Toward a feedback-insensitive semiconductor laser

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Toward a Feedback-Insensitive Semiconductor Laser

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(Invited Paper)

Abstract—We present a route toward design and fabrication of a conceptually new type of optical feedback insensitive integrated semiconductor ring laser with a weak optical isolator included in the ring. Although the approach has not resulted in the clear advantages that were aimed at, this detailed account of the process we believe is valuable to readers active in the field. After a summary of optical-feedback sensitivity in semiconductor lasers, we review various attempts toward reducing this sensitivity and discuss the feasibility of the concept of weak intra-cavity isolation. The design, model and theory of the novel integrated ring laser device are presented. The observed 5 dB of isolation and 3 dB increase of tolerance for external optical feedback demonstrate the feasibility of the intra-cavity isolation concept. However, the observed output performance of the single-mode laser, both with and without activated intra-cavity isolation, suggests the presence of a spurious intra-cavity reflection, strongly coupling the directional modes. Due to this coupling, the sensitivity to external optical feedback is comparable to that of a Fabry–Pérot type laser. Therefore, an alternate route is indicated toward a less complex laser cavity with potentially less intra-cavity reflection and better tolerance for external optical feedback.

Index Terms—Semiconductor ring laser, photonic integrated circuit, external optical feedback, optical isolation.

I. INTRODUCTION

SOON after the first semiconductor diode lasers came into operation in 1962, the coherence and stability properties of their emitted light became known to be highly sensitive to external optical feedback (EOF), i.e., reflections of a fraction of the output light back into the laser cavity [1], [2]. Reproducibility and dynamical stability of the performance of semiconductor lasers, notably in integrated settings are becoming ever more important. In this respect, the sensitivity of semiconductor laser properties such as the linewidth, wavelength, relative intensity noise (RIN) and output power to small parasitic reflections threatens reliable operation when a semiconductor laser is integrated as part of a larger optical circuit on a chip.

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Although in case of fiber-optic settings it is quite possible to use Faraday-rotation based optical isolators or circulators, the involvement of magnetic material is undesirable in most generic chip fabrication processes [3], among others due to lattice mismatch issues. Investigating other ways of preventing on-chip EOF raises the more general question as to whether it is possible to realize an integrated semiconductor laser that is virtually insensitive to EOF and is suitable as building block on a photonic chip. In other words, can we design and fabricate a feedback-insensitive integrated semiconductor laser using only the building blocks available in generic integration platforms and that is insensitive to EOF, i.e., whose linewidth, wavelength, RIN and output power remain constant regardless of feedback strength? In this invited paper we will report on our unsuccessful, though informative, attempt towards this *Holy Grail* of integrated semiconductor lasers.

In Section II we will overview in a historic perspective the reasons why and to what extent semiconductor lasers are sensitive to EOF. Then in Section III we will discuss various proposed solutions to reduce or minimize the feedback sensitivity without using magnetic materials. The approach we ultimately follow is to include a non-magnetic optical isolator with modest forward-to-backward transmission ratio within the optical ring laser cavity inside the laser chip. Section IV describes this conceptually new approach and demonstrates the feasibility. The mask design for the integrated laser will be presented here in some detail, where the optical isolator is based on the two cascaded RF phase modulators developed by Doerr *et al.* [4].

Since the laser design is based on the ring laser geometry, we will discuss in Section V some special properties and peculiarities of semiconductor ring lasers that are particularly relevant for the theoretical description of our laser. We are then prepared to formulate in Section VI the theory for this laser (subsection A) and the cascaded RF modulators, including its validation (subsection B). With the help of these theories the predicted qualities of feedback insensitivity can be quantified as function of the achieved isolation. Substantial reduction of EOF-sensitivity is predicted already for modest isolation, i.e., -30 dB (-0.1 dB) EOF for 3 dB (10 dB) isolation.

The characterization of our fabricated laser is described in Section VII. Here we will present measurements of the laser output powers, directionality and linewidth as function of the amount of EOF. An increased tolerance for EOF of 3 dB is observed, but, unfortunately, due to a parasitic reflection within the ring, this modest suppression of optical feedback effects

could not be improved. A critical evaluation of the full enterprise will be given in Section VIII, followed by the conclusion and outlook in Section IX.

II. EOF SENSITIVITY OF SEMICONDUCTOR LASERS

The influence of EOF on the dynamical behavior of semiconductor lasers has been studied in an overwhelmingly large number of papers over the last 4 decades. In this respect, we mention the publications by [2], [6]–[16] and references therein, which give a fairly complete introduction into the existing literature on this topic.

The central question in the present section is why semiconductor lasers are so vulnerable to EOF. There are several reasons for this. First of all, these lasers operate with typically high gain, i.e., $\approx 50 \text{ cm}^{-1}$ and have rather small facet reflectivities of $\approx 30\%$ which makes them rather “open” to the outside world. Hence, external optical signals can easily enter the laser cavity. Secondly, as the operation point of the laser is a state of equilibrium that can easily be perturbed by external optical signals, this can lead to enhanced noise and even unstable behavior. Qualitatively this can be explained by considering how the laser in equilibrium responds to perturbations, which in fact follows from the dynamical model described below.

A simple rate-equation model that adequately describes many aspects of the dynamical behavior of single-mode semiconductor lasers with EOF is given by the famous so-called Lang-Kobayashi equations [7] reading

$$\frac{dE}{dt} = \frac{1}{2} (1 + i\alpha) \xi N E + \gamma e^{i\phi_{fb}} E(t - \tau), \quad (1)$$

$$\frac{dN}{dt} = \Delta J - \frac{N}{T} - (\xi N + \Gamma) |E|^2, \quad (2)$$

where E is the slowly-varying complex amplitude of the optical electric field, N is the inversion with respect to the clamped value at laser threshold in the absence of EOF, and the second term in the right-hand side of (1) is the contribution due to EOF. The full electric field is represented as

$$E(t) = |E(t)| \cos(\omega_0 t + \varphi(t)), \quad (3)$$

with ω_0 the optical frequency of the solitary laser, i.e., in the absence of feedback and $\varphi(t) \equiv \arg(E(t))$.

In (1), ϕ_{fb} is the feedback-related phase shift, given by

$$\phi_{fb}(t) = -\omega_0 \tau, \quad (4)$$

and τ is the external delay time associated with the externally reflected signal. Furthermore, ξ is the linear gain coefficient, a measure for the optical transition strength and γ the feedback rate, a measure for the amount of feedback, and defined as [7]

$$\gamma \equiv T \sqrt{R/(1-T)} / \tau_r \quad (5)$$

where T is the transmission of the output facet, R is the external reflectivity and τ_r the cavity roundtrip time. ΔJ is the injection current with respect to the solitary laser threshold, T the inversion lifetime and Γ the photon decay rate or inverse photon lifetime. Finally, α is the linewidth-enhancement parameter, a scalar quantifying the coupling of amplitude to phase variations.

A typical value for α is 2-3 for quantum well (QW) active material, >5 for bulk material and close to 0 for quantum dots (QD). Semiconductor lasers with large α are more sensitive to EOF than small α lasers.

The system of coupled equations (1) and (2) forms a set of delay-differential equations of infinite dimensionality in the sense that the initial condition has to be defined over a continuum of time for a uniquely determined solution. Eq. (1) without the EOF term ($\gamma = 0$) and Eq. (2) describe the solitary laser and that system forms a two-dimensional system. In fact, equations (1) and (2) with $\gamma = 0$ can be derived from three coupled non-linear equations in which the short response time of one variable, the polarization, allows its adiabatic elimination (see [16], p. 107). These three coupled equations are equivalent to a simple form of the Haken-Lorenz equations (see [17], p. 276), well known for their capability to describe chaotic dynamics.

With no EOF applied, the steady state with constant amplitude $E_0 \neq 0$ and inversion N_0 is obtained by solving $\frac{d|E|}{dt} = \frac{dN}{dt} = 0$. This yields the equilibrium values

$$N_0 = 0, |E_0| = \sqrt{\frac{\Delta J}{\Gamma}}. \quad (6)$$

After a perturbation of the system out of this equilibrium the system evolves back to the equilibrium following a spiraling motion in the two-dimensional space spanned by $(N, |E|)$ around the point (6) with rotation frequency $\sqrt{\Omega_R^2 - \lambda_R^2}$ and damping rate λ_R , where

$$\Omega_R = \sqrt{\xi \Delta J}, \lambda_R = \frac{1}{2} \left(\frac{1}{T} + \frac{\xi \Delta J}{\Gamma} \right). \quad (7)$$

Usually, Ω_R and λ_R are referred to as the relaxation oscillation frequency and damping, respectively. The relaxation oscillation plays an important role in semiconductor lasers, with typical values $\Omega_R/2\pi \approx 5 \text{ GHz}$ and $\lambda_R \approx 5 \times 10^9 \text{ s}^{-1}$. Strictly speaking, it should be mentioned that above, but very close to the laser threshold current, the oscillation is critically damped and there is no spiraling.

The above-given simple analysis for the solitary laser illustrates that for normal operation well-above threshold, the system possesses an intrinsic resonance (the periodic exchange of energy between the inversion and the photon field). In the absence of any external disturbance the corresponding relaxation oscillation is damped. When the laser is driven by an outside source, sustained relaxation oscillations may be excited as a first step towards further destabilization and line broadening [8]–[13]. Driving forces could for instance be current modulation or the injection of light from another laser, but also EOF. Excited relaxation oscillations can lead even to chaotic oscillations and dramatic line broadening due to EOF [18], [19] or external optical injection [20]. A criterion indicating the instrumental role of α for the onset of sustained relaxation oscillations due to EOF is given in [21] as

$$f_{ext,c} \approx \frac{\tau_r^2 \Gamma^2 R}{4(1-R)^2} (1 + \alpha^2) / \alpha^4, \quad (8)$$

valid for $\alpha > 1$ and where $f_{ext,c}$ is the critical feedback fraction (ratio of reflected power and output power), τ_r is the laser cavity

roundtrip time, Γ is the photon decay rate and R is reflectivity of the out-coupling facet of the FP-type laser facing the feedback circuit.

III. PROPOSED SOLUTIONS TO REDUCE FEEDBACK SENSITIVITY

Already since a long time it has been realized that ideal ring lasers can be more resistant against EOF than Fabry-Pérot lasers simply because external reflections from the dominating lasing mode with a certain sense of rotation will end up in the other mode with opposite sense of rotation, provided the other mode is sufficiently suppressed. Many papers can be found analyzing the behavior of semiconductor ring lasers whether or not subject to external EOF. We mention the references [22]–[33], without claiming completeness.

Several approaches to laser designs with reduced EOF sensitivity therefore have the semiconductor ring laser (SRL) as central element. However, approaches with Fabry-Pérot lasers are also found, notably distributed feedback (DFB) lasers with QD active material [34], or using PT complex coupling [35]. Matsuda *et al.* [34], detected virtually no feedback sensitivity up to 10 dB of EOF and the proposed laser by Ke *et al.* [35] is predicted to show similar EOF sensitivity.

It was demonstrated in 2015 by D'Agostino *et al.* [36] that in a FP-type semiconductor laser with on-chip external optical feedback, the relaxation oscillation was suppressed within injection-current intervals for which the relaxation-oscillation frequency was near an external-frequency resonance. Zhao *et al.* [37] demonstrated in 2018 that in those current intervals the deteriorating influence of a parasitic reflection with 10^{-4} reflectivity and external delay time of 0.3 ns in such a laser could be successfully mitigated.

It has been shown recently that QD lasers show a much reduced sensitivity to EOF compared to QW lasers [67], [68]. This is explained by their low value of α which can even be zero [69]. In general, low values of α reduce the tendency for EOF-induced excitation of relaxation oscillations and coherence collapse, a trend already described by (8). This has initiated an interesting line of research towards feedback-resistant lasers [67], [68]. We also mention the promising development towards III-V lasers directly grown on silicon [68], [69], [72].

Another interesting line of research is found in refs. [24], [25] and [28] and involves the so-called S-ring laser, in which a cross-over waveguide connects two opposite sides of the ring, guiding light from one sense of rotation into the other, but not the other way around. Under lasing conditions, this topology favors directional operation, where the ratio of clockwise (CW) to counter clockwise (CCW) output power is observed as large as 13 dB in Hohimer *et al.* [24], 25 dB in Cao *et al.* [25] and 30 dB in Withers *et al.* [28]. The S-shaped micro laser idea was revived in Ren *et al.* [38], where two of these lasers are coupled and operated under PT-symmetric conditions so as to achieve unidirectional single-mode operation. However, none of these references reports on the sensitivity to EOF in these lasers.

In fact, a simple rate-equation analysis [39] for this type laser reveals that the approach to the equilibrium state of unidirectional operation is not exponential in time, but critically slowed down. This is because at the lasing condition, the inversion is clamped at its threshold value and above threshold all excess pump energy flows into the dominant mode intensity. At the same time, the counter-propagating mode is still at the lasing threshold, because (due to reciprocity) it experiences the same roundtrip loss as the dominant mode. The counter-rotating mode reaches zero-intensity equilibrium by a $1/t^2$ power law, while the dominant mode reaches equilibrium with the same power law, such that the total power remains constant. Given this situation, the feedback from the dominant mode ending up in the counter-rotating mode - which is at lasing threshold - will build up relatively large intensity, as the back-to-equilibrium restoring force of the counter-rotating mode is essentially lacking. As both modes share the same inversion, this will perturb the dominant mode relatively strongly. Such a scenario was checked by numerical integration of the rate equations [40].

In our device to be described in the next section, a weak optical isolator within the ring is the crucial element instead. Using this device the counter-propagating mode is kept below threshold such that it is restored to equilibrium by a strong force. We will first give a short introduction on optical isolators. In order to avoid discussion about what an optical isolator is and what is not, we refer to [41] and we will follow Doerr *et al.* [4] by regarding an optical isolator as a two-port device with an asymmetric scattering matrix, unlike a linear reciprocal device.

To make an integrated laser immune to EOF it is currently not possible to place an optical isolator at the output of the laser as is commonly done in fiber- and free space optics since a suitable integrated optical isolator with sufficient isolation is not available [3]. On-chip isolation has been demonstrated, but either it requires significant extra steps in the processing of the wafer [42], [43], provides limited isolation [44], or presents a high insertion loss [45]. Also, many isolators are narrow-band [44]–[46] requiring some tuning mechanism to align them to the lasing wavelength.

A precursor of [4] was proposed in 2009 by Yu and Fan [47] and is based on the principle of dynamic modulation applied to one arm of a Mach-Zehnder interferometer. In Ramezani *et al.* [48], a unidirectional optical wave-guiding structure is proposed where the uni-directionality stems from the fact that the system is PT-symmetric and nonlinear. The same principle underlies the nonreciprocal transmission in a nonlinear photonic-crystal Fano structure that can be applied as an optical isolator (Yu *et al.* [49]).

A promising isolator on the basis of a cerium substituted yttrium iron garnet (Ce:YIG) is presented in the work by Pintus *et al.* [50], where a metal micro-strip on top of a micro ring forms an integrated electromagnet. The induced magnetic field lifts the degeneracy of CW-CCW resonance wavelengths. On this basis, successful optical isolators and circulators were fabricated, but for us this is not a suitable way to go.

Fig. 1. Sketch of a feedback insensitive ring laser subjected to EOF. Lasing in a single longitudinal mode is ensured by the filter and by the cavity itself, while the isolator ensures unidirectional laser operation. EOF is modeled by a point-reflection that reflects a fraction R of the optical power. τ is the feedback delay time.

IV. THE EINDHOVEN LASER

The key idea to achieve the desired feedback insensitivity is to separate the EOF from the lasing mode, which is realized by employing the ring laser architecture. If the ring laser operates in a directional mode, the EOF will return to the mode running in the reverse direction. The backwards propagating mode can then influence the lasing mode in two ways: Firstly it can affect the carrier density in the active material of the laser, and thereby affecting the gain that is experienced by the lasing mode. This effect can be reduced by minimizing the amount of light in the reversed mode. Secondly, the reversed mode can affect the lasing mode if there is any direct optical coupling between the two, such as caused by a parasitic reflection. Therefore, the cavity has to be carefully designed to prevent intra-cavity reflection as much as possible.

The laser designed by us is a ring laser similar to the laser presented in [70], but with an isolator included as part of the ring, see Fig. 1. In order to demonstrate the feasibility of this novel intra-cavity isolator concept, a fiber-based semiconductor ring laser was built with discrete components. It contains a Faraday isolator and a semiconductor optical amplifier as gain-providing element. The Faraday isolator does not impose a modulation on the laser light, contrary to the isolator that will be applied in the integrated laser. It is shown in [65] that qualitative agreement between theory and experiment was obtained even though the theory is for single-mode operation while the fiber laser is multi-mode. In any case, this fiber-based laser has confirmed the validity of the concept for reduced sensitivity to EOF.

We then implemented the laser in a photonic integrated circuit. For the isolator we adopted the phase-modulator cascade proposed by Doerr *et al.* [4]. This type of devices was analyzed and characterized by us in detail in [51]. Ideally, the RF-driven modulators produce a typical phase-modulated spectrum, redirecting all energy to side peaks at multiples of the RF-modulation frequency in the light propagating in the backward direction, while in the forward direction the light passes unaltered. The side peaks are suppressed by the filter included in the ring laser. The isolator thereby introduces a loss difference between the CW and CCW modes of the laser, increasing the lasing threshold for one mode with respect to the other and forcing the laser to operate in the mode with lowest loss. In the example of Fig. 1, the lasing mode with lowest loss is the CW mode and the EOF light will return to the non-lasing CCW mode.

The first step in the design of the integrated ring laser is to decide on the RF operating frequency of the modulator tandem. This frequency influences three aspects of the laser cavity: (a) the spacing between the modulators in the tandem, (b) the required bandwidth and free-spectral range (FSR) of the intra-cavity filter and (c) the required modulation amplitudes of the voltages applied to the modulators (due to a frequency-dependent modulation efficiency of the modulators). The spacing between the modulators should be small in order to minimize the cavity length, increasing the mode spacing and thereby facilitate single-mode lasing. This requires a high modulation frequency. Furthermore, a filter with a higher bandwidth can be used for higher modulation frequencies, reducing its complexity. However, higher modulation frequency results in lower modulation efficiency. In general, a higher modulation frequency reduces the complexity of the optical design at the expense of increased complexity in the electrical design. In order to make this tradeoff, the electro-optical frequency response of the available phase modulators should be considered. As shown in [51], a modulation amplitude of 1.2 rad in both modulators is required for maximum isolation. This corresponds to 3V electrical modulation amplitude. On the other hand, the electro-optical frequency response efficiency of the modulators at this amplitude diminishes rapidly with increasing frequency with a 3dB bandwidth at 7.5 GHz. [66]. Therefore, an acceptable compromise of 5 GHz was selected as operating frequency.

The implementation of the narrow-bandwidth filters leads to a cavity length of several centimeters, with 13 intra-cavity MMI-couplers. This will result in a round-trip loss of approximately 20 dB. The length of the SOA is 1230 μm , corresponding to a net modal gain of 20 dB at a pump current density of 2 kA/cm². This is feasible for laser operation. In the SMART photonics integration platform [5], MMI-couplers are the most frequently used couplers and they have been found to be very reproducible. These couplers show approximately -30 dB reflections [52], which should be well within our requirements. For the design of the RF-modulator tandem, various trade-offs were made, which results in a total length of the two modulators of approximately 2.6 mm.

The last step in the design of the laser cavity is the filter. The goal of the filter is twofold: to ensure single-mode operation and to suppress the sidebands generated by the UPM. The first requirement is achieved by a filter transmission below 95% for each of the side modes over the full gain bandwidth of the SOA. Suppression of the side bands that are generated by the UPM requires transmission values below 10% at 5, 10 and 15 GHz from the transmission maximum.

The two requirements can be met simultaneously by including three types of filters, (a) a course filter (regular asymmetric Mach-Zehnder interferometer, AMZI) with a length difference of 37.23 μm , FSR = 2.2 THz and 95%-transmission level at 158 GHz, (b) an intermediate filter containing three arms with length differences of 258 μm and 880 μm , leveraging the Vernier effect, with a stop band starting at 20 GHz and (c) a fine filter containing four filter arms with length difference $\Delta L = 4093 \mu\text{m}$, corresponding to an FSR of 20 GHz. For layout reasons, the shortest arm is 4940 μm long. Each arm contains an ERM of

Fig. 2. Layout of the single-mode laser. Metal is shown in yellow, the tandem RF modulators are shown in light blue; the DC modulators for tuning the various filters are shown in dark blue; the SOA is colored red and the MMIs are green.

1.9 mm to allow for full tunability of the passband with FSR of 20 GHz and local transmission minima at 5, 10 and 15 GHz. It should be noted that the intermediate and fine filters have 50%–25%–25% and 50%–25%–12.5%–12.5% splitting ratios over the arms, respectively, with most power coupled to the longer waveguides. This allows a layout in which the filters can be characterized independently of the laser. Together, these filters should be capable of single-mode operation and suppression of side modes generated by RF-modulation.

Fig. 2 depicts the layout of the single-mode laser. The coarse filter is situated at the very mid right and the loops in the middle below the SOA are part of the fine filter. The intermediate filters are in the lower left quadrant, below the out-coupling MMI in the mid left and the tandem ERM's in the upper left quadrant. An extensive description of the layout in Fig. 2 and the various considerations underlying this concept can be found in [53].

It can be seen that the footprint of the laser is very large and that the laser cavity includes many components. This is mainly caused by the modulation based isolator that is used in this laser. In principle it is possible to replace such an isolator by an isolator based on the magneto-optic effect. This would significantly relax the constraints on the intra-cavity filter and remove the need for the UPM and several of the ERM's, thereby reducing the size of the laser considerably. Such an isolator is not yet available in the platform that we used and its development was outside the scope of this research. Magneto-optic isolators have however been demonstrated in similar platforms.

V. RING LASER FACTS AND PECULIARITIES

A crucial ingredient of a ring laser is the ring-shaped closed waveguide. For a symmetric ring laser, this waveguide supports a set of degenerate longitudinal modes, corresponding to the two senses of rotation of the light, i.e., CW or CCW. A pioneering

study of the mode competition in a multi-mode semiconductor ring laser is given in Centeno Neelen *et al.* [22], while a fairly complete analysis of the bifurcation structure is presented in Gelsens *et al.* [54] based on the phenomenological cross and self-saturation model [56], [57]. In the lasing situation, cross saturation in the active medium (inversion grating) induced by the two counter-rotating modes pushes the laser towards bi-stable operation, i.e., both CW and CCW lasing directions are supported as stable equilibrium states, but not simultaneously. Back scattering, on the other hand, implies coupling of equal amounts of CW and CCW, thus pulling towards standing-wave type operation. Since back scattering is a linear process and saturation is non-linear, the drive toward bistability will ultimately overrule the tendency to form standing waves for increasing pump strength. The cross saturation is a consequence of spatial hole-burning in the active material providing the inversion. Back scattering could be due to irregularities in the waveguide or due to a localized, intended or spurious, reflection from an interface or connection. In the transition regime, i.e., for intermediate values of the pump strength, interesting behavior can be expected, notably regimes of tristability, stable oscillations and bistability of two partial-directional states, where the net flow of energy is either CW or CCW. These scenarios are crucially dependent on the phase involved in the back reflection [22], [54]–[57].

As described in the previous section, we include an optical isolator in the ring laser, aiming to keep the CCW below threshold, while the CW is lasing. Nevertheless, the cross saturation and back-scattering mechanisms are still active and should be accounted for in the theoretical description of our laser in the next section.

VI. THEORY FOR THE EINDHOVEN LASER

Most of the theory for our laser can be found in [51], [58], [59] and will be summarized here. In [58] it is assumed that

neither back scattering nor hole-burning-induced cross saturation is present. Rate equations are formulated for the CW and CCW modes and the inversion for the case of isolator-induced round-trip losses, in the presence of EOF and taking spontaneous emission noise into account. By use of these rate equations the RIN spectrum and linewidth of the lasing mode are calculated as indications of the quality of the laser output as functions of the isolation and EOF strength. The main predictions are that if the intra-cavity isolation is only 3 dB the laser will be immune up to -30 dB of EOF; if the isolation is 10 dB, immunity against up to as much as -0.1 dB EOF can be achieved.

In [59] a theoretical study is given as to what extent the main predictions are robust against the inevitable presence of back scattering and cross saturation. In case of sufficiently strong isolation an analytic expression for the directionality in the presence of EOF is derived, which shows that the effects of EOF and back scattering are similar in structure and corroborates the predictions in [58]. Subsection A provides a brief overview of the results of this theoretical analysis of the laser. A theoretical model to describe the operation of the cascade of phase modulators is given in [51]. This model is validated by measurements and will be briefly summarized in subsection B.

A. Ring Laser Theory

The rate equations for the ring laser with optical isolation, back scattering and inversion grating-induced cross saturation are given by

$$\frac{dE_{cw}}{dt} = \frac{1}{2} (1 + i\alpha) \xi (N_0 E_{cw} + N_1^* E_{ccw}) + K e^{i\varphi_{bs}} E_{ccw}; \quad (9)$$

$$\begin{aligned} \frac{dE_{ccw}}{dt} = & -\frac{1}{2} \Delta\Gamma E_{ccw} + \frac{1}{2} (1 + i\alpha) \xi (N_0 E_{ccw} + N_1 E_{cw}) \\ & + K e^{i\varphi_{bs}} E_{cw} + \frac{1}{2} \gamma e^{i\varphi_{fb}} E_{cw} (t - \tau); \end{aligned} \quad (10)$$

$$\frac{dN_0}{dt} = \Delta J - \frac{N_0}{T_0} - (\Gamma + \xi N_0) I - \xi (N_1 E_{cw} E_{ccw}^* + c.c.); \quad (11)$$

$$\frac{dN_1}{dt} = -\frac{N_1}{T_1} - (\Gamma + \xi N_0) E_{cw}^* E_{ccw} - \xi N_1 I. \quad (12)$$

Here, E_{cw} and E_{ccw} are the respective CW and CCW complex field amplitudes in the center of the SOA (see Fig. 2); $I = |E_{cw}^2| + |E_{ccw}^2|$ is the total intensity in units of photon numbers; N_0 is the inversion (number of electron-hole pairs) with respect to the threshold value; N_1 is the inversion-grating (complex) amplitude in the same dimensionless units. The parameters are listed in Table I and variables in Table II.

In (10) the parameter $\Delta\Gamma$ represents the additional intensity loss rate for the CCW mode with respect to the CW loss rate (Γ), induced by the isolator. The formula for $\Delta\Gamma$ in [58] can be expressed as $\Delta\Gamma = (1 - T_{iso})/\tau_r$, where T_{iso} is the ratio of transmissions for CCW and CW through the isolator and τ_r the roundtrip time. In the next subsection we will discuss a model for the isolator consisting of the two tandem ERM's. Furthermore, the feedback rate γ is defined, similar to (5), as $\gamma \equiv T\sqrt{R}/\tau_r$, where T is the transmission of the output coupler,

TABLE I
PARAMETER LISTING

Parameter symbol	Name	Typical value
α	Linewidth enhancement factor	2.5
ξ	Differential gain	$1 \times 10^4 \text{ s}^{-1}$
Γ	Cavity loss	$1 \times 10^{11} \text{ s}^{-1}$
$\Delta\Gamma$	Isolator-induced loss difference	$1 \times 10^{10} \text{ s}^{-1}$
K	Back scatter coupling rate CCW $\leftrightarrow$ CW	$1 \times 10^6 \text{ s}^{-1}$
φ_{bs}	CCW $\leftrightarrow$ CW back scatter phase	Arbitrary
γ	Feedback rate	$1 \times 10^8 \text{ s}^{-1}$
τ	Feedback delay time	$3.3 \times 10^{-9} \text{ s}$
ω_0	Optical frequency at threshold	$2\pi \times 10^{14} \text{ s}^{-1}$
φ_{fb}	Feedback phase; $-\omega_0\tau$	Arbitrary
ΔJ	Injection current w.r.t. threshold	10^{18} s^{-1}
T_0	Inversion lifetime	$1 \times 10^{-9} \text{ s}$
T_1	Inversion grating lifetime	$1 \times 10^{-14} \text{ s}$

TABLE II
VARIABLES LISTING

Variable	Name
E_{cw}	Weakly time-dependent CW complex mode amplitude; $E_{cw} = \sqrt{I_{cw}} e^{i\varphi_{cw}}$
E_{ccw}	Weakly time-dependent CCW complex mode amplitude; $E_{ccw} = \sqrt{I_{ccw}} e^{i\varphi_{ccw}}$
N_0	Inversion w.r.t. threshold; real. (# of e-h pairs)
N_1	Inversion grating amplitude; complex. (# of e-h pairs)
I_{cw}	CW mode intensity; # of CW photons
I_{ccw}	CCW mode intensity; # of CCW photons
ϵ	Directionality, $\epsilon \equiv \sqrt{I_{ccw}/I_{cw}}$
I	Total intensity; $I \equiv I_{cw} + I_{ccw}$; total # of photons
φ_{cw}	CW mode phase
φ_{ccw}	CCW mode phase

R is the effective external reflectivity measured at the output coupler and it should be noted that the feedback light couples into the non-lasing mode.

It is shown in [59] that if the laser operates close to the steady-state equilibrium and the isolation is strong enough that $\Delta\Gamma \gg \xi T_1 \Delta J$ while $\Delta\Gamma \gg K$ and $I_{ccw} \ll I_{cw}$, the following expression holds in good approximation:

$$\begin{aligned} \epsilon & \equiv \sqrt{I_{ccw}/I_{cw}} \\ & \approx \frac{2K + \gamma}{\Delta\Gamma} \sqrt{1 - \frac{K\gamma}{(K + \frac{\gamma}{2})^2} [1 - \cos(\varphi_{bs} - \Psi_{fb})]}, \end{aligned} \quad (13)$$

which combines all relevant quantities in one single analytic expression. The isolation strength $\Delta\Gamma$ is order 10^{10} s^{-1} , the side-wall backscatter rate K is order 10^6 s^{-1} [71] and the feedback rate γ is at most order 10^8 s^{-1} . It then follows from (13) that $\epsilon \leq \frac{2K + \gamma}{\Delta\Gamma} \approx 10^{-2}$, meaning that the conditions for the validity under which (12) was derived are well met. It is shown in [58] that with the above-derived directionality, $\epsilon \leq 10^{-2}$, full insensitivity to external feedback could be achieved in terms of RIN and linewidth.

Numerical device simulations have been performed using a commercial time domain traveling wave circuit simulator (PICWave). In this simulator, similar to the analytical model, it is assumed that only one transverse mode is supported by the waveguide. The simulated structures are discretized along the longitudinal direction and in the time domain. In the simulations a circuit similar to that of Fig. 2 was implemented using an

Fig. 3. Schematic representation of a UPM consisting of the tandem ERMs combined with a spectral filter ($\approx$). Both modulators are driven by a single frequency RF signal with potentially different amplitude and with phase difference ϕ . The distance between the centers of the modulators is D .

ideal power splitter as an output coupler, an SOA that showed realistic characteristics, a UPM consisting of two phase modulators and a filter consisting of four serially placed asymmetric Mach-Zehnder interferometers (AMZIs). The AMZIs had free spectral ranges of 10 GHz, 20 GHz, 200 GHz and 2 THz respectively. In the simulations more than 40 dB of side-mode suppression was achieved [64].

Next, compliance with the analytical model was studied. A number of simulations were run for values of the external reflectivity R ranging from 0 to 1 and for delay time $\tau = 3.3$ ns. For each simulation, the laser was allowed to stabilize in the steady state, after which the ratio between the CW and CCW mode intensities (ε^2), central wavelength, linewidth and RIN were determined. It was found that ε^2 was approximately equal to 25 dB for all R between 1 and 100%, whereas 30 dB was predicted by the analytical model. The deviation can be explained because a fraction of the light that is converted to a different frequency by the UPM, but that is not completely filtered by the filter is converted back to the original wavelength in a second pass through the UPM. The isolation imposed by the UPM and filter combination, can therefore expected to be slightly lower than would be expected based on a single pass through the UPM and filter combination. Furthermore, the central wavelength, linewidth and RIN number were found to be unaffected within the simulation accuracy.

B. Model of Unidirectional Phase Modulator

The unidirectional phase modulator (UPM) is an essential part of the Eindhoven laser and consists of two tandem ERMs, as schematically shown in Fig. 3. As mentioned before, this configuration is inspired on Doerr *et al.* [4]. Ideally the tandem ERMs acts as a single phase modulator in the backward propagating direction, while not affecting the light in the forward direction, hence the name unidirectional phase modulator. The phase-modulated backward-propagating light is passed through the filter and the generated side bands are attenuated, reducing the total power in this propagation direction. Because light in the other direction is not modulated, this light passes the filter without attenuation. Combined, the UPM and the spectral filter therefore provide optical isolation.

The construction of the phenomenological model of the UPM starts from a single ERM. This component is commonly used in InP based PICs as a voltage-driven phase modulator [60], [61].

Each of the two ERMs is modelled as a lumped element, which is justified because their lengths are shorter than one tenth of the wavelength of the RF driving signals. Since a change in refractive index inevitably changes the absorption of the material, it can be expected that the modulators introduce unwanted amplitude modulation as was experimentally found in [62], [63]. For that reason, residual amplitude modulation (RAM) is included in the model. The ERMs have a non-linear phase-voltage relationship, which we approximate by a second order polynomial. Throughout the model we assume that the non-linearity is instantaneous. The transmission of a single ERM is then modelled as

$$T(t) = A(V) \exp(i\Phi(V)), \quad (14)$$

where A denotes the modulation amplitude of the optical field amplitude, Φ the phase modulation amplitude and V the voltage at the modulator, i.e., $V = V_0 + V_1 \sin(\omega t + \psi)$, with ω the angular frequency of the electrical driving signal and ψ the effective electrical phase, which models the phase difference between the two modulators taking into account the propagation time between the modulators.

The model for the complete UPM is obtained by multiplying the transmission of each individual ERM. For the details we refer to [51]. Here it is shown that the effective electrical phases are different for forward and backward propagation. In [51] it is also shown that the model can be simplified by conveniently grouping terms in such a way that an effective ERM is obtained that shows the same behavior as the UPM. Because of the direction dependence of the effective phase difference, this effective ERM is different for both directions. The respective transmissions in forward (+) and backward (−) direction can then be expressed in the form similar to (14) as

$$T^\pm(t) = A^\pm \exp(i\Phi^\pm), \quad (15)$$

with

$$A^\pm = A_0 + A_1^\pm \sin(\omega t + \Psi_1^\pm) + A_2^\pm \sin(2\omega t + \Psi_2^\pm), \quad (16)$$

$$\Phi^\pm = \Phi_0 + \Phi_1^\pm \sin(\omega t + \Psi_1^\pm) + \Phi_2^\pm \sin(2\omega t + \Psi_2^\pm). \quad (17)$$

Here, $A_1^\pm$ and $A_2^\pm$ are the respective linear and quadratic effective residual amplitude modulation and $\Phi_1^\pm$ and $\Phi_2^\pm$ are the respective linear and quadratic effective phase modulations. In the special case that the modulators are linear, and have equal modulation amplitudes, the following analytic expression for the relative power in each of the comb lines can be derived,

$$P_n^\pm \approx \left| J_n \left(\frac{\bar{\Phi}^2}{2} \sqrt{2 + \cos\psi^\pm} \right) \right|^2, \quad (18)$$

where J_n is the n -th order Bessel function of the first kind, $\bar{\Phi}$ the total phase modulation amplitude and $\psi^\pm$ the respective forward and backward effective electrical phase differences, which ideally should be π and 0, respectively.

The UPM model was experimentally validated using a separately fabricated integrated version of the UPM, identical to the UPM in Fig. 2. An extensive description and discussion of the set up can be found in [51]. The validation results are presented in Fig. 4. In (a) a measured spectrum of the light transmitted by

Fig. 4. Measured spectra for various RF imbalances and effective RF phase differences. Subfigure (a) presents a single measured spectrum, where the relative frequency is the optical frequency relative to the frequency of the incoming light wave. Subfigures (b)–(d) show the power in the central five peaks in these spectra as a function of effective phase difference $\psi^\pm$ for three values of modulation imbalance $\hat{\Phi}_1$. The colors used for the data in subfigures (b)–(d) correspond to colors of the peaks in subfigure (a). Note that the fitted curves fall inside most of the error bars, indicating that our model includes all relevant parameters.

the UPM for $\psi = 0.75 \pi$ and $\hat{\Phi}_1 = 0.005$. The subfigures (b), (c) and (d) show the results of the full model as a solid line after fitting to all experimental data simultaneously for three different modulation imbalances. The experimental data are presented as error bars that span two standard deviations of the measurement error. Very good agreement is obtained indicating the model captures all relevant effects. The maximum achievable intra-cavity isolation is estimated from the extreme values for the central mode (blue curve) in Fig 4(c) as 5dB.

VII. MANUFACTURING AND CHARACTERIZATION

The laser laid out in Fig. 2 was fabricated by Smart Photonics through the JePPiX multi-project wafer service [5]. A photograph of the fabricated laser is shown in Fig. 5. The first step in the laser operation was to align the various filter stages. This was done for a pump current of 150mA. At this fixed filter setting, the LI-characteristic of the laser without activated UPM was measured and is shown in Fig. 6. It is immediately apparent

Fig. 5. Photograph of the single-mode laser. Parts of other structures are visible at the top, which are not discussed here.

that the LI curve is very erratic. This is explained by the very delicate operating point of the laser. Due to the increased pump current, the chip is locally heated, slightly changing the group

Fig. 6. Light-current characteristics for CW and CCW light, after correcting the CW-power for the excess propagation loss difference of 12.2 dB. The UPM was not activated. The laser threshold is 100 mA. Until 160 mA the directionality $\varepsilon \approx 1.8$. Between 160 and ≈ 250 mA mode hopping and multi-mode operation occurs, while above 250 mA the output power is limited by thermal roll over. Samples were taken at 10 mA intervals.

index of the waveguides in the vicinity of the SOA. This leads to a misalignment in the filters, most notably in the fine filter stage, and results in mode-hopping and multimode operation of the laser at currents for which the filter was not optimized.

It was found in a different measurement, using an external laser, that the loss from the right output to the SOA is 12.2 dB larger than from the the left output, due to the asymmetric location of the SOA in the ring cavity. This means that the CW output power should be multiplied by a factor 16.6 in order to compare with the CCW output power. For injection current values between the laser threshold ≈ 100 mA and ≈ 160 mA the directionality at mid-SOA location is found to be $\varepsilon \approx 1.8$. Between 160 and ≈ 250 mA mode hopping and multi-mode operation occurs, while above 250 mA the output power is limited by thermal rollover.

An explanation for the bias in directionality $\varepsilon \approx 1.8$ is attributed to an unintended intra-cavity reflection in combination with non-uniform gain distribution in the SOA. In fact, an optical-frequency-domain reflectometry (OFDR) measurement gives evidence for a reflection located at the out coupler (see [51], p.122)). A back-of-the-envelope calculation using the roundtrip conditions for the directional intensities easily shows that this may lead to a directionality at the center of the SOA given by

$$\varepsilon = \sqrt{\frac{g_2}{g_1}} e^{a(L_C - \frac{L}{2})}, \quad (19)$$

with L_C the distance of the MMI out coupler from the SOA (measured in the CCW-direction); L the total roundtrip length of the ring cavity, a the average intensity loss per cm and g_1, g_2 are the effective gains of the respective right and left halves of the SOA. From the estimated roundtrip loss (see [53] p. 93) of 20dB, we deduce $a \approx 0.9 \text{ cm}^{-1}$. With $L \approx 5 \text{ cm}$ and $L_C \approx 1.7 \text{ cm}$, (19) yields a gain-asymmetry ratio $\frac{g_2}{g_1} \approx 13.7$. This is not unrealistic since observation of Fig. 3 shows that the bias-current electrode is asymmetrically connected to the SOA, which makes non-uniformity of the gain quite likely.

The measurement presented in Fig. 7 shows the characteristics for the case where the phase modulator tandem was activated and

(a) $\phi = -90^\circ$

(b) $\phi = +90^\circ$

Fig. 7. LI-curves of the laser for phase differences ϕ of -90° and $+90^\circ$ (sub-figures (a) and (b), respectively). The operating point of the laser was found using an injection current of 150 mA, indicated by the vertical line. At other currents the laser is not guaranteed to be single mode. Also shown is the average power in the two directions to indicate the erratic behaviour of the total output power which is explained by significant changes in the spectral profile of the light as a function of the pump current. Samples taken at 1 mA intervals.

set with an RF phase difference of -90° and $+90^\circ$, respectively in (a) and (b). The same 12.2 dB correction due to different waveguide loss was taken into account. The isolation has led to directionalities $\varepsilon \approx 2.3$ in (a) and $\varepsilon \approx 4.4$ in (b). Hence, the effect of isolation at the settings $\pm 90^\circ$ demonstrates a change in directionality of $\Delta\varepsilon \approx 2.1$. Comparing the characteristics in Figs. 6 and 7 confronts us with the apparent inconsistency that the applied isolation has created increased directionality for both isolation directions. This is attributed to a change in spectral content due to the activation of the UPM.

To test the sensitivity to EOF, the CCW-output is connected to a set up with adjustable external-reflection. This will couple the light from the CCW mode into the CW mode and supplies EOF to the laser. First it will be shown that the intra-cavity isolator does reduce the sensitivity to EOF of the laser, but not to the extent predicted by the theory and then the likely reason for this discrepancy will be attributed to the unforeseen intra-cavity reflection.

In Fig. 8 the measured CCW power is shown versus the external reflectivity without UPM activation. The corresponding feedback ratio at the laser output is obtained by multiplying the external reflectivity by 0.1 to account for the two times 5 dB coupling loss (nominal, back and forth). A clear sensitivity threshold in terms of output power can be seen at $\approx 10^{-2}$ external reflectivity; this corresponds to -30 dB effective feedback strength. The

Fig. 8. EOF dependence of the CCW output without UPM, showing the sensitivity threshold at ≈ -20 dB external reflectivity (-30 dB feedback ratio).

Fig. 9. CCW-output power for two settings of the RF phase difference. The horizontal scale at the bottom of the axis shows the measured reflectivity of the EOF-circuit, measured from its fiber connector. The scale at the top provides a value for the feedback rate as defined in Section III A and includes coupling loss. The effect of the intra-cavity isolation is shown by the difference between the two curves. The measured powers for low values of EOF are different from those in Fig. 7 due to the use of several additional power splitters and their associated splitting loss.

laser output dependence on EOF with activated UPM is shown in Fig. 9 for two different settings of the RF-phase difference of the UPM, corresponding to suppression of the CW-mode ($+90^\circ$) and CCW-mode (-90°), respectively. In both cases the EOF circuit was connected to the CCW output. The feedback sensitivity threshold in terms of the laser output power is now at -27 dB.

Compared to the sensitivity of the laser without RF-modulation (Fig. 7), the laser when operating under $+90^\circ$ RF-phase difference isolation condition shows EOF-sensitivity reduction of 3 dB in the output intensity. In order to investigate more subtle effects of EOF, the linewidth of the CCW mode is determined using a delayed self-heterodyne setup. This was done for various amounts of EOF and for both settings of the RF phase difference. For weak EOF, a Lorentzian line shape is obtained, but for higher feedback strength additional peaks appear in the spectrum. For this reason it is not possible to fit a Lorentzian to the measured spectrum. The effect of EOF on the linewidth is therefore illustrated by measuring the 20 dB width of the central peak for each spectrum where possible and then converting to the 3 dB linewidth assuming a Lorentzian shape.

Fig. 10. The linewidth of the CCW-output with intra-cavity isolation as a function of feedback strength. Due to the appearance of external cavity modes, the linewidth cannot be determined using a fit to a Voigt profile. The linewidth is therefore determined by taking the 20 dB width of the peak and calculating the linewidth from this value.

Fig. 11. Delayed self-heterodyne spectra measured at the CCW output for an injection current of 150 mA and for an RF phase difference of $+90^\circ$. The appearance of external-cavity modes is clearly visible.

The resulting data are presented in Fig. 10 and again show the limited influence of the intra-cavity isolator on the sensitivity to EOF.

In Fig. 11 delayed self-heterodyne spectra are shown versus EOF strength and for an RF phase difference of $+90^\circ$. The spacing between the extra peaks that occur at higher feedback strengths is approximately 12 MHz and this corresponds to the round-trip length (83 ns) to the external reflector. Therefore, these peaks originate from external cavity modes, which can exist only when light from the external reflector is coherently coupled into the lasing mode. This is due to the CW-CCW coupling caused by the on-chip spurious reflection and makes our ring laser behave under EOF similarly to a Fabry-Pérot laser.

VIII. DISCUSSION

There is no debate that the laser here investigated does not perform up to its intended qualifications, but the good thing is that lessons can be learnt from that. A major disadvantage of the current laser design is its huge footprint and its complexity. This can be attributed mainly to the modulation-based isolator. We have demonstrated that this isolator enables 5 dB of isolation, but it requires a fine filter to remove the modulation-induced side frequencies at ± 5 GHz. This filter adds 11.5 mm to the cavity length and the two included modulators another 5.6 mm.

All these components increase the complexity of the laser and enlarge the risk of spurious reflections inside the laser cavity, deteriorating the performance of the laser.

One problem can be solved by using an isolator based on the magneto-optic phase shift. Such an isolator typically occupies less space than the two ERMs. In addition, such isolators do not require an additional spectral filter. The cavity length can therefore be greatly reduced. As a result the mode spacing is increased and the requirement for single mode lasing on the intra-cavity filter is relaxed. For such a laser, the design presented in [70] remains feasible. We therefore believe that magneto-optic isolators can significantly improve the performance of the laser. Such isolators were not available in our platform however and their fabrication was outside the scope of this work.

Another improvement would be to use QD gain material in the laser, as the linewidth enhancement factor for these lasers is much smaller than for QW lasers. In combination with the intra-cavity isolator and components free of back-reflections, the ring laser remains a most promising candidate for reduced EOF-sensitivity.

IX. CONCLUSION AND OUTLOOK

A literature search on methods to create immunity of a semiconductor laser to EOF led us to the idea of an integrated ring laser equipped with an optical isolator included in the ring cavity. By increasing the roundtrip loss of one directional mode with respect to the mode running in the other direction, the laser threshold will be at first instance characterized by the excitation of laser operation in one direction, but (spurious) back reflections could still involve the counter-running mode as well. Providing sufficiently strong intra-cavity isolation should maintain lasing in the desired direction while not coupling the two propagation directions optically, even in the case of eventual EOF. The integrated laser chip manufactured following these ideas was characterized and the EOF-dependence of the laser output power was observed and quantified. The isolation was achieved by an intra-cavity modulation-based isolator, which was shown to provide 5dB of isolation.

However, relatively strong immobility of the directionality as function of applied intra-cavity isolation strongly indicates the unfortunate presence of an unexpected complication, notably caused by an unintended intra-cavity reflection at the out coupler MMI in combination with asymmetric SOA gain. While this conjecture is confirmed by a simple model, external-feedback measurements show external-cavity modes in the spectrum and strong linewidth reduction of the central wavelength versus EOF. Evidently, due to the spurious reflection, the ring laser modes are strongly coupled even with isolation, causing the laser to show external-cavity modes in response to EOF, in a way similar to Fabry-Pérot type lasers. Nevertheless, by comparing observed curves of CCW-power versus EOF-strength for cases with and without intra-cavity isolator, a reduction in EOF-sensitivity of 3 dB is demonstrated. Intra-cavity isolation is therefore demonstrated to be a feasible concept, but further reduction of feedback effects requires elimination of spurious reflections.

This study has shown that modulation-based isolators greatly increase the complexity of the laser design to the extent that reliable operation of our laser is severely hampered. However, integrated magneto-optic isolators provide a promising route to isolators with a smaller footprint. By integrating such an isolator inside the laser cavity, the requirement on the isolation value is relaxed and the insertion loss of such an isolator can be reduced.

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