Dual-wavelength lasers on generic foundry platform

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Abstract—We propose and implement four simple and compact dual-wavelength laser concepts integrated in a Photonic Integrated Circuit (PIC) based on a InP generic foundry platform. In a first step, we arrange two detuned Distributed-Bragg-Reflectors (DBR) in either a sequential or in a parallel order, acting as narrowband wavelength selective cavity mirrors. In a second step, we close the cavities by using either a third DBR or by using a Multimode-Interference-Reflector (MIR). We present LI-characteristics and optical spectra emitting around 1550 nm with wavelength separations of 1 nm or 10 nm and evaluate their particular potential for simultaneous dual-wavelength emission. In addition, we find either one or multiple equal power points as well as complete switches when the gain current is being tuned. We discuss the characteristics and limitations of each concept including arranging the detuned DBRs in a sequential or parallel order.

Index Terms—Semiconductor Laser, Dual Wavelength Laser, Photonic Integrated Circuit.

I. INTRODUCTION

Dual-wavelength semiconductor lasers gained interest in recent years for various applications related to THz and mmWave generation [1] [2], velocimetry [3] or all optical signal processing [4]. Different techniques have been developed to generate dual-wavelength emission. The simplest way is to combine the beams of two separate semiconductor laser sources, which usually results in bulky setups and poses a challenge to stabilize mechanically. Although this allows for a great flexibility in spectral tuning and the precise control of their optical power, semiconductor lasers with intrinsic multi-wavelength selection like edge-emitting quantum-dot lasers can emit from the ground and excited state at the same time, yet usually require asymmetrical biasing [5], low temperatures [6] or embedded gratings [7] to achieve a dual-wavelength emission. External optical grating feedback adds an additional degree of emission control to extend their operation range [8] [9], but demands high mechanical and thermal stability. In [10], dual wavelength emission in the 1300-1500 nm region, separated by up to 174 nm, was demonstrated using an external cavity, however, with a challenging alignment for the individual modes. Lasers with integrated optical feedback promise a higher thermal and mechanical stability. A dual-wavelength DBR laser emitting around 1080 nm was demonstrated with a tuneable dual-wavelength emission between 0.3 nm and 6.9 nm in [11]. Generic foundry platforms offer an easy and affordable access to a mass manufacturing process and customized laser sources can be designed. Different multi-wavelength semiconductor lasers emitting around 1550 nm have already been demonstrated: In [12], multiple lasers were combined to achieve a 16-channel laser source with spectral separations of 0.8 nm. In [13], a four-channel Fabry-Perot laser spectrally depaered by 3.2 nm and in [14], a four-channel ring laser with 1.336 nm spectral separation has been demonstrated, both based on integrated external feedback as the control mechanism. Although these lasers are already integrated and can emit on multiple wavelengths, they are based on arrayed-waveguide-gratings as the wavelength selective element which poses challenges in the design processes as they have a large foot print and lack in ease of use due to multiple gain sections and control currents.

In this work, we propose four simple and compact dual-wavelength lasers concepts and demonstrate their implementation onto the generic multi project wafer platform offered by SmartPhotonics. Using their provided set of building blocks, our designs are based on two different wavelength separations of either 1 nm or 10 nm. The gain-current serves as the only parameter to control their emission properties. We expect the lasers to exhibit a controllable switch from one longitudinal mode to the other due to the blue shift of the gain-spectrum as the gain current is being tuned. Our goal is to achieve a simultaneous dual-wavelength emission at these transition points. Although we obtain dual-wavelength emission for all designs, we clearly observe that simultaneous emission and switching behavior vary particularly from design to design.

II. DUAL-WAVELENGTHS LASER DESIGNS

The four layouts implemented and studied in this work are depicted in Fig. 1. Two narrowband DBRs (DBR1 & DBR2) act as the wavelength selective elements and are arranged either in parallel (I & III) or sequentially (II & IV). To close the cavity, either a broadband MIR (I & II), or a third DBR (DBR3 in III & IV) is used. The layouts based on a MIR allow for a large and variable spectral wavelength separation within the gain bandwidth. A precise design for the DBR reflectivities is essential to achieve an equal gain for a particular wavelength separation. The DBRs of our MIR based layouts are designed to have a spectral separation of 10 nm to avoid any interference between the DBRs. On the other hand, the layouts based on three DBRs use a much wider bandwidth for DBR3 which reflects at both wavelengths generated by DBR1 and DBR2. The required spectral overlap limits the wavelength splitting to about 1 nm but allows for a
loss control when their wavelengths and subsequently their spectral overlap is tuned. In layouts I & II, 2-port MIRs are used to provide a reflectivity of about 0.4 for the laser cavities. The parameters for all DBRs were determined using the PIC simulator Lumerical Interconnect, where each layout was optimized for dual-wavelength emission with equal optical powers. The design wavelengths $\lambda_1$, $\lambda_2$, and $\lambda_3$ for each DBR are listed in Table I together with their lengths, reflectivities and bandwidths, determined for each laser cavity. DBR1 in layouts II & IV were implemented with a short length to achieve a large free spectral range for both cavities - created by DBR1 & DBR2 - to be single mode. The coupling coefficient is fixed to $50 \text{ cm}^{-1}$ and the maximal DBR length to $500 \mu\text{m}$. For layouts III & IV, we implemented a $0.3 \mu\text{m}$ longer wavelength for DBR1 & DBR2 onto the PIC compared to the wavelengths of $\lambda_1 = 1539 \text{ nm}$ and $\lambda_2 = 1540 \text{ nm}$ used in the simulations as their wavelengths can be tuned experimentally. As DBR3 in layout III has a high reflectivity and DBR1 & DBR2 are transparent to each other, we combined their outputs with a multi-mode interference (MMI) coupler to maximize the optical output power. To achieve the most compact footprint on the PIC, we used deeply etched components wherever beneficial, shown by a gray background in Fig. 1. All SOAs have a length of $500 \mu\text{m}$ and are operated at a maximal power of about $-8.5 \text{ dBm}$.

### Experimental Results

A Thorlabs Pro8 system controls the current and temperature of the gain section and the PIC. An Apex AP2083A (resolution down to $5 \text{ MHz} / 40 \text{ fm}$) allows for measuring the optical spectra as well as the optical power. All measurements were performed at a temperature of $20^\circ\text{C}$. A lensed fiber was used to couple the light out of the PIC. The presented results were performed on three different PICs from three different wafers which provides also insight into the robustness and reproducibility of each layout. Key results for each layout are given in Table I with the spectral separation $\Delta\lambda$ and the wavelengths acquired experimentally together with the best values found for the optical power, the side mode suppression ratio (SMSR) and the longitudinal mode separation.

**Layout I:** The measured LI curve is depicted in Fig. 2(a) without current applied to any DBR. Lasing starts at $28 \text{ mA}$ at the shorter wavelength of $1531.8 \text{ nm}$, corresponding to DBR1. At $35 \text{ mA}$, the longer wavelength of $1542.2 \text{ nm}$ starts to emit, corresponding to DBR2. Both modes behave similarly with an increase in optical power and show a wide range of equal optical power between 65 and $80 \text{ mA}$. A gain current of $49 \text{ mA}$, a switch to another longitudinal mode occurs within the longer wavelengths. The highest optical power, with about $-12 \text{ dBm}$ for each mode, is achieved at a gain current of $80 \text{ mA}$, the corresponding optical spectrum is depicted in Fig. 2(b). The separation of the two modes is $10.4 \text{ nm}$ with multiple side modes appearing for each wavelength with a SMSR of at least $38.5 \text{ dB}$. Although this laser seems like the ideal choice for a dual-wavelength laser, across different PICs only a single mode emission occurred, suggesting a high requirement for smaller DBR tolerances for this layout.

**Layout II:** The currents were set to $5 \text{ mA}$ for DBR1 and $4 \text{ mA}$ for DBR2 to achieve a single mode emission for each wavelength. The resulting LI curve is depicted in Fig. 3(a). The laser starts to emit from the longer wavelength of $1547.6 \text{ nm}$ and at a gain current of $67 \text{ mA}$, the shorter wavelength of $1536.7 \text{ nm}$ starts to emit and increases rapidly in optical power while the longer wavelength experiences a drop. With a further increase of the gain current, the two modes compete with each other, resulting in multiple power exchanges. The optical spectrum at a gain current of $85 \text{ mA}$ is depicted in Fig. 3(b) with a wavelength separation of $10.9 \text{ nm}$, an equal optical output power of about $-8.5 \text{ dBm}$ and a SMSR...
of at least 41.5 dB. The wavelengths are shifted 1.5 nm to longer wavelengths, indicating high variances in the target wavelengths of the DBRs across the wafers. Multiple equal power points are found by this layout, changing the DBR currents does not change the overall behavior of the multiple power exchanges, but shifts the equal power points slightly to different currents. This layout is best suited to achieve a simultaneous dual-wavelength emission as reproducible behavior across the different chips could be found.

**Layout III:** Due to the implementation of longer wavelengths for DBR$_1$ and DBR$_2$ of 0.3 nm mentioned above, a current of 0 mA, 2 mA and 8 mA had to be injected to DBR$_1$, DBR$_2$ and DBR$_3$, respectively, to achieve the LI curve depicted in Fig. 4 (a), (b) and (c), respectively. The optical spectrum at the equal power point is shown at a gain current of 81 mA (b, top) and 82 mA (b, bottom).

![Fig. 3. Layout II: Wavelength resolved LI curve (a), shown are the shorter and longer wavelengths in blue and red, respectively, the total power is shown in black. The optical spectrum (b) is shown at a gain current of 85 mA.](image)

![Fig. 5. Layout IV: Wavelength resolved LI curve (a), shown are the shorter and longer wavelengths in blue and red, respectively, the total power is shown in black. The optical spectrum is shown at a gain current of 81 mA (b, top) and 82 mA (b, bottom).](image)

![Fig. 4. Layout III: Wavelength resolved LI curve (a), shown are the shorter and longer wavelengths in blue and red, respectively, the total power is shown in black. The optical spectrum (b) is shown at a gain current of 81 mA.](image)

All proposed structures except layout II start to emit on the shorter wavelength, followed by emission on the longer wavelength. This can be altered by the DBR reflectivities, the applied DBR currents (layout III & IV) or the influence of a temperature gradient caused by biasing a neighboring SOA. The change in emission from the longer to the shorter wavelength in layout II can be explained by the blue shift of the gain spectrum with increasing gain current. The tuning of the gain current induces a shift of the whole spectrum by about 0.04 nm/mA to longer wavelengths due to the change in refractive index by the higher current density. All structures showed simultaneous or sequential dual-wavelength emission even though reproducibility of layout I is poor. Each of the layouts II, III & IV showed reproducible results across different PICs and wafers and suggest a good robustness of the designs. Layouts I & III with a parallel DBR arrangement are simple to design due to their symmetric composition and can have the same large DBR lengths with high reflectivities. However, their transparency to each other results in high intracavity losses which have to be compensated by the SOA and therefore result in lower optical output powers. Layout I seems to be prone to deviations in the DBR reflectivities which can lead to a different gain for each wavelength and a potential single mode emission. This asymmetric gain can be compensated in layout III by the tuning of the DBRs. The layouts II & IV with sequentially arranged DBRs show lower losses but require a careful design in their lengths to provide equal gain for both wavelengths. They showed to have the highest optical output power at multiple equal optical

### IV. Discussion

All proposed structures except layout II start to emit on the shorter wavelength, followed by emission on the longer wavelength. This can be altered by the DBR reflectivities, the applied DBR currents (layout III & IV) or the influence of a temperature gradient caused by biasing a neighboring SOA. The change in emission from the longer to the shorter wavelength in layout II can be explained by the blue shift of the gain spectrum with increasing gain current. The tuning of the gain current induces a shift of the whole spectrum by about 0.04 nm/mA to longer wavelengths due to the change in refractive index by the higher current density. All structures showed simultaneous or sequential dual-wavelength emission even though reproducibility of layout I is poor. Each of the layouts II, III & IV showed reproducible results across different PICs and wafers and suggest a good robustness of the designs. Layouts I & III with a parallel DBR arrangement are simple to design due to their symmetric composition and can have the same large DBR lengths with high reflectivities. However, their transparency to each other results in high intracavity losses which have to be compensated by the SOA and therefore result in lower optical output powers. Layout I seems to be prone to deviations in the DBR reflectivities which can lead to a different gain for each wavelength and a potential single mode emission. This asymmetric gain can be compensated in layout III by the tuning of the DBRs. The layouts II & IV with sequentially arranged DBRs show lower losses but require a careful design in their lengths to provide equal gain for both wavelengths. They showed to have the highest optical output power at multiple equal optical
power points for layout II and at a single mode emission for layout IV. For the MIR based layouts I & II, single mode emission for both wavelengths is achieved, confirming this layout to be a versatile approach for a varying wavelength separations. In the DBR based layouts III & IV, active control of each wavelength is achieved by the relative tuning of the DBRs. Depending on the set of currents for the DBRs, a single mode emission for both wavelengths as well as the desired dual wavelength emission is possible. The combined outputs of DBR$_1$ & DBR$_2$ in layout III were implemented to study their influence on the laser output. As the laser has a low output power, using this approach could be beneficial to improve the performance of layout I. Using a 1-port MIR to close the cavity could result in lower losses and a higher output optical power. The temperature of the PIC has a major impact on the DBR performance, wavelength shifts ranging from 0.11 nm/°C to 0.19 nm/°C to longer wavelengths when increasing the temperature could be found. Hence, controlling the temperature can be used to match the experimental to the expected wavelengths. An extensive study on the DBR tuning for each layout is however left for further investigation.

V. CONCLUSION

To conclude, we presented four different compact laser concepts capable of achieving simultaneous dual-wavelength emission at 1550 nm. Key results are summarized in Tab.

![Table II: Key experimental results for each layout.](image)

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