# 114-nm Wavelength Tuning Range of a Vertical Grating Assisted Codirectional Coupler Laser with a Super Structure Grating Distributed Bragg Reflector

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***Abstract*—A vertical grating assisted codirectional coupler laser with a super structure grating distributed Bragg reflector is demonstrated. A record stepwise tuning range of 114 nm was measured with good side-mode suppression. The tuning behavior of the device is investigated showing a potential of a tuning range exceeding 100 nm with complete wavelength coverage.**

## I. Introduction

Widely tunable monolithic semiconductor lasers are important for wavelength division multiplexed (WDM) networks and optical measurement systems. Wide stepwise tuning ranges have been reported for a number of different laser structures [1]–[6], such as 51 nm in a Y-laser [4], 105 nm in a super structure grating distributed Bragg reflector (SSG-DBR) lasers [5], and 74 nm in a vertical grating assisted codirectional coupler with rear sampled grating reflector (GCSR) laser [6]. Complete wavelength coverage over 40 nm was also demonstrated for SSG-DBR lasers, electrically tuned [7] and thermally tuned [8].

The GCSR laser is based on the optical filter proposed by Willems *et al.* [9], where the wide tuning range of the grating assisted codirectional coupler is combined with the high spectral selectivity of the sampled DBR (S-DBR). We replaced the S-DBR by an SSG-DBR, which can be designed to offer a high reflectivity over a wide reflection envelope bandwidth [5], [10]. The SSG-DBR was designed to provide a reflection bandwidth larger than 100 nm, matching the tuning range of the coupler.

## II. Laser Structure

The laser structure is schematically shown in Fig. 1. It consists of a gain section, a coupler section with a grating period of 15 $\mu$m for coarse tuning, a phase tuning section for fine tuning (continuous tuning) and a reflector (SSG-DBR) section for medium tuning. The cross section in the different parts of the laser is also shown. The light from the gain section is wavelength selectively coupled from the lower waveguide to the upper one in the coupler and reflected back in the reflector. To prevent feedback of the light that is not coupled to the upper waveguide, the lower waveguide is left planar in the reflector section which essentially terminates it. Thus, the laser cavity extends from the cleaved facet at the left-hand side of the gain section to the SSG-DBR section top waveguide.

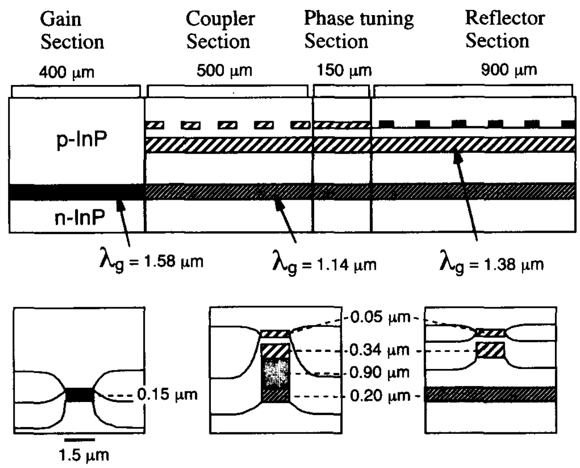


Fig. 1. Longitudinal and transverse cross section of the GCSR laser.

In the fabrication process lasers with different coupler length, coupler grating pitch and design of the SSG were included in one batch. The fabrication of the lasers includes five epitaxial steps and is described in [6]. However, some improvements in the process were made for the present batch. A new mask set was used in which we introduced a phase tuning section. The simple sampled reflector in the former batch was replaced by an SSG-DBR, described in the next section. The gratings were made by electron beam lithography and wet etching through a separate grating layer for a better control of the coupling coefficient. The electrode separation resistance was increased to 500 kΩ.

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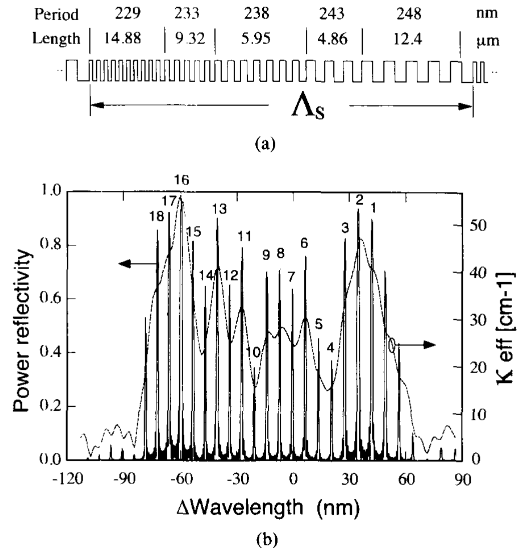


Fig. 2. (a) The super structure grating inside one sampling period of the SSG-DBR with $\Lambda_S = 45$ $\mu$m. (b) Calculated reflectivity and effective coupling coefficient of a lossless SSG-DBR with ten sampling periods and $\kappa = 140$ cm$^{-1}$.

## III. SSG-DBR Structure

One sampling period of the SSG-DBR is depicted in Fig. 2(a). It consists of five segments with different pitches and different lengths. The sampling period was chosen to 45 $\mu$m, giving a desired peak separation of about 7 nm. The pitches and lengths of the grating segments within a sampling period were optimized using a matrix based program [11]. For the first time, the reflectivity of the SSG-DBR was designed to partly compensate for the gain profile, which is one limitation of the tuning range. Complete compensation may be difficult to achieve due to the change of the gain profile if the threshold carrier density varies during tuning. The calculated reflectivity is shown in Fig. 2(b) for a reflector with ten sampling periods. The envelope function for the effective coupling coefficient of the SSG, as defined in [7], is included. Reflection peaks are obtained over a 125 nm wide window with higher reflectivity on the edge of the window where the gain is expected to be low.

## IV. Tuning Measurements

Five laser of the described design from one wafer were measured. All wavelength measurements were made at a constant gain current and a fixed heat sink temperature of 20 °C. The coupler center-wavelength without current in the coupler section is about 1610 nm. The output power of the lasers was typically 1–2 mW with zero tuning currents, and decreased to 0.5 mW toward the end of the tuning range.

The tuning characteristic of the laser can be divided in three parts. The coarse tuning is obtained when changing the coupler current alone. The laser is tuned in large steps corresponding to the peak separation of the SSG-DBR as shown in Fig. 3. The steps are 7 nm and the total tuning is 114 nm for the best laser, which is the highest value ever reported for monolithic lasers.

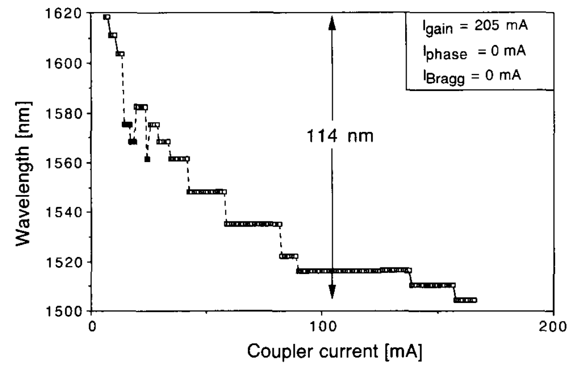


Fig. 3. Coarse tuning of the GCSR laser.

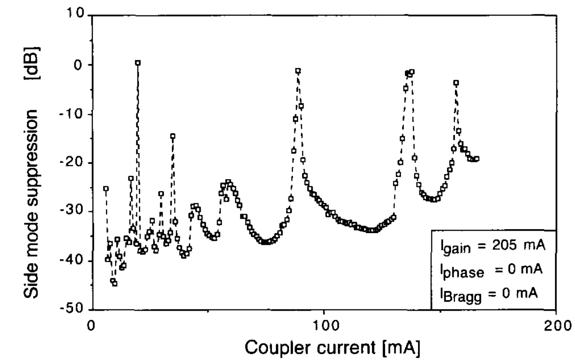


Fig. 4. Side-mode suppression under coarse tuning.

All measured lasers have tuning ranges exceeding 100 nm. Fig. 4 shows the side-mode suppression under coarse tuning. The laser remains single-mode with side-mode suppression ratio usually better than 20 dB, only degraded as expected, in the proximity of a mode jump. Some peaks are missing in the tuning curve giving tuning steps of $n$-times 7 nm. This can be explained by looking at the calculated reflection spectrum of the SSG-DBR. If the peak number one correspond to the first accessed wavelength, then, the wavelengths that are missing correspond to the peaks 4, 5, 10, 12, and 14. These have much lower reflectivity than the neighboring peaks and the filtering of the coupler is not narrow enough to select peaks 10, 12, and 14. Lasing could even occur at the first side lobe of the filter transmission characteristic of the coupler (filled squares in Fig. 3) if the lower side lobe transmission in the coupler is compensated by a higher reflectivity in the reflector. This explains why peaks 4 and 5 are not lasing. A more regular reflectivity from the SSG-DBR and/or a more selective coupler should improve the tuning characteristic of the laser.

The medium tuning is obtained when the coupler current and reflector current are changed simultaneously in the following scheme. First, one of the reflection peaks of the SSG-DBR is selected by injecting a suitable current in the coupler. Then, the reflector peak pattern is tuned toward shorter wavelength by injecting current in the reflector, while the selected peak is tracked for maximal coupler transmission by slightly increasing the coupler current. Fig. 5 shows the medium tuning when

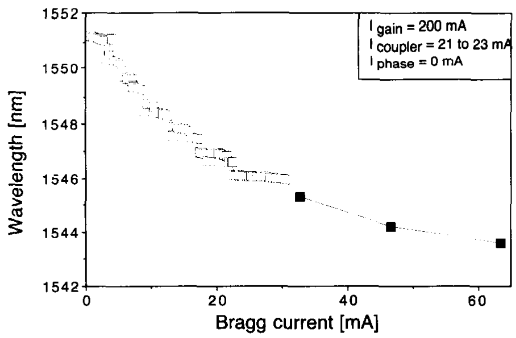


Fig. 5. Medium tuning for one peak of the SSG-DBR as a function of the reflector current. The coupler current is increased by 2 mA simultaneously. The filled squares correspond to measurements below threshold.

the coupler current is tuned only by 2 mA. The wavelength jumps of 0.2 nm correspond to different longitudinal modes of the cavity. Some jumps are separated by about 0.8 nm, which corresponds to the 400-$\mu$m-long cavity defined by internal reflection at the butt-joint between the gain section and the coupler section and the cleaved facet of the gain section. The former reflection should be reduced with a better butt-joint. The side mode suppression under tuning remains greater than 20 dB between the mode jumps, but is reduced at larger currents due to increasing losses in the reflector section caused by free carrier absorption which, finally, will inhibit the laser to lase. However, the tuning of the peak can still be observed in the spontaneous emission spectrum showing that a tuning of more than 7 nm is possible (filled square in the curve). This tuning is large enough to cover the SSG-DBR peak separation, which is a condition for complete wavelength coverage [7]. A similar medium tuning range is obtained for each peak selected by different bias of the coupler.

The fine tuning is performed by changing the current in the phase tuning section. The truly continuous tuning range of about 0.2 nm, is defined by the longitudinal mode spacing of the cavity. This corresponds to a cavity length of 1900 $\mu$m in good agreement with the length of the laser.

By combining the three tuning mechanisms, any wavelength in the tuning range could be reached in a properly designed GCSR laser. First, the coarse tuning is used to select the closest reflection peak on the longer wavelength side of the desired wavelength. Then, by medium tuning, the selected peak is tuned to the closest cavity mode within a cavity mode tuning range. Finally, the lasing wavelength can be continuously tuned to the desired wavelength by fine tuning. This can be repeated for any wavelength within the coarse tuning range. The potential of total wavelength coverage larger than 100 nm is thereby demonstrated, and should be achieved in a properly designed laser.

## V. Conclusion

We presented an improved design of the GCSR laser in which was included a phase tuning section and an SSG-DBR having a partly gain compensating reflection envelope for wide tuning range.

A one-current controlled coarse tuning range of 114 nm with single-mode operation was demonstrated. The irregularities in the tuning characteristic are explained by the reflection characteristic of the SSG-DBR. An improved design containing a larger number of grating segments should give the regular and easy tuning expected for this device. The tuning function of the different electrodes is demonstrated, showing the potential of a total wavelength coverage larger than 100 nm in a properly designed GCSR laser.

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