

# FIRST INTEGRATED CONTINUOUSLY TUNABLE AWG-BASED LASER USING ELECTRO-OPTICAL PHASE SHIFTERS

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## SUMMARY

In this paper, we present a novel continuously tunable arrayed-waveguide grating (AWG) based laser. Electro-optical phase shifters in the array arms allow for wavelength tuning over the complete AWG free spectral range. Preliminary measurements with a single electrode show tuning over a range of 6 nm.

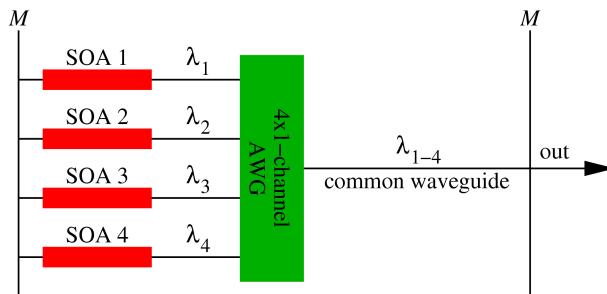
## KEYWORDS

optoelectronic devices, integrated optoelectronics, semiconductor lasers, electro-optical phase shifters

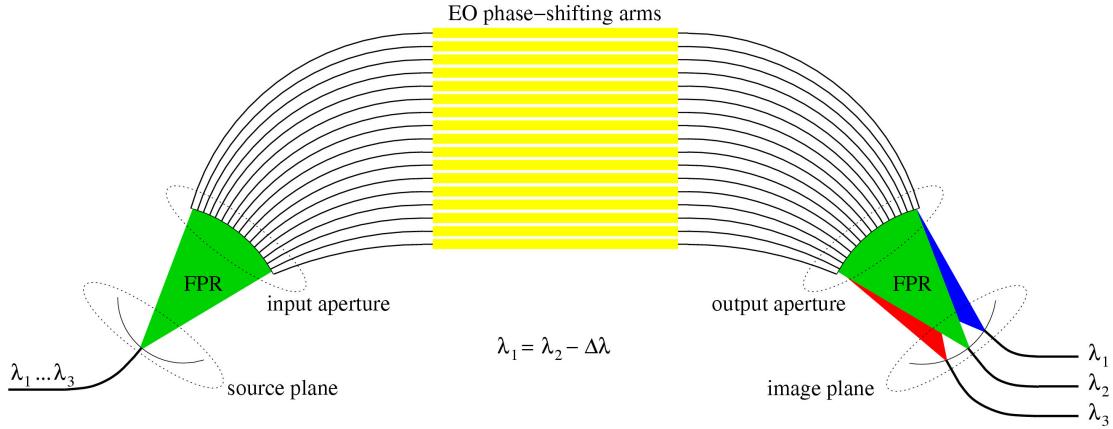
## INTRODUCTION

An AWG-based laser (AWGL) can be used as a multiwavelength laser [1], which can generate multiple wavelengths simultaneously, or as a discretely tunable laser source [2]. It uses an array of SOAs connected to the demultiplexed ports of an intra-cavity AWG, while a passive common output waveguide is connected to the multiplexed port, as shown in Figure 1. Cleaved facets act as mirrors  $M$  to form a Fabry-Pérot cavity. Since each amplifier in an AWGL is connected to a different AWG port inlet, biasing different amplifiers generates different wavelengths, spaced by the predefined AWG channel spacing. Its digital control is an advantage over accurate analog control needed in tunable distributed feedback or distributed Bragg reflector lasers, which are based on precise phase tuning by current injection or temperature tuning. A disadvantage of this digital control is that wavelengths in between the AWG wavelength grid can only be reached by slow (ms-speed) temperature tuning at a tuning rate of about  $\sim 0.12 \text{ nm}^{\circ}\text{C}$  [3]. Furthermore, temperature tuning can shift the laser wavelength only over a few nm. To reduce the switching time down to the cavity build-up time (ns-range) and to increase the tuning range to the complete AWG free spectral range, we propose and demonstrate the integration of an electro-optically (EO) tunable AWGL. In principle, a single SOA is sufficient to address the whole tuning range. However to ensure that the central wavelength of the AWG is close to the center of the SOA gain curve, a series of SOAs has been included, each using a different wavelength channel of the AWG.

The first EO tunable AWGs were demonstrated in [4] and [5]. An input waveguide carries a number of wavelengths spaced by the AWG channel spacing  $\Delta\lambda$  into the first free propagation region (FPR) (Figure 2). In this FPR, the light from the input waveguide is no longer laterally confined and diverges. Light collected at the input aperture of the array propagates through the arms to the output aperture. In the second FPR, the light constructively interferes in one focal point in the image plane. For the central wavelength  $\lambda_c$ , the length difference between the arms equals an integer number times  $2\pi$ . Consequently, this wavelength is projected in the middle of the image plane. For other wavelengths, the phase front in the second FPR is tilted which results in a



**Figure 1. Schematic of an AWGL. The Fabry-Pérot laser cavity consists of a SOA-array, an AWG and a common output waveguide.**



**Figure 2. Schematic of an electro-optical tunable AWG.**

different position of the focal point in the image plane. By placing different output ports at the appropriate positions, each output collects a different wavelength. Continuous tuning is now provided by electro-optical phase shifters in the array arms. By biasing the phase shifters such that a linear phase change is induced across the array aperture, the equi-phase plane in the output FPR can be tilted. Note that for large tuning, the actual phase shift is the required phase shift modulo  $2\pi$ . The maximum tuning range is limited by the AWG free spectral range (FSR), which is the wavelength spacing between two adjacent diffraction orders.

#### DESIGN AND FABRICATION

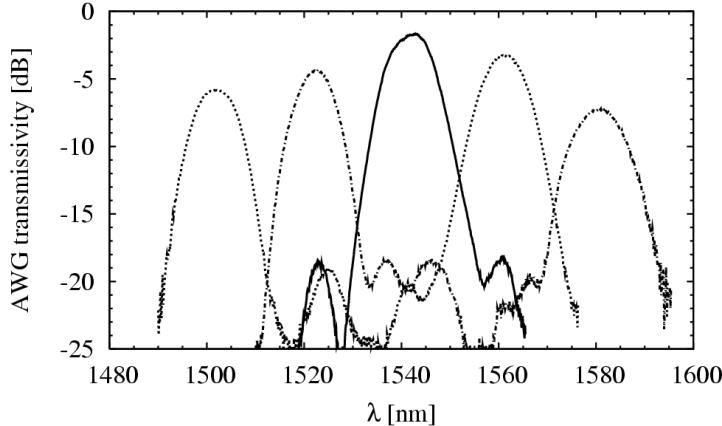
The AWG was designed with a 60 nm FSR, which allows for a large tuning range. We implemented a channel spacing of 20nm in order to keep the size of the AWG small. Four input waveguides were connected to a SOA; SOA 1 and 4 will, therefore, generate the same wavelength. The AWG only has 13 array waveguides. This number is sufficient for keeping the cross talk level less than -10 dB and consequently for preventing lasing at the AWG side lobes.

Ridge-type waveguides were used for the AWGL. All epitaxial layers were grown by low-pressure metal-organic vapour phase epitaxy at 625 °C. The SOA active layer consists of a 120-nm-thick Q1.55 layer between two 190-nm-thick Q1.25 layers. The structure was covered by a 200-nm-thick p-InP layer. Next, the active layer stack was butt joint to a Q1.25 layer for the passive sections as described in [6]. In the third epitaxy step, a 1300-nm thick p-InP cladding layer (for the phase shifters) and the p-InGaAs contacting layer were grown. All waveguides were etched 100 nm into the Q1.25 guiding layer. The passive waveguides and phase shifters are 3  $\mu\text{m}$  wide, while the amplifiers are 2  $\mu\text{m}$  wide. The phase shifting sections in the array have a length of 5 mm permitting a phase change of  $2\pi$  without significant attenuation losses. For the maximum phase shift of  $2\pi$  a reverse bias of  $\sim 5$  V is needed.

A 70-nm-thick PECVD-SiN<sub>x</sub> layer served as an etching mask for the waveguides. The pattern was defined using contact photolithography with positive photo resist and transferred to the SiN<sub>x</sub> layer by CHF<sub>3</sub> reactive ion etching (RIE). Waveguides were etched in two steps employing an optimised CH<sub>4</sub>-H<sub>2</sub> RIE etching process. The isolation between the phase shifters was realised by etching the p-InP cladding using a selective wet-chemical etchant, until an etch-stop layer was reached. The amplifiers and phase shifters were passivated with a 350-nm-thick PECVD-SiN<sub>x</sub> layer before the metalization step. A further description of the fabrication can be found in [7].



**Figure 3. Photograph of the realized device (size: 1.7x8.2 mm<sup>2</sup>).**



**Figure 4. Measured AWG pass bands for three channels. Note that the measured channel spacing and FSR are the designed 20 nm and 60 nm, respectively.**

#### MEASUREMENT RESULTS

We started the device characterization by determining the laser *CW* threshold currents. The lowest value was measured to be 78 mA at 15 °C. At a bias acurrent of 100 mA, the output power for laser channel 2 at the common output port was 0.18 mW, including 5 dB coupling loss to a lensed fiber. These values are typical for AWGLs [8] without booster amplifier. Afterwards, we investigated the AWG passbands. These were measured by biasing the SOAs under threshold (one at a time). The power levels (in dBm) measured at the common output and the SOA output were subtracted, while accounting for the difference in waveguide length. The results are depicted in Figure 4. For all passbands, the cross talk level of the the AWG is below 15 dB, which is more than sufficient for this application. Channel 2 shows the lowest insertion loss (2 dB). These curves were measured without biasing the phase shifters in the array arms. The phase shifters can not only be used for wavelength tuning, but also for pass band shaping [4].

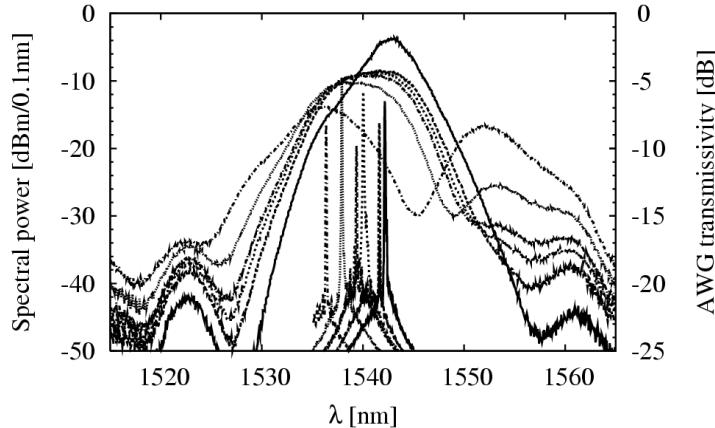
Since AWG channel 2 showed the lowest insertion loss, we used this channel for characterizing the tuning performance. We started with inspecting the response on a single electrode. We biased one of the phase shifters near the center of the AWG since these waveguides contain the highest optical intensity. Bias voltages were varied from -1.14 V to +0.42 V. As can be observed in Figure 5, the shape of the AWG passbands, measured in the same manner as described above, is changed significantly. This causes a shift in the maximum of the passband, which can be used to tune the laser wavelength: the laser frequency is shifting to the wavelength where the net gain (gain minus losses) is highest. The zoom-in on the right-hand side of the figure shows a shift of 6 nm, which we consider very promising for a net tuning voltage of 1.5V applied at a single electrode.

From Figure 6 it is visible that most laser peaks are multimode. This is caused by two reasons. Firstly, the laser cavity is large (>1cm). This results in a very small longitudinal mode spacing (<0.03 nm). Secondly, the AWG passbands are very wide (FWHM >5 nm) and therefore they contain a large number of longitudinal modes. Figure 3 shows that a shorter cavity length can be obtained by positioning the AWG closer to the SOA array, although the cavity length remains determined by the phase-shifter length. The AWGL showed preference for lasing at predefined wavelengths, spaced approximately 1 nm apart. This is probably caused by one or more internal reflections in the laser cavity.

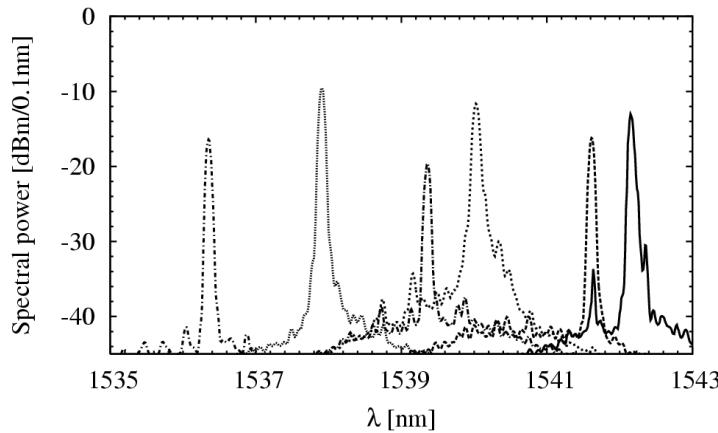
After this measurement with a single electrode, we planned to investigate the response while using multiple electrodes to address all phase shifters in the AWG. Unfortunately, the chip was broken before. We are planning to fabricate a new sample.

#### CONCLUSIONS

We have experimentally demonstrated the first integrated continuously tunable laser that uses an electro-optically tunable AWG. A wavelength shift of 6 nm has been demonstrated by biasing a single electrode with 1.5 V. By using a multi-probe to tune all phase shifters in the AWG simultaneously, we expect to tune the laser peaks over a much large range within the 60 nm FSR.



**Figure 5. Measured AWG passbands (unit at right y-axis) and laser peaks (unit at left y-axis).**



**Figure 6. Observed laser spectra. Biasing one array arm from -1.14V, -0.42V, 0V, 0.1V, 0.42V to 1.14V gradually shifts the laser peak to longer wavelengths.**

#### ACKNOWLEDGEMENS

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