Invited Paper

New widely tunable edge-emitting laser diodes at 1.55 μm developed in the European IST-project NEWTON

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ABSTRACT

Widely tunable lasers are generally considered as the transmitters of future WDM optical communications. Electronically tunable edge-emitting laser diodes are of particular interest as they can switch the wavelength in tens of nanoseconds and thus offer great potential for new networking concepts such as optical packet or burst switching, label switching, bandwidth on demand, ...

In this paper we discuss new concepts for such widely tunable laser diodes which are studied in the framework of the European IST project NEWTON (NEw Widely Tunable laser diodes for Optical Networks).

INTRODUCTION

Only a few types of monolithic, edge-emitting and electronically tunable laser diodes with a wide tuning range of several tens of nm have so far been fabricated and are commercially available (for an overview see ref. [1-2] and the references contained therein,). However, these ‘first’ types all suffer from a number of serious drawbacks such as limited output power, time-consuming characterisation, difficult stabilisation, or fabrication complexity. E.g. most of these existing devices included a reflector section at both sides of the gain section and tuning of this reflector section causes increasing absorption which in turn limits the maximum output power that can be obtained over the wavelength range. One type, the GCSR laser (Grating Coupler Sampled Reflector laser) doesn’t exhibit this problem, but is difficult to fabricate since it is not a planar structure. Finally, all existing device concepts required at least 3 tuning currents, which implies long characterisation times.

Within the European IST-project NEWTON, we have therefore investigated and developed a few new types of monolithic, widely tunable edge-emitting laser diodes which don’t exhibit the aforementioned drawbacks. These include the Modulated Grating Y-branch laser diode or MG-Y laser and the sampled grating or superstructure grating tunable twin-guide laser diode or (S)SG-TTG laser diode. In addition, concepts for a widely tunable filter based on ring resonators and with a potential to be integrated with a gain section to form a tunable laser diode are studied. These three different structures are discussed in the following sections and attention is given to their fabrication, their operation principles, their performance and their control. For the lasers to be developed within the project the following target specifications were set: Tuning range: 32 nm, Ex-facet output power: 10 dBm, Side mode rejection: > 40 dB.

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MODULATED GRATING Y-BRANCH LASER

The Modulated Grating Y-branch laser is a DBR-type laser in which the reflections from two parallel reflectors (with modulated gratings, yielding multi-peak reflection spectra with different peak separation) are combined (via the additive Vernier effect) through a Y-junction. A schematic of the fabricated structure is shown in Figure 1. In this schematic structure, there is a differential phase section to ensure that constructive interference of the reflections from both reflectors can be obtained at the wavelength where the peaks from both reflection spectra overlap. Also, the interference of the reflections from both parallel reflectors is obtained in a multi mode interference coupler. As can be seen from Figure 1, the device can be fabricated using standard DBR laser processing. Moreover, there is no front reflector (in which the absorption increases with the injected tuning current) and hence a low output power variation with tuning and a high maximum output power.

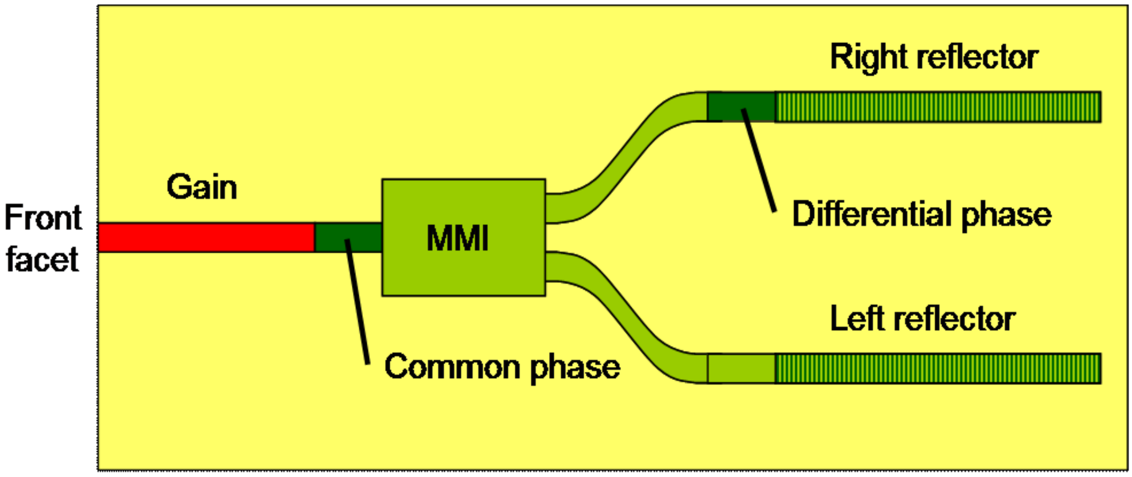


Figure 1: Schematic of the structure of the MG Y-branch laser diode.

From simulations it became clear that the additive Vernier effect may give a better selectivity than the multiplicative Vernier effect that has been used earlier in the (S)SG-DBR laser diodes reported in [3,4]. This is illustrated in Figure 2, which gives the reflection spectra of the two reflectors (denoted left reflector and right reflector in Figure 1 and having a different superperiod) and of their interference (as would be obtained left from the MMI in Figure 1) and of their product (as would be obtained if both reflectors were put each on a different side of a gain section as in a SG-DBR laser). One can clearly see that a better suppression of the 2nd largest peaks is obtained in the case of the additive Vernier effect. However, it should also be clear that, unlike in the case of the multiplicative Vernier effect, the peaks that are even more distant from the main peak still show considerable strength. This may cause problems if the reflection peak overlap occurs far from the gain peak. A mode near the gain peak and with still rather large total reflection may start lasing instead of a mode near the overlapping peaks. In the project, a careful laser design has been successfully used to avoid this problem.

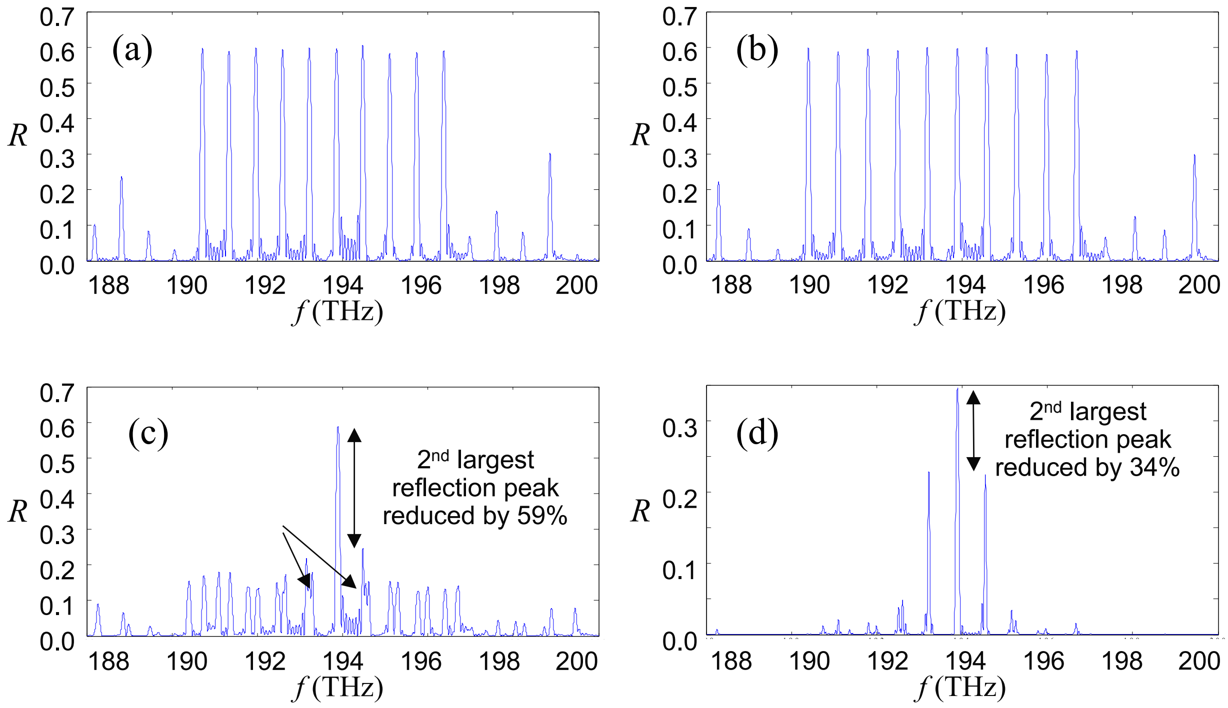


Figure 2: Reflection spectra of reflector 1 (a), reflector 2 (b), their interference (additive Vernier) (c) and their product (multiplicative Vernier) (d).

The first fabricated devices of this laser type have shown continuous tuning over 5 to 6 THz with good side mode suppression (over 40 dB of SMSR) and ex-facet output power levels as high as 29 mW. The high output power levels were obtained after AR-coating the front facet for a reflectivity of 5%. Power variation over the tuning range was limited to 1.5 dB [5]. Figure 3 shows the output power and the side mode rejection that are obtained for all the ITU channels between 192 and 196 THz. From these first devices as well as from simulations it also became clear that the differential phase section is not necessary for the right design of the reflectors. All the characteristics shown in Figure 3 were thus obtained without current into the differential phase section. The tuning currents necessary to obtain the tuning range of Figure 2 were below 15 mA for the reflector currents and below 1 mA for the phase section current.

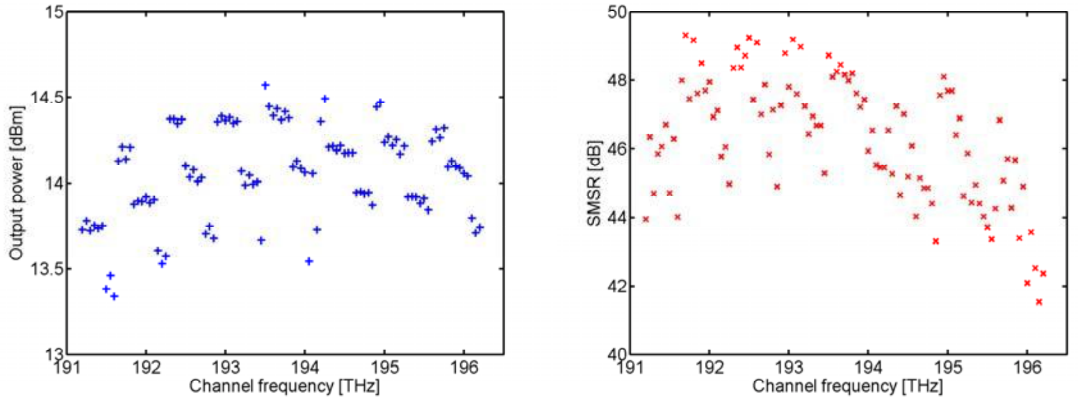


Figure 3: Output power (a) and side mode rejection (b) of the MG Y-branch laser diode for the different ITU frequencies.

SAMPLED GRATING TUNABLE TWIN-GUIDE LASER

The Tunable Twin-Guide laser with Sampled or Superstructure Grating ((S)SG-TTG laser) is based on the original TTG laser concept, but has two sections with sampled or superstructure gratings for Vernier-effect tuning. This laser is in essence still a DFB laser and hence a phase tuning section is not required, which in turn facilitates a fast device characterisation. A schematic structure of the device is shown in Figure 4. Ideally, there is a π phase shift in the middle of the device and the facets are AR-coated. The device acts as a two section, quarter-wave shifted DFB laser, of which the effective refractive index in both sections can be changed by the two tuning currents. This tuning of the effective refractive index occurs through carrier injection in a tuning layer that is vertically separated from the active layer. Moreover, if two reflection peaks from both sections overlap (and this can be obtained with appropriate tuning), one automatically obtains lasing at the wavelength where these reflection peaks overlap [6]. As a result, no phase section is needed and only two tuning currents are required to obtain full wavelength coverage with high side mode rejection. Since the laser essentially acts as a $\lambda/4$-shifted DFB laser, a very large side mode rejection can be obtained and there is a potential for high power operation and even for direct modulation up to high frequencies of 10 GHz and more. Furthermore the device can be rather short.

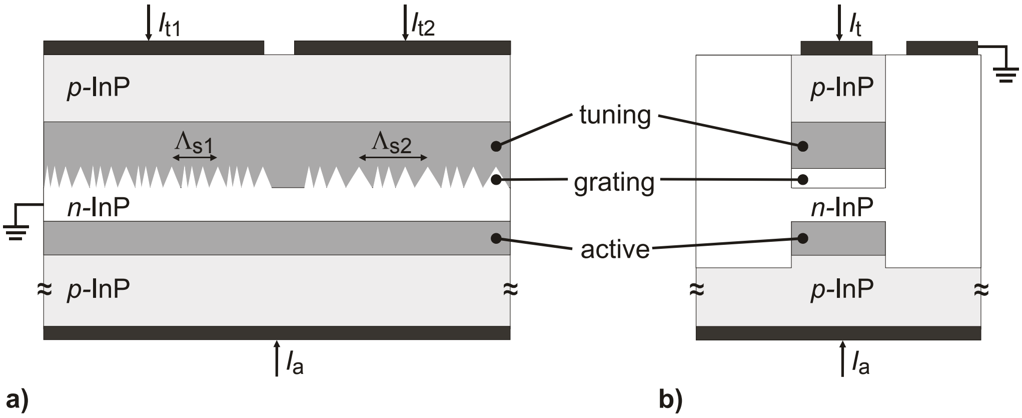


Figure 4: Schematic structure of the SG TTG laser diode: (a) side view and (b) cross section.

The fabrication process of the widely tunable (S)SG-TTG laser diode is compatible with standard processing technology used for buried heterostructure lasers. However, the device structure requires an unconventional lateral current injection scheme. The electron current has to pass through a long *n*-InP channel (see Figure 5), which is sandwiched between *p*-InP layers, before it reaches the active and tuning region. The corresponding interfaces between *n*- and *p*-InP form a forward biased *p*-*n*-homojunction under normal device operation. Moreover, they also coincide with regrowth interfaces and, therefore, any crystal damage or contamination that is incorporated at these interfaces leads to increased recombination and deteriorates the current confinement of the device structure. Hence, a thorough optimization of the fabrication process is required to achieve efficient current injection.

The first fabricated devices showed only a moderate tuning efficiency due to residual parasitic currents. Thus the tuning region can only provide a wavelength shift of the grating reflection spectra by ~ 2 nm. Despite this, the (S)SG-TTG laser is capable of tuning over a wavelength range of 28 nm (from 1534 to 1562 nm) by utilizing the Vernier-effect. Within this tuning range five supermodes can be observed. Each of these five supermodes is continuously tunable over a wavelength range between 0.45 and 1.5 nm (as indicated in Figure 6) without any mode-hops. The SMSR remains between 25 and 37 dB over the whole tuning range. Hence, the expected high side-mode suppression is achieved without the need for an additional phase tuning section, which is required in DBR laser structures to adjust the position of the cavity mode. Furthermore, it is worth noting that the devices are only 600 μm in length and therefore significantly shorter than comparable monolithic widely tunable laser diodes. Ex-facet output powers of up to 12 mW at 100 mA of active region current have been observed from AR-coated devices.

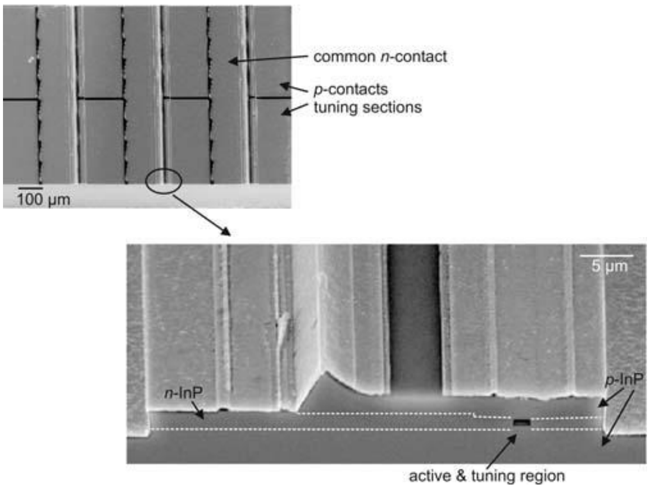


Figure 5: SEM images showing an (S)SG-TTG laser chip. The dashed white lines in the lower image indicate the location of the InP *p*-*n*-homojunctions. The common *n*-contact is situated on the left hand side of the ridge and the electron current is injected via the *n*-InP channel into the active and tuning regions.

The tuning range of 28 nm is presently on partially accessible due to the limited continuous tuning range of the devices. However, one has to take into account, that this first device generation has not yet been optimized for a large continuous tuning range and, therefore, design optimization along with further technological improvements is expected to result in full wavelength coverage of the aforementioned tuning range.

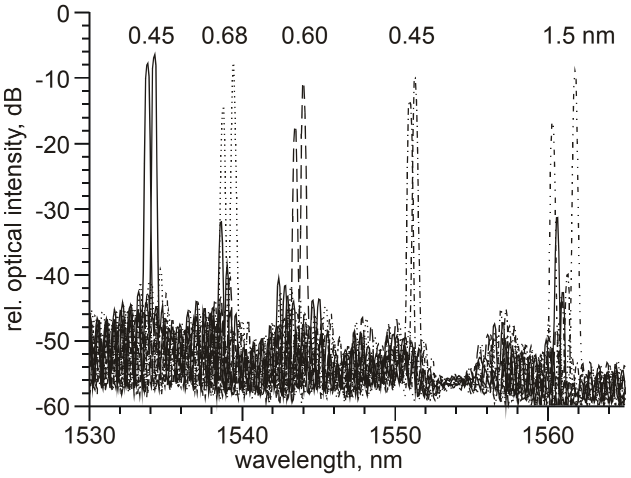


Figure 6: Spectra showing the upper and lower limits of five supermodes of an SG-TTG laser. Continuous tuning can be carried out in between the shown limits. The continuous tuning range of each supermode is indicated in the upper part of the image.

In summary, it follows from simulations as well as from measurements on the first fabricated devices of this laser type that continuous tuning over a wide range of about 30 nm and with high side mode rejection can be achieved with just two tuning currents.

WIDELY TUNABLE FILTERS BASED ON RING RESONATORS

Finally, we are also investigating the feasibility of a widely tunable laser based on a combination of a gain section with a phase section and two ring resonators. Ring resonators can give very narrow transmission peaks and can be used to obtain a large tuning enhancement and hence tuning with small tuning currents, as discussed in [9]. Moreover, all transmission peaks have the same strength and a very large tuning range can result. In the project we are focusing on widely tunable filters only and such devices are currently being fabricated. We also focuss on disk resonators instead of ring resonators because of their inherent low scattering loss.

The fabrication focuses on a vertical integration scheme for the integration of straight waveguides and disk resonators, as shown in Figure 7. Such a vertical scheme avoids the extremely high demands on the accuracy of the lithography of the horizontal scheme. In this vertical approach, the straight waveguides are first etched on one side of the epitaxial layer stack. This sample is then bonded onto a transfer substrate by means of the polymer BCB. The original substrate is removed and the disk is then defined on the back surface. Figure 8 (a) shows a photograph of such a fabricated disk resonator. Fig. 9 shows a SEM picture of a fabricated microring resonator. The disk is on top and is clearly visible, the straight waveguides underneath are also visible. On top of the ring is a Cr resistor contact for thermo-optic tuning. The disk resonators show very good filter characteristics, shown in Figure 8 (b), with Q-factors ranging from 2500 to 10000.

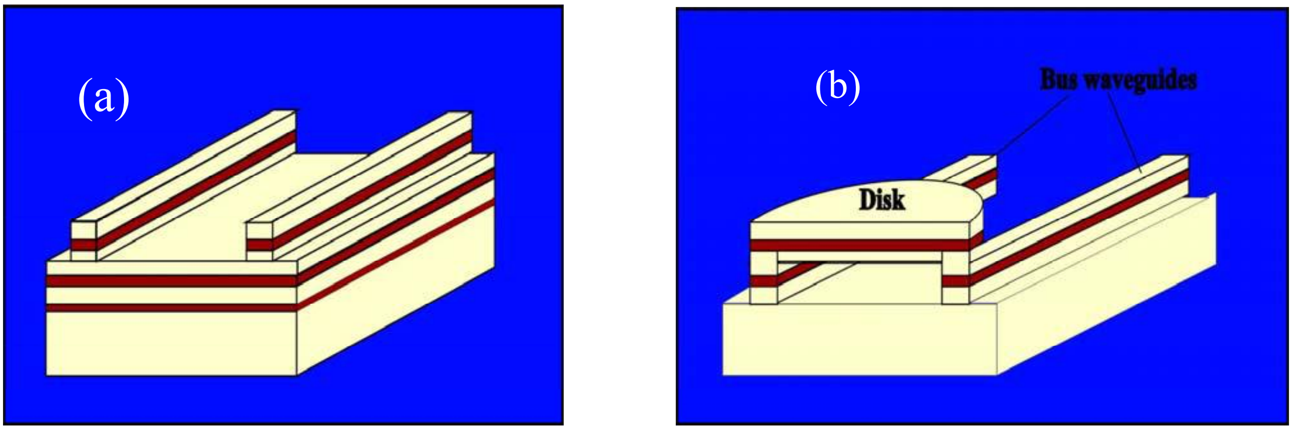
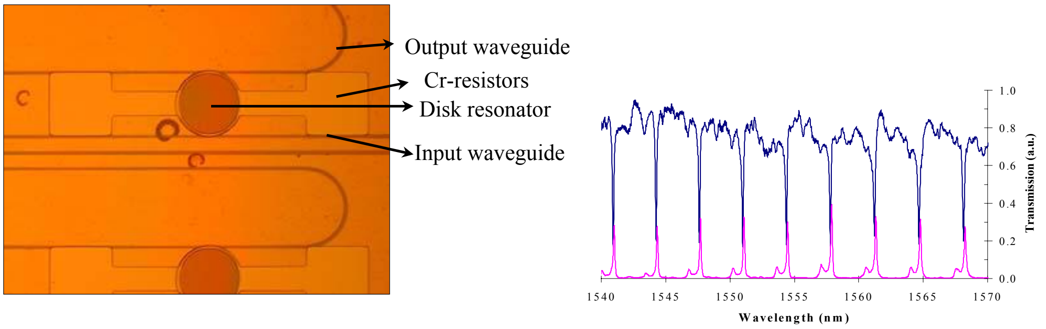


Figure 7: Fabrication scheme of the disk resonator: (a) the fabrication of the straight waveguides and (b) the transfer (upside down) to a new substrate and the etching of the disk.



(a)

(b)

Figure 8: Disk resonator with straight waveguides fabricated using a vertical integration scheme (a) and filter characteristics of the resonator at drop and pass port (b).

Some effect of higher order modes is visible in Figure 8 (b). This can be avoided by carefull design of the bus waveguide and the bend waveguide so as to avoid excitation of this higher order bend mode. To do this the modal fields are calculated by means of a commercial mode solver (Fimmwave by Photondesign) and the overall power coupling coefficient is calculated by integrating the coupled mode equations with a fourth order Runge Kutta method. In the case of coupling from a straight waveguide to a bend the classical coupled mode equations have to be altered as described in [10]

Due to the low thermal conductivity of the polymer thermo-optic tuning of the microringresonators is very efficient. . Using thermal tuning, 50 nm tuning has been obtained with 50 mW of heating power[8].
The tuning is performed by Cr-resistors that are applied on top of the microrings and can be seen in Figures 8 (a) and 9.

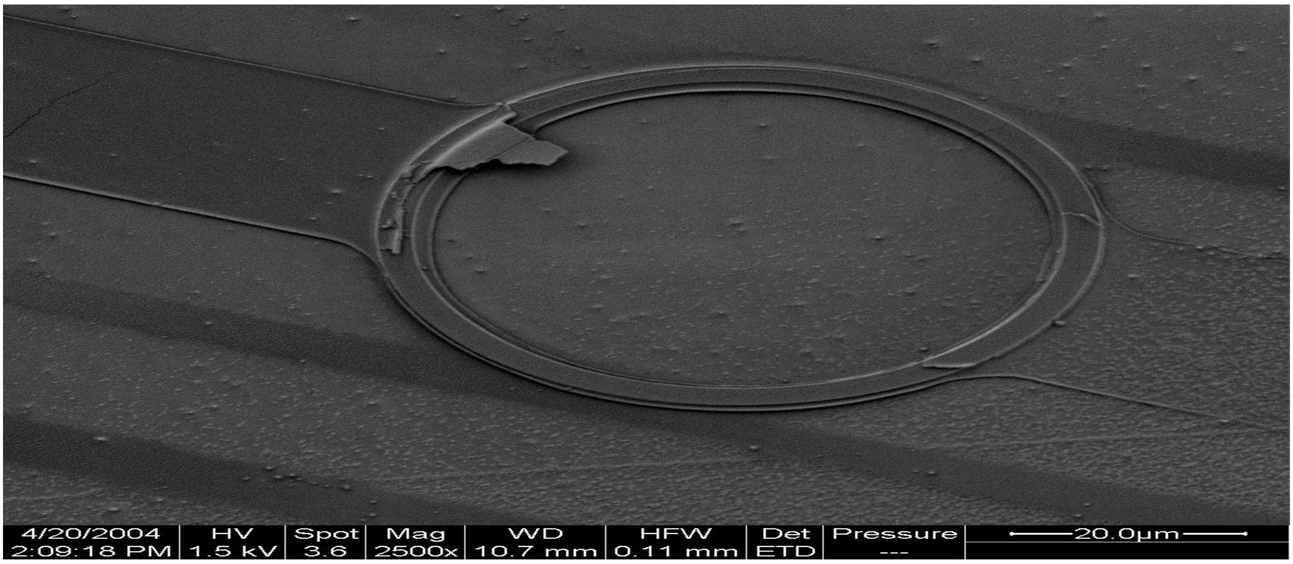


Figure 9: an SEM picture of a vertically integrated microring resonator

CONCLUSION

We have presented the results that have been obtained so far for a number of new widely tunable, edge-emitting laser diodes with electronic tuning. It has been demonstrated that all these new tunable laser diodes have significant advantages over previously existing tunable laser diodes of the same category.

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