

Monolithically integrated continuously tunable InP-based quantum-dot laser source in the 1.6 to 1.8 μ m wavelength region

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We present our first experimental results of a monolithically integrated continuously tunable laser source for optical coherence tomography in the 1.6 to 1.8 μ m wavelength region. The InP-based active-passive integrated ring laser system contains three 8mm long InAs/InP(100) quantum-dot amplifiers and two electro-optically tunable filters. Initial results show a tuning range of at least 20nm, 25dB side mode suppression and a linewidth better than 0.05nm. We present details on the calibration and performance of the tuning filters in the laser.

Introduction

Lasers that have the ability to make wavelength scans over wide ranges, e.g. 100nm or more, are useful tools for spectroscopy, gas detection and frequency domain optical coherence tomography (FD-OCT). Such laser systems are typically bulk solid-state laser systems or semiconductor lasers with external micro-electro-mechanical systems (MEMS) filter. These systems are however limited in scan speed or scanning flexibility due to the mechanical movement of the tuning mechanism. We have developed a fully monolithic integrated semiconductor laser system that can make continuous sweeps of 100nm up to 200nm in the 1.6 to 1.8 μ m wavelength range and with a linewidth better than 0.07nm. With this tunable laser it will be possible to scan the complete wavelength range at a 50kHz repetition rate. In this paper we present the design of the tunable laser, followed by a description of the calibration process of the intra cavity tunable filters and the results. Finally we will present some initial laser tuning results.

Laser Design

The InP based laser we have designed and fabricated basically consists of two quantum dot (QD) semiconductor optical amplifiers and two electro-optically (EO) tunable filters used in a ring laser topology.

In this laser the QD-amplifiers are chosen to generate and amplify light in the desired 1.6 to 1.8 μ m wavelength region. The desired central wavelength of the gain spectrum of these QD-amplifiers can be adjusted during the growth process by controlling the size of the QDs[1]. Furthermore due to the inhomogeneous broadening the bandwidth of the gain spectrum will be more than 100nm which is necessary to tune the laser over at least 100nm. Strained InGaAs quantum well SOAs can nowadays also be tuned towards 1700nm however the gain bandwidth of these amplifiers is limited to approximately 50nm. An extensive study on the gain from the QD amplifiers is given in [2].

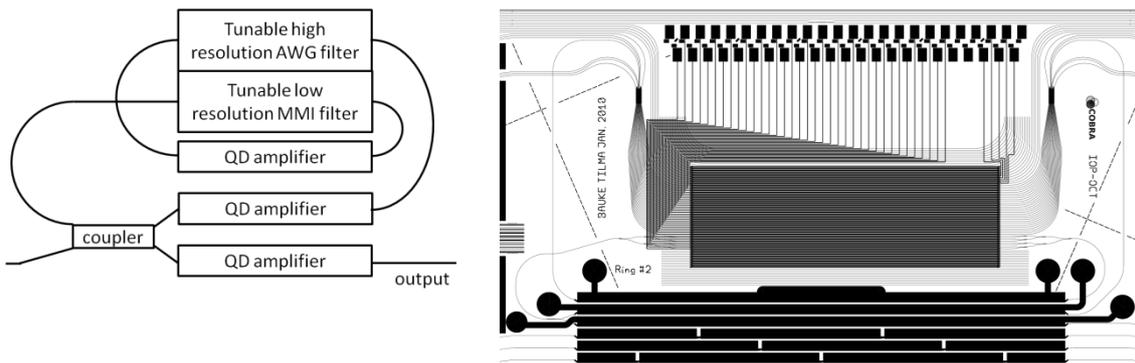


Fig. 1. schematic design tunable laser and mask design

The two intra cavity EO tunable filters are used to tune the lasing wavelength of the ring laser. The first filter, the high resolution (HR) filter is an arrayed waveguide grating (AWG) based filter with a 0.5 nm full-width-half-maximum (FWHM) and a 10nm free spectral range (FSR) (at 1700nm). The second filter, the low resolution (LR) filter, is an MMI-tree based filter with a 25 nm FWHM and a 210 nm FSR. The HR-filter is used as a sharp wavelength filter to allow a maximum of 3 ring laser cavity modes with a 0.02 nm mode spacing and to suppress other neighbor ring cavity modes. The LR-filter is used to select one pass-band of the HR-filter. Both filters are tunable with the EO phase modulators (PHM) in the arms of the filters. More information on the specific design issues of both filters are given in [3].

In Fig. 1 a schematic design of the ring laser is given as well as the mask design. In the center the AWG based HR-filter is located containing 28 arms. Directly beneath this filter the LR-filter is located containing 8 arms. In both filters 5mm long PHMs are included in the arms to make the filter tunable. In the lower part the two 8 mm long QD ring amplifiers are located as well as the 8mm long QD output amplifier. Beneath these amplifiers the design also contains three multi-section amplifiers to determine the gain in the QD-amplifiers [2]. Furthermore, the HR-filter contains a number of extra output channels which can be used to calibrate the filter and to monitor the power in the ring cavity. The total length of the ring laser cavity is 43.5 mm.

The laser has been fabricated according to the standard active-passive integration technology used at COBRA [3].

Filter calibration and characterization

Before the laser can be used as tunable laser both filters and their EO-PHMs have to be calibrated. The individual phase shift characteristics of the PHM have been determined by applying a voltage scan over a single PHM in the filter and measuring the optical transmission of the filter in a small wavelength region within the centre of a transmission peak. The transmitted optical power will vary when the voltage is scanned due to field induced electro-optical effects and free carrier depletion based electro-optical effects which change the refractive index in the PHM[4]. The output power can be described according to:

$$P = A + C \cdot \cos(a \cdot V^2 + b \cdot V + c) \quad (1)$$

In this function P is the measured optical power, V the applied voltage on one PHM, A is the mean output power, C the amount of power carried by the single PHM, a the quadratic phase change, b the linear phase change and c the offset in the phase change. The coefficients a , b and c describe the phase shift characteristics.

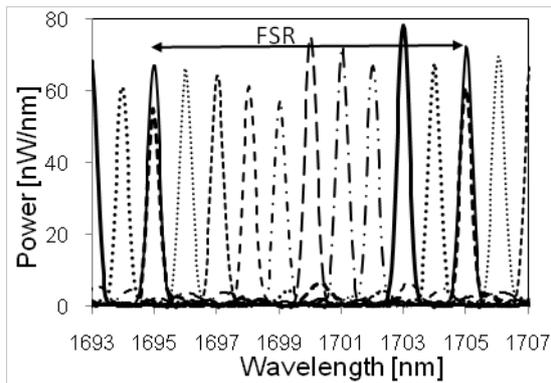


Fig. 2a. Measured power spectrum for 11 different tuning wavelengths of the HR-filter from 1695nm to 1705nm in 1nm steps.

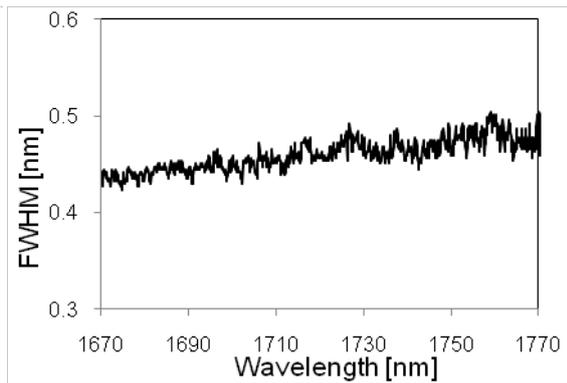


Fig. 2b. Measured FWHM of the HR-filter tuned between 1670nm and 1770nm in 0.1nm steps.

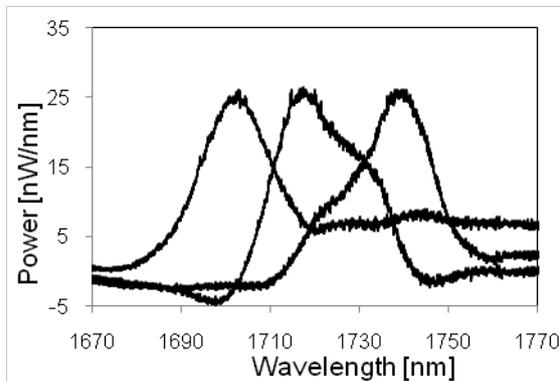


Fig. 2c. Measured power spectrum from the LR filter subtracted by the ASE spectrum of the output amplifier for the tuning wavelengths 1700nm, 1720nm and 1749nm.

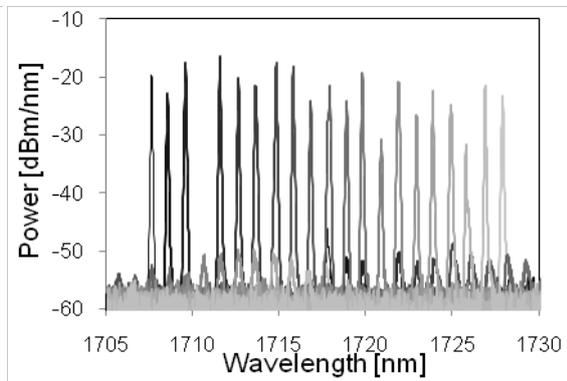


Fig. 2d. Initial laser tuning spectra showing twenty separate lasing spectra tuning between 1707nm and 1782nm.

These coefficients were determined for each PHM in both filters by measuring the output power as a function of the applied voltage to the PHM and a fit of (1) to the recorded data. For the HR-filter the central QD amplifier in the ring (biased at 1A) is used as a broadband light source and the optical output power is measured from one of the test output channels of the HR-filter on the left side of the chip. For the LR-filter the top QD-amplifier (biased at 1A) is used as a broadband light source and the optical output power is measured through the QD output amplifier (biased at 400mA).

Within the HR-filter we were able to calibrate 26 of the 28 PHMs and in the LR filter all 8 PHMs. In most PHMs the linear phase shift term b was dominant and had a phase shift efficiency of approximate 1.53V/rad at 1670nm to 1.35V/rad at 1770nm.

When the a , b and c coefficients are known for all the different PHMs in both filters the filters could be tuned in a predictable way as demonstrated below. In Fig. 2a the measured power spectrum is given for 11 different tuning wavelengths within one FSR from 1695nm to 1705nm in 1nm steps. A series of measurements have been performed in which the HR filter is tuned between 1670nm and 1770nm in 0.1nm steps. The central wavelength of the HR-filter was in all measurements within ± 0.1 nm from the target wavelength. The measured FWHM of the HR-filter is given in Fig. 2b and was in all cases less than the designed 0.5nm.

The LR-filter is less straight-forward to measure. Due to the indirect measurement of the filter characteristics through the output amplifier, the determined filter shape is

influenced by the ASE from the QD ring amplifier, the wavelength dependent gain in the output amplifier and the ASE from the output amplifier. To have an indication if the filter works as designed we measured the output spectrum at different filter wavelengths between 1693nm and 1745nm in 1nm steps and subtracted the ASE spectrum from the QD output amplifier (not completely independent from the injected light through the LR-filter). These measurements show a tuning accuracy of the LR-filter within ± 10 nm from the target wavelength and a FWHM < 26 nm. In Fig. 2c three determined spectra are given for filter tuning settings at 1700nm, 1720nm and 1740nm.

Laser results

When both filters are calibrated the ring laser can be used and tuned in a predictable way. The initial measurements were performed with two times 1200mA injected in both intra cavity QD ring amplifiers. The lasing performance is measured at one of the test outputs of the HR-filter. In Fig 2d the first lasing spectra obtained are presented for 20 lasing wavelengths between 1707nm and 1728nm. The line width of the laser output observed in the spectra was 0.049nm which is equal to the resolution of the optical spectrum analyzer. The spectral suppression in the rest of the spectrum was 25-35dB. Further exploration of the laser to increase the tuning bandwidth, the power stability and absolute power level is in progress.

Conclusion

We presented the design of a monolithically integrated continuously tunable QD laser in the 1.6 to 1.8 μ m wavelength region. The laser basically consists of two QD amplifiers and two EO-tunable filters embedded in a ring laser topology. Measurements on the HR-filter show a bandwidth less than 0.5nm and a tuning accuracy better than ± 0.1 nm. Measurements on the LR-filter show a bandwidth less than 26nm and a tuning accuracy better than ± 10 nm. These LR-filter measurements results are however influenced by the indirect measurement method. The initial laser tuning results are given over 20nm. These measurements show a linewidth of 0.049nm and a 25-35dB suppression in the rest of the spectrum.

Acknowledgment

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