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Widely tunable multimode-interference based coupled cavity laser with integrated interferometer

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Abstract: We present a simple to process tunable laser, fabricated in a low-cost generic fabrication process and based on two coupled Fabry-Perot cavities. The complex coupling coefficients of the coupling element are analytically derived from a 3x3 MMI using coupled mode theory and chosen to maximize the SMSR during lasing operation. Additionally, one of the cavities contains a reflective interferometer, which acts as coarse wavelength selector. This interferometer is derived from a Michelson Interferometer, by replacing the two independent mirrors with our optimized coupling element, leading to a doubled Free Spectral Range. As a result, we obtained a tuning range of 26 nm with potential for beyond 40 nm, a SMSR larger than 40 dB and fiber coupled power up to 9 dBm.

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References and links

1. Introduction

Tunable lasers are an essential element for telecommunication and enable a great variety of applications through integration into complex photonic integrated circuits based on the generic integration approach [1]. At present, most tunable sources are integrated via reflective gratings or narrow bandwidth tunable optical filters. For the first, a high lithographic resolution and an additional epitaxial growth are required. Examples are the digital super mode distributed feedback laser (DS-DBR) [2], grating Y-branch laser [3] and distributed feedback (DFB) laser arrays [4]. In the second approach, the wavelength selection is achieved through tunable wavelength selective circuits, which are realized by concatenating optical filters on chip. The resulting laser suffer from additional insertion loss determined by the number of employed filter stages. Examples are AWG lasers [5–7], ring-filtered lasers [8] and Mach-Zehnder based lasers [9].

Alternatively, a single mode laser can be obtained by coupling of two multimodal laser cavities. The coupled geometry was one of the first integrated tunable laser designs since it is conceptually
simple to fabricate. First attempts were made by creating a narrow gap in between two SOAs. Different experimental demonstrations of coupling schemes based on serially [10–12] and laterally coupled lasers [13] showed that the need for precise control of the coupling coefficients and strict fabrication tolerances, resulted in poor reproducibility and side mode supression ratio (SMSR). Lately, further attempts were made using grating based coupling sections, which nonetheless require high fabrication precision [14] for optimal performance. Recently, Coupled Cavity Lasers (CCLs) with telecom suitable mode selectivity have been reported, using half-wave Multimode Interference devices (MMIs) without imaging properties [15–19] or star-couplers [20]. Ease of fabrication, small footprint and tuning ranges of several ten nanometer, make them excellent tunable sources for integration into low-cost processes.

In this work we expand on the coupled cavity approach by our recently introduced coupling mechanism [21], which is established through self-imaging between two coherent phase-delayed signals at the input of a 3x3 MMI coupler. Furthermore, instead of coupling two similar cavities, we include a novel reflective interferometer in one laser cavity. This allows to coarsely select the lasing wavelength of the coupled system, extending the tuning range to several tens of nanometer. Compared to our previous results [22], we will present an analytical derivation of the interferometer response and show how the reflective interferometer is used to self-stabilize the laser.

The interferometer is derived from a Michelson interferometer by replacing the two independent mirrors by our optimized coupling element mentioned above. This adaption effectively doubles the Free Spectral Range (FSR) of the interferometer and allows therefore for a significantly increased coarse tuning range of the coupled system. We experimentally demonstrate 26 nm tuning range, SMSR larger than 40 dB, MHz line width and a fiber coupled power up to 9 dBm.

2. Multimode interference based coupled cavity laser

The device is schematically depicted in Fig. 1. Two Fabry-Perot cavities of different length, each containing an amplifier and a phase tuning section, are coupled via a 2-Port reflector with amplitude coupling coefficients $C_x$ and $C_b$ and reflectivity $r_2$. Without loss of generality, it shall now be assumed that the cavity containing SOA$_1$ is denoted as primary cavity, while the one containing SOA$_2$ shall be the secondary cavity. The primary cavity is terminated with a cleaved waveguide termination and the secondary cavity by an integrated partial reflector, forming the respective output ports with reflectivity $r_1$ and $r_3$ of the laser.

The mode selection mechanism is based on the Vernier effect, established between cavities of different length, as schematically shown in Fig. 1. The longitudinal mode spacing of the primary cavity is $f_1$, while the mode spacing of the secondary cavity is defined as $f_2$. As a result of the length difference of the cavities, the lasing wavelength $\lambda_0$ is addressed, when longitudinal modes of the cavities coincide. However, longitudinal modes will also coincide after the combined FSR of the cavities $f_V = M f_1 = N f_2$, where $M$ and $N$ represent an integer number of longitudinal-mode frequencies in between $f_V$. After some rearranging and under the assumption that $M = N + 1$, it can be shown that [23]:

$$f_V = \frac{f_1 f_2}{|f_1 - f_2|}$$

Consequently, if the cavities are chosen of similar length, $f_V$ is much larger than the longitudinal mode spacing of each individual cavity and lasing is likely to occur at a multiple of $f_V$. If there is no other wavelength selection mechanism, $f_V$ has to be chosen such that the gain profile of the SOAs selects only one of these longitudinal modes competing for lasing operation.

The novelty in the present design is the reflective interferometric device (RID), with complex reflection coefficient $r_3(\lambda)$, which is formed by a 2x2 Multimode-Interference splitter and imbalanced waveguide sections which connect to a reflective MMI identical to the 2-port reflector,
Fig. 1. Schematic of extended CCL with coupling element and novel reflective interferometric device outlined by the dashed box. $C_x$, and $C_b$ denote the complex coupling coefficients between the cavities. The two integrated mirrors with reflectivity $r_2$ are identical components and introduced in more detail in section 3.

outlined by the dashed box in 1. It introduces a modulation of the secondary cavity spectrum, which restricts the local roundtrip gain bandwidth and enforces lasing on one longitudinal mode of the Vernier spectrum. A length difference $\Delta L_M$ between the two interferometer arms, allows to coarsely adjust the wavelength of the laser over the free spectral range of the interferometer:

$$f_M = \frac{\lambda_0^2}{n g \Delta L_M}$$

Compared to a conventional Michelson interferometer, there is factor two missing in the denominator of eq. (2), which follows from the replacement of the two independent mirrors normally utilized, with the mirror element we use for coupling of the cavities. The detailed working principle will be given in section 4. For now, we assume that near the lasing peak, $r_3(\lambda)$ can be approximated as a conventional Michelson interferometer and the coarse tuning of the laser can be obtained by adjusting the imbalance of the RID by using the phase sections $\phi_3, \phi_4$.

The fine tuning of the lasing mode is achieved by adjusting the longitudinal modes of the cavities using the phase sections $\phi_1, \phi_2$. During this process, a photo current is generated in a detector connected to the 2x2 MMI. Due to the 90 Degree phase shift introduced inside the MMI, the lasing mode which coincides with the interferometer reflection peak produces the smallest detector current. In this way the laser can be stabilized by minimizing the detector current.

For the appropriate selection of coupling coefficients, we can rely on a number of different studies, which discuss the effect of the coupling coefficients on the stability of the laser [15,24–26]. In this work we use on the results for a laser proposed by He [15], which similar to ours, uses a 2-Port reflector at the closed end of the cavities. His findings show that maximal SMSR of the laser is obtained with $C_b \approx 0.8$ and $C_x \approx 0.2e^{j\pi}$. The same study among the others mentioned above, indicates that a phase difference of $\pi/2$ between coupling coefficients resembles a particularly bad operation condition for coupled cavities, for which little mode selectivity is obtained. Furthermore, a recently derived analytical formula shows that the frequency bandwidth of locking minimizes for a phase difference near $\arctan(\alpha) = \pm \pi/2$ with alpha the linewidth-enhancement parameter [27]. Consequently, the precise control of the phase relation between the two coupling coefficients is of momentous importance for the laser performance. We will demonstrate in the next section, how we can obtain these ideal coupling coefficients over a sizable wavelength interval using a 3x3 MMI.

3. Multimode interference reflector design

In [21] we have shown the superior behavior of the CCL with MMI-based coupling. In Fig. 1 this coupling element is indicated by MIR. It is in fact a 2-port reflector made of a 3x3 MMI with built-in reflector and using only the outer ports. The principle is indicated in Fig. 2 and the underlying theory will now be presented, using a full modal propagation analysis as
Fig. 2. A schematic of a 3x3 MMI, followed by BPM simulations of the device of 10 μm width under different excitations of the input. The first simulation shows single input excitation (b), after which the two outer inputs are excited with a phase difference of π (c) and 0 (d). The dashed lines in (c) and (d) represent a 45 degree corner to form the integrated mirror.

It will be assumed that the input field $\Psi_{in}$, is decomposed into the guiding modes $\psi_\nu$ of the multimode waveguide,

$$\Psi_{in}(y) = \sum_{\nu=0}^{m-1} c_\nu \psi_\nu(y)$$

where $c_\nu$ represents field excitation coefficients, that can be estimated from a simple overlap integral. The field distribution at a distance $L$ can then be expressed as superposition of all guided modes:

$$\Psi_{out}(y) = \sum_{\nu=0}^{m-1} c_\nu \psi_\nu(y) e^{i\phi} = \sum_{\nu=0}^{m-1} c_\nu \psi_\nu(y) e^{i\frac{\nu(\nu+2)\pi L}{L_\pi}}$$

where $L_\pi$ is a geometrical constant which describes the beat length of the two lowest order modes with difference in propagation constants $\Delta \beta$, defined as:

$$L_\pi = \frac{\pi}{\Delta \beta} \approx \frac{4n_r W^2}{3\lambda_0}$$

with $n_r$ the effective refractive index, $W$ the width of the waveguide and $\lambda_0$ the wavelength in vacuum. Generally speaking, the method decomposes an input field into the guided waveguide modes of the multimode section, propagates these independently and recombines them to calculate the output field.

### 3.1. Single input excitation

For single input excitation, the 3x3 geometry produces images of equal intensity at the beat length $L_\pi$. Figure 2(b) displays the simulated beam propagation inside a 10 μm wide multimode section where $L_\pi$ is indicated. From the figure, we identify three images at $L_\pi/2$ which will be further investigated.
First, we excite an external port. Then using eq. (3), we split the input field in its even and odd parts:

\[ \psi_{in}(y) = \sum_{\nu} c_{\nu} \psi_{\nu}(y) + \sum_{\nu, \neq 3, 11} c_{\nu} \psi_{\nu}(y) \]  

(6)

After propagation to \( L_{\pi}/2 \), the field can be written as:

\[ \psi_{out}(y) = \sum_{\nu} c_{\nu} e^{i\phi_{\nu}} \psi_{\nu}(y) + j \sum_{\nu, \neq 3, 11} c_{\nu} \psi_{\nu}(y) \]  

(7)

So far, this is quite general. For the sake of concreteness, a simple model is used, which takes into account the first three guided modes of the multimode waveguide. After evaluating eq. (7) for the first three modes, we obtain:

\[ \Psi_{out} = \frac{1}{6} \sqrt{6} \psi_0 + j \frac{1}{2} \sqrt{3} \psi_1 - \frac{1}{3} \sqrt{3} e^{-2\pi i/3} \psi_2 \]  

(8)

Now we define \( \theta_i \) as the normalized transverse distribution function corresponding to an input field at port \( i \), where \( i = 1, 0, -1 \). Then the transverse modes are taken as:

\[ \psi_0 = (\theta_1 + 2\theta_0 + \theta_{-1})/\sqrt{6} \]  

(9)

\[ \psi_1 = (\theta_1 - \theta_{-1})/\sqrt{2} \]  

(10)

\[ \psi_2 = (-\theta_1 + \theta_0 - \theta_{-1})/\sqrt{3} \]  

(11)

In this approximation the inverse relations are:

\[ \theta_0 = \frac{1}{3} \sqrt{6} \psi_0 + \frac{1}{3} \sqrt{3} \psi_2 \]  

(12)

\[ \theta_1 = \frac{1}{6} \sqrt{6} \psi_0 + \frac{1}{2} \sqrt{3} \psi_1 - \frac{1}{3} \sqrt{3} \psi_2 \]  

(13)

\[ \theta_{-1} = \frac{1}{6} \sqrt{6} \psi_0 - \frac{1}{2} \sqrt{3} \psi_1 - \frac{1}{3} \sqrt{3} \psi_2 \]  

(14)

Now, using eqs. (12)-(14), we can write eq. (8) as:

\[ \Psi_{out} = \theta_1 \left( \frac{1}{6} + \frac{1}{2} j + \frac{1}{3} e^{-2\pi i/3} \right) + \theta_0 \left( \frac{1}{3} - \frac{1}{3} e^{-2\pi i/3} \right) + \theta_{-1} \left( \frac{1}{6} - \frac{1}{2} j + \frac{1}{3} e^{-2\pi i/3} \right) \]  

\[ \equiv \theta_1 C_b + \theta_0 C_c + \theta_{-1} C_x \]  

(15)

Where the numbers in the brackets correspond to the coupling coefficients of the MMI in transmission at \( L_{\pi}/2 \). Evaluating these numbers leads to:

\[ C_b = \frac{\sqrt{3} - 1}{2\sqrt{3}} j = 0.21 j \]  

(16)

\[ C_c = \frac{3 + j\sqrt{3}}{6} = 0.5 + 0.29 j \]  

(17)

\[ C_x = -\frac{\sqrt{3} + 1}{2\sqrt{3}} j = -0.79 j \]  

(18)

Thus at \( L_{\pi}/2 \) three images are present with unequal intensities. By recognizing a 180 degree phase difference between the two lateral outputs, we identify a potential 2x2 coupler in the 3x3
geometry for coupled lasers, if the central waveguide is excluded. The values obtained from the BPM simulations are \( C_b \approx 0.21 \), \( C_c \approx 0.57e^{j\pi/3} \) and \( C_x \approx 0.78e^{j\pi} \) and thus in good agreement with eqs. (16)-(18). We note that \( C_b \) and \( C_x \) are of the correct magnitude, except for a common overall factor \( j \) which has no influence on the relative phases, when compared to the ideal values as discussed in section 5 but inverted. We will correct for this at the end of this section.

3.2. Anti-resonant imaging

The presence of three inputs for coupling two cavities, implies a significant imaging loss in general. However, no light is lost if the two outer inputs are simultaneously excited with almost equal intensities and a phase difference of 180 degree. In this case, destructive interference occurs in the central output at multiples of \( L_{\pi}/2 \), as shown in Fig. 2(c). This follows directly from eqs. (16)-(18) by linear superposition, which for the case of inputs 1 and -1 at the outer input ports yields \( j \) at both outer output ports and 0 at the output center port.

3.3. Resonant imaging

Thirdly, we will investigate the case of two equal inputs at different outer ports with phase difference 0 or \( 2\pi \), such that the total input field is symmetric. In this case we have an input of 1 at both two outer input ports, which yields \( \pm 0.58j \) at the two respective output outer ports and 1 + 0.58j at the output center port. By taking absolute squares of these numbers, it is found that most intensity is found in the central output, more precisely about 4/6 of the output field. From the BPM in Fig. 2(d), we find a value of approximately 70%, which is in good agreement.

By comparing this with the anti-resonant case, for which the central output vanishes, this property will be exploited when coupling the two lasers through the MMI-reflector device to be introduced in the next section. Placed inside the coupled laser geometry, this will automatically lead to optimization of the laser operation, as the laser tends to lase on the mode with the lowest threshold. In more abstract terms, the laser locks to the anti-resonant imaging condition and hence enforces the \( \pi \) phase relation between the cavities. This is fully confirmed by the rate-equation analysis by one of us [29].

3.4. Multimode interference reflector design

Following the considerations above, a reflective device is obtained by placing a corner mirror at \( L_{\pi}/4 \), as indicated in Fig. 2(c) by the dashed lines. Light that enters the multimode region will be reflected at the corner mirror and propagate back, to form an image at the input ports. Due to the 45 degree symmetry of the corner reflector, it inverts the coupling coefficients given in eqs. (16)-(18). Hence, the reflector coefficients now read \( C_b \approx -0.79j \), \( C_c \approx 0.21j \) and \( C_x \) is unchanged, but the latter is irrelevant in view of the removal of the middle waveguide, allowing compact mirrors by reducing the width of the MMI. The mirror coefficients are now close to ideal for our laser geometry, as they coincide with the values proposed by He [15]. Finally, we will call this device MIR\(-\pi\) as it will enforce the required phase conditions in the coupled cavity configuration.

4. Reflective interferometer design

Next, we will study the working principle of the interferometer. The proposed configuration is displayed in Fig. 3. Compared to a conventional Michelson interferometer, the novelty lies in the replacement of the two independent mirrors, by the reflector designed in section 3 which connects both branches at the end. This allows for light to be exchanged between the two branches. As introduced in section 3.4, it is assumed that \( C_x \) and \( C_b \) are the amplitude cross and bar coupling coefficients respectively. At the input of the interferometer a 2x2 MMI is placed, which acts as symmetric splitting element with coupling coefficients \( a_x \) and \( a_b \).
If an electric field $E_0 = 1$ is launched at one input, the transmission of the two different paths is written as:

$$E_1 = a_b C_b e^{2ikL_1} + a_x C_x e^{ik(L_1+L_2)}$$  \hspace{1cm} (19)

$$E_2 = a_x C_x e^{ik(L_1+L_2)}$$  \hspace{1cm} (20)

With $E_b = a_b E_1 + a_x E_2$ we write:

$$E_b = a_b^2 C_b e^{2ikL_1} + a_b a_x C_x e^{ik(L_1+L_2)} + a_x^2 C_b e^{2ikL_2} + a_b a_x C_x e^{ik(L_1+L_2)}$$  \hspace{1cm} (21)

In case of 2x2 MMI with equal splitting ratio, $a_b = 1/\sqrt{2}$ and $a_x = i/\sqrt{2}$, and hence after some manipulation, the reflectivity is expressed as:

$$I_b = |E_b|^2 = |C_b|^2 \sin^2(k\Delta L_M) + |C_x|^2 - 2\sin(k\Delta L_M)Re(C_b C_x^*)$$  \hspace{1cm} (22)

where $\Delta L_M = L_2 - L_1$. Now, let us assume a few practical examples.

1) $C_x = 1$ and $C_b = 0$:

A trivial solution of eq. (22) is obtained, which leads to $I_b = 1$, a broadband mirror. The coupling coefficients are obtained by connecting the two branches with a waveguide of arbitrary length. This device is also known as loop mirror.

2) $C_x = 0$ and $C_b = 1$:

Here, the case of two independent mirrors is studied and thus, eq. (22) reduces to the classical Michelson response:

$$I_b = \sin^2(k\Delta L_M)$$  \hspace{1cm} (23)

3) $C_b = |C_b|$ and $C_x = |C_x|e^{i\pi}$:

This is the case of MIRs derived from conventional 2x2 MMIs [30]. It is quickly found that eq. (22) reduces to:

$$I_b = |C_b|^2 \sin^2(k\Delta L_M) + |C_x|^2$$  \hspace{1cm} (24)

This implies a constant component, which is modulated with strength $|C_b|^2$. It is an interesting result, as we can fix the extinction ratio of the reflected spectrum, by adapting the mirror splitting ratio. For symmetric coupling coefficients, a 3 dB modulation is obtained.

4) $C_b = |C_b|$ and $C_x = |C_x|e^{i\pi}$:

This configuration follows from the insertion of a mirror like our MIR−π used also for the coupling of the cavities. After some rearranging it follows from eq. (22) that:

$$I_b = (|C_b|\sin(k\Delta L_M) + |C_x|)^2 =$$

$$|C_b|^2 \sin^2(k\Delta L_M) + 2|C_b||C_x|\sin(k\Delta L_M) + |C_x|^2$$  \hspace{1cm} (25)

This is a peculiar result, as it contains a quadratic and linear sinusoidal component. The linear component oscillates with half the frequency compared to the quadratic term. Therefore, we
obtain a slowly varying envelope that effectively doubles the FSR through amplitude modulation. This effect is amplified by the fact that the MIR-π will be forced periodically into the resonant imaging mode, hence light is focused into the tip of the device as shown in Fig. 2(d) and therefore the reflection of the mirror is reduced. We take this into account by multiplying eq. (22) with 
\[ R = 0.6 + 0.4 \sin(k \Delta L_M) \]
where the coefficients were selected according to the 2D FDTD simulations of the MIR-π, presented in earlier work [21]. Finally, because of its π-dependence, we name this device π-Michelson.

To illustrate the new feature of this structure, we provide a numerical example with \(|C_b| = 0.79\) and \(|C_x| = 0.21\) in Fig. 4, compared to the result of a conventional Michelson with same arm-length difference. Here, the linearly varying component mentioned above, is identified as suppression of every second peak in the reflection spectrum and hence the FSR is doubled. Because the interferometer contains also a quadratic term, the FWHM of the reflection spectrum is maintained almost equal to a Michelson interferometer. Inside our laser configuration, this device provides a doubled coarse tuning range, with negligible impact on the SMSR.

A further advantage of the interferometer is that it provides an additional control signal by measuring \(I_x = |E_x|^2\):

\[
E_x = a_b a_c c_b e^{2ikL_2} + a_b^2 c_x e^{ik(L_1+L_2)} + a_x a_b c_b e^{2ikL_1} + a_x^2 c_x e^{ik(L_1+L_2)}
\]  

where with \(a_b = 1/\sqrt{2}\), \(a_x = i/\sqrt{2}\), \(C_b = |C_b|\) and \(C_x = |C_x|e^{i\pi}\) we obtain:

\[
I_x = |c_b|^2 \cos^2(k\Delta L_M)
\]

This implies that our control signal has an offset with respect to \(|r_3|^2\). According to the results of Fig. 4, \(|r_x|^2\) is minimal when the mirror is excited with a wavelength corresponding to the reflection peak of \(|r_3|^2\).

This is an interesting feature because it suggests that a high value of \(|r_x|^2\) can be interpreted as a misalignment of the laser wavelength with the respect to the main reflection peak. If a
photo detector is placed on-chip to measure $|r_3|^2$, the source can be tuned to generate a minimal photo current on the detector. This enables an automatic alignment of the lasing wavelength with respect to the main reflection peak of the interferometer.

For the verification of the model presented above, a test structure has been fabricated. For the experiment, we chose an imbalance of 330 $\mu$m, which permits to measure many periods of the spectrum over a small measurement range. The experimental setup to measure the reflection of the interferometer is depicted in Fig. 5. The structure was measured in reflection using a circulator and an anti-reflection coating at the input. The laser is tuned to reproduce the wavelength dependent reflection spectrum on the power meter. The measurement in Fig. 6 is compared to a simulation using eq. (25). Besides minor ripples created by a residual reflection between waveguide input and the MIR–$\pi$ reflector, we obtain an excellent agreement and as predicted a suppression of every second reflection peak, leading to an effectively doubled FSR.

### 5. Threshold equation

In this section we continue with a description of the threshold condition in the presence of coupling. As one of the first tunable lasers was in fact a CCL, a number of studies describing the coupling mechanism can be found in literature [24–26]. In all cases, the presence of a secondary cavity is understood as a modifying multiplication factor in the reflectivity of the primary cavity. In this work we follow the approach for a 2-Port coupled laser proposed by He [15] and determine therefore the threshold condition for the primary cavity in the presence of a secondary cavity:

$$C_b r_1 r_2 e^{2(g_1 + k)L_1} + C_b r_3 r_2 e^{2(g_2 + jk)L_2} - (C_b^2 - C_x^2) r_1 r_3 r_2^2 e^{2(g_2 + jk)L_2} e^{2(g_1 + k)L_1} = 1$$

(28)

However, to include our interferometer into the model, we define $r_3$ under consideration of the derivation of section 4. Hence it is defined as $|r_3|^2 = I_b = |r_2|^2 (|C_b| \sin(k\Delta L_M) + |C_x|)^2$, where $\Delta L_M$ is the arm-length difference in the interferometer and $r_2$, $C_b$ and $C_x$ are reflectivity and coupling coefficients of the MIR–$\pi$ coupler.

In order to predict the tuning range and mode selectivity it is necessary to estimate the length of the cavities and the interferometer. The design described here consists mainly of SOAs and phase sections as seen in Fig. 1. The length of the phase sections depends on the operation principle. Relying on the description of the generic integration platform used in this work [1] current based phase sections are as short as 100 $\mu$m, while reverse biased sections are in the order of 1 mm. Taking into account 500 $\mu$m SOAs, MMIs and connecting waveguides, we estimate cavity lengths in the order of 1.6 mm for current injection and 3.6 mm for the reverse biased approach respectively.

With the coupling coefficients and geometry of the laser defined, it is possible to solve the threshold eq. (28) numerically. More precisely, the threshold gain $g_0$ at the reference wavelength
Fig. 7. Threshold gain ratio between main mode and next two competitors for different reflectivities of coupling mirror $r_2$. Solid lines are the closest side mode, while dashed lines represent the competitor one combined FSR away. The output of the laser is formed by a facet with $r_1 = 0.55$ and the interferometer follows $|r_3|^2 = |r_2|^2(|C_b| \sin(k L_M) + |C_x|)^2$, where $\Delta L_M$ is the arm-length difference in the interferometer and $r_2$, $|C_b| = 0.79$ and $|C_x| = 0.21$ are reflectivity and coupling coefficients of the integrated mirror.

$\lambda_0$ is compared to the solutions obtained for wavelengths at a distance of $f_1$ and $f_V$. These distances correspond to the closest side mode, and the competitor after the combined FSR of the cavities. For the simulations it is assumed that $g_1 L_1 = g_2 L_2$, which leads to equal round trip gain provided by the SOAs of the coupled cavities. For the coupling mirror, we assumed a reflectivity of $r_2 < 1$ accounting for loss due to imperfect sidewalls of the reflector, e.g. sidewall angle and roughness.

In Fig. 7(a) the solutions to eq. (28) are shown as normalized threshold gain ratio between main mode and competitors, for a cavity length of $L_1 = 1.6$ mm and $r_1 = 0.55$. Furthermore, $\Delta L_M$ of the interferometer is chosen as $20 \ \mu m$, providing a coarse tuning range of approximately $36$ nm. The solid line represents the suppression of the closest side mode at a distance $f_1$, while the dashed line represent modes $f_V$ away from the lasing mode.

It is further seen, that the dashed and solid curves of same color intersect, suggesting that the interferometer allows to suppress the remaining candidates for lasing, preselected by the Vernier filtering. A normalized threshold ratio of $g/g_0 < 0.9$ appears to be feasible for all displayed values of $r_2$ and hence according to the model proposed in [31], the SMSR is expected in the $50$ dB range for an output power of a few mW, leaving enough room to achieve tuning ranges well beyond $40$ nm. The oscillatory behavior of the dashed lines, follows directly from the Vernier theory. It is caused by the fact that only for length ratios which obey the condition $M + 1 = N$, the Vernier filter operates according to eq. (1). In all other cases, the resonances will not periodically coincide after the combined FSR, creating additional mode suppression.
This effect is documented for silicon based coupled micro rings with high finesse and known as Vernier resonance splitting [32].

The simulation was repeated for the case of reverse biased phase sections and thus we assume $L_1 = 3.6$ mm. Here, the Vernier tuning range is smaller and consequently, the imbalance of the interferometer is adapted. In the simulations as performed in Fig. 7(b) a value of $\Delta L_M = 25$ $\mu$m is chosen, with an equivalent tuning range of 28 nm. The result is similar to the current injection based design, but with differences in gain between 5% and 10%. According to [31], this still results in SMSR above 40 dB.

6. Characterization

In this section we characterize a laser based on the theory as discussed above which was fabricated using the generic integration approach [1], together with other designs on a shared wafer. The device is shown in Fig. 8 and corresponds to the schematic introduced earlier in Fig. 1. It is based on an InGaAsP/InP multiple quantum well structure, monolithically integrated with transparent ridge waveguides based on 500 nm bulk InGaAsP with $Q(1.25)$. The optical path length difference between the cavities is 9.5%, with a geometrical length of 3.6 mm for the smaller cavity which contains also the interferometer. Each cavity contains a 500 $\mu$m SOA. To reduce the footprint the SOAs have been fabricated in close proximity, with a pitch of 10 $\mu$m. All electro-optic phase modulators (EOPMs) are 1 mm long and operated in reverse bias. The imbalance of the

Fig. 9. (a) LI curves when the main cavity current is altered, while the external cavity is kept constant. The legend indicates the value in mA. (b) Spectrum of laser when each SOA is biased with 90 mA.
The π-Michelson interferometer was chosen as 25 μm.

For the experiments the laser was placed on a copper sub-mount with a thermo-electric cooler controlled at 15 °C. The electrodes are biased with independent sources under continuous-wave (CW) operation. An isolator is used to prevent residual back reflections into the laser cavity which might introduce undesired laser dynamics. The light is collected using a lensed fiber placed at the output facet of the primary cavity.

The laser reaches threshold when a current of 20 mA is injected into each SOA. Several L-I curves of the laser are recorded while maintaining a constant current in the secondary cavity, which holds the interferometer. The results are shown in Fig. 9(a) with a fiber coupled power of up to 9 dBm when each SOA is driven with approximately 100 mA. As the maximum output power is achieved approximately for symmetric current injection, the reflection provided by the reflective interferometric device is estimated to be similar to the cleaved facet. This follows from the interference effect inside the coupling mirror, which leads to highest reflection values for equal intensities at its inputs. The major fraction of this loss is caused by the integrated reflector, induced by the angle and roughness of the mirror sidewall.

A typical spectrum when both SOAs are biased with 90 mA is given in Fig. 9(b), with a SMSR above 40 dB for the closest side mode and those one combined FSR away. The mode spacing is 87 pm.

6.1. Coarse tuning

The coarse tuning of the laser is achieved by tuning the interferometer. For this purpose a reverse biased voltage is applied to the phase sections of the interferometer while the laser is monitored with the optical spectrum analyzer. By operating the interferometer in push-pull configuration, a tuning range of 26 nm was achieved. The spectra are depicted in Fig. 10 for the case where each SOA was biased with 70 mA. The lasing mode switches discretely, with a step size of approximately 1 nm. This is determined by the Vernier effect between the cavities of different length. The SMSR is maintained above 40 dB over the entire tuning range.

6.2. Fine tuning

The fine tuning of the laser is demonstrated by varying the cavity phase sections, with no bias applied to the interferometer. During this process the photo current generated by the detector is recorded. The result is shown in Fig. 11(a), for different currents injected into the SOAs. The cavity phase shifters $\phi_{1,2}$ were operated in push-pull configuration, which is reflected by the
positive voltage values around the zero-bias operation point. During the tuning the laser switches longitudinal modes discretely, which is represented by step like changes of the photo current. A plateau in the figure suggests a stable operation condition for the laser. However, a high photo current implies that the selected longitudinal mode is misaligned with respect to the reflection peak of the interferometer.

With reduction of the photo current, the lasing mode is tuned to coincide with the maximum of the reflection peak. In the present experiment, we observe mode hop instabilities, which increase the measured photo current in the region of the recorded minimum and hamper the complete reproduction of the detector signal. However, by tracking the minimum photo current, for different SOA currents, the required voltage to maintain the same longitudinal mode is found. In the given example, an increase of 10 mA for the SOAs requires a reduction of the phase shifter voltage from 12 V to 9 V. Based on this approach, the recorded spectra for different SOA currents up to 80 mA are shown in Fig. 11(b). The spectra were shifted manually upwards in the representation to facilitate the discrimination of the measured signals. From the symmetry of the spectra we deduce that the interferometer is well aligned with respect to the selected longitudinal mode and as a result the laser is kept stable with a SMSR above 40 dB.

7. Conclusions

In conclusion, we have experimentally demonstrated a novel active-passive integrated Coupled Cavity Laser. The coupling between the two cavities is reliably established via self-imaging of two phase delayed signals in a 3x3 Multimode Interference Coupler. The coupling is proven to be tolerant against power fluctuations of the cavities and the phase delay is self-regulated over the operation range. The laser is simple to fabricate, compact and can be fully integrated with standard processes into photonic integrated circuits. It offers a control signal with which the laser can be stabilized with SMSR larger than 40 dB, while providing a tuning range via the integrated phase sections of 26 nm and a fiber-coupled power of 9dBm.

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