effective loss difference between CCW and CW direction.

APPENDIX

A. Extinction ratio versus reflections

An analytical expression for the extinction ratio in the presence of a single reflection R is derived. Since the CCW pulse is dominating one might treat this as an energy reservoir, and approximate the change in CCW pulse energy during one roundtrip with:

$$T_R \frac{\partial E_{CCW}}{\partial T} = 0 \quad (7)$$

For the CW pulse the change in pulse energy in one round trip is split into two parts, one describing the evolution for the noise energy E_{CWN} and the other the evolution of the reflected energy E_{CWR} . They are approximated with:

$$T_R \frac{\partial E_{CWR}}{\partial T} = [L_R(E_{CCW}) - 1] E_{CWR} + R E_{CCW} \quad (8)$$

$$T_R \frac{\partial E_{CWN}}{\partial T} = [L_N(E_{CCW}) - 1] E_{CWN} + E_N \quad (9)$$

E_N is the added noise energy per round trip, and L_R and L_N are the attenuation coefficients seen for the reflection into the CW direction and the CW noise respectively. Both attenuation factors are dependent on the gain window created by E_{CCW} . This is written explicitly, but will be left out in the remaining part of the derivation.

The interesting point for these rate equations is at steady state, when $\partial E_{CWR}/\partial T = 0$, $\partial E_{CWN}/\partial T = 0$ and

$\partial E_{CCW}/\partial T = 0$. By solving (7)-(9) one obtains the extinction ratio:

$$r_e = 10 \log \left(\frac{E_{CCW0}}{E_{CWR} + E_{CWN}} \right) = 10 \log \left(\frac{1}{\tilde{N}} \frac{\alpha_R \tilde{N}}{R + \alpha_R \tilde{N}} \right) \quad (10)$$

In this $\tilde{N} = E_N/(\alpha_N E_{CCW0})$, and E_{CCW0} is the constant energy solution to (7), which must be determined from the mode locking conditions. The effective loss $\alpha_{R,N}$ comes from a first order approximation of the attenuation term $L_{R,N} = e^{-\alpha_{R,N}} \approx 1 - \alpha_{R,N}$, which is valid for small losses.

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