# Tunable twin-guide laser diodes for wide wavelength tuning at 1.55 $\mu$m

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## ABSTRACT

Widely tunable lasers are generally considered as key components of future optical communication networks. However, practically all widely tunable lasers that have been fabricated so far suffer from drawbacks, like elaborate calibration procedures that are required for each specific device, low output powers, and limited direct modulation capabilities.
To overcome the aforementioned issues, the sampled or superstructure grating tunable twin-guide or (S)SG-TTG laser diode has been suggested recently. In this paper we will focus on the operation principle, the fabrication, and performance of the first widely tunable twin-guide laser diodes.
The devices operate at ~ 1.55 $\mu$m wavelength. By means of Vernier effect tuning, the continuous tuning range of ~ 2 nm is extended to an overall tuning range of 28 nm. Within this tuning range, five supermodes are useable and can be continuously tuned without any mode hops. The side-mode suppression ratio remains between 25 and 37 dB over the whole tuning range. Without any tuning currents applied, a maximum output power of 12 mW has been achieved.

**Keywords:** semiconductor lasers, tunable lasers, wide wavelength tuning, Vernier-effect tuning, sampled gratings, superstructure gratings

## 1. INTRODUCTION

Widely tunable laser diodes with a tuning range of several tens of nm are being considered as key components for future fiber optical communication networks[1] and are highly attractive light sources for gas sensing applications[2] as well as for fiber Bragg grating (FBG) based sensor devices.[3] The first widely tunable lasers have already been presented more than a decade ago. However, despite the large field of application, only a very limited amount of devices has been developed since then (an overview can be found in Refs. 4,5), and practically all of the presently available types suffer from several serious drawbacks. For example device characterization is a very common issue: since typically three or even more tuning currents are required to adjust the emission wavelength, the device calibration that is required for every single laser diode becomes time-consuming and, therefore, also expensive. Further drawbacks include limited output power, limited direct modulation capabilities and fabrication complexity.
Only recently, the sampled or superstructure grating tunable twin-guide or (S)SG-TTG laser diode, has been suggested.[6] This novel widely tunable laser is based on the tunable twin-guide laser with distributed feedback (DFB-TTG)[7] and is essentially a two-section phase-shifted DFB laser. Thus, very large side-mode rejection can be obtained and there is a potential for high power operation (which has already been demonstrated for DFB-TTG laser diodes[8]), and even for direct modulation up to high frequencies of 10 GHz and more. In contrast to previously fabricated widely tunable lasers, the (S)SG-TTG laser requires only two tuning currents to achieve wide quasi-continuous wavelength tuning. This facilitates fast device characterization and easy device control.
In this paper we will present results on the performance of the first sampled grating tunable twin-guide laser diodes. The organization of this paper is as follows: First of all, the operation principle of the device will be explained in Section 2. Subsequently, the fabrication process is summarized in Section 3 and also comments will be given here on some key fabrication steps that largely determine the device performance. Section 4 will then focus on the device characteristics and finally conclusions will be drawn in Section 5

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## 2. DEVICE PRINCIPLE

The tunable twin-guide laser with sampled or superstructure gratings is based on the tunable twin-guide laser with distributed feedback (DFB-TTG), but employs two tuning sections with sampled gratings (SGs) or superstructure gratings (SSGs) for Vernier-effect tuning instead of an DFB grating. Schematic drawings of the device are depicted in Fig. 1.

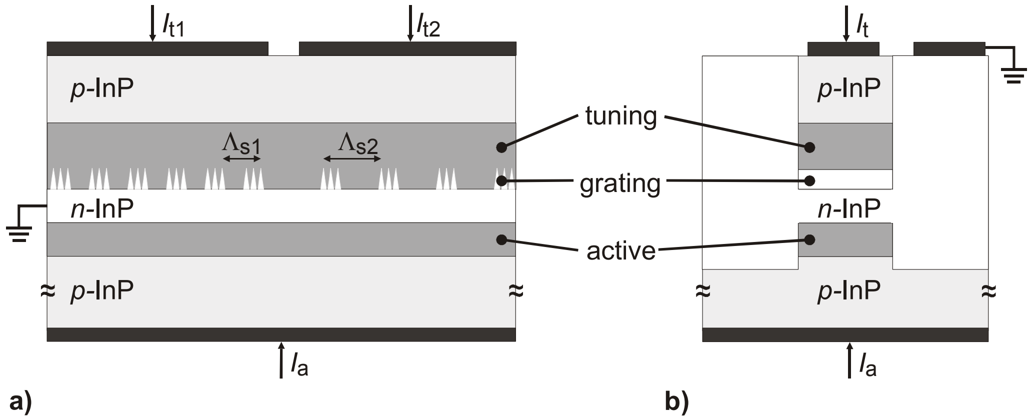


Fig. 1. Schematic drawings of a widely tunable SG-TTG laser diode.
a) longitudinal cross-section, b) lateral/transverse cross-section.

One of the main features of this design is the vertical integration of active layer, tuning layer and gratings. From an optical point of view, the device structure forms a single-mode waveguide, whose effective refractive index can be changed by current injection into the tuning layer. Longitudinal single-mode operation is achieved by the use of (S)SGs, which not only provide reflection at the Bragg wavelength (as would be the case for a DFB grating) but provide a comb-like reflection spectrum (Fig. 2a). The reflection peak spacing is determined by the sampling or superstructure period $\Lambda_{s1,2}$, which is slightly different for the gratings of tuning section 1 and 2. Therefore, Vernier-effect tuning[9] can be employed to overcome the tuning limit that is imposed by the maximum achievable refractive index change. Lasing automatically occurs at the wavelength where reflection peaks from both sections overlap (Fig. 2b). Hence, an additional phase tuning section, which is usually required to adjust the position of the cavity mode in longitudinally integrated DBR-type lasers, is needless.

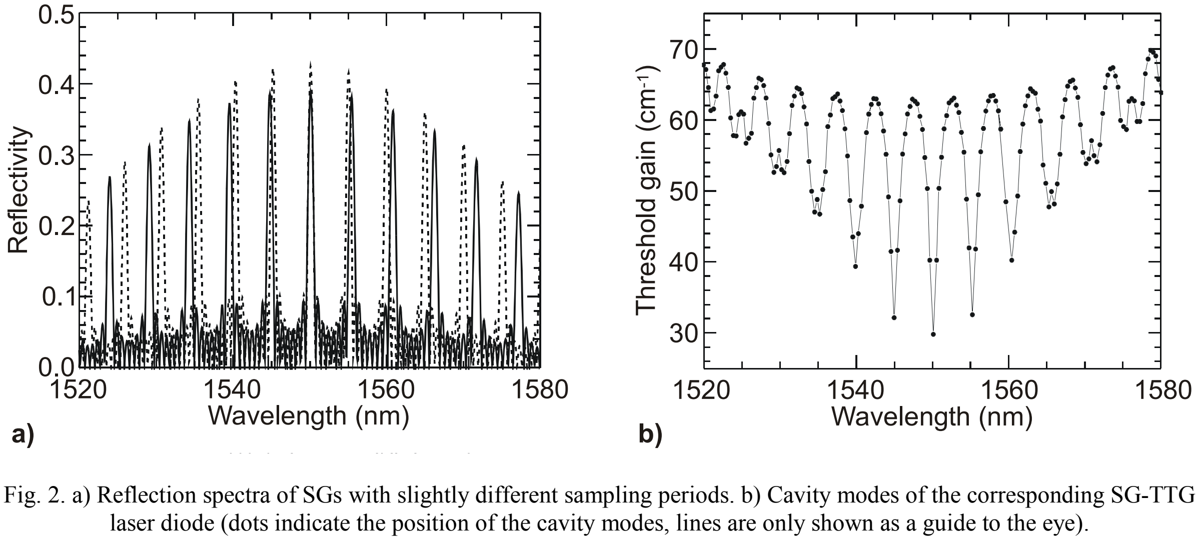


Fig. 2. a) Reflection spectra of SGs with slightly different sampling periods. b) Cavity modes of the corresponding SG-TTG laser diode (dots indicate the position of the cavity modes, lines are only shown as a guide to the eye).

As a result, quasi-continuous wavelength coverage with high side-mode suppression is achieved with only two tuning currents, which essentially facilitates fast characterization. Tuning of only one section leads to a transition from one pair of reflection peaks to another and, thereby, to a large wavelength jump, a so-called supermode hop. On the other hand, both sections can also be tuned simultaneously in such a way that the reflection peaks keep on overlapping and one obtains continuous wavelength tuning.
The tuning behavior of the (S)SG-TTG laser significantly differs from previously presented widely tunable multisection DFB lasers with (S)SGs.[10] Although the device structures are similar from an optical point of view, they are completely different from an electrical point of view. The tuning sections in an (S)SG-TTG laser are electrically decoupled from the active region of the device and, therefore, any arbitrary combination of wavelength shifts of the two (S)SG reflection spectra is obtainable, which is absolutely necessary to achieve full wavelength coverage. In contrast, in a widely tunable multisection DFB laser, tuning is brought about by changing the carrier density inside the active region. However, due to gain-clamping, the refractive indices of both sections cannot be adjusted independently from each other and, therefore, only certain discrete wavelengths are obtainable.
Besides the aforementioned points, one should also mention that the devices can be rather short. In fact, the results presented in this paper are from 600 $\mu$m long devices, which is about a factor of 2 – 3 shorter than other monolithic widely tunable lasers.

## 3. FABRICATION

The widely tunable twin-guide lasers have been manufactured using the GaInAsP/InP material system. The five epitaxial growth steps that were necessary for the device fabrication have been carried out by chemical beam epitaxy (CBE) and by metal-organic vapor phase epitaxy (MOVPE).
Fabrication starts with CBE growth of the basic structure, containing the strained-layer multi quantum well active region (photoluminescence peak at ~ 1.54 $\mu$m) and the *n*-InP layer that separates active and tuning region. Subsequently gratings are formed in the *n*-InP separation layer and are overgrown with the bulk GaInAsP tuning layer ($\lambda_g$ = 1.37 $\mu$m) in another CBE growth step. This is followed by stripe mesa etching and selective area regrowth of *n*-InP by MOVPE in order to laterally embed the stripe mesa. After that, two more selective area epitaxy steps are carried out in CBE to form the upper InP *p*-*n*-homojunction and the *p*-InP cladding. Finally, passivation and metallizations are applied to finish the device.

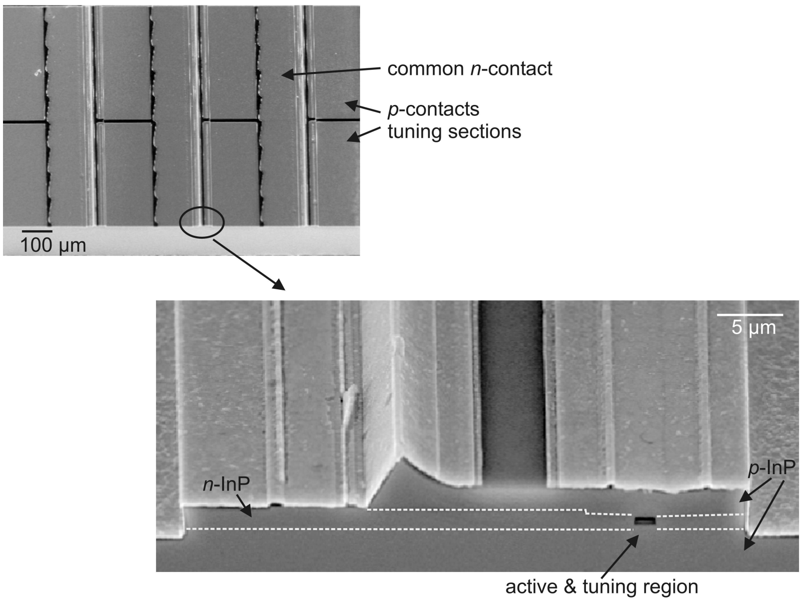


Fig. 3. SEM images showing an SG-TTG laser chip. The dashed white lines in the lower image indicate the location of the InP *p*-*n*-homojunctions. The common *n*-contact is situated on the left hand side of the ridge and the electron current is injected into the active and tuning regions via the *n*-InP channel.

The fabrication process of the TTG laser is in large parts compatible with standard processing technology used for buried heterostructure lasers. However, some differences arise from the rather unconventional lateral current injection scheme. Before reaching the active and tuning layer, the electron current has to pass through a long *n*-InP channel (see Fig. 3), which is sandwiched between *p*-InP layers. The corresponding interfaces between *p*- and *n*-InP form forward biased *p*-*n*-homojunctions under normal device operation. Moreover, the current confinement of this structure is solely due to the differences in bandgaps of active and tuning layer and the surrounding InP and, therefore, the quality of the InP *p*-*n*-homojunctions is of uttermost importance. Unfortunately these *p*-*n* interfaces also coincide with regrowth interfaces. Any contamination or crystal damage that is incorporated at these interfaces leads to increased recombination and thereby deteriorates the current confinement of the device structure. Besides this, the increased carrier recombination at the InP homojunction results also in an additional heat generation, which counteracts the refractive index change of the tuning layer and further limits the achievable continuous tuning range. Thus, a thorough optimization of the numerous regrowth interfaces is required to achieve an efficient current injection and a large continuous tuning range.

## 4. RESULTS AND DISCUSSION

Besides the widely tunable SG-TTG lasers, also DFB-TTG laser diodes have been fabricated on the same wafer. Since the later ones have been intensively studied in the past and a lot of data is available for comparison, they allow for a very reliable assessment of the general device performance. In particular, potential issues that are not associated with the wide tunability but are rather related to the fabrication process can be more easily identified from DFB-TTG lasers. Therefore, first results of the DFB-TTG lasers will be presented and discussed, before treating the widely tunable SG-TTG laser diodes.

### 4.1 Characteristics of DFB-TTG laser diodes

The data presented in the following is from 500 $\mu$m long DFB-TTG lasers with as-cleaved facets. For characterization the devices were mounted upside up on a copper heatsink that was kept at 20 °C. Fig. 4 shows the light output power – current characteristic of a mounted device. The lasing threshold is reached at a current of 6 mA. At first the power increases linearly. However, saturation of the light output power starts at a current of around 90 mA and limits the output power to about 12 mW. The saturation of the light output at high active region injection currents is well known for TTG lasers and is due to the onset of leakage currents across the backside *p*-*n*-homojunction. From a comparison with literature data, one can conclude that the quality of the epitaxial interface that coincides with the backside *p*-*n*-homojunction is very good. In fact, to the best of our knowledge this is the highest output power that has ever been achieved from a TTG laser without using blocking layer technology.

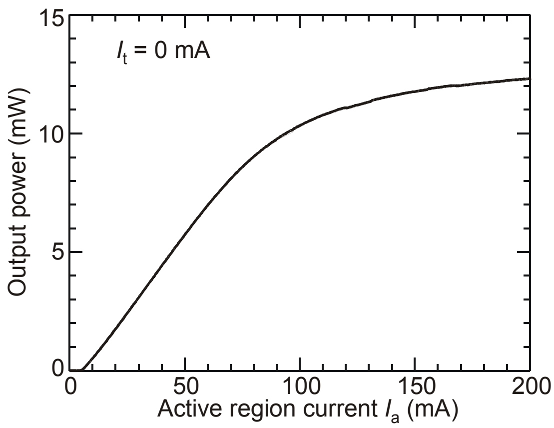


Fig. 4. *L-I* characteristics of a DFB-TTG laser diode.

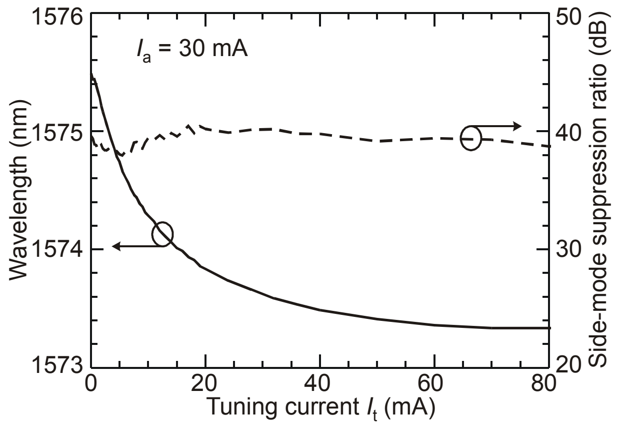


Fig. 5. Emission wavelength and side-mode suppresion ratio versus tuning currents

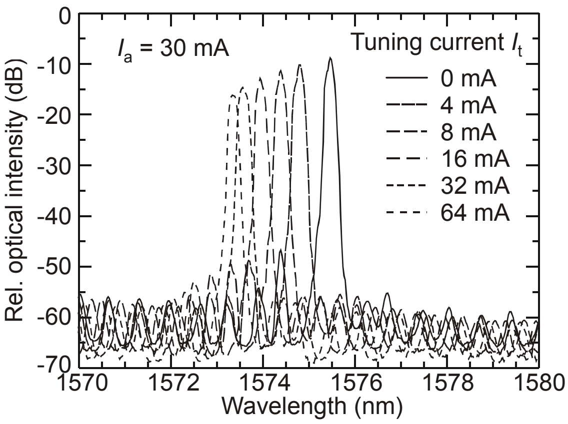


Fig. 6. Spectra at various tuning currents

Fig. 5 depicts the dependence of emission wavelength and side-mode suppression ratio (SMSR) on the tuning current. As can be seen, the wavelength decreases monotonically from 1575.5 nm to 1573.3 nm with increasing tuning current. The SMSR remains almost constant between 38 and 40 dB. The tuning behaviour is also illustrated in Fig. 6, which shows optical emission spectra at various tuning currents. No irregularities are observed and a total continuous tuning range of 2.2 nm is obtained by electronic tuning due to the free-carrier plasma effect.

However, the tuning range of 2.2 nm is not in agreement with the theoretical expectations. From the present device design one can expect a tuning range of about 4.0 – 4.5 nm. Hence, the present results indicate that the tuning efficiency is most probably impaired by leakage currents across the frontside *p*-*n*-homojunction. These leakage currents lead to an undesirable heat generation in the vicinity of the tuning region and thereby counteract the refractive index change due to the plasma effect. Ultimately this leads to a smaller tuning range.

In conclusion, there is still significant potential for an improvement of the continuous tuning range by which the reflection spectra can be shifted. Although a continuous tuning range of 2.2 nm is not enough to obtain full wavelength coverage over a tuning range of several tens of nm, it is nevertheless enough to address several supermodes within this range.

### 4.2 Characteristics of widely tunable TTG laser diodes with sampled gratings

Having discussed the performance of the DFB-TTG lasers, we will now focus on the widely tunable SG-TTG laser diodes. After fabrication they were cleaved to a cavity length of 600 $\mu$m, which comes down to about 300 $\mu$m of length for each of the two tuning sections. In order to pronounce the reflections of the SGs, both facets were AR-coated with a quarter-wave-thick $Al_2O_3$ film. Characterization was carried out with upside up mounted devices at 20 °C heatsink temperature.

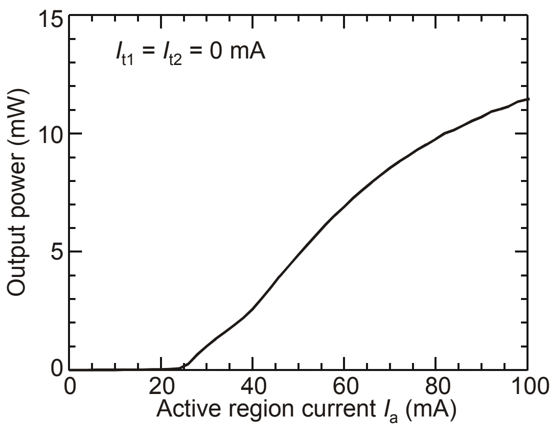


Fig. 7. *L*-*I* characteristics of an SG-TTG laser diode.

First of all Fig. 7 shows a typical *L-I* characteristic. As can be seen, lasing threshold is reach at 24 mA. The threshold current is significantly higher than for the DFB-TTG lasers. This is, on the one hand, because the widely tunable SG-TTG lasers have been AR-coated, and on the other hand, because of the low SG reflectivity (the grating only makes up about 10% of the laser length). Therefore mirror losses are substantially higher, resulting in an increased threshold current. As in the case of the DFB-TTG lasers, the light output power saturates due to the onset of leakage currents and a maximum output power of 12 mW is achieved.

The tuning behavior of the device is depicted in Fig. 8, where emission wavelength as well as SMSR are shown as function of the two tuning currents $I_{t1}$ and $I_{t2}$. From these plots one can easily recognize four supermodes. These are characterized by a high SMSR, which remains between 25 and 37 dB over the whole tuning range. Furthermore, it is worth mentioning that also a fifth supermode is addressable, but not visible in Fig. 8 since a very precise adjustment of the tuning currents is necessary. A compilation of spectra from the five different supermodes is shown in Fig. 9. For each supermode, one spectrum of the upper and lower limit of the supermode is depicted along with the continuous tuning range of the supermode, which is varying between 0.45 and 1.5 nm. As can be seen, the overall tuning range of the SG-TTG laser diode amounts to 28 nm (from 1534 to 1562 nm). However, full wavelength coverage is not possible with the rather limited continuous tuning range of ~ 2 nm.

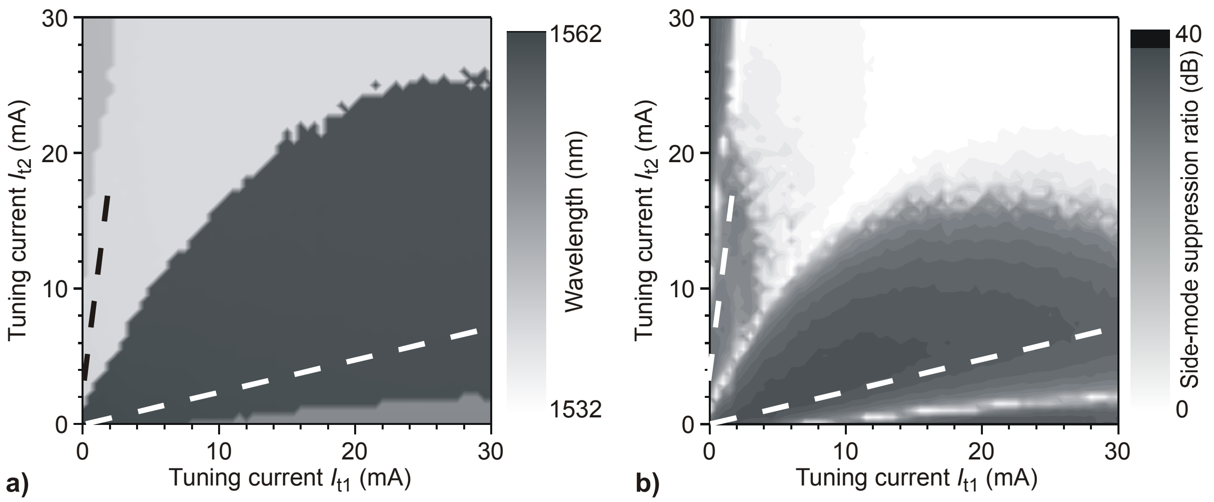


Fig. 8. Tuning behavior of emission wavelength (a) and SMSR (b) of an SG-TTG laser.
The dashed lines indicate the tuning curves shown in Fig. 10.

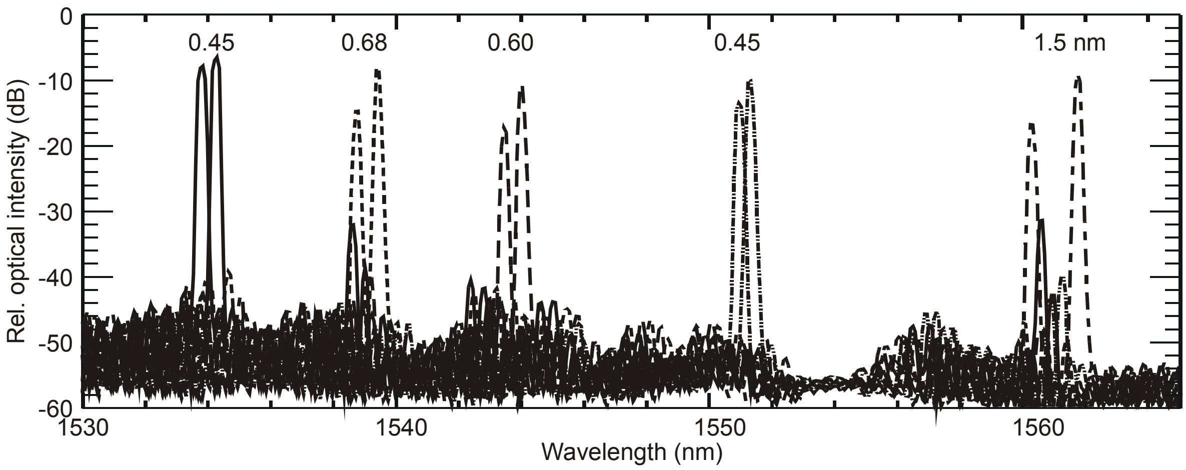


Fig. 9. Spectra showing the upper and lower limits of the five supermodes. The continuous tuning range of each supermode is indicated in the upper part of the image.

The continuous tuning range of a supermode is basically determined by the performance of the tuning region as wells as by the order the supermode. The upper limit is given by the maximum wavelength shift that is obtainable from the tuning region. As discussed in the previous section, this is ~ 2 nm for our present devices. Moreover, the higher the order of the supermode, the smaller the continuous tuning range will become, since a certain amount of wavelength shift is already necessary to overlap the higher order reflection peaks of the SGs. This amount of tuning is no longer available for the continuous tuning of the corresponding supermode.
Without any tuning currents applied, single-mode emission at a wavelength of 1561.6 nm with an SMSR of 32 dB is observed. This is also the supermode, where the central reflection peaks of the SG are lined up, and therefore it exhibits the largest continuous tuning range of all supermodes. The variation of wavelength and SMSR of this main supermode is illustrated in Fig. 10 along with data of a second supermode. As can be seen, the tuning behavior within a supermode is very regular and truly continuous. Only slight variations of the SMSR are observed.

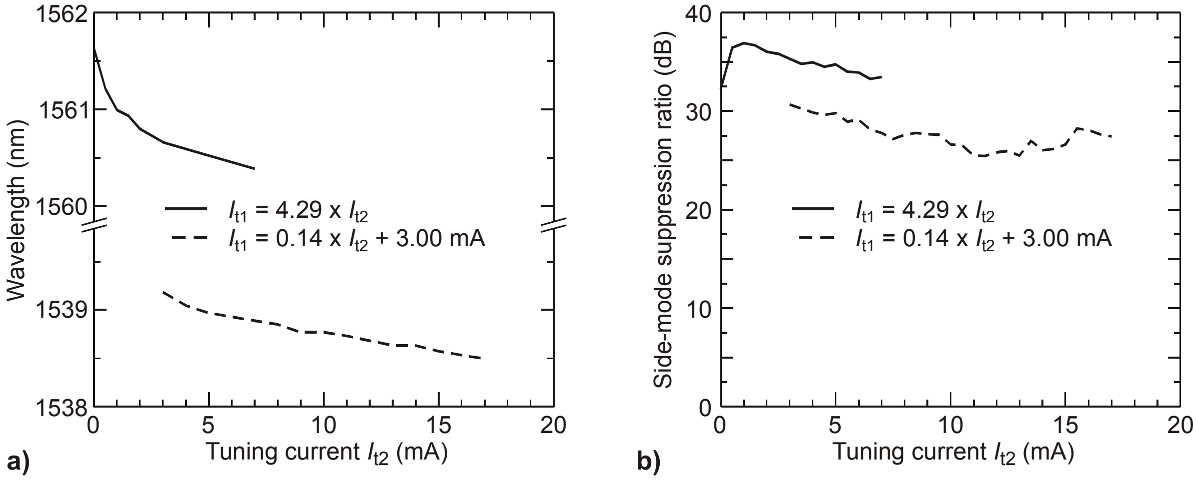


Fig. 10. Variation of emission wavlength (a) and SMSR (b) during continuous tuning
(for two selected supermodes, shown as dashed lines in Fig. 8).

The supermode hops take place fairly regular. However, one has to mention that the grating center wavelength (1562 nm) and the gain peak (1535 nm) are not aligned. This situation is schematically depicted in Fig. 11. With increasing tuning currents, supermode hops only take place towards shorter wavelength or towards the gain peak, respectively. Essentially, the detuning of grating center wavelength and gain peak balances to some extent the difference of gain and mirror losses for higher order reflection peaks that are situated closer towards the gain maximum (i.e. on the left hand side of the reflection peak maximum). Of course, the opposite is true for higher order reflection peaks that are situated further away from the gain maximum (i.e. on the right hand side of the reflection peak maximum).

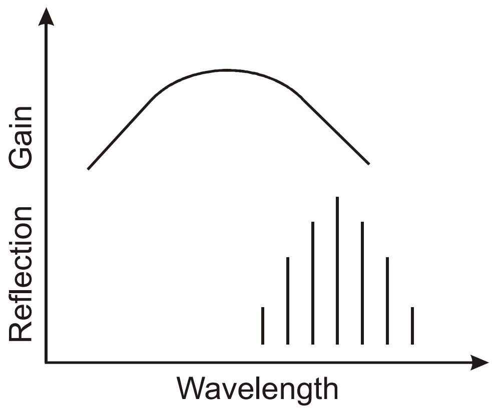


Fig. 11. Detuning of gain peak and SG reflection spectrum.

## 5. CONCLUSIONS

The first generation of the widely tunable twin-guide laser diodes have clearly proven the design concept of the SG-TTG laser. Wide wavelength tuning over a 28 nm wavelength range (from 1534 to 1562 nm) has been achieved. Wide quasi-continuous wavelength tuning along with high SMSR has been demonstrated with only two tuning currents, which facilitates easy and fast device characterization and control.
Due to residual parasitic currents, the devices show only a moderate tuning efficiency. The rather small continuous tuning range of 2 nm is limiting the overall device performance and presently prevents full-wavelength coverage of the aforementioned tuning range. However, the present generation of devices has not yet been optimized for a large continuous tuning range and, therefore, there is still significant potential for improvements. Further technological refinements along with a device design that is geared towards a large continuous tuning is expected to result in full-wavelength coverage.

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