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# Widely Tunable Monolithically Integrated Lasers Using Intracavity Mach-Zehnder Interferometers

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## ABSTRACT

Using monolithic integration technology we have designed and fabricated tunable lasers in the 1.5  $\mu\text{m}$  region with a demonstrated tuning range of 60 nm and single mode operation. This performance is achieved using intracavity tunable Mach-Zehnder interferometers that use voltage controlled phase modulators. In this paper we will discuss design considerations and advantages of such tunable lasers.

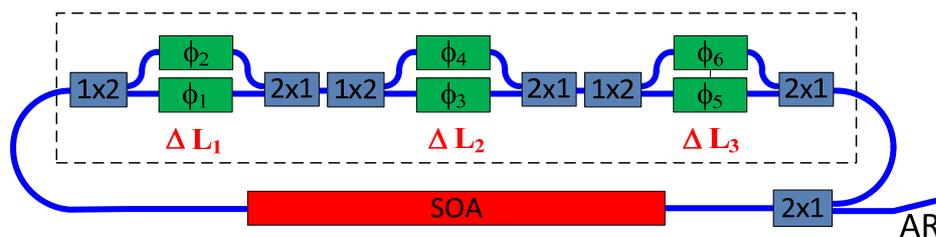
**Keywords:** semiconductor laser, photonic integration, tuneable laser.

## 1. INTRODUCTION

For optical gas sensing of several gas species a widely tunable single longitudinal mode laser is desirable. This is particularly true when there is background interference from other unknown gas species. The laser should be able to scan continuously over a few GHz around a wide range of wavelengths to cover as many species as possible. This is the motivation the development of integrated extended cavity ring lasers with a widely tunable intracavity wavelength filter with a simple control mechanism. The wavelength discrimination mechanism is based on a sequence of asymmetric Mach-Zehnder interferometers (AMZI) that can be tuned using voltage controlled electro-refractive phase modulators. Such a design is shown to have potential for a wide wavelength tuning range using only a few (e.g. four) control voltages that consume a small amount of power compared to e.g. tunable DBR gratings, as well as a stable wavelength calibration over time. Devices have been designed and fabricated as a Photonic Integrated Circuit (PIC) which is realized in a multi project wafer (MPW) run within the COBRA active-passive integration platform [1]. The lasers operated in the 1.5  $\mu\text{m}$  wavelength range to demonstrate the capabilities. Characterizations of the fabricated PIC show we can achieve single-mode (longitudinal) operation and a wide tuning range. Good agreement with preliminary simulations and design objectives [2] were obtained. The designs are transferable to an integration platform operating around 2  $\mu\text{m}$ .

## 2. LASER GEOMETRY

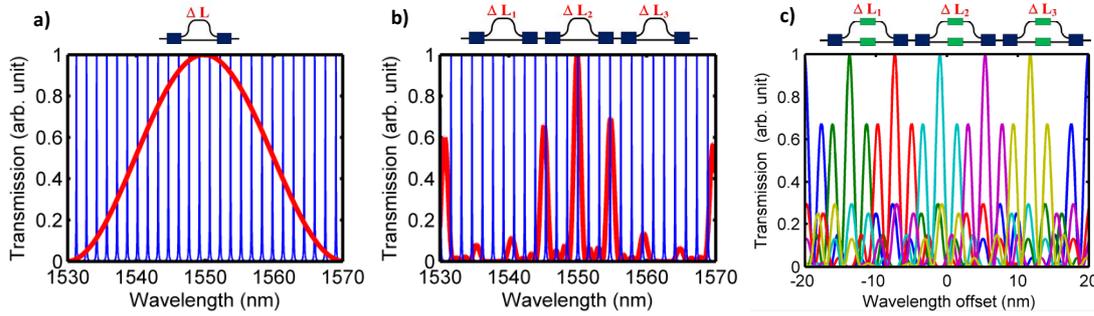
In this paper we present results on a laser geometry that is schematically depicted in Figure 1. An extended ring cavity is formed and consists of semiconductor optical amplifier (SOA) providing optical gain, a tuneable optical band-pass filter and multimode interference couplers (MMI) with straight and curved passive waveguides connecting all components.



**Figure 1.** Schematic representation of the extended cavity ring laser with a AMZI based intracavity wavelength selection filter. The ring cavity consists of a three stage wavelength filter (dashed box), semiconductor optical amplifier (SOA), and 2x1 MMI coupler used for coupling out the optical signal. All components are connected with passive waveguides (in blue).

The wavelength selective filter is fully realised in passive waveguide components. It consists of three tuneable AMZIs in series. A transmission of an individual AMZI is periodic with respect to the frequency (wavelength) with a free spectral range  $FSR = c/\Delta L_x$  with  $c$  being the speed of light in vacuum and  $\Delta L_x$  an optical path length unbalance. The unbalanced interferometric configuration enables a tuning mechanism in which a change of the respective optical phase by  $2\pi$  between the arms tunes the filter over one full FSR of the AMZI. The physical length of the optical waveguides in the arms can be defined on a micrometer scale and efficient voltage controlled phase shifters ( $\phi$ ) are available within the integration platform used. Therefore AMZI based filters with a tuning range in the order of tens of nanometers (a few terahertz) can be realized [3], [4]. A single AMZI features a sinusoidal transmission spectrum, which in many cases which in combination with the fundamental

mode structure of the laser cavity and the gain profile of the SOA is not sufficient to achieve a single mode operation. The mode selection principle of a single AZMI filter overlapped with a resulting longitudinal cavity mode profile is depicted in Fig. 2(a).



**Figure 2.** The transmission profiles of a filter (shown in red color) consisting of (a) a single AMZI and (b) a series of three unbalanced interferometers; longitudinal cavity modes are indicated in blue with the separation frequency scaled up for clarity (c) Examples of filter's transmission envelope for several phase shifter settings, with the control signals  $S_\phi$  applied within  $S_{2\pi}$

The selectivity of such a filter can be improved by combining several identical AMZI in series resulting in increased finesse of the filter, or alternatively using a sequence of AMZIs with uneven optical unbalances ( $\Delta L_1 \neq \Delta L_2 \neq \Delta L_3$ ) allows one to select the required longitudinal mode of the ring laser cavity. A transmission profile of a three stage serial AMZI filter is shown in Fig. 2(b). A relatively simple and predictable tuning scheme can be used when phase shifters  $\phi$  ( $\phi=1,2,..6$ ) of equal lengths are used in the AMZIs, as shown in Figure 1. The equal lengths of phase shifters mean that in principle the same control signal  $S_{2\pi}$  is required in order to achieve a phase delay of  $2\pi$  in each stage of the filter. Furthermore, as the unbalances  $\Delta L_{1,2,3}$  are fixed, a simple linear relationship between the change in control signals  $\Delta S_{1,2,3}$  and the frequency detuning  $\Delta f$  of the series of three AMZIs exists. The required control signals can be calculated from the required detuning  $\Delta f$  as follows:

$$\Delta S_\phi = \frac{\Delta f}{v_g} S_{2\pi} \Delta L_\phi \quad (1)$$

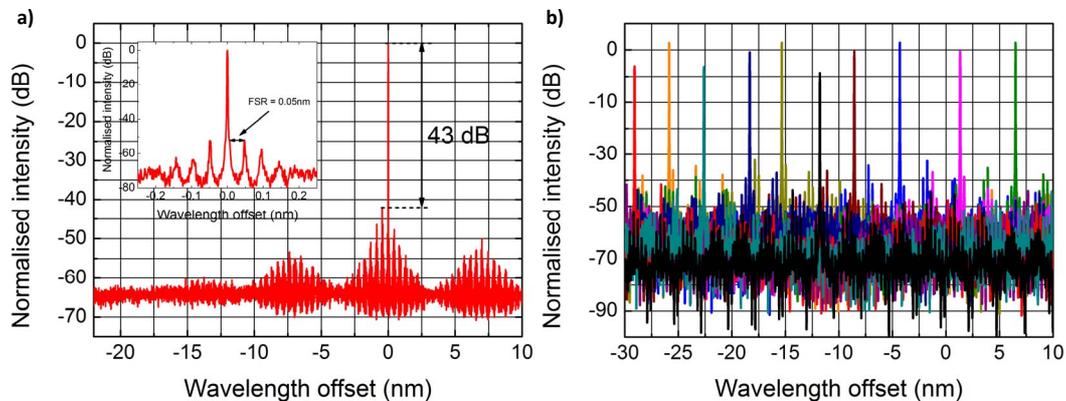
with  $v_g$  being a group velocity. With the relationship given by Eq. 1 a set of  $S_\phi$  control signals within  $S_{2\pi}$  can be calculated to allow for continues frequency tuning of the filter over its full FSR, as depicted in Figure 2(c).

### 3. Photonic Integrated Circuit

In the COBRA active-passive integration platform a set of basic building blocks (BB) is offered, which can be combined in the form of complex photonic integrated circuits. All of these BB are allocated on one type of an epitaxial layer stack grown on InP substrate, being either optically active or passive. The active layer stack is capable of on-chip light generation, amplification and absorption at wavelength at around 1.5  $\mu\text{m}$ . The passive layer stack can support low optical loss ridge waveguides. The extended cavity ring laser as depicted in Fig. 1. was designed and fabricated within this technology. The cavity consists of a three stage optical band-pass filter (dashed box in the Fig. 1), a 1 mm long semiconductor optical amplifier, and two  $2 \times 1$  MMI couplers used for coupling out the optical signal, all components are connected with passive waveguides. The ring cavity features an overall average length of  $L_R = 18$  mm with corresponding fundamental free spectral range of 5 GHz ( $\sim 5$  nm). The three individual AMZIs are formed by  $2 \times 1$  MMIs, passive waveguides, and a 1.8 mm long phase shifters ( $\phi$ ) in each branch to allow for wavelength tuning and calibration. The optical unbalances  $\Delta L_1$ ,  $\Delta L_2$  and  $\Delta L_3$ , were selected to be 15  $\mu\text{m}$ , 89  $\mu\text{m}$ , 1530  $\mu\text{m}$  respectively. The AMZI with the smallest FSR (number 3) determines the side mode suppression ratio with the neighbouring cavity modes. The other two AMZIs suppress the other transmission maxima of the number 3 AZMI. Such a combination of the AMZIs allows for wide tuning range while maintaining a single-mode operation. The optical output is angled with respect to the cleaved edge of the chip and antireflection coated in order to reduce impact of potential back-reflections.

Simulations of this ring laser with a time domain circuit simulator (PICwave<sup>TM</sup>) show that side-mode suppression ratios in the excess of 30 dB can be achieved at any operation point within the 3 dB bandwidth of the SOA as depicted in Fig. 3. An example of a simulation result with single mode operation is presented in Fig. 3(a). The envelope of the three AMZI filters transmission spectrum can be recognised. The spectrum near to the lasing wavelength with neighbouring cavity modes at FSR of 0.05 nm (5 GHz) is shown in the inset. The spectral results obtained from several (shorter) simulations run for different settings of the voltage applied to

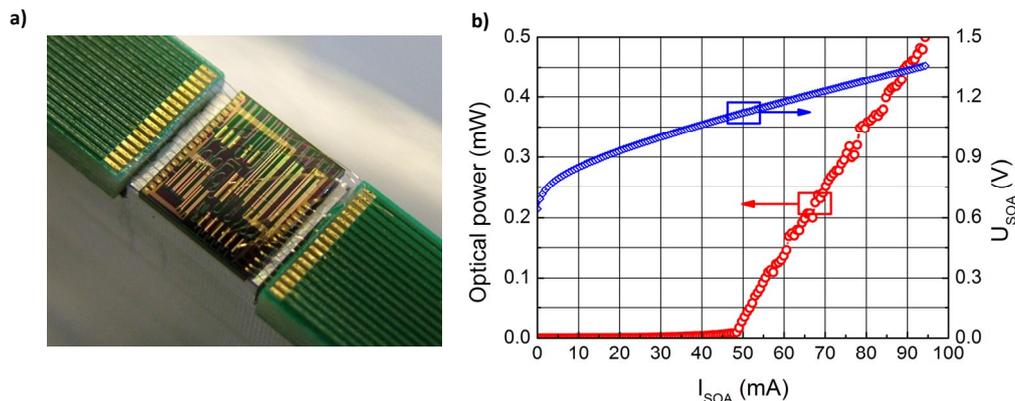
one of the phase shifters in the coarse AMZI stage of the filter  $U_{\phi_5}$  are presented by overlapping curves in Fig. 3(b). A tuning range over the full gain bandwidth ( $\sim 40$  nm) of the amplifier is demonstrated. The irregularities in the maximum power result from a non-optimised alignment of the three staged of the AMZI filter and cavity resonance; only one phase shifter was scanned. Furthermore as the simulations were run for shorter time the spectra resolution and noise differ from this presented in the Fig. 3(a).



**Figure 3.** Spectral output provided by a photonic circuit simulator from a designed PIC based ring laser. **(a)** Spectral features of a selected operation point showing a single mode operation with SMSR of  $\sim 43$  dB. Inset: Close scale view of the lasing mode and neighbouring cavity modes at  $FSR = 0.05$  nm (5 GHz). **(b)** Optical spectra simulated for several various sets of biasing signals applied to three phase shifters, showing a tunability potential across the whole bandwidth of an amplifier used in the simulations ( $\sim 40$  nm).

#### 4. Experimental results

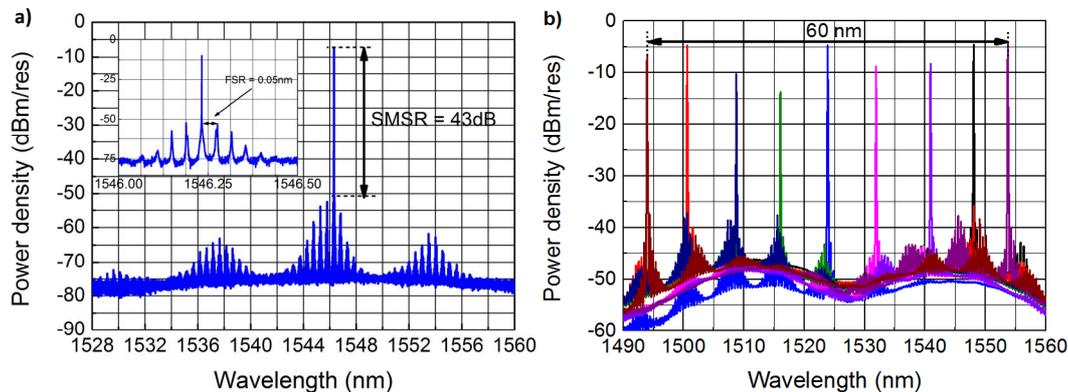
The fabricated PIC chip is mounted on aluminum block and electrical contacts of phase shifters and SOA are wire bonded to electrical signal distribution PCBs for an ease of control and characterization as can be seen in Fig. 4(a). The aluminum sub-mount is temperature stabilized with a passive water cooling system. Optical signal is collected with an antireflection coated lensed fiber and fed with a standard single mode fiber to the measurement equipment being an optical power meter and high resolution (20 MHz) optical spectrum analyzer. At the temperature of  $15^\circ\text{C}$ , the threshold current has been measured at  $I_{th} = 48$  mA as shown in Fig. 4(b). The slope resistance is  $R_{sl} = 5.5 \Omega$ . A single-mode operation with the SMSR of 43 dB at the bias current  $I_{SOA} = 134$  mA has been achieved as depicted in Fig. 5(a). Spectral properties are in good agreement with the values targeted during the design process and show close overlap with the output of circuit simulator depicted in Fig. 3(a).



**Figure 4.** Characteristics of the device fabricated in COBRA MPW run: **(a)** photonic integrated circuit chip with a number of tunable lasers mounted on aluminium block with electrical contact wire-bonded to two PCBs; **(b)** optical power and SOA voltage versus bias current characteristics of tested device indicate threshold current  $I_{th} = 48$  mA and a slope resistance  $R_{sl} = 5.5 \Omega$ .

The wavelength tuning potential was investigated by applying reverse voltages to two phase shifters  $\phi_2$  and  $\phi_5$  corresponding to fine and coarse stages of the intracavity AMZI band-pass filter. The SOA section was biased at  $I_{SOA} = 140$  mA, and the remaining phase shifters were grounded. Resulting optical spectra recorded with a standard resolution (0.05 nm) OSA at 9 different sets of  $U_{\phi_2}$  and  $U_{\phi_5}$  are overlapped and shown in Fig. 4(b). The wavelength tuning range of 60 nm was observed around 1525 nm for the  $I_{SOA}$  and  $T_{WC}$  used. Irregularities in

the peak power ( $\leq 10$  dB) are a consequence of using only two phase shifters for this experiment. In this way therefore the alignment of all three stages of the AMZI filter and fundamental cavity resonance is non-optimal.



**Figure 5.** Measurements of the laser fabricated in a COBRA MPW run: (a) a high resolution (20 MHz) optical spectrum recorded with the SOA section DC biased at  $I_{SOA} = 134$  mA ( $\sim 2.5$  of  $I_{th}$ ) and temperature set at  $15.5$  °C. Inset: Detailed view of the lasing mode with neighbouring cavity side modes with  $FSR = 0.05$  nm (5 GHz); (b) Optical spectra recorded with a standard resolution 0.05 nm for various sets of reverse voltages applied to two phase shifters:  $\phi_2$  and  $\phi_s$ , while others were set at 0 V (p-contacts grounded).

## 5. SUMMARY

A widely wavelength tunable ring geometry laser with an intracavity wavelength filters based on AMZI was designed and fabricated on the COBRA photonic integration platform at  $1.5 \mu\text{m}$ . The measurement results obtained show a good performance in terms of single mode operation and the tuning range, these are also in a good agreement with the preliminary simulations performed with a travelling wave circuit simulator. An average optical power of several mW assuming 5 dB coupling efficiency can be achieved. The results show that a wide tunability of a laser can be achieved using only a few voltage control signals.

## ACKNOWLEDGEMENTS

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