# Characterization of integrated electro-optically tunable cascaded filters for tunable laser purposes

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*In this contribution we present our results on the tunable arrayed waveguide gratings designed and fabricated to be used in a tunable ring laser structure in the 1600 to 1800nm range. To be able to tune the two cascaded filters over 100 to 200nm the wavelength dependent phase shifting in the phase shifters have been measured. With the knowledge of the wavelength dependency in the phase shifters we are able to tune the AWG over the full wavelength range.*

## 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 and 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 are currently developing a fully monolithically integrated semiconductor laser system that can make continuous sweeps of 100nm up to 200nm in the 1600nm to 1800nm wavelength range and a linewidth better than 0.07nm. With this tunable laser it should be possible to scan the complete wavelength range with a 50kHz repetition rate. To realize such a laser a continuously scanning intra-cavity tunable filter is necessary to select the desired wavelength in a laser cavity. A possible solution is a filter based on a tunable arrayed waveguide grating (AWG)[1]. Advantages of these filters are: the continuous scan capability over its free spectral range; the absence of heating in the filter (only tens of μA current flow through the modulators which are reversely biased P-I-N junctions).
In this paper we present the fabrication and characterization results we have on the AWG based tunable filters we have realized on InGaAsP/InP.

## Design and Fabrication

The specifications of the tunable filter are imposed by the specifications of the laser [2]. To summarize, the complete filter in the laser cavity should have a pass band with a full width half maximum (FWHM) of 0.5nm and tunable over 200nm. The design we have made [2] is a combination of two filters. The first filter is a high resolution tunable AWG having 28 arms and a free spectral range (FSR) of 10nm (at 1700nm) which fulfils the requirement on the width of the bandpass filter. The second filter is a low resolution filter designed to suppress the unwanted higher order peaks of the first filter. For this low resolution filter two versions have been realized. The first design is a tunable AWG having 11 arms and a FSR of 210nm which is laid out in an S-shape to implement the small path length differences necessary for such a large FSR. In the second design the AWG is replaced by a tree-level multimode interference (MMI) tree. A schematic picture of the three designs is given in Fig. 1.

The designs of the filters are specifically modified from standard designs to obtain an equal distance between all the PHMs which form the longest sections in the arms of the filters. This is done to minimize the phase error in the arms induced by loading-effects in the etching. For this reason extra test waveguides with the same spacing are added around the outer arms of the filters.

The device is fabricated in our generic integration technology which uses a $CH_4$-$H_2$ two-step reactive-ion dry etch process to create shallow etched waveguides and an electrical isolation between the PHMs. The structures are planarized using polyimide. Evaporated Ti-Pt-Au metal pads contact the PHMs to apply a voltage on the PHMs. The backside of the n- InP substrate is metalized to create a common ground contact.

## Characterization

The tunable filters presented in this paper are designed to be used for transverse electric (TE) polarized light in the 1600-1800nm wavelength region. The results in this paper are obtained with TE light in the 1450-1640nm wavelength region on the high resolution AWG filter. Later on these results will be extended to the other filters and
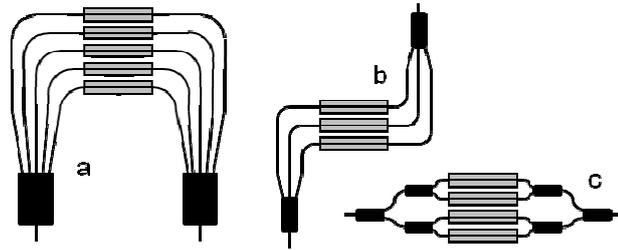


Fig. 1 Schematic picture of the three filter designs, the gray areas are the PHM. (a) High resolution AWG filter. (b) Low resolution AWG filter in S-shape (c) 2-Level MMI tree filter.

the longer wavelength region. The optimization for TE polarization is because only the TE light is amplified in the quantum dot optical amplifier we intend to use in the laser.

*Phase shift characteristics*

Before the tunable filter can be tuned in a controllable way, the characteristics of the PHM must be determined. The working of the PHMs are based on field induces electro-optical effects and free carrier depletion based electro-optical effects which change the reflective index in the PHM [3]. Applying a reverse biased voltage over the PHM changes the refractive index, and therefore also the optical path length of the PHM. The exact phase shift characteristics of each PHM have been determined by tuning the PHM in the filter over a voltage range and measuring the optical response of the filter in a small wavelength region (factor 10 smaller then the bandwidth of the filter). The transmitted optical power will vary when the voltage is scanned due to the change in optical path length which brings the output light of the arm in phase or anti-phase with the other arms. The output power can be described according to:

$$P = A + C \cdot e^{(-D \cdot V)} \cdot \cos\left(a \cdot V^2 + b \cdot V + c\right) \tag{1}$$

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, $D$ the attenuation coefficient of the light in the 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 characteristics of the PHM and must be determined to control the PHM. These coefficients where determined for each PHM by measuring the output power as a function of the applied voltage to the PHM and fit (1) to the recorded data.

Within the high resolution AWG filter 15 PHMs out of 28 PHMs could be characterized properly. Others could not be operated due to issues with the electrical connections to the chip or low signal strength due to fabrication defects.

In the ideal case, the offset in the phase change, $c$, is 0rad for all PHMs at the central wavelength of the filter. Due to variations in the layer stack and imperfections in the fabrication process this offset can vary. We have tried to minimize the errors due to non-uniform processing by fixing the distance between the PHMs. The values we have found for $c$ all lie between -1.2rad and 0.8rad.

The linear phase change, $b$, should be the same for all PHMs at the same wavelength. This term is however wavelength dependent due to the change in mode size. We have determined the $b$ coefficients for the PHMs for a set of wavelengths between 1450nm and 1640nm. In fig 2 the average $b$ coefficient is given including the statistical error.

The quadratic phase change, $a$, was in all measurements approximately -0.1rad/$V^2$ and independent on the wavelength.
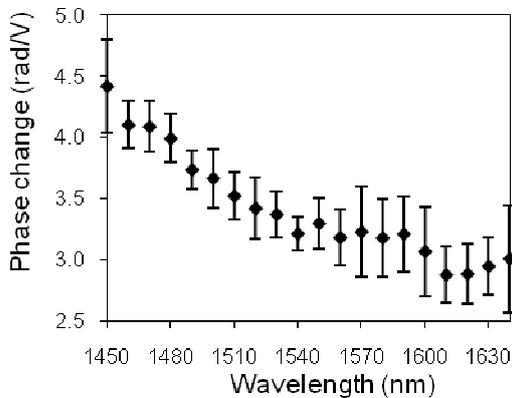
Fig. 2 Wavelength dependent linear phase shift coefficients. The average phase change and statistical error from 15 (5mm) PHMs in the high resolution filter are given.
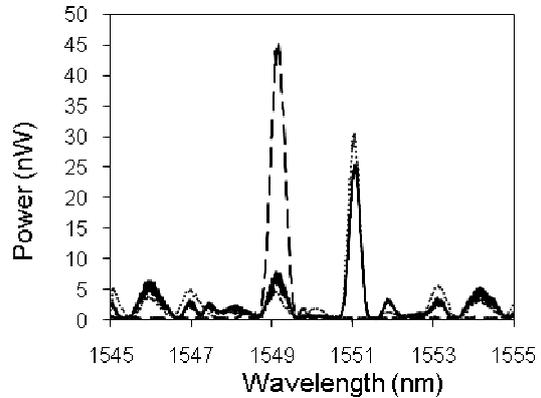
Fig 3. Filter response optimized at 1549.2nm the central wavelength of the filter (dashed), tuned from the central wavelength to 1551nm (solid) and optimized at 1551nm (dotted)

## Tuning the filters

If all PHM coefficients are known a translation must be made from the coefficients to the desired wavelength. First of all, the wavelengths of the static FSR peaks $\lambda_{FSRp}$ should be measured from the transmission spectrum without any voltage applied to the PHMs. This includes the central wavelength on which the filter is designed but also all the higher order peaks. These wavelengths are the reference wavelengths of the filter from which the filter can be tuned. From this series of FSR peaks the wavelength difference $\Delta\lambda_{FSR}$ between 2 peaks can be calculated. This should be done between all FSR peaks to determine the wavelength dependency of $\Delta\lambda_{FSR}(\lambda)$ over the complete wavelength range. With a linear fit over all points a $\Delta\lambda_{FSR}(\lambda)$ can be determined for all wavelengths. For example in the high resolution filter this $\Delta\lambda_{FSR}(\lambda)$ changes linearly over the wavelength range from 8.72nm at 1600nm to 11.34nm at 1800nm.

Now, if we want to tune the filter to a certain wavelength $\lambda_F$ we have to detune the filter from its nearest FSR peak $\lambda_{FSRp}$ to $\lambda_F$. From the difference between these two wavelengths, $\Delta\lambda_{tun} = \lambda_F - \lambda_{FSRp}$, the increase in optical path length difference between two arms in the AWG $\Delta\varphi_+$ can be calculated according to:

$$\Delta\varphi_+ = \frac{\Delta\lambda_{tun}}{\Delta\lambda_{FSR}(\lambda_F)} \cdot 2\pi \tag{2}$$

To apply this increase in optical path length difference in the tunable filter, the increase in phase $\Delta\varphi_i$ in each arm can be calculated by:

$$\Delta\varphi_i = \left(i \cdot \Delta\varphi_+\right)\mathrm{mod}\left(2\pi\right) \tag{3}$$

with $i$ being the filter arm number (start counting at the shortest arm with 0). The voltage needed to apply the phase shift in a single PHM can be calculated by solving:

$$\Delta\varphi_i = \cos\left(a_i V_i^2 + b_i V_i + c_i\right) \tag{4}$$

in which $a_i$, $b_i$ and $c_i$ are the three calibrated coefficients and $V_i$ the voltage necessary to change the optical path length of PHM $i$ with $\Delta\varphi_i$ radians.

This procedure should be done for both filters to tune the cascaded filters to the desired wavelength.

### Tuning results

With the calibrated coefficient and the procedure described above we were able to tune the high resolution AWG in a predictable way. In Fig. 3 the dashed line represents the filter response when all the phases are set to 0rad according to the coefficients determined at 1549.2nm (central wavelength of the filter). From this starting point the voltages on the PHMs are calculated and set to tune the peak wavelength to 1551nm. The solid line in Fig. 3 gives the resulting filter response. To prove that the tuning was optimal, the filter was optimized at 1551nm by determining the coefficients at this wavelength and set all the phases to 0rad. The dotted line in Fig. 3 gives the resulting filter response. From Fig. 3 it can be seen that the tuning from 1549.2nm to 1551nm on the basis of the predicted values was already close to the optimized filter setting for 1551nm. The difference in peak height between the response at 1549.2nm and 1551nm is due to the fact that 15 PHMs out of 28 PHMs were properly controlled. The other PHMs do not contribute to the shift to 1551nm but form a minor filter peak at 1549.2nm. The measured FWHM and FSR of this filter are respectively 0.41nm and 8.1nm which equals the design values at this wavelength.

## Conclusion

We presented the fabrication and characterization of tunable AWGs to be used in an integrated continuously tunable laser. The phase shift coefficient of the PHM where determined from measurements. With these coefficients we were able to calculate the necessary voltages and tune the filter to the desired wavelength in a predictable way.

### Acknowledgement

## References

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