Design and simulation of a two-section Fabry-Pérot sampled grating distributed Bragg reflector laser for dense wavelength-division multiplexing applications

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Abstract. We report the theory of operation and time domain model (TDM) simulation results for a two-section Fabry-Pérot sampled grating distributed Bragg reflector (FP/SGDBR), 100-GHz, step-tunable laser [sidemode suppression rate (SMSR) > 38 dB]. Although the main idea, the Vernier effect, was previously published, we present for the first time these two-section combinations for this specific sort of application. © 2002 Society of Photo-Optical Instrumentation Engineers. [DOI: 10.1117/1.1428296]

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1 Introduction

The rapid growth of wavelength-division multiplexing (WDM) technology is putting pressure on optoelectronic (mainly semiconductor laser) manufacturers, to design improved wavelength-specific components. While the emphasis today is on very narrow channel spacing for dense WDM (DWDM) systems, not all applications may require the associated cost and complexity of network management. The step-tunable laser is becoming a main building block for DWDM applications. In this paper,1,2 we present a simple step-tunable laser design based on the Vernier effect3 with a 38 dB sidemode suppression rate (SMSR), 10 channels, and an output power of 10 mW in each channel. These results were recorded according to the time domain model (TDM) simulation results.

This design consists of two sections (Fig. 1). The first section is a Fabry-Perot (FP) laser with a suitable length to provide the required mode spacing. This mode spacing will be the required channel step (for example, 100 GHz). Integrated with this FP laser, a sampled grating filter with a filter comb peak spacing of 110 GHz. The FP modes will see different reflectivities from both facets. One facet will provide to all FP modes a reflectivity of 0.3 (Fig. 1), while the other facet will provide the modes the reflectivity of the sampled grating distributed Bragg reflector (SGDBR) combs separated in frequency by 110 GHz and centered around the Bragg frequency. Due to the 10-GHz spacing difference between the FP modes and the comb reflectivities, only one FP mode will spectrally coincide with one of the filter comb peaks and will be reflected and amplified, while neighboring ones will be 10, 20, 30, ... GHz far from the reflection combs (Fig. 2). Consequently, at the FP output facet, we will only get one FP mode while the others will be highly attenuated as they were reflected from only one of the two FP facets. By varying the injected current into the SGDBR section, the filter combs will be shifted due to the electron-plasma effect. Hence, the filter coinciding with the lasing mode will be shifted and this mode will be attenuated like its former neighboring modes. However, the adjacent filter will coincide with the neighboring FP mode and all other modes will be attenuated, and so on for other channels.

2 Design Consideration

Two main parameters can influence this design performance in terms of the channel number and quality (SMSR): the filter peak spacing $S_p$ of the SGDBR section...
The output power/channel, could be increased using two methods. The first is to increase the injected current into the FP section, which will increase the FP mode power. However, for a longer device lifetime, we should not operate the FP section at high injection current. Alternatively, by increasing the comb reflectivity, the output power could also be increased. It was previously explained in the Introduction and in Fig. 1 that each mode is reflected by the FP mirror and the SGDBR comb. Increasing the SGDBR comb reflectivity \( R(q) \) will increase the output power. The comb reflectivity is governed by the following equation:

\[
R(q) = \tanh^2 \left[ \kappa(q)L_t \right].
\]

Increasing the total length of the SGDBR section \( L_t \) will not only increase the reflectivity and the channel power, but will also reduce the BWBN of the comb filters according to Eq. (2), which will fulfill telecommunications requirements for a high SMSR with a high optical power. However, for the coupling coefficient, its increase will increase the comb reflectivity, which will increase the output power, but the comb filters BWBN will also increase according to Eq. (2), reducing the SMSR per channel, which is disadvantageous for DWDM telecommunications requirements.

### 3 Laser Structure Geometrical and Physical Parameters

The TDM (Refs. 5 and 6) simulation of sampled grating distributed-feedback (DFB) lasers and tunable SGDBR structures were previously done and experimentally verified. Our work here is based on some of the physical parameters of FP and SGDBR sections already published in the literature. Table 1 gives the main active layer design parameters for bulk InP-based materials.

The SGDBR period selected in the simulation is 340 mms. Substituting this value into Eq. (1) and using a value of 4 for the group refractive index (Table 1), we get a spacing between SGDBR filters of 110 GHz, which was the required value in the previous section.

According to Eq. (3) the \( KL \) product selected results in a reflection coefficient of 0.7. According to Eq. (2), using the

\[
\Delta \lambda_{BW} = \frac{c}{2 \mu_s L_p}, \quad (1)
\]

where \( \Delta \lambda_{BW} \) is the spectral spacing between combs, \( c \) is the speed of light, \( \mu_s \) is the group refractive index, and \( L_p \) is the sampled grating period length.

\[
\Delta \lambda_{BW}(q) = \frac{\lambda^2}{\pi \mu_s} \left[ k(q)^2 + \left( \frac{\pi}{L_t} \right)^2 \right]^{1/2}, \quad (2)
\]

where \( \Delta \lambda_{BW}(q) \) is the BWBN of the two first zeroes of filter number \( q \), \( k(q) \) is the effective coupling coefficient of filter number \( q \), and \( L_t \) is the sampled grating section length.

These two equations are the main design equations for that structure. If the comb spacing is reduced, for example, to 105 GHz instead of 110 GHz, the channel number will be doubled. However, this will be for the sake of the BWBN, which must be reduced to maintain the same SMSR values as the FP modes become closer. To reduce the BWBN according to Eq. (1), the SGDBR length \( L_t \) must increase or the coupling coefficient \( k(q) \) must decrease. However, technological limitations governing the lowest controllable coupling coefficient values limit the BWBN, and consequently the SMSR.

Fig. 1 Schematic diagram of the two-section step-tunable laser.

Fig. 2 Channel selection by SGDBR filter tuning.
parameters in Table 1 and substituting for $\lambda$ to be equal to 1.55 $\mu$m (InP-based material), the BWBN of the SGDBR filter (in gigahertz) is equal to $\sim$20 GHz, which is adequate for this 10-channel design, as once the filter is selected and centered to the FP mode, the two neighboring FP modes will be at the zeroes of the two neighboring filters.

Equation (3) gives a prediction for the sensitivity of the output power to the uncertainty or tolerance of the fabricated gratings in the SGDBR section. As an example, a reduction of 10% in the coupling coefficient results in a reflection coefficient reduction to 0.63. This power sensitivity could be reduced by increasing the SGDBR length due to the nature of the reflection coefficient function $\tanh$, which is a converging function to unity. The same tolerance in coupling coefficient will result, according to Eq. (2), in a BWBN reduction of 1.2%, which is advantageous for the SMSR. Due to the high technological precision in defining the grating and sampled grating period using electron-beam lithography, the tolerance of the sampled grating period $L_p$ is practically negligible.

4 TDM Simulation Results and Interpretation

Figure 3 shows the current range of each channel output. The figure is divided into three sections (A, B, and C). From 40 to 65 mA, the output frequency jump is not in a stepwise form. This is due to the poor current density;
which is not high enough to control the filter combs shift by the plasma effect. In section B, the step tuning is launched for a total of 6 channels. In part C, the number of channels increased to 8. In part C, the 50-, 150-, 250-, and 350-GHz channels are absent from part B, due to the weak current effect on filter combs below 65 mA (part A). The channel repetition in parts B and C is due to the scanning of the filter combs on the same FP modes. The channel jump between $f = -550$ GHz and $f = +350$ GHz in the current range 110 to 116 mA is due to the rescanning of the FP modes by filter comb lying 10 channels far from the latest range 110 to 116 mA is due to the rescanning of the FP channels occurred, as already mentioned (Fig. 3). Figure 4 shows the simulation results for an injected current $I_{SGDBR} = 113$ mA. We can clearly see the selected mode of section B at $f = -550$ GHz, with the onset of the section C channels. Increasing the current to 115 mA, a jump of 10 channels occurred, as already mentioned (Fig. 5), leading to a selection of the channel at $f = +350$ GHz. Figure 6 shows the output spectrum of a channel at an injected SGDBR current of 170 mA and a relative frequency of $-350$ GHz with an SMSR of $-40$ dB and output power of 8.5 mW. The sidemodes appearing below the selected channel are the unselected FP modes.

The SMSR in Figs. 4 and 5 is lower than the SMSR of Fig. 6. This is certainly due to current operation at the edge of the current span/channel. In Fig. 4, $I_{SGDBR} = 113$ mA is the ending edge of the current span for $f = -550$ GHz, and in Fig. 5, the lasing mode at $I_{SGDBR} = 115$ mA is at the starting edge of the current span for $f = +350$ GHz (see Fig. 3). At the edge of any current span, the filter is not centered with the selected FP mode in both cases ($I_{SGDBR} = 113$ and 115 mA). To achieve the highest filter/mode coincidence, it is recommended to operate in the middle of each current span/channel to get the highest SMSR, as in Fig. 6. As an example, for the channel at $-50$ GHz (see Fig. 3), an operating current around 138 mA will give the best SMSR. The second advantage due to the filter/channel coincidence will be the greatest reduction of the thermal influence on SGDBR filter if it is spectrally shifted due to heating effect.

Unless the laser structure will be thermally controlled as usual using a temperature controller, temperature variation is unavoidable. This variation will mainly influence the effective refractive index, and consequently, the selected sampled grating filter will be shifted from the lasing FP channel. This shift could lead to a channel cancellation or damping. A step-tunable laser could also be obtained by using a four-section (a two-section SGDBR as reflectors with a slight difference in grating periods, one gain section, and one phase section) continuously tunable laser source.

In this design, each frequency is selected by adjusting the four currents injected into the four different sections using four different current sources. To operate as a step-tunable laser, microprocessor-controlled electronic storage and feedback elements are used to store the four different current values for each selected channel. Although having four sections monolithically integrated fed with four different current sources will increase the cost as well as complexity, the main advantage is the tuning of the channel spacing (steps). But, having SGDBR sections on each side of the FP laser acting as a mirror, will increase the device sensitivity to any temperature variations, and in this case, the reflection comb shift due to temperature variation will occur on both SGDBR reflectors, influencing the position of both comb filters. Consequently, the selected channel will have more probability of fading away. Moreover, with aging, the two SGDBR reflectors could behave differently with temperature, leading to the same consequences.

As compared to the design discussed here, we have two current sources, one of the main advantages is that we require only one SGDBR section acting as a reflector on one side, while the other is the classic FP mirror, which has relatively the same reflectivity to all the channels. Thus, if due to temperature variation the SGDBR comb does shift, this will occur on only one reflection side of the FP laser, as the other side is the FP mirror, which is influenced slightly due to temperature variation.

A hybrid design based on the same Vernier effect, with an FP section feeding an external sampled grating fiber were experimentally verified. These experimental results confirm the validity of our approach, but we expect higher output power instead of $-30$ dBm, since by monolithic
integration, we solved the difficult problem of optical alignment and (laser/fiber) coupling losses.

Lifetime considerations are important in telecom applications. It is well known that higher current injection reduces the lifetime of a semiconductor laser. Due to repetition of most of the channels in sections B and C, it is not necessary to extend an SGDBR current of 170 mA. Operating in a current range from 67 to 128 mA will enable using the full device capacity (all 10 channels, 6 channels from section B and 4 channels from C). Consequently, the lifetime of the SGDBR section in that way could be increased while maintaining use of the full tuning range. The only reason to increase current into the FP section is to obtain a higher power/channel. Reducing the current of the FP section used in Table 1 will influence only the power output per channel without influencing the device theory of operation.

5 Conclusion

We presented modeling results for a two-section FP/SGDBR laser diode, showing that this structure acts as a step-tunable laser. Considering the design parameters used, 10 100-GHz-spacing channels can be obtained for a tuning current range varying from 95 to 175 mA. The advantage of this monolithic design lies in its size compactness (two-sections) and an SMSR>38 dB for an output channel power exceeding 8 mW.

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References


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Biographies and photographs of the other authors not available.