Dual-wavelength laser with phase-controlled optical feedback loop for rapid switching

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Abstract *We propose a novel technique to pilot the power balance in a dual-wavelength laser design. This technique, based on phase-controlled optical feedback, allows for very fast switching with only one control parameter.*

Introduction

Dual-wavelength lasers (DWL) have gained interest in recent years for various applications related to all optical signal processing[1] or THz and millimeter generation to fulfill further demands on increasing data rates of wireless communication[2][3][4].
State of the art DWLs or multi-wavelength lasers come in different flavors. One solution that has been proposed is to combine multiple cavities to have a compound laser with controllable multi-wavelength light emission. In ref.[5], for example, multi-wavelength emission has been achieved by using a 16 channel arrayed waveguide grating. However, this laser takes up a relatively large footprint on a Photonic Integrated Circuit (PIC) and multiple control parameters are needed, one Semiconductor Optical Amplifier (SOA) per channel, to balance out the power per wavelength. Other DWLs intrinsically lase at two wavelengths, for example, some quantum dot lasers[6]. However, controlling the power in each wavelength is difficult to achieve as there is no easy way to control each wavelength independently.
Here, we propose a novel technique to control a DWL based on phase-controlled optical feedback. With this approach, it becomes possible to balance the power for each wavelength or induce a rapid switch between wavelengths through a single control parameter. We experimentally test and demonstrate the relevance of the proposed technique through an implementation on a Photonic Integrated Circuit (PIC) manufactured on a generic foundry platform. Thus, we show that our scheme can be monolithically integrated with the laser, but also that the resulting footprint for the complete system is minimized.

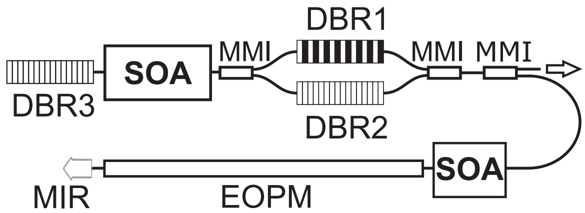

Fig. 1: The phase-controlled optical feedback DWL design as implemented on a PIC. A dual-wavelength laser coupled to a feedback section. The EOPM, part of the feedback section, is used to induce the switch. (Abbreviations are explained in the text.)

System design

The design can conceptually be split up in two parts: a DWL on one side, coupled to a phase-controlled feedback section on the other side. The feedback being the key element of our control technique as briefly explained below.
The laser cavity itself, shown in the upper part of figure 1, is build up from three Distributed Bragg Reflectors (DBRs). The two DBRs in parallel (DBR1 and DBR2) act as wavelength selective elements. A third DBR closes the cavity. This third DBR has a central wavelength in between that of the other two DBRs, to overlap the reflectivity spectrum. In between, a SOA provides the required gain. Design parameters are given in table 1. For a more in depth discussion of this DWL we refer to previous work[7][8].
The laser is designed to emit at two distinct wavelengths without any external forcing. However, there are no possibilities to easily control the power balance or switch efficiently from one wavelength to the other. To gain control of the DWL, we exploit the Fabry-Perot effect in the optical feedback cavity. If a mode resonates between the DWL facet and the mirror at the end of the feedback cavity it will experience a gain boost. And, the other way around, if it is anti-resonant the effective gain is reduced.

We now propose a feedback section which can tune between resonating for either mode while anti-resonating for the other mode, thus allowing for a controlled switch.

The crucial point we use to design such a feedback cavity, is the difference in absolute wavelength between the two modes. As these modes propagate, the relative phase difference increases due to the difference in absolute wavelength. Eventually, the relative phase difference will become pi after a certain distance. At that point, if the light reenters the laser cavity, one mode would be resonant and the other would be anti-resonant, i.e. exactly what we need to induce the switch forcing the laser to favor the resonant wavelength. Changing the feedback phase for both wavelengths then allows to change which one is resonant. Adding a phase-modulator in the feedback cavity therefore makes the system tunable.

Now, for our specific design, the feedback section is made up of a Multi-Mode Interference coupler (MMI), SOA, Electro-Optic Phase Modulator (EOPM) and Multi-mode Interference Reflector (MIR). The MMI is a 85/15 splitter, thus 15% of the output of the laser goes to the feedback section. The SOA is used to adjust the feedback strength. The EOPM can shift the phase up to 2π by applying a voltage of -8V. The specific lengths of these devices are shown in table 1. As pointed out, the total feedback length should be quite precisely set with respect to the wavelength difference in the DWL.

Tab. 1: Design parameters of the system.

Device	length $[\mu m]$	Central λ $[nm]$
DBR1	450	1541.3
DBR2	450	1539.3
DBR3	350	1540.0
SOA	500	/
Feedback SOA	300	/
EOPM	1200	/

	$\lambda 1[nm]$	$\lambda 2[nm]$	$\Delta\lambda[nm]$
Design	1540.7	1539.4	1.3
Experiment	1543.6	1543.2	0.4

Experimental results

The Photonic Integrated Circuit (PIC), on which the design is implemented, is controlled by a Thorlabs Pro8 system. The temperature of the PIC is fixed to 20° C with thermo-electrical cooling. The EOPM voltage is regulated with a voltage source (Agilent, E3649A). The laser light is out-coupled with a standard lensed fiber. We measured the optical spectra and power with an Apex AP2083A (resolution down to 5 MHz / 40 fm).

In figure 2 the LI curve of the DWL without feedback is shown. The laser threshold is 57 mA. Around 74 mA the laser is in dual-wavelength emission state, lasing at 1543.2 nm and 1543.6 nm with a 0.4 nm separation. Table 1 compares the design wavelengths with the measured ones. The measured wavelengths are longer, which might be due to an effect of fabrication tolerances or the temperature[8]. As pointed out, the wavelength separation is crucial for the control technique as it determined the length of the feedback section. For this DWL we measured it to be much lower than designed, therefore the needed phase difference might not be large enough. However, as we shall show, the switching technique still works. Although further evaluation of the robustness against such variation are still required, this observation is particularly encouraging.

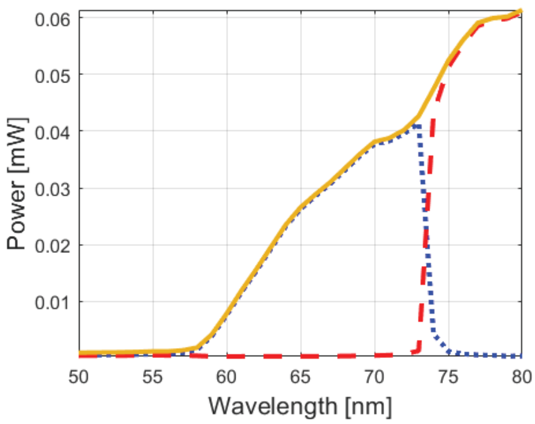

Fig. 2: LI curve of the dual-wavelength laser. The upper curve (full yellow line) is the full power measured. The other curves are the power in each mode. This shows that by increasing the gain, the laser shifts from one mode to the other. Around 74 mA current is the equal power point.

At this equal power point, when the laser is in dual state emission, we switch on the feedback section by turning on the feedback SOA. The current we applied is set at 9.4 mA, enough to suppress one mode of the DWL, but not too much to avoid triggering others modes or dynamical behaviour. Figure 3 shows the switching behavior when tuning the EOPM voltage. Either wavelength can be turned on or off with a suppression ratio of more than 25 dB. This shows that the switching mechanism is effective in suppressing either mode by using only one control parameter. The switching mechanism is robust for a change in the laser injection current, switching remains possible over a range of 12 mA current, around the equal power point of the DWL. In the DWL case, without feedback, at the extremes of this range, the other lasing mode is non-existent (see figure 2), showing the advantages of using feedback. This does come at the cost of suppression ratio. Further away from the equal power point, one mode does not fully suppress the other anymore. Likewise, further away from the equal power point, for one mode the EOPM voltage range where the mode is 'on' shrinks. We also point out that, although the absolute wavelengths and wavelength separation are significantly different from design (shown in table 1), the switching mechanism still shows effective switching.

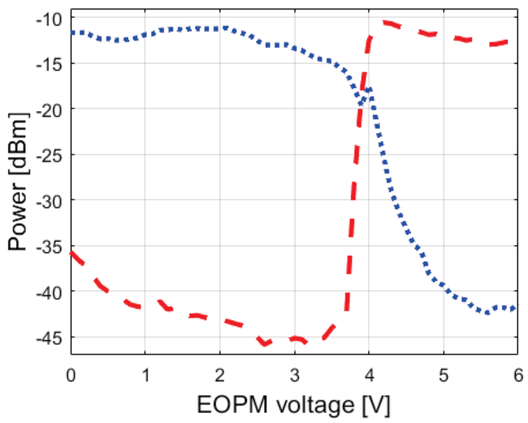

Fig. 3: Tuning of the EOPM voltage versus the power in each mode. The applied voltage is negative. The switch occurs at -4V. Blue dotted curve, one which is turned on from 0 to -4V, is the shortest wavelength. Red dashed curve, which is turned on from -4 V to -6 V, is the longest wavelength

A final experiment showed that the switching occurs very fast, in the order of nanoseconds, as shown in figure 4. We measured this by applying a fast alternating square wave voltage applied directly to the EOPM, coming from an arbitrary waveform generator with a 1 GHz bandwidth, to induce a switch. The rise time of this square voltage is 1 ns. An optical filter is used to measure only one wavelength and the signal is then measured with a photodiode and an oscilloscope. We measured a total switching time in the order of 5 ns. The delay before the switch occurs is about 4 ns, from then it takes about 1 ns second for the mode to be fully 'on'. This is in the same order or faster compared to filtered feedback controlled multi-wavelength lasers[9][10]. The switch off delay was a bit longer, in the order of 10 nanoseconds. However, neither the electrical connection nor the on-chip metal tracks have been optimized for RF signals. Since significant deterioration of the input signal could be observed, it is likely that the switching dynamics would directly be impacted. As a result, optimization of the chip and setup for RF signals could also lead to further speed improvements possibly below the nanosecond.

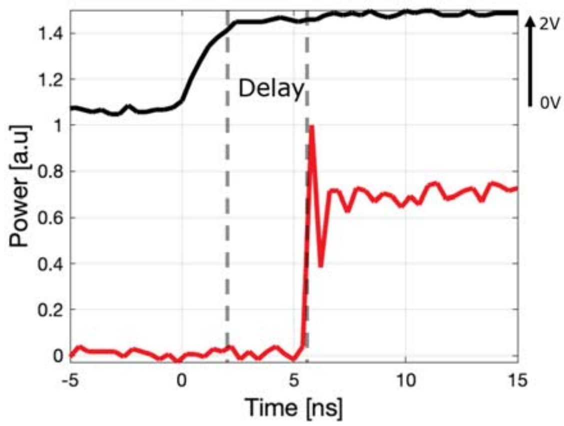

Fig. 4: Top black curve is the aplied voltage step. Lower red curve is the measured optical power in the switched on mode. A 4 ns delay is the biggest part of the total switching time.

Conclusions

We have presented a dual-wavelength laser build up from a simple design of multiple DBRs. Using phase-controlled optical feedback we show that the balance in power between the two wavelengths can be tuned with only one parameter, the EOPM voltage. We have shown that it is possible to switch between the wavelength with a high suppression ratio of up to 25 dB and beyond[11]. In addition, this approach appears to provide switching capability at a fast pace in the nanosecond range, and possibly faster.

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