A Monolithically Integrated Tunable Single Longitudinal Mode Extended Cavity Ring Laser Using Intracavity Mach-Zehnder Interferometers

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A ring geometry laser with a wavelength tunable intracavity filter is demonstrated. The device is realized as a photonic integrated circuit and fabricated within COBRA InP active-passive multi project wafer run. The device under test features a three stage asymmetric Mach-Zehnder interferometer filtering scheme allowing for a single mode operation with the side mode suppression and contrast ratios of 43 dB and 60 dB respectively when the laser is DC biased at 2.5 times of the threshold current.

Introduction

An extended ring laser with an intracavity wavelength filter for gas sensing applications is proposed. The wavelength discrimination mechanism is based on a sequence of asymmetric Mach-Zehnder interferometers (AMZI) and has potential for a wide wavelength tuning range. The device is 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. Preliminary characterizations of the fabricated device reveal a single-mode (longitudinal) operation, showing a good agreement with initial simulations and design objectives [1].

Laser geometry

The laser under investigation has a geometry as schematically depicted in Fig. 1. It consists of semiconductor optical amplifier (SOA) providing optical gain, the AMZI based wavelength selective filter and a multimode interference coupler (MMI) for coupling out the optical signal. All elements are connected with straight and curved passive waveguides forming an extended ring cavity.

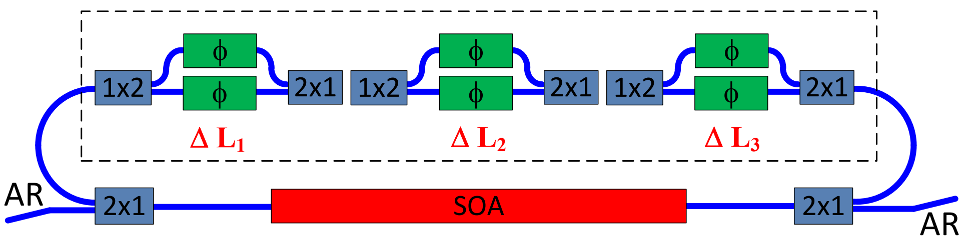

Fig. 1. Schematic diagram of extended cavity ring laser with AMZI based intracavity wavelength selection filter. The ring cavity consists of a three stage wavelength filter (dashed box), semiconductor optical amplifier (SOA), and two 2x1 MMI couplers used for coupling out the optical signal. All components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

In the presented configuration, the wavelength filter consists of three AMZIs in series. A transmission of an individual AMZI is periodic with respect to the frequency (wavelength) with a free spectral range FSR=c/ΔL_x with c being the speed of light in vacuum and ΔL_x an optical path length unbalance. The unbalanced interferometric configuration enables a tuning mechanism in which a change of the respective optical phase by 2π between the arms tunes the filter over one full FSR regardless of its value. Provided that the length of optical waveguides can be defined on a micrometer scale and efficient phase shifters are available within the integration platform used, AMZI based filters with a tuning range in the order of tens of nanometers (a few terahertz) can be realized [2], [3]. A single AMZI features a finesse of 2 (sinusoidal profile) which in many cases does not suffice when combined with the fundamental mode structure of the laser cavity and a gain profile of semiconductor material to achieve a single mode operation. The mode selection principle of a single AZMI filter combined with resulting longitudinal cavity mode selection is depicted in Fig. 2(a).

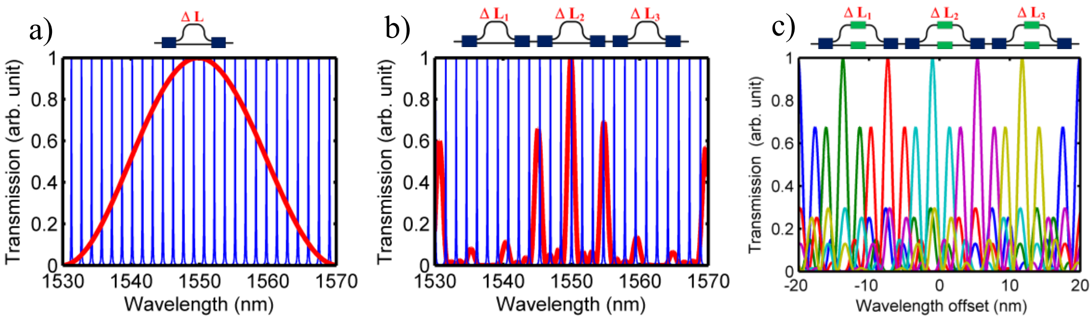

Fig. 2. The transmission profiles of a filter (shown in red color) consisting of (**a**) a single AMZI and (**b**) a series of three unbalanced interferometers; longitudinal cavity modes are indicated in bluewith the separation frequency scaled up for clarity (**c**) Examples of filter's transmission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

A combination of several AMZI in series can improve the finesse of the filter, or using a sequence of AMZIs with e.g. decreasing optical unbalances ($\Delta L_1<\Delta L_2<\Delta L_3$) allows one to select the required longitudinal mode of the ring laser cavity. A transmission profile of a three stage serial filter is shown in Fig. 2(b). A relatively simple and predictable tuning scheme can be used when phase shifters ϕ (ϕ=1,2,3) of equal lengths are used in the AMZIs, as shown in Fig. 1. The equal lengths means the phase shifters require the same control signal $S_{2\pi}$ for a phase delay of 2π. 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 Δf of the series of three AMZIs exists. The required control signals can be calculated from the required detuning Δf as follows:

$$\Delta S_\phi = \frac{\Delta f}{v_g} S_{2\pi} \Delta L_\phi \qquad \text{Eq. 1}$$

with v_g being a group velocity. With the relationship given by Eq. 1 a set of S_ϕ 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 Fig. 2(c).

Photonic Integrated Circuit

In the COBRA active-passive integration platform a set of basic building blocks (BB) which can be combined in the form of complex photonic integrated circuits is available. All of these BB are allocated on either active or passive layers stacks grown on InP substrate. The extended cavity ring laser as depicted in Fig. 1. was designed and fabricated within this technology. The ring cavity consists of a three stage wavelength filter (dashed box in the Fig. 1.), a 1 mm long semiconductor optical amplifier, and two 2x1 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 (~5 nm). The three individual AMZIs are formed by 2x1 MMIs, passive waveguides, and a 1.8 mm phase shifter (ϕ) in each branch to allow for wavelength tuning and calibration. The optical unbalances ΔL_1, ΔL_2 and ΔL_3, were selected to be 15 µm, 200 µm, 1529 µm respectively. Such a combination of the AMZIs allows for tuning range of ~40 nm 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.

Modeling of this ring laser with the PICwave™ circuit simulator shows 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(a).

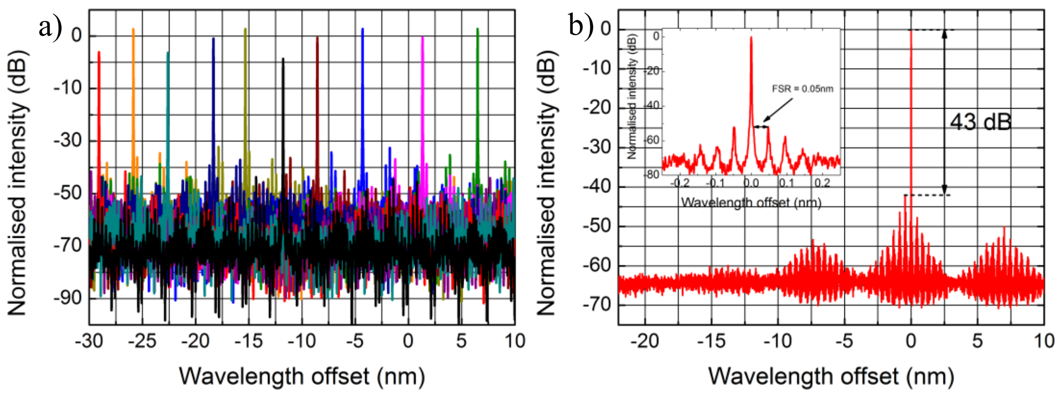

Fig. 3. Spectral output provided by a photonic circuit simulator from a designed PIC based ring laser, for various sets of biasing signals applied to three phase shifters, showing a tunablity potential across whole bandwidth of an amplifier (**a**). Spectral features of a selected operation point showing a single mode operation with SMSR of ~43 dB. Inset: Close scale view of the lasing mode and neighboring cavity modes at FSR =0.05 nm (5 GHz) (**b**).

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. 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 15.5 $^{\circ}$C, the threshold current has been measured at I_{th}= 48mA as shown in Fig. 4(a). The slope resistance is R_{sl}=5.5 Ω. 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. 4(b). Spectral properties are in good agreement with the values targeted during the design process.

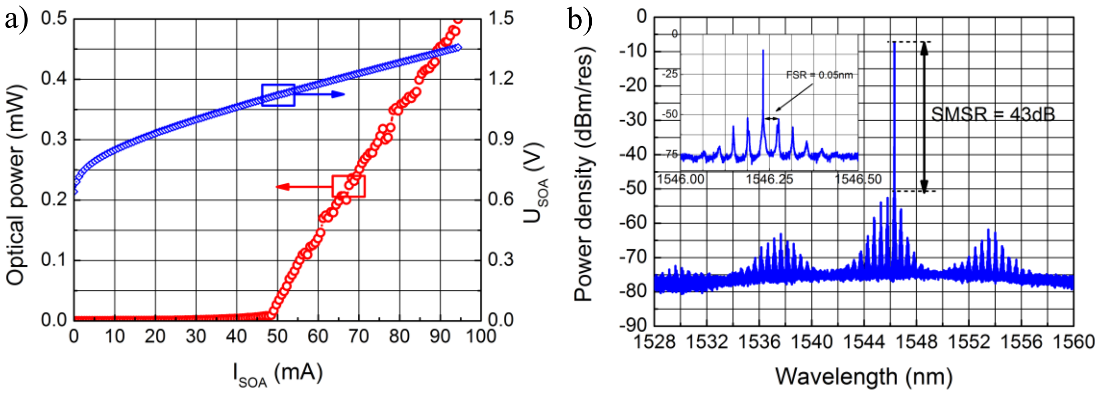

Fig. 4. Characteristics of the device fabricated in COBRA MPW run: optical power and SOA voltage versus bias current characteristics of tested device indicate threshold current I_{th}=48mA and a slope resistance R_{sl}=5.5 Ω; (**a**) a high resolution optical spectrum recorded with SOA section DC biased at $I_{SOA=}$134 mA (~2.5 of I_{th}) and temperature set at 15.5 °C. Inset: Detailed view of the lasing mode with neighboring cavity side modes, FSR=0.05 nm (5 GHz). (**b**)

Summary

A tunable ring geometry laser with an intracavity wavelength filters based on AMZI was designed and fabricated on the COBRA photonic integration platform at 1.5µm. The measurement results obtained show a good performance in terms of single mode operation and an optical power of several mW assuming 5 dB coupling efficiency to the fiber, which is also in good agreement with the simulations.

Acknowledgement

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