Vrije Universiteit Brussel

Control of dual-wavelength laser using monolithically integrated phase-controlled optical feedback

Pawlus, Robert; De Mey, Robbe Jan; Breuer, Stefan; Virte, Martin

Published in:
Control of dual-wavelength laser using monolithically integrated phase-controlled optical feedback

DOI:
10.1117/12.2557305

Publication date:
2020

License:
Unspecified

Document Version:
Final published version

Link to publication

Citation for published version (APA):
Pawlus, R., De Mey, R. J., Breuer, S., & Virte, M. (2020). Control of dual-wavelength laser using monolithically integrated phase-controlled optical feedback. In M. Sciamanna, R. Michalzik, K. Panajotov, & S. Hofling (Eds.), *Control of dual-wavelength laser using monolithically integrated phase-controlled optical feedback* (Vol. 11356, pp. 1-6). [1135606] (Proceedings of SPIE - The International Society for Optical Engineering; Vol. 11356). SPIE. https://doi.org/10.1117/12.2557305

Copyright
No part of this publication may be reproduced or transmitted in any form, without the prior written permission of the author(s) or other rights holders to whom publication rights have been transferred, unless permitted by a license attached to the publication (a Creative Commons license or other), or unless exceptions to copyright law apply.

Take down policy
If you believe that this document infringes your copyright or other rights, please contact openaccess@vub.be, with details of the nature of the infringement. We will investigate the claim and if justified, we will take the appropriate steps.

Download date: 10. Apr. 2024

PROCEEDINGS OF SPIE

SPIEDigitalLibrary.org/conference-proceedings-of-spie

Control of dual-wavelength laser using monolithically integrated phase-controlled optical feedback

Pawlus, Robert, de Mey, Robbe, Breuer, Stefan, Virte, Martin

Robert Pawlus, Robbe de Mey, Stefan Breuer, Martin Virte, "Control of dual-wavelength laser using monolithically integrated phase-controlled optical feedback," Proc. SPIE 11356, Semiconductor Lasers and Laser Dynamics IX, 1135606 (1 April 2020); doi: 10.1117/12.2557305

Event: SPIE Photonics Europe, 2020, Online Only

Downloaded From: https://www.spiedigitallibrary.org/conference-proceedings-of-spie on 09 Nov 2020 Terms of Use: https://www.spiedigitallibrary.org/terms-of-use

Control of dual-wavelength laser using monolithically integrated phase-controlled optical feedback

Robert Pawlus[a], Robbe de Mey[a], Stefan Breuer[b], and Martin Virte[a]

[a]Brussels Photonics (B-PHOT), Dept. of Applied Physics and Photonics (TONA), Vrije Universiteit Brussel, Pleinlaan 2, 1050 Brussels, Belgium
[b]Institute of Applied Physics, Technische Universität Darmstadt, Schlossgartenstrasse 7, 64289 Darmstadt, Germany

ABSTRACT

In this conference proceeding, we present a novel technique to control the emission of dual-wavelength lasers. Using a well designed external cavity, we demonstrate that tuning the optical feedback phase allows to efficiently tailor the output power balance between the two wavelengths emitted by the laser. With this technique, a complete switch between one and the other mode can also be achieved and we report a suppression ratio up to 40 dB. Due to its simplicity, the structure can be monolithically integrated easily with the laser itself and offers a precise control of the dual-wavelength emission using a single control parameter.

Keywords: semiconductor laser, optical feedback, dual-wavelength laser, Photonic integrated circuit

1. INTRODUCTION

The capability for a single laser device to emit simultaneously at two distinct wavelengths is a desirable feature for various applications from the generation of high-frequency signals in the mm-wave or THz range,[1] to new sensing schemes[2] or telecommunication systems. In all these examples, there is a strong need to control the emission of the semiconductor dual-wavelength lasers (DWLs) either to precisely balance the output power between the two wavelengths or to quickly switch from one to the other wavelength. Unfortunately, this step remains an issue as DWLs are notoriously difficult to control.
In short, we can distinguish two categories of DWLs. On the one hand, we have devices that intrinsically emit at only two distinct wavelengths: they either contain frequency selective elements in their cavity - e.g. cavities closed by Distributed Bragg Reflectors (DBRs)[3] - or their gain medium is providing gain in two relatively narrow bands - e.g. in dual-state emitting quantum dot semiconductor lasers.[4] In this case, the DWLs can be as compact as other similar semiconductor lasers and typically exhibit robust dual-wavelength emission properties but often limited to a certain range of operating conditions. To put it differently, the devices offer no real control of their emission properties besides the temperature and the injection current which are ill-suited to the targeted purpose. On the other hand, devices with a broadband emission can be turned into DWLs by using external forcing such as filtered optical feedback.[5–7] These solutions offer a great flexibility in terms of wavelength balancing, switching or tuning. However, they typically require simultaneous control of several forcing parameters to achieve a good result. Moreover their increased complexity leads to a much larger footprint.

In this work, we try to take the best of both worlds and propose a new control scheme using only a small and simple external cavity which allows to control the DWL emission through a single control parameter. We demonstrate its viability and report convincing performances using a fully integrated demonstrator manufactured on a generic foundry platform.

Further author information: (Send correspondence to R.P. or M.V.)
R.P.: E-mail: robert.pawlus@b-phot.org
M.V.: E-mail: martin.virte@vub.be or martin.virte@b-phot.org

Semiconductor Lasers and Laser Dynamics IX, edited by Marc Sciamanna, Rainer Michalzik, Krassimir Panajotov, Sven Höfling, Proceedings of SPIE Vol. 11356, 1135606
© 2020 SPIE · CCC code: 0277-786X/20/$21 · doi: 10.1117/12.2557305

Downloaded From: https://www.spiedigitallibrary.org/conference-proceedings-of-spie on 09 Nov 2020
Terms of Use: https://www.spiedigitallibrary.org/terms-of-use

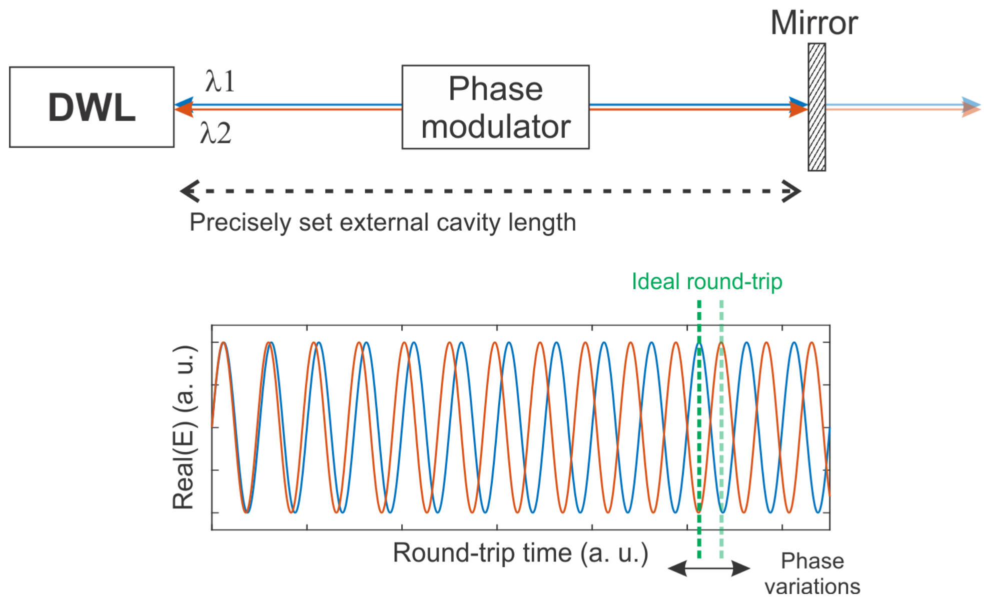

Figure 1. Graphical summary of the proposed control technique. The top schematic shows a possible minimal implementation in which the dual-wavelength laser (DWL) is subject to optical feedback, with control of the feedback phase through the phase modulator. The bottom diagram highlights how the external cavity round-trip time should be defined and the expected impact of a phase modulation.

2. OPERATING PRINCIPLE

The core idea of the proposed technique is to exploit the Fabry-Perot effect in the optical feedback cavity to selectively boost or suppress one of the two wavelengths emitted by the laser. While the impact of optical feedback on dual-wavelength lasers has already attracted a certain interest to trigger dual-wavelength emission,[8] reduce the noise[9] or control the wavelength power balance,[10,11] none of the solutions previously envisaged allowed to completely take over the laser emission. For instance, in Ref.,[8] the proposed approach could not suppress the excited state emission, and in Refs.[10,11] only a very partial control was obtained.

Here, we aim at achieving complete control, i.e. the possibility to fully suppress any mode. Our approach is further detailed in figure 1 where we show a schematic of a possible minimal implementation. It should be clear however that figure 1 is a mere example and that many different implementations are possible, including e.g. splitters, optical amplifiers or two-side emitting lasers. If the emitted wavelength resonates in the feedback cavity formed by the laser facet and the external mirror, then it will experience a gain boost. Alternatively, if the wavelength is anti-resonant it will see a slight increase of its losses. To selectively boost or suppress one wavelength, the cavity should ideally be designed to obtain a relative phase shift of π between the two wavelength after the propagation in the cavity, i.e. the two wavelengths are out-of-phase. This is shown in the bottom part of figure 1 where the ideal round-trip time is highlighted. Intuitively, this ensures that only one wavelength can be resonant at any given time and that the best selectivity is achieved.

Next, we need to tune the external cavity to select which wavelength will experience a gain boost. To do so, we have to vary the external cavity length at the wavelength scale, but, at such short scale, this is equivalent to changing the feedback phase. In practice, the former can be achieved using a piezo-electric actuator, while the latter can be done with a phase modulator. In terms of speed, precision and integration capability, the phase modulator should be preferred if possible. The targeted effect is displayed in figure 1 where phase variations lead to a change of the effective round-trip, and, thus, of the resonant mode from λ_1 to λ_2.

Downloaded From: https://www.spiedigitallibrary.org/conference-proceedings-of-spie on 09 Nov 2020
Terms of Use: https://www.spiedigitallibrary.org/terms-of-use

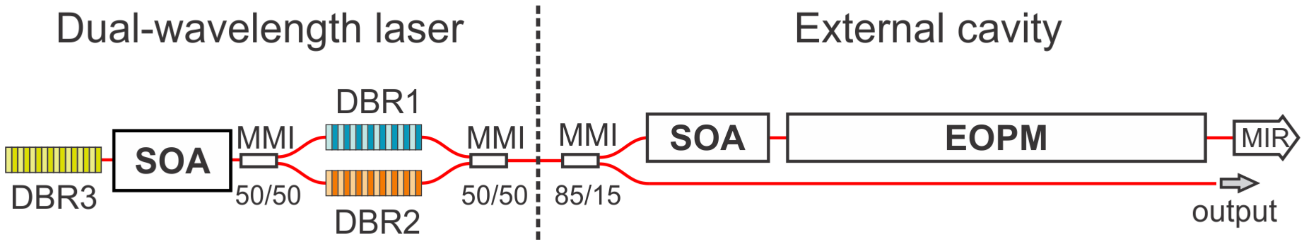

Figure 2. Schematic of the demonstrator implemented on a photonic integrated circuit. The dual-wavelength laser structure is shown on the left and the external cavity on the right. Electrical isolation sections, mode filters and shallow/deep waveguide transitions are not shown for clarity. The specifications of each component is given in the text. The reflection spectra of DBR 1 and 2 have a limited overlap and are therefore mostly transparent to the other emission wavelength. This output therefore leads to much higher output power and stronger feedback.

3. INTEGRATED DEMONSTRATOR

To put the proposed concept into practice, we require dual-wavelength lasers which are, unfortunately, not yet widely and reliably available commercially. In addition, the compactness and simplicity of our scheme would be best demonstrated in a monolithically integrated system. Thus, we decided to implement our demonstrator on the generic foundry platform of SMART Photonics in the frame of a Multi-Project Wafer run.[12,13] Besides being a relatively accessible solution for researchers without in-depth expertise in photonic integration, all devices and systems manufactured in this framework are by essence mass-manufacturable and compatible with other schemes made on the same platform.
Here, we used DBR-based dual-wavelength devices which have partially been described elsewhere.[14] Although we have studied many different DWLs, we focus here on one specific structure whose schematic is shown in Figure 2. Two DBRs of 450 μm length are placed in parallel. They both have slightly detuned center wavelength fixed at $\lambda_1 = 1541.5$ nm and $\lambda_2 = 1539.5$ nm respectively, while the cavity is closed by a third DBR with a center wavelength at 1540 nm. The center wavelength of the 3rd DBR closing the laser cavity is slightly detuned and fixed at 1540 nm instead of 1540.5 nm which would have been exactly at the frequency between the center wavelength of the two DBRs placed in parallel. This is done on purpose because the DBRs can all be electrically tuned to longer wavelengths by current injection. We therefore expect this detuning to give us a certain control margin of the reflectivity at each emission wavelength, which could help us achieve dual-wavelength emission. A semiconductor optical amplifier of 500 μm length is placed inside the laser cavity to provide gain.

As described in the previous section, these DWL are coupled with an external cavity with the goal of controlling their emission. We use a 85/15 MultiMode Interference (MMI) splitter with the 85% output sent to the chip edge for outcoupling and the 15% one connected to the external cavity. In addition, we include a semiconductor optical amplifier and an electro-optic phase modulator (EOPM) with a length of 300 μm and 1200 μm respectively to ensure that we have all the necessary flexibility to investigate the impact of the phase-controlled feebdack on the laser behavior. In particular, the 1.2 mm EOPM is expected to provide up to a 2π phase shift for a voltage of approximately -8V and possibly up to a 4π phase shift at the highest voltages. The phase-shift values are of course doubled compared to the typical specification of the foundry because we consider that the beam will go two times through the phase modulator while doing a cavity round trip. The cavity is then closed with a broadband MultiMode Interference Reflector. The emission wavelengths are estimated based on simulations using the Photonic Circuit Simulator INTERCONNECT from Lumerical including the model library of the SMART Photonics development kit; i.e. the model parameters of the different components being fitted to match the typical behaviour experimentally recorded by the foundry. The estimated wavelengths are then used to define the external cavity round trip time and thus the cavity length. Of course, the splitter, the amplifier and the EOPM already impose a minimal length for the cavity. Thus, we select the shortest round-trip time giving a suitable π phase shift between λ_1 and λ_2 corresponding to a cavity length longer that the minimal length imposed. Besides a reduced footprint, the interest of taking the minimal length for the external cavity is to remain in the corresponding short cavity regime.[15] Indeed, in this case, the laser is known for being more robust against feedback perturbation which would be detrimental here. In our integrated demonstrator, the

Downloaded From: https://www.spiedigitallibrary.org/conference-proceedings-of-spie on 09 Nov 2020
Terms of Use: https://www.spiedigitallibrary.org/terms-of-use

external cavity has a total length of 2.8 mm.
A Pro8 system from Thorlabs is used to control all amplifiers and the overall temperature of the Photonic Integrated Circuit which is fixed at 20 °C. The EOPM is controlled using a separated DC source (Agilent, E3649A). The laser light is out-coupled using a standard lensed fiber and all measurements are performed optically using a high-precision optical spectrum analyzer from APEX (AP2083A, resolution down to 5 MHz / 40 fm).

4. EXPERIMENTAL MEASUREMENTS AND PERFORMANCE EVALUATION

Before testing the proposed scheme, we first verify that the DWL is indeed emitting at the two intended wavelengths (without optical feedback). Despite the detuning of the center wavelength of DBR3, we could obtain dual-wavelength emission but only in a current range of several mAs. In fact, varying the gain current leads to a switching between the two wavelength, and simultaneous emission is only achieved close to the switching point. By tuning DBR3, we obtain better dual-wavelength emission characteristics. We therefore fix the DBR current to 10 mA. With this configuration, around the switching point, we measure $\lambda_1 \approx 1541.8\,nm$ and $\lambda_2 \approx 1542.7\,nm$ which is about 2.5 nm longer than the designed wavelength, and with a narrower separation of 0.9 instead of 1 nm. These deviations are however not surprising and well within the expected manufacturing variability range. We then investigate the impact of optical feedback on the DWL emission. Although switching between the two wavelengths can be observed in a rather wide range of operating point, the suppression ratio can fluctuate significantly. Here, we present a positive, but representative case obtained for a gain current of 50 mA. Turning on the amplifier of the external cavity with a current of 15 mA, and with an EOPM voltage of 0 V, i.e. equivalent to a connection to ground, the λ_1 emission appears to be strongly dominant, as can be seen in Figure 3(a). The λ_2 emission is severely suppressed by more than 30 dB. When increasing the EOPM voltage (in absolute value, as only a negative voltage can be applied on the EOPM), we first observe an increase of the λ_2 suppression up to about 40 db - as can be clearly seen in the optical spectrum shown in Figure 3(a) - , until a sudden switching is observed at a voltage of -2 V. At this point, λ_2 is turned on while the emission at λ_1 is suppressed. The situation seems rather symmetrical with the suppression ratio being in a similar range between 30 and 40 dB, see Figure 3(c) for the optical spectrum after switching. A further increase of the EOPM voltage leads to a second smoother switching after which λ_1 becomes again the dominant wavelength. Beyond that, the pattern seems to repeat itself which is consistent with the expected specifications leading to a 2π phase shift around -8V.

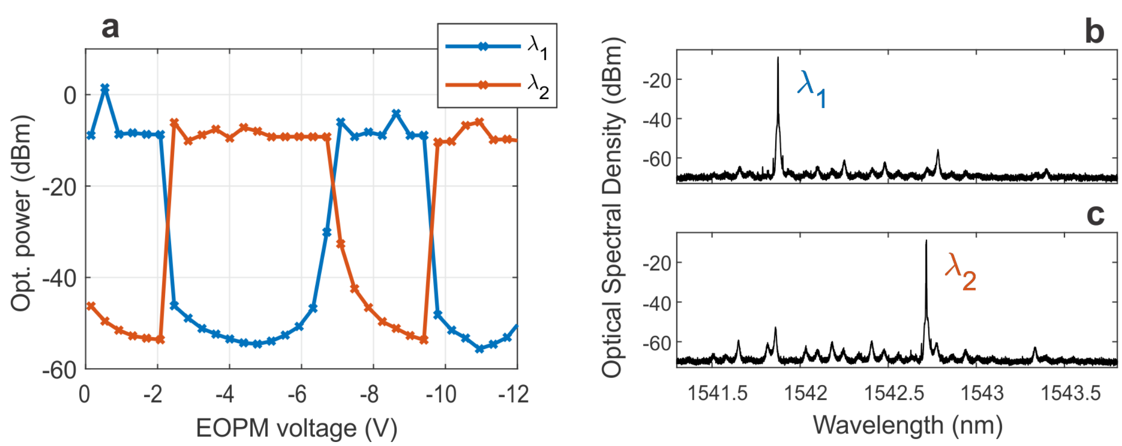

Figure 3. (a) Example of a wavelength switching behaviour induced by variations of the optical feedback phase with $\lambda_1 \approx 1541.9\,nm$ in blue and $\lambda_2 \approx 1542.7\,nm$ in red. A current of 15 mA is sent to the semiconductor optical amplifier of the external cavity. The electro-optic phase modulator (EOPM) is expected to provide a 2π phase shift at a voltage of approximately -8 V. (b, c) Optical spectra obtained for a EOPM voltage of -2 and -3.2 V for (b) and (c) respectively.

Downloaded From: https://www.spiedigitallibrary.org/conference-proceedings-of-spie on 09 Nov 2020
Terms of Use: https://www.spiedigitallibrary.org/terms-of-use

5. DISCUSSION AND PERSPECTIVES

The experimental results obtained with our demonstrator confirm that the proposed technique can indeed be a suitable approach to gain more control over DWL emission. We report a strong and repetitive complete switching between two wavelengths with suppression ratios of more than 40 dB. With the configuration highlighted in this contribution, the required precision on the control parameter - i.e. the EOPM voltage - is quite low if the target is to switch completely between the two wavelengths. However, to balance the output power emission at each wavelength clearly requires a finer tuning of the EOPM voltage; nonetheless, a precision of the order of a few mVs are likely to be sufficient.

In this contribution, we did not discuss the impact of the feedback strength, i.e. how much light is sent back to the laser cavity after the round-trip in the external cavity. While this is indeed a crucial point in practice, a detailed investigation of its impact in our demonstrator did not appear to be relevant at this stage. Indeed, we observed similar performances for a relatively large range of feedback strengths and it did not appear to be a crucial parameter. If the feedback is too weak, it might become impossible to suppress the dominant mode. If the feedback is too strong, dynamical instabilities might be triggered. Nevertheless, both behaviour were only observed in the extreme side of the possible control range offered by our demonstrator. Moreover, besides some gain variations, changing the current of the amplifier in the cavity also lead to variations of the feedback phase. Both are potentially wavelength dependent and could not be quantified with our current setup. Further analysis of the effect of the feedback strength is therefore left for further investigations.

Finally, the impact of the laser characteristics on the reported behaviour - in particular, the coupling and the differences between the two emission processes, i.e. gain/loss differences - remains to be investigated. At this point, the performances of a given system cannot be predicted. For instance, we intuitively expect a link between the gain difference and the suppression ratio that can be achieved, but we do not have yet any supporting data with respect to this point. This lack of course calls for an in-depth theoretical and experimental study to fully validate the proposed scheme.

6. CONCLUSION

To conclude, we have demonstrated that a phase-controlled optical feedback using a precisely designed external cavity can efficiently be used to selectively boost/suppress a given emission wavelength from a dual-wavelength laser. The reported behavior has been consistently obtained in different DWL structures and for different wavelength separation. Although many features remain to be analyzed in more details, these results are promising and give already an important insight on the possible viability of this technique for industrial applications.

ACKNOWLEDGMENTS

The authors acknowledge support from the Research Foundation - Flanders (FWO) (grants 1530318N, G0G0319N), the METHUSALEM program of the Flemish Government, Dr. Hans Messer Stiftung (personal grant SB) and the German Research Foundation (DFG) (grant 389193326).

REFERENCES

[1] Harter, T., Ummethala, S., Blaicher, M., Muehlbrandt, S., Wolf, S., Weber, M., Adib, M. M. H., Kemal, J. N., Merboldt, M., Boes, F., Nellen, S., Tessmann, A., Walther, M., Globisch, B., Zwick, T., Freude, W., Randel, S., and Koos, C., "Wireless THz link with optoelectronic transmitter and receiver," *Optica* **6**, 1063 (aug 2019).

[2] Gioannini, M., Dommermuth, M., Drzewietzki, L., Krestnikov, I., Livshits, D., Krakowski, M., and Breuer, S., "Two-state semiconductor laser self-mixing velocimetry exploiting coupled quantum-dot emission-states: experiment, simulation and theory.," *Opt. Express* **22**(19), 23402–14 (2014).

[3] Roh, S. D., Member, S., Yeoh, T. S., Member, S., Swint, R. B., Member, S., Huber, A. E., Woo, C. Y., Hughes, J. S., and Coleman, J. J., "Dual-Wavelength InGaAs – GaAs Ridge Waveguide Distributed Bragg Reflector Lasers with Tunable Mode Separation," *IEEE Photon. Technol. Lett.* **12**(10), 1307–1309 (2000).

[4] Markus, A., Chen, J. X., Paranthoën, C., Fiore, A., Platz, C., and Gauthier-Lafaye, O., "Simultaneous two-state lasing in quantum-dot lasers," *Applied Physics Letters* **82**(12), 1818–1820 (2003).

Downloaded From: https://www.spiedigitallibrary.org/conference-proceedings-of-spie on 09 Nov 2020
Terms of Use: https://www.spiedigitallibrary.org/terms-of-use

[5] Docter, B., Pozo, J., Beri, S., Ermakov, I. V., Danckaert, J., Smit, M. K., and Karouta, F., "Discretely tunable laser based on filtered feedback for telecommunication applications," *IEEE Journal on Selected Topics in Quantum Electronics* **16**, 1405–1412 (sep 2010).

[6] Ermakov, I. V., Beri, S., Ashour, M., Danckaert, J., Docter, B., Bolk, J., Leijtens, X. J., and Verschaffelt, G., "Semiconductor ring laser with on-chip filtered optical feedback for discrete wavelength tuning," *IEEE Journal of Quantum Electronics* **48**(2), 129–136 (2012).

[7] Carpintero, G., Rouvalis, E., Lawniczuk, K., Fice, M., Renaud, C. C., Leijtens, X. J. M., Bente, E. A. J. M., Chitoui, M., Dijk, F. V., and Seeds, A. J., "95 GHz millimeter wave signal generation using an arrayed waveguide grating dual wavelength semiconductor laser," *Opt. Lett.* **37**(17), 3657–3659 (2012).

[8] Naderi, N. A., Grillot, F., Yang, K., Wright, J. B., Gin, A., and Lester, L. F., "Two-color multi-section quantum dot distributed feedback laser," *Optics Express* **18**, 27028 (dec 2010).

[9] Pawlus, R., Breuer, S., and Virte, M., "Relative intensity noise reduction in a dual-state quantum-dot laser by optical feedback," *Optics Letters* **42**, 4259 (nov 2017).

[10] Virte, M., Breuer, S., Sciamanna, M., and Panajotov, K., "Switching between ground and excited states by optical feedback in a quantum dot laser diode," *Appl. Phys. Lett.* **105**, 121109 (sep 2014).

[11] Virte, M., Pawlus, R., Sciamanna, M., Panajotov, K., and Breuer, S., "Energy exchange between modes in a multimode two-color quantum dot laser with optical feedback," *Optics Letters* **41**(14), 3205 (2016).

[12] Smit, M., Leijtens, X., Ambrosius, H., Bente, E., Van Der Tol, J., Smalbrugge, B., De Vries, T., Geluk, E. J., Bolk, J., Van Veldhoven, R., Augustin, L., Thijs, P., D'Agostino, D., Rabbani, H., Lawniczuk, K., Stopinski, S., Tahvili, S., Corradi, A., Kleijn, E., Dzibrou, D., Felicetti, M., Bitincka, E., Moskalenko, V., Zhao, J., Santos, R., Gilardi, G., Yao, W., Williams, K., Stabile, P., Kuindersma, P., Pello, J., Bhat, S., Jiao, Y., Heiss, D., Roelkens, G., Wale, M., Firth, P., Soares, F., Grote, N., Schell, M., Debregeas, H., Achouche, M., Gentner, J. L., Bakker, A., Korthorst, T., Gallagher, D., Dabbs, A., Melloni, A., Morichetti, F., Melati, D., Wonfor, A., Penty, R., Broeke, R., Musk, B., and Robbins, D., "An introduction to InP-based generic integration technology," *Semiconductor Science and Technology* **29**(8), 083001 (2014).

[13] Augustin, L. M., Santos, R., Den Haan, E., Kleijn, S., Thijs, P. J., Latkowski, S., Zhao, D., Yao, W., Bolk, J., Ambrosius, H., Mingaleev, S., Richter, A., Bakker, A., and Korthorst, T., "InP-Based Generic Foundry Platform for Photonic Integrated Circuits," *IEEE Journal of Selected Topics in Quantum Electronics* **24**, 1–10 (jan 2018).

[14] Pawlus, R., Breuer, S., and Virte, M., "Compact dual-wavelength lasers on InP generic foundry platform," in [*2019 Conference on Lasers and Electro-Optics Europe and European Quantum Electronics Conference, CLEO/Europe-EQEC 2019*], Institute of Electrical and Electronics Engineers Inc. (jun 2019).

[15] Karsaklian Dal Bosco, A., Ohara, S., Sato, N., Akizawa, Y., Uchida, A., Harayama, T., and Inubushi, M., "Dynamics Versus Feedback Delay Time in Photonic Integrated Circuits: Mapping the Short Cavity Regime," *IEEE Photonics Journal* **9**, 1–12 (apr 2017).

Downloaded From: https://www.spiedigitallibrary.org/conference-proceedings-of-spie on 09 Nov 2020
Terms of Use: https://www.spiedigitallibrary.org/terms-of-use