Directional power distribution and mode selection in micro ring lasers by controlling the phase and strength of filtered optical feedback

Guy Verschaffelt¹,³,* and Mulham Khoder²,³

¹Applied Physics Research Group (APHY), Department of Applied Physics and Photonics, Vrije Universiteit Brussel, Pleinlaan 2, 1050 Brussels, Belgium
²Brussels Photonics (B-PHOT), Department of Applied Physics and Photonics, Vrije Universiteit Brussel, Pleinlaan 2, B-1050 Brussels, Belgium
³Both authors contributed equally to this work
*guy.verschaffelt@vub.be

Abstract: We discuss the design and characterization of a micro ring laser with on-chip filtered optical feedback. The laser and feedback section have been fabricated on a generic photonic integration platform using only standard building blocks. The filtering process in the feedback scheme is based on the reflection from a distributed Bragg reflector. We include several control pads in the feedback section which allows us to control separately the wavelength, the strength and the phase of the filtered feedback. By controlling the phase of the feedback, we can fine-tune the longitudinal mode selection and wavelength of the laser output, while changing the strength of the feedback allows us to control the power distribution between the two directions of the micro ring laser. Numerical simulations reproduce our experimental observations.

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References and links
1. Introduction

Optical feedback is one of the well known approaches to change and/or control the output of semiconductor lasers [1–3]. When a part of the laser output is guided back to the laser’s cavity after spectral filtering, this process is called filtered optical feedback (FOF). FOF can e.g. be used to obtain single-mode operation, to select or tune the frequency of the laser light [4], or to investigate dynamical regimes of the laser’s output. The effect of the FOF on the dynamical behavior of lasers has been investigated experimentally and numerically in several studies, including but not limited to: the study of periodic oscillations and non linear dynamics, appearance of low frequency fluctuations, bifurcation bridges, the study of noise effects on the dynamics of FOF lasers and developing a rate equation model and a traveling wave model to take FOF into account [5–13].

There are several ways to achieve this optical filtering in the feedback path, e.g. using diffraction gratings [14], arrayed waveguide gratings (AWGs) [15], or by inserting a Fabry-Perot interferometer in the external cavity to produce filtered light [16]. The filter which is used to achieve the FOF can be either external as in [13, 17] where a beam splitter or a mirror is used to couple the light in and out of the filter, or the FOF can be integrated on the same chip with the
laser as in [18] where an AWG has been used to digitally tune the wavelength of a Fabry-Perot laser.

These integrated filters have also been used in combination with semiconductor ring lasers (SRLs). These SRLs have some unique features linked to the presence of two directional modes: the SRL can lase in the clockwise (CW) and/or in the counterclockwise (CCW) direction. These directional modes can e.g. be used to implement all-optical switching [19] and optical memory [20]. The practical use of SRLs is often made difficult because of their multi-mode output and/or because the emission wavelength is not well controlled as the laser cavity does not contain a strong wavelength selection mechanism. Such multi-mode emission is not preferred in most applications which often require single-mode emission at a well-defined wavelength, eventually with the possibility to tune this wavelength [21].

For this reason, several studies have proposed to use FOF to control the emission wavelength of SRLs [22, 23]. In [22] we have applied this concept using two AWGs which are mutually connected via four semiconductor optical amplifiers (SOAs) gates. The FOF-section in this device was integrated on the same chip as the laser and it provides so-called self-feedback in both directions: the light in each direction is re-injected in the same direction after passing through the FOF loop. Using this device, we have demonstrated digital wavelength tuning, multi-wavelength laser emission [24] and fast wavelength switching [25]. This device also has some limitations. In order to have a sufficient spectral resolution in the FOF, the AWGs are typically quite large in such a design. Even more importantly, for the device discussed in [22], it is not possible to independently control the phase of the feedback. In [24, 25], however, we have shown that phase of the feedback may play an important role in choosing the emitted mode.

SRLs with unidirectional cross-feedback have also been proposed in literature. In [23] a monolithically integrated external distributed Bragg reflector (DBR) section has been used as filtering element to tune the SRL. In this device, one directional mode is reflected by the FOF section in the opposite direction, but not vice-versa. Such a design has an additional interesting feature: the directional symmetry of the SRL is broken by the FOF, which should lead to a dominant lasing direction. Conventional feedback in such a laser (e.g. from fibre facets or other partially reflecting external components) will be injected in the suppressed directional mode and hence it can be expected that such a laser will be less sensitive to optical feedback. The results in [23] have shown the possibility to achieve single mode emission with a side mode suppression ratio (SMSR) of 30 dB. In addition, a wavelength switching time of 450ps has been observed. But also in this device, no independent control of the feedback phase was foreseen in the design. Moreover, the strength of the FOF could not be directly tuned. The dominant longitudinal mode (LM), and hence also the emission wavelength can be changed by thermal tuning of the DBR reflectivity spectrum, but fine-tuning of the selected mode is not easy: when the laser hops to the another LM, it will often skip a few adjacent modes.

Therefore, in this paper we will discuss the design and experimental characterization of an SRL with on-chip FOF and with independent control of the strength and phase of the FOF section. Our design is based on the standard building blocks of the generic Jeppix platform [26] for photonic integrated lasers. The FOF section in our design is based on DBR mirrors and implements cross-feedback between the two directions of the SRL, such that the feedback can be used both to control the emission wavelength and to enhance one of the directional modes. We have included several control pads with which we can tune the fabricated laser’s emission wavelength, and control separately the feedback strength and phase of FOF. We will illustrate experimentally that fine-tuning of the selected LM (and thus also of the wavelength) can be achieved by tuning the phase of the feedback. Tuning of the feedback strength can be used to control the asymmetry of the power emitted in the two directions. Finally, we will also discuss numerical simulations using a rate equation model, which are used to interpret our experimental observations.
2. Device description and working principle

The device has been designed using the commercial software MaskEngineer from PhoeniX Software using the standard building blocks from the Oclaro foundry on which platform the fabrication has been done. A microscopic image of the device is shown in Fig. 1. The design of our device consists of an SRL and two feedback arms. Each of these main parts consists of several sub-components, which are detailed in the following paragraphs.

![Microscopic image of the tunable ring laser integrated with two filtered feedback arms.](image)

Fig. 1. Microscopic image of the tunable ring laser integrated with two filtered feedback arms.

The SRL in our design has a race-track geometry. It consists of two straight Semiconductor Optical Amplifiers (SOAs) and two 2x2 Multi-Mode Interference (MMI) couplers which are connected with one another using waveguides. The SOAs are used as the amplifying regions of the laser cavity. Each SOA has a length of 300 \(\mu m\) and they can be pumped using a common metallic pad.

One side of each SOA is connected to a 2x2 MMI-coupler with a length of 80 \(\mu m\) and a coupling ratio of 50\% to each output port. The MMI at the top of the SRL couples part of light out of the chip in both the CW and the CCW directions using output waveguides that are angled at 7° with respect to the chip facets in order to reduce reflections to the SRL at these interfaces. The MMI at the bottom of the SRL is used to couple part of the laser’s power to the feedback arms. These MMI couplers are used as a replacement of directional couplers (which are more commonly used in SRLs) as these directional couplers were not supported by the fabrication platform.

The other side of each SOA is connected to a curved strong passive waveguide which is used to close the ring cavity. These curved waveguides are deep-etched, hard-walled waveguides that allow tight waveguide bends because the beam is well-confined in the structure. The active parts of the chip are made in a weak active waveguide, which is formed by a shallow-etched ridge structure. A waveguide transition element has to be placed whenever the design goes from an active/passive weak waveguide to a strong passive waveguide. Such a transition element is placed at both sides of each SOA in the SRL shown in Fig. 1.

The two lower ports of the MMI coupler at the bottom of the SRL in Fig. 1 are connected to the feedback arms. Each feedback arm consists of a 100 \(\mu m\) long phase shifter (PS), a 100 \(\mu m\) long SOA and a DBR mirror. Changing the current injected in the PS can be used to control the phase of the filtered feedback, whereas the current injected in the SOA controls the strength of the feedback. Changes in the SOA current will also lead to (unintentional) changes in the feedback phase as the SOA’s refractive index slightly depends on this current. The last component in the feedback arm is a DBR mirror which is used to reflect specific wavelengths. The DBR has a length of 200 \(\mu m\) leading to an intensity reflection coefficient of 0.58. To get a Bragg wavelength of 1550 nm, we used a grating pitch of 237.5 nm while a nominal value of 50 cm\(^{-1}\) is used for the grating coupling coefficient. At both sides of the SOAs in the feedback arms, there is an isolation
waveguide such that the phase shifter, the SOA and the DBR are electrically isolated and can be individually controlled. The DBR is followed by a weak-to-strong waveguide converter, after which the output waveguides from the FOF branches are also connected to the chip facets under an angle of 7 degrees.

Feedback arm 1 reflects the CCW direction into the CW direction of the SRL, and feedback arm 2 reflects the CW direction into the CCW direction (i.e. we implement cross-feedback). All LMs emitted by the SRL are coupled to the feedback arms. The reflected wavelength can be tuned by sending current through the DBRs. If the SOAs in the feedback arms are not biased or reverse biased, they absorb the light and no feedback returns to the ring cavity. However, if a SOA is forward biased, the light beam emitted by the SRL is amplified when traveling through the SOA. The spectrally filtered light reflected by the DBRs will pass back through the SOA and the phase section, and finally this beam is coupled back in the SRL via the MMI coupler. If the feedback light is in phase with the original laser field, we expect to favor and have emission in an LM that is spectrally aligned with the reflection band of the DBR. The wavelength tuning can then be achieved either by changing the DBR’s Bragg wavelength or by changing the feedback parameters in the feedback arms.

3. Device characterization: SRL without feedback

The temperature of the laser is stabilized at 21 °C using a Peltier cooler and a thermistor heat sensor placed beneath the chip. Electrical probes are used to bias the SRL and the different components in the feedback section. The light emitted by the SRL in the CW and CCW direction is collected using two lensed fibers that can be connected to different measurement devices. The fiber alignment is done in such a way that we collect equal amounts of power in the two directions when the device current is below the threshold current. We use a Newport 2832-C dual channel optical power meter to measure the optical output power, an Ando AQ6317B optical spectrum analyzer to measure the spectra and a 4 GHz Tektronix CSA7404 oscilloscope with a 2.4 GHz photodiode to record time traces of the output power.

We start the characterization of the device without feedback by measuring the power distribution between the two directions (CW and CCW) as a function of the injected current. This is shown in Fig. 2. As can be seen in this figure, the threshold current of the device is 30 mA, and the SRL is bidirectional for all currents above the threshold. The laser emits in the two directions with slightly more power in the CW direction than in the CCW direction. The absence of a bistable unidirectional regime in Fig. 2 indicates that the backscattering [27] is large in this device, probably caused by reflections in the MMI couplers. We used the oscilloscope to measure time traces of the device’s output, in which we did not notice any alternate oscillations or other dynamical fluctuations in the intensity.

Next, we measure the optical spectrum at the device’s output (see Fig. 3). The measured LM spacing is around 0.2 nm. We notice that the device’s output is multi-mode close to the threshold. For specific values of the pump current, the device emits in a single LM (see e.g. the spectrum at 45 mA in Fig. 3). At larger pumping currents, the device output is typically multi-mode as is illustrated by the spectrum measured at 55 mA in Fig. 3. Remark that at higher temperatures, the LMs and thus also of the laser emission shifts to longer wavelengths, but we still observe similar behavior as what is observed at 21 °C.

4. Device characterization: SRL with single feedback

We investigate in this section the effect of the feedback on the device’s output. We apply feedback only in one direction and we investigate the effect of the different components in the feedback arm. For the experiments discussed on this section, we only use FOF from feedback arm 1 in Fig. 1.
4.1. Role of the phase shifter section

One novelty of our device is that we can experimentally investigate the effect of the phase of the feedback separately from the effect of the strength of the feedback. We use three probes in this measurement. One probe is used to bias the SRL at 60 mA, the second is used to bias the SOA at 40 mA. The third probe is used to change the phase of the feedback by changing the current in the phase section of the feedback.

In Fig. 4 we plot the peak emission wavelength when changing the current $I_{\text{phase}}$ in the phase section. We also plot the corresponding Side Mode Suppression Ratio (SMSR) between the largest and second largest peak in the optical spectrum. When $I_{\text{phase}} = 0 \text{mA}$, the peak emitted wavelength is 1551.264 nm and the SMSR is 40dB, indicating that the laser emits a single LM. When we compare this to the spectra in Fig. 3, it is clear that the FOF is able to make the SRL single-longitudinal mode at a wavelength that corresponds to the reflection band of the DBR in the feedback arm. We also notice from Fig. 4 that, although the DBR reflection band has a width of about 2 nm that is much larger than the LM mode spacing of 0.2nm, only a single LM is selected by the FOF. When $I_{\text{phase}}$ is increased, the SRL successively jumps to adjacent LMs at lower wavelengths, showing that the feedback phase can be used to fine tune the LM that is selected by the FOF. When further increasing $I_{\text{phase}}$, the SRL jumps back to the LM at 1551.263 nm when $I_{\text{phase}} = 0.9 \text{mA}$. This seems to indicate that the feedback phase has undergone a shift over $2\pi$ when $I_{\text{phase}}$ is changed from 0 mA to 0.9 mA. For still larger values of $I_{\text{phase}}$, this pattern repeats itself but now the change needed in $I_{\text{phase}}$ in order to obtain a $2\pi$ phase shift becomes much larger. This indicates that the phase change in the phase section is not linearly dependent on $I_{\text{phase}}$. 
Fig. 4. Peak wavelength (top) and SMSR (bottom) of the device’s output as a function of the current injected in the phase section in feedback arm 1, while the SRL is biased at 60 mA and the SOA in feedback arm 1 is biased at 40 mA.

4.2. Role of the feedback strength

We first characterize the SOA in the feedback arm by investigating the gain and gain saturation of this SOA. For this purpose we measure the transmitted power through the mirror for different pumping currents of the SOA. This measurement of the power transmitted through the DBR is done by aligning the lensed fiber with the bottom output waveguide at the left-hand side of Fig. 1.

Fig. 5. Transmitted power through the DBR as function of the pumping current of the SOA in feedback arm 1: (left) no current is applied to the SRL, (right) SRL is biased below threshold at 25 mA.

Measuring the gain of a particular LM that propagates though the SOA is made difficult above threshold because the SOA current will also influence the LM selection and thus the power distribution between the LMs. Therefore, we estimate how the SOA gain changes with current by measuring below threshold. First, we measure the transmitted power while the SOA current is increased from 0 to 50 mA without applying any current on the SRL. Then we repeat this measurements when the SRL is pumped below the threshold at 25 mA. The results of these measurements are shown in Fig. 5. In both curves, the transmitted power increases first linearly when increasing the SOA current, but this increase in power saturates around 20 mA. Therefore,
we can also assume that the SOA gain saturates above 20 mA.

![Graph showing power distribution between the CW and CCW directions as function of the current applied to the SOA in feedback arm 1 while the SRL is biased at 80 mA.]

Next, we investigate the effect of the feedback strength on the device’s output by measuring the output power in the two directions versus the SOA current when the laser pump current is fixed above threshold. The result of this measurement is shown in Fig. 6. As the feedback in feedback arm 1 returns to be re-injected in the CW direction, the power in the CW direction is enhanced by the feedback and it becomes larger than the power in the CCW direction. The power difference between the directional modes becomes larger when the SOA current is increased, and this power difference saturates around 20 mA (which corresponds to the current at which the SOA gain saturates). This change in the power distribution between the two directions shows that it is possible to use FOF to force the SRL to emits in a unidirection mode in a controlled way. This can be useful to make the SRL less sensitive to external optical feedback, as this external feedback will then be re-injected into the suppressed directional mode [28]. Using the SOA in feedback arm 2 leads to similar results with the dominant direction in that case being the CCW direction.

In Fig. 7 we show the spectrum of the light emitted by the SRL in the CW direction at a laser injection current of 55 mA and when the SOA in the feedback path is pumped at 40 mA (the phase section is not pumped). As can be seen from this figure, the laser emits in a single longitudinal mode at 1551.3 nm with a large SMSR. This is in stark contrast with the highly multi-mode spectrum that we obtained in Fig. 3(c) at the same laser pump current but without pumping of the feedback SOA, illustrating the wavelength selection caused by the filtered feedback.

![Graph showing optical spectrum measured in the CW direction when the SRL is pumped at 55 mA, the SOA is pumped at 40 mA and the phase section is not pumped.]

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4.3. Role of the DBR

We characterize the DBR by measuring the transmission spectrum of the DBR in feedback arm 1. To achieve that, we pump the SOA in feedback arm 1 at 30 mA without pumping the SRL. The SOA will then emit broad-band spontaneous emission, which will be filtered by the DBR. The measured DBR transmission spectrum is shown in Fig. 8, and shows a drop in the transmitted power around 1550.3 nm. The width of the dip in the transmitted power is 2 nm. This shows that the DBR reflection band has a width of 2 nm that is centered at 1550.3 nm, which corresponds to the wavelengths of the LMs selected for lasing in Fig. 4.

Fig. 8. Spectrum of the light transmitted through the DBR in feedback arm 1 when the SOA in the same feedback arm is biased at 30 mA without pumping the SRL.

Next, we investigate the change in the DBR reflection spectrum when a current is send through the DBR. Such a current can be used to shift the center wavelength of the DBR reflection band.
The central reflected wavelength as function of the current send through the DBR is shown in red in Fig. 9. From this figure it can be seen that by increasing the current of the DBR from 0 to 5 mA, the center wavelength of the DBR’s reflection spectrum decreases from 1550.3 nm to 1545.2 nm.

We also measure the change in the emitted peak wavelength of the SRL when we change the reflectivity of the DBR. In this measurements, the pumping current of the SRL and of the SOA in feedback arm 1 are fixed at 80 mA and 20 mA, respectively. By increasing the current of the DBR in feedback arm 1 from 0 to 5 mA, we notice that the emitted peak wavelength decreases from 1551 nm to 1545.2 nm as can be seen from the blue curve in Fig. 9. As can be seen by comparing the different curves in Fig. 9, the change in the peak wavelength of the SRL due to a change in the current of the DBR agrees well with the corresponding change in the center wavelength of the DBR reflection spectrum. This shows that the emitted peak wavelength jump from one LM to another LM depending on the spectral position of the DBR. In Fig. 9 we also show the SMSR when changing the current send through the DBR. The SMSR remains larger than 20dB, indicating single LM emission in the entire tuning range of the DBR current. We want to remark that not all LMs are addressed in Fig. 9: the SRL often skips adjacent modes when the output switches from one LM to another by changing the DBR current. However, the tuning of the feedback phase discussed above in Section 4.1 can be used to fine-tune the selected LM in the DBR reflection band. Finally, we also want to remark that we obtain similar results when using feedback arm 2, but then the roles of the CW and the CCW modes are reversed.

5. Device characterization: SRL with double feedback

In this section, we describe the behavior of the SRL when we use feedback arms 1 and 2 simultaneously. Our initial aim of this study is to investigate if controlled multi-wavelength emission is supported by the laser or not. For this purpose, we spectrally tune the DBR in feedback arm 1 slightly away from the reflection of the DBR in feedback arm 2, such that both feedback arms can excite different longitudinal modes. By way of example, we have tuned the DBRs such that the center wavelength of feedback arm 1 is at 1554 nm while the center wavelength of feedback arm 2 is at 1552 nm. (We remark that the experiments in this section have been done on a different laser as the one used before, but it shows very similar behavior as that discussed in Section 4 when only one feedback arm is used).

In Fig. 10 we show the peak wavelength, the SMSR and the power in the CCW direction as a function of the current injected in the SOA of arm 2, for a fixed current of 42 mA being pumped into the SOA of arm 1.

![Graphs showing peak wavelength, SMSR, and power in the CCW direction](image-url)
1554 nm is not reflected back into the CW mode as it is not spectrally aligned with the mirror in arm 2. So, when the laser emits around 1554 nm, the behavior of the device is very similar to what we observe when we only pump the SOA in feedback arm 1. The SMSR is larger that 20dB, indicating single-longitudinal mode emission. When we gradually increase the current in the SOA of arm 2, the peak wavelength shifts to a mode around 1552 nm at a current of 44 mA. At the same current, the SMSR drops almost to zero, and thus the main peak and the first side mode contain almost equal amounts of optical power. For currents higher than 46 mA injected in the SOA of arm 2, we observe emission around 1552 nm with a high SMSR, i.e. the emission occurs again in a single LM. Now, we observe a strong increase in the power in the CCW direction: the mode selection is imposed by the reflection from the DBR in arm 2 and this reflection enhances the emission in the CCW direction.

The previous measurement is complemented in Fig. 11 by the optical spectrum at specific values of the SOAs’ pump current. The SOA current in arm 1 is again fixed at 42 mA. If the SOA current in arm 2 is small (see Fig. 11, left), the SRL shows stable emission in an LM close to 1554 nm corresponding to the DBR of arm 1. At high currents (see Fig. 11, right), the emission has switched to an LM close to 1552 nm corresponding to the DBR in arm 2. In between (see Fig. 11, middle) there is a transition region where the SMSR is small and multiple LMs are emitted. We want to remark here that we did not observe square-wave oscillations in the directional optical power within the bandwidth of our detection system, as was observed in [12] in the long-delay limit. Still, the emission corresponding to Fig. 11(b) is not stable dual mode emission, but rather an excitation of several LMs at the same time. Also for other combinations of the SOA currents, we never observed stable dual mode emission in the presented device.

6. Numerical simulations

We perform numerical simulations to investigate the effect of different parameters of the feedback on the device ‘s output and to interpret our experimental results. We use a two-directional mode rate equation model of the SRL [27, 29] extended with Lang-Kobayashi terms to take into account the effect of optical feedback [30]. In this model, Eqs. (1)-(2) describe the evolution of the slowly varying complex electric fields $E_{cm}$, $E_{ccwm}$ of the CW and CCW directions, respectively. The number of carriers $N$ is described by Eq. (3). These equations are:
When one of the LMs is enhanced by FOF, the intensity of this mode (LM

We calculate the intensity when the SOA in one feedback arm is pumped. In that case, we observe that the SRL emits in

where \( m \) refers to different LMs. In this simulation we take \( k_d \) (at least for low SOA currents, for which the SOA gain is not saturated). Therefore, the feedback strength is increased by numerical integrating of the Eqs. (1)-(3). The results are shown in Fig. 12) decreases. This can be understood based on the direction of the cross-feedback: the FOF is

These simulation results are in good correspondence with the experimentally observed behavior, as the power in the CW direction is close to the power in the CCW direction (see Fig. 2), and thus enhances lasing in this directional mode.

Furthermore, in Fig. 12 we take both feedback phases equal to 0. When \( \eta_1 \) is close to zero, Fig. 12 shows that both LM1 and LM2 are active and have the same intensity. If we increase \( \eta_1 \), the CW and CCW intensities of LM1 increase while the CW and CCW intensities of LM2 rapidly decrease. We also notice that by further increasing the feedback strength \( \eta_1 \), the intensity of LM1 is increased in the CW direction while its intensity in the CCW direction is decreased. This can be understood based on the direction of the cross-feedback: the FOF is re-injected in the SRL in the CW direction, and thus enhances lasing in this directional mode.

6.1. Effect of the feedback strength

We calculate the intensity \( |E_m^{CW(CCW)}|^2 \) of different directional and longitudinal modes when the feedback strength is increased by numerical integrating of the Eqs. (1)-(3). The results are shown in Fig. 12 for different values of the feedback strength \( \eta_1 \) experienced by longitudinal mode LM1. When one of the LMs is enhanced by FOF, the intensity of this mode (LM1 in Fig. 12) increases while the intensity of the other mode (LM2 in Fig. 12) decreases.

The feedback strength can be considered to be proportional to the current injected in the SOA (at least for low SOA currents, for which the SOA gain is not saturated). Therefore, the feedback strength is set to zero for one of the LMs (\( \eta_2 = 0 \)), while the feedback strength \( \eta_1 \) for the other mode is varied. Furthermore, in Fig. 12 we take both feedback phases equal to 0. When \( \eta_1 \) is close to zero, Fig. 12 shows that both LM1 and LM2 are active and have the same intensity. If we increase \( \eta_1 \), the CW and CCW intensities of LM1 increase while the CW and CCW intensities of LM2 rapidly decrease. We also notice that by further increasing the feedback strength \( \eta_1 \), the intensity of LM1 is increased in the CW direction while its intensity in the CCW direction is decreased. This can be understood based on the direction of the cross-feedback: the FOF is re-injected in the SRL in the CW direction, and thus enhances lasing in this directional mode. These simulation results are in good correspondence with the experimentally observed behavior when the SOA in one feedback arm is pumped. In that case, we observe that the SRL emits in
a single LM when the SOA’s current is sufficiently large. Also, we experimentally observed in Fig. 6 that the difference in the intensity of the two directions of the enhanced mode increases as the SOA current is increased.

![Figure 12](image_url)

**Fig. 12.** Intensity of two modes LM₁ and LM₂ in the CW and the CCW direction as a function of the feedback strength η₁ while η₂ = θ₂ = θ₁ = 0.

### 6.2. Effect of the feedback phase

We now keep the feedback strengths fixed and investigate the role of the feedback phases by simulating Eqs. (1)-(3) for various values of θ₁ and θ₂. We take the feedback strengths equal for the two LMs considered in the simulations (η₁ = η₂ = 5 ns⁻¹). In Fig. 13(a), we plot the simulated modal intensities when changing θ₁ from 0 to 2π while keeping θ₂ equal to 0. It can be seen that the intensities in the CW and CCW directions change when changing the feedback phase. Initially, for θ₁ = 0, the two LMs have an equal amount of power, but LM₂ is gradually switched off when θ₁ increases. LM₁ is dominant when θ₁ is in the range [0.3π - π]. Then, LM₁ is gradually switched off for larger values of θ₁. When θ₁ is in the range [1.3π - 1.8π], LM₁ is switched off, whereas θ₁ > 1.8π results in LM₁ being gradually increased. The range of θ₁ for which LM₁ is selected is non-trivial: the FOF introduces also a phase shift between the CW and the CCW direction of a particular LM (due to the appearance of so-called external cavity modes [2]) and the selection of the dominant LM depends on both this phase difference and the phases θ₁ and θ₂ of the feedback loops.

It is also clear that there is a difference in the intensity between the two directions of the dominant mode, but this difference between the directional modes is only weakly dependent on the feedback phase. We thus notice from Fig. 13 that the feedback phase can determine the dominant LM but its effect on the dominant directional mode (CW or CCW) is weak and is limited to small changes in the intensity of each directional mode. The dominant direction mode is determined by the direction of the cross feedback while the strength of the feedback can change the difference in the intensity of the two directions.

Next, we repeat the calculation but this time using a larger value for the feedback strengths (η₁ = η₂ = 10 ns⁻¹). The simulated intensities when changing θ₁ from 0 to 2π while keeping θ₂ equal to 0 are shown in Fig. 13(b). The results are very similar to the results in Fig. 13(a), with the only change being that the difference between the directional mode power has increased, which is in agreement with the results shown in the previous section in Fig. 12. The strength of the feedback thus has no influence on the selection of the LM, provided that it is strong enough to enforce lasing in a single LM.
Fig. 13. Intensities of the two modes $LM_1$ and $LM_2$ in the CW and the CCW direction as a function of the feedback phase $\theta_1$ while (a) $\eta_1=\eta_2=5\mathrm{ ns}^{-1}$, $\theta_2=0$, and (b) $\eta_1=\eta_2=10\mathrm{ ns}^{-1}$, $\theta_2=0$.

7. Conclusions

In this paper, we discussed the design and characterization of an SRL with on-chip integrated FOF, where the implemented FOF follows a cross-feedback scheme. The device has been fabricated with the generic Jeppix fabrication platform [26] using only a set of standard photonic building blocks. We have shown that asymmetric FOF, i.e. feedback that is only re-injected in one directional mode, can be used to obtain unidirectional emission from the ring. If the feedback strength is sufficiently large, lasing in a single longitudinal mode will happen. Furthermore, the strength of the feedback controls the asymmetry in the power distribution between the directional modes. The wavelength of the laser can be changed by spectrally shifting the reflection band of the DBR in the feedback loop, but control over the phase of the feedback loop is needed to fine-tune the selection of the longitudinal mode and thus also to fine tune the emitted wavelength.

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