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Integrated Tunable Optical Filters on InP for Continuously Tunable Lasers

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***Abstract*-We have realized a set of electro-optically controlled tunable arrayed waveguide gratings and present wavelength dependent calibration results for its tuning. These filters are designed to be used in a monolithically integrated tunable laser.**

I. INTRODUCTION

Lasers that have the ability to make wavelength scans over 100nm or more are useful tools for frequency domain optical coherence tomography (FD-OCT). We are currently developing monolithically integrated InP/InGaAsP quantum dot semiconductor laser systems that can make continuous sweeps of 100nm up to 200nm in the 1600 to 1800nm wavelength range, at repetition rates of up to 50kHz and with a linewidth better than 0.07nm. Such properties are desirable for FD-OCT and surpass the capabilities of available tunable semiconductor lasers [1]. To realize such a laser a continuously scanning intra-cavity tunable filter based on electro-optically tunable arrayed waveguide gratings (AWGs) [2][3] has been realized. The most relevant advantages of using such filters are: a 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 results on realizations of tunable AWG designs that have been optimized for minimal phase errors.

II. DESIGN AND FABRICATION

The specifications of the tunable filter are imposed by the specifications of the laser [4]. 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 [4] is a combination of two tunable 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 tunable AWG with a FSR of 210nm (at 1700nm) and a FWHM of 28nm. The two filters in series will fulfill the requirements for the laser. For the low resolution filter two versions have been realized and tested. The first design is a tunable AWG with a FSR of 210nm. It 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 free propagation region has been replaced by a tree-level multi-mode interference (MMI) tree which is practical since only 8 arms are sufficient. For tunability 5mm long electro-optic phase modulators (PHMs) are included in all arms of the waveguide arrays.

The designs of the AWGs 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 AWGs. 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. This constant spacing also increases the reliability of the fabrication of the electrical contacts on top of the PHMs.

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.

III. 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. Later on these results will be extended to the longer wavelength region. The optimization for TE polarization is chosen because of the domination of TE light in the laser.

A. Phase shift characteristics

The exact phase shift characteristics of the PHMs have been determined by tuning a single 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 field induced electro-optical effects and free carrier depletion based electro-optical effects which change the refractive index in the PHM [5]. The output power can be described according to:

$$P = A + C \cdot e^{(-D \cdot V)} \cdot \cos(a \cdot V^2 + b \cdot V + c)\,. \qquad (1)$$

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 phase shift characteristics. These were determined, for each PHM, by measuring the output power as a function of the applied voltage to the PHM and a fit of (1) to the recorded data.

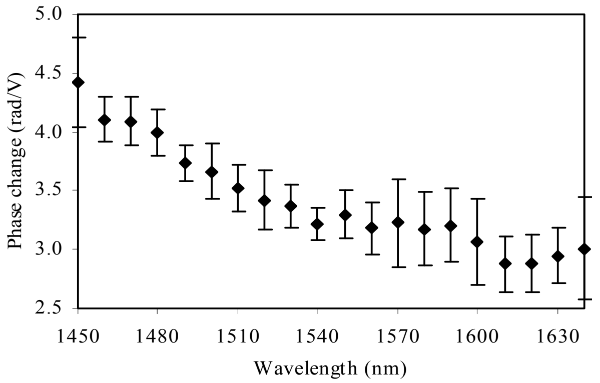

Fig. 1. Wavelength dependent linear phase shift coefficients. The average phase change and statistical error from 15 PHMs in the high resolution filter are given.

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 or low signal strength. The offset in the phase change, *c*, is ideally 0rad for all PHMs at the central wavelength of the filter. The values we have found all lie between -1.20rad and 0.8rad. This indicates that the phase error due to non-uniform processing is small.

The linear phase change, *b*, should be the same for all PHMs at the same wavelength. To be able to predict the behavior of the filter over a wavelength range of several 100nm, the wavelength dependency of the *b* coefficient was studied. The *b* coefficient was determined for al 15 PHMs and for a set of wavelengths between 1450nm and 1640nm. In Fig. 1. the average *b* coefficient is given including the statistical error.

The quadratic phase change, *a*, was in all cases approximately -0.1rad/V^2 and independent of the wavelength.

B. Tuning results

When the *a*, *b* and *c* coefficients are know for all the different PHMs the filter could be tuned in an a predictable way as demonstrated below. In Fig. 2 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. 2 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. 2 gives the resulting filter response. From Fig. 2 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.

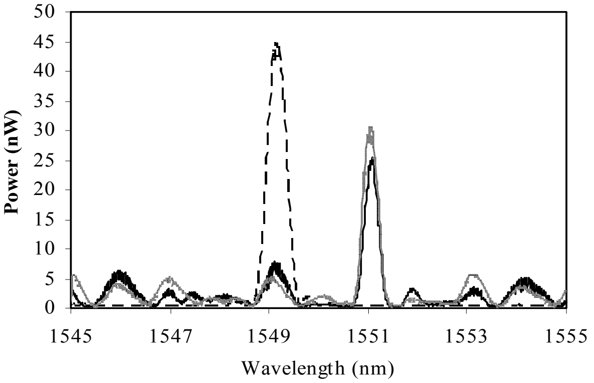

Fig. 2. Filter response optimized at 1549.2nm the central wavelength of the filter (dashed), tuned from the central wavelength to 1551nm (solid) and optimized at 1551nm (dotted).

Measurements on the PHMs in the two other low resolution filters show the same phase shifting efficiency as the high resolution filter. The spectral performance of both filters is sufficient. The insertion loss of the MMI based filter is approximately 6.5dB lower due to its more compact design. This is therefore the preferred design.

IV. CONCLUSION

We presented the realization of tunable AWGs to be used in an integrated continuously tunable laser. The phase errors in the arms of the AWG are minimized by fixing the distance between the phase modulators. Measurements on the realized tunable AWGs prove this small phase error. The phase shift efficiency was strongly wavelength dependent over the 1450-1640nm range. Tuning the AWG in a predictable way was demonstrated.

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