Integrated filtered feedback laser: stability study

D. Zhao, W. Yao, D. Lenstra, K. Williams, and X.J.M. Leijtens

Eindhoven University of Technology, Dept. of Electrical Engineering, De Zaale, 5612 AJ, Eindhoven, the Netherlands

A monolithically-integrated, InP, multi-wavelength laser based on filtered feedback is presented. We demonstrated single-mode operation at each channel with a side mode suppression ratio (SMSR) of over 40 dB. The stability of the laser is experimentally investigated as a function of the electrically controlled feedback phase at different feedback delay times. The existence of a laser injection current interval, where the relaxation oscillations (ROs) are damped independent of the feedback phase value is demonstrated at feedback delay time of $3 \cdot 10^{-10}$ *s.*

Introduction

Monolithically integrated multi-wavelength lasers (MWLs) are promising components for optical comb sources and future wavelength-division multiplexing (WDM) systems [1-2]. They offer a reduction in the number of optical connections, and a route to simplified control. Arrayed waveguide gratings (AWG) based MWLs have been widely studied. Among them, filtered feedback MWLs have been demonstrated as a good approach for single-mode operation, narrow linewidth or fast switching [3-5]. Zhao et al. have reported a filtered feedback MWL which obtains single-mode operation with over 40 dB side mode suppression ratio (SMSR) and narrow linewidth of ~150 kHz [4]. However, the laser exhibited sustained relaxation oscillations (ROs), which are strongly dependent on the feedback phase.

The modulation of the feedback phase requires a feedback phase shifter in each channel, which increases the footprint and the number of electrical inputs and is sensitive to the ambient temperature change. Lenstra et al. reported a theoretical study on the role of the feedback delay time in the suppression of ROs independent of the feedback phase value [6]. Based on this, we have implemented feedback with delay time in our design, studying the role of feedback strength and phase. In addition, we explore the role of spurious reflections, and develop methods to compensate it.

Device design and fabrication

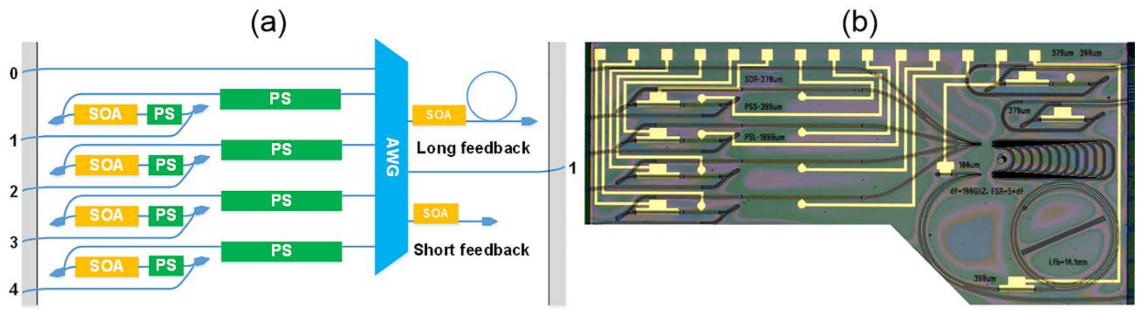

Fig. 1: (a) Schematic diagram and (b) microscope photograph of a filtered feedback multi-wavelength laser.

The schematic and the microscope photograph of the monolithically integrated filtered feedback MWL are shown in Fig. 1 (a) and (b), respectively. There are four laser channels with identical FP laser designs, each of them consisting of two multimode interference reflectors (MIRs) with a typical power reflection *R* of 0.38, a 370-μm-long SOA and a 300-μm-long phase shifter (0.08°/mA) and an additional 1000-μm-long phase shifters

(0.27°/mA) between the FP lasers and an AWG for control of the feedback phase. The AWG is used for wavelength selection of the FP lasers; it has a channel spacing of 100 GHz and a free space range (FSR) of 500 GHz. The transmission through AWG can be measured by injecting light at port 0 from the left side and collecting light at port 1 from the right side.

To investigate the role of the feedback delay time, we have connected two of the AWG inputs to two channels with different length of waveguides, corresponding to an external roundtrip time τ of $1 \cdot 10^{-10}$ s (short feedback) and $3 \cdot 10^{-10}$ s (long feedback), respectively. The shorter length is close to the value used in Ref. [4] and the longer length matches the value that is proposed in Ref. [6] for the suppression of ROs independent of the feedback phase value. In each channel, there is a SOA for switching on or off the feedback and for its strength control and a MIR with expected power reflection R of 0.79 as a back reflector.

The devices were fabricated by Smart Photonics through the JePPIX.eu multi-project wafer service.

Measurements

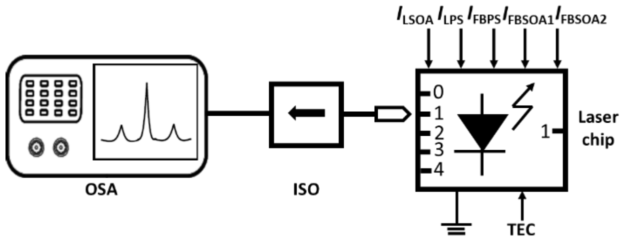

Fig. 2: The measurement setup. I_{LSOA}, I_{LPS}, I_{FBPS}, I_{FBSOA1}, I_{FBSOA2} represent forward/reverse bias that are driven to the electrical contacts of SOAs and phase shifters; the numbers represent the I/O ports of the device; TEC is the temperature controller; ISO is an optical isolator; OSA is an optical spectrum analyzer.

The measurement setup is depicted in Fig. 2. The laser chip is placed on a copper chuck and maintained at a temperature of 18 ℃ with a thermoelectric cooler (TEC) and water cooling. The electrical contacts of SOAs and phase shifters are driven in forward/reverse bias using low-noise current/voltage sources. I_{LSOA} is the laser injection current, I_{LPS} and I_{FBPS} are the currents on the phase shifters in the laser cavity to tune the laser phase and in the external feedback path to tune the feedback phase, respectively. I_{FBSOA1} and I_{FBSOA2} are the currents on the SOAs in the short and long feedback path to control the feedback strength, respectively. To switch off feedback, we apply a reverse bias of -3 V to the SOA in the unwanted path. A lensed anti-reflection coated fiber placed at the angled output of the laser is used to collect the light. An optical isolator (ISO) is connected to the fiber to prevent undesired back reflections into the laser. An optical spectrum analyzer (OSA) with a high resolution of 0.16 pm (APEX AP2041B) is used to detect the lasing spectra.

Results and discussion

The blue line in Fig. 3 (a) shows a zoom of the spectrum of one of the FP lasers slightly below threshold for the case where both feedback paths are switched off. The longitudinal modes are spaced by about 0.3 nm, which corresponds to a frequency spacing of 38 GHz. The dashed lines in Fig. 3 (a) show the estimated AWG filtering function for each laser with the long feedback on. The estimation is based on the designed channel spacing of 100 GHz and the measured passbands of the AWG channel 0 to 1. To obtain a single mode operation, we switch on one of the feedback paths. At a certain laser injection current, by adjusting the laser phase, feedback strength and phase, we can obtain single mode operation. It is realized by aligning one of the FP longitudinal modes with the peak of the wanted AWG passband. Fig. 3 (b) shows superimposed lasing spectra of the four channels while operating each channel separately, the simultaneous operation is not demonstrated in this work. The laser injection currents are all 50 mA, the laser phase, feedback strength and phase in each channel are adjusted. The single-mode operation at each channel with SMSR of over 40 dB is demonstrated.

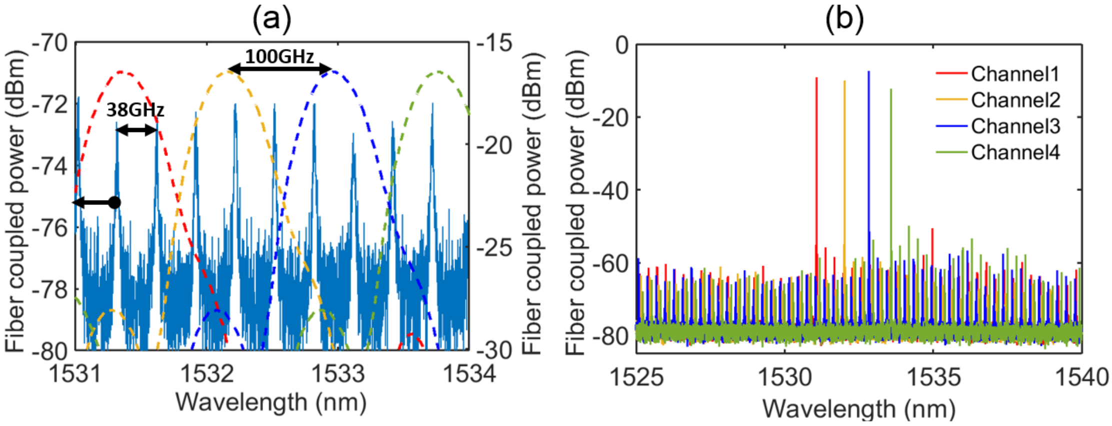

Fig. 3: (a) A zoom of the spectrum of the FP laser at subthreshold and the estimated AWG filtering function for each laser with the long feedback on. (b) Superimposed lasing spectra of the four channels while operating each channel separately.

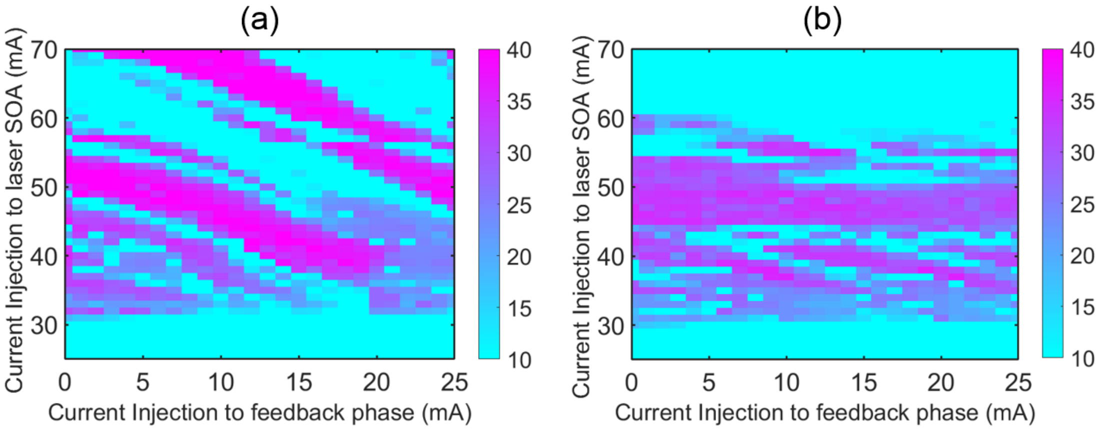

Fig. 4: Measured stability map for feedback phase of the (a) short and (b) long feedback path, the color bar shows the SMSR in dB.

According to Lenstra [5], the ROs stay damped for all feedback phase values when the RO-frequency f_{RO} is resonant with the external roundtrip time τ.

$$f_{\mathrm{RO}}\tau \cong 1,2,3, \ldots \quad (1)$$

The premise is that the feedback coupling parameter C should be close to 1.

$$C = \gamma\tau\sqrt{1+\alpha^2} \quad (2)$$

$$\gamma = r_{ext}\frac{1-r^2}{\tau_{in}\cdot r} \quad (3)$$

where γ is the feedback rate, α of 2.6 is the linewidth-enhancement parameter, r of 0.6 is the reflectivity of the laser mirror, τ_{in} ·of $2.2 \cdot 10^{-11}$ s is the internal round trip time of the laser cavity, r_{ext} is the effective reflectivity of the feedback and can be adjusted by the current injection to the feedback SOA. To satisfy the premise, we extract the required

r_{ext} and thus the amplification coefficient of the SOAs for the case of short and long feedback paths. Accordingly, the injection currents to the SOAs are estimated, which are around 2 and 6 mA, respectively.

For feedback with an external roundtrip time of $1 \cdot 10^{-10}$ s, we cannot find a laser injection current interval below the break down current that satisfies eq. (1). For the feedback with external roundtrip time of $3 \cdot 10^{-10}$ s, $f_{\mathrm{RO}}\tau$ equals to 1 at laser injection currents of 1.4 times threshold and associated RO frequencies of 3.3 GHz. The theoretical prediction is experimentally demonstrated by activating the laser in channel 1 and the short and long feedback separately. The lasing spectra at different laser injection current and feedback phase are recorded, the laser phase and feedback strength are fixed. Fig. 4 shows the measured stability map for feedback phase varying 2π of the (a) short and (b) long feedback path, the color bar shows the SMSR in dB. With the long feedback, we obtain a current interval from 45 mA to 50 mA without ROs at all feedback phase values.

It is important to know that the instability of the laser, shown as the light blue spots in Fig. 4, is not only caused by ROs but also multi-mode lasing. So the stability map in Fig. 4 (b) doesn't totally match Lenstra's prediction[5], because he solely considers the effect of ROs on single-mode lasers. There are several issues that we have observed in our measurements that cause multi-mode lasing. First, spurious reflections for example from the active-passive butt-joint introduce extra cavities in the laser, which increases the possibility of multi-mode lasing. Second, there are multiple AWG passbands within the gain peak, so the selection of the lasing mode in a particular passband is difficult. To select only the AWG passband that we want, we can use the Distributed Bragg Reflector (DBR) lasers to replace the FP lasers or chirp the AWG arm lengths to have one dominant passband for wavelength selection [7].

Conclusions

An InP-based, monolithically-integrated multi-wavelength laser with short and long delay time of filtered feedback is characterized. The single-mode operation at each channel with SMSR of over 40 dB is demonstrated. The ROs at all feedback phase values are damped at laser injection currents of around 1.4 times threshold for the feedback with external roundtrip time of $3 \cdot 10^{-10}$ s.

Acknowledgement

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References

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