Design and simulation of a dual mode semiconductor laser using sampled grating DFB structure

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Abstract: A dual mode laser source is proposed. It is based on a sampled grating DFB laser constituted with alternating DFB and FP sections. The basic principles of this device are presented, and its behaviour is studied through modelling. It is shown that mode spacing in the millimetre-wave domain (here 60 GHz) can be achieved with relatively short devices using a common DFB structures coupling coefficient.

1 Introduction

Fibre-radio systems are promising techniques for future picocellular telecommunication systems. It is possible to benefit from fibreoptics for high bit rate telecommunications, and from radio transmission for user mobility. Because of the restricted spectrum available at microwave frequencies, new frequency bands in the millimetre wave region are very attractive. Moreover, this millimetre wave frequency band is naturally attenuated in air. Consequently, the same frequency channel could be reused beyond the picocell area. We will suggest a semiconductor laser design that can be used in generating this millimetre wave.

A comparison between the different techniques of millimetre wave signal generation at photo receiver point was recently studied [1, 2]. Among these, the dual-mode optical source can be achieved using master–slave combination of laser diodes [3, 4], hybrid mode locking [5] or specifically designed semiconductor laser sources, so-called ‘dual mode’ lasers [2, 6, 7]; this last solution is the purpose of this paper. The goal here is to generate two optical modes whose frequencies are separated by the desired millimetre wave frequency; as an example, we chose here 60 GHz but it can be tuned to another frequency of interest.

Dual mode semiconductor laser designs were previously investigated involving dual DFB structures [6]; here we use the sampled grating structure as a dual mode basis. The main difference compared with the previously mentioned solution is that this design only needs one DC bias current.

2 Sampled grating DFB (SGDFB) laser structure description

Dual mode lasers can be obtained with DFB structures for which the usual effort to lift the mode degeneracy was not taken into consideration. The coupling coefficient and the total laser length are the two main parameters governing the frequency separation between modes. The mode separation is approximately given by the following expression [6]:

$$\Delta f \approx \frac{1.5\sqrt{2}}{\pi n_e \tanh(\kappa L)} \cdot c K$$

where: $\Delta f$ = the mode frequency separation in a DFB laser; $c$ = the light velocity in vacuum; $n_e$ = the effective refractive index; $\kappa$ = the coupling coefficient of the DFB structure; $L$ = the total DFB laser length.

So, if we want to get a mode separation of 60 GHz, we need a long laser or a small coupling coefficient. As an example [6], the result was achieved with a 2 mm long laser and a coupling coefficient of 9 cm$^{-1}$. If we want to reduce the laser length, it will therefore be essential also to decrease the coupling coefficient. For example, a 1 mm laser length would need a coupling coefficient lower than 3 cm$^{-1}$. However, it seems difficult to technologically control such reduced coupling coefficient values. Besides, a too low coupling coefficient value all over the laser length could possibly turn it into a multimoded laser source. The structure we propose is designed with the aim of reducing the ‘effective’ coupling coefficient $\kappa$ using usual technologies compatible with conventional coupling coefficients. The structure of concern here consists of alternating DFB and FP sections pumped by a single current source (Fig. 1). Using such a structure, we can expect to get a reduced effective coupling coefficient by increasing the FP section length. A square wave function will sample the DFB structure according to its duty cycle. So, it can be seen (Fig. 2) that the refractive index of this structure will be equal to the refractive index of the conventional DFB (Fig. 2) multiplied by the Fourier series expansion of the spatial square wave function (Fig. 2).
where \(E(z)\) is the complex amplitude of the electric field, which is assumed to only depend on the propagation direction \(z\). In a conventional DFB laser, the reason for the coupling between modes is the periodic term in the refractive index factor. Looking at the above sampled grating index (eqn. 2) we realise a series of periodic terms with different periodicities. This Fourier series expansion inserted into Maxwell equation will end up with a series of coupling coefficients, and consequently a corresponding series of reflection coefficients. So, instead of having a single reflection coefficient centred around the Bragg frequency, this structure will generate a series of reflection filters (Fig. 3). The following equations (eqns. 4–7) were already proposed and demonstrated for sampled grating DBR laser [8, 9], so we can express the reflectivity peak of each comb filter of order \(q\) as:

\[
R_p(q) = \tan^2(\kappa(q)|L_p|) \tag{4}
\]

where \(\kappa(q)\) is the coupling coefficient of the \(q\)th Fourier component of the sampled grating structure and \(L_p\) is the total laser length. The coupling coefficient \(\kappa(q)\) is related to the coupling coefficient of the DFB case by the following equation:

\[
\kappa(q) = \kappa(0) \sin(qh)e^{-\pi q h} \tag{5}
\]

where \(h\) is the DFB filling factor which is equal to \(L_u/L_p\). The spacing \(S_p\) between the reflectivity comb peaks is equal to:

\[
S_p = \frac{\lambda^2}{2\mu g L_p} \tag{6}
\]

where \(\mu_g\) is the group refractive index and \(\lambda\) is the Bragg wavelength of the DFB section. The bandwidth of each comb to the first nulls is given by:

\[
\Delta \lambda_{\text{bw}}(q) = \sqrt{\frac{\lambda^2}{2\mu g L_p} \left[\kappa(q)^2 + \left(\frac{\pi}{L_p}\right)^2\right]} \tag{7}
\]

Consequently, by introducing DFB sections periodically in the FP structure, we introduce a periodic filter with a periodicity in terms of optical frequencies. This can be illustrated by the schematic given in Fig. 3 where we show the modes of the Fabry-Perot cavity and we superimpose

\[
\nabla^2 E(z) + k_0^2 n_{sg}^2 E(z) = 0 \tag{3}
\]
the filter due to the periodic DFB section. The two central modes \((q = 0)\) are governed by eqn. 1 with an equivalent coupling coefficient given by eqn. 5. For these two central modes, the coupling coefficient will be given by:

\[
\kappa(q) = \kappa(o) h
\]  

(8)

Eqn. 8 is one of the main design equations of this laser structure. Thanks to the \(h\) factor \((-1\) introduced in the coupling coefficient, the latter could be reduced to the necessary value required for the 60 GHz mode spacing starting with a conventional coupling coefficient and consequently a suitable laser length. If this filter is well designed, we can, moreover, expect to cancel all modes except two of those centred inside the primary \((q = 0)\) reflection comb bandwidth. To precisely study the effect of the geometrical and physical parameters of this dual mode laser structure, we use a sophisticated numerical TDM model.

3 Laser numerical model

A quantitative study for this structure, using the laser parameters presented in Table 1, was done using the time domain model (TDM) [10–12], which is based on solving the following coupled waves equations:

\[
\begin{align*}
\frac{1}{V_g} \frac{\partial}{\partial t} F(z, t) &= - (i\delta - g + z_a) F(z, t) + i\kappa_{FR} R(z, t) + G(z, t) \\
\frac{1}{V_g} \frac{\partial}{\partial t} R(z, t) &= - (i\delta - g + z_a) R(z, t) + i\kappa_{PR} F(z, t) + G(z, t)
\end{align*}
\]  

(9)

where the above parameters refer to:
- \(F(z, t)\) = forward wave
- \(R(z, t)\) = backward wave
- \(G(z, t)\) = spontaneous noise term
- \(V_g\) = group velocity
- \(\delta\) = detuning factor
- \(\kappa_{FR}\) = coupling coefficient for reverse wave to forward
- \(\kappa_{PR}\) = coupling coefficient for forward wave to reverse

Table 1: Laser geometrical and physical parameters used in the simulation

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>driving current</td>
<td>80 mA</td>
</tr>
<tr>
<td>laser length = contact length (L_c)</td>
<td>710 (\mu)m</td>
</tr>
<tr>
<td>active region thickness (d)</td>
<td>0.1 (\mu)m</td>
</tr>
<tr>
<td>active region width (w)</td>
<td>2 (\mu)m</td>
</tr>
<tr>
<td>confinement factor (\Gamma)</td>
<td>0.3</td>
</tr>
<tr>
<td>group refractive index (\mu_g)</td>
<td>4</td>
</tr>
<tr>
<td>differential gain (a)</td>
<td>2.7 \times 10^{-20} (\text{m}^2)</td>
</tr>
<tr>
<td>transparency carrier density (N_0)</td>
<td>1.8 \times 10^{14} (\text{m}^{-3})</td>
</tr>
<tr>
<td>auger recombination factor (C)</td>
<td>4.10^{-41} (\text{m}^6\text{s}^{-1})</td>
</tr>
<tr>
<td>biomolecular recombination (B)</td>
<td>8.6 \times 10^{-17} (\text{m}^2\text{s}^{-1})</td>
</tr>
<tr>
<td>linear carrier lifetime (\tau)</td>
<td>4 \times 10^{-9} (\text{s})</td>
</tr>
<tr>
<td>linewidth enhancement factor (\eta_l)</td>
<td>3</td>
</tr>
<tr>
<td>inversion factor (\eta_{inv})</td>
<td>2.5</td>
</tr>
<tr>
<td>nonlinear gain compression (\eta)</td>
<td>1 \times 10^{-29} (\text{m}^3)</td>
</tr>
<tr>
<td>waveguide loss (\alpha_w)</td>
<td>2000 (\text{m}^{-1})</td>
</tr>
<tr>
<td>gain full width half maximum (\text{FWHM})</td>
<td>100 nm</td>
</tr>
<tr>
<td>coupling coefficient (\kappa)</td>
<td>3500 (\text{m}^{-1})</td>
</tr>
<tr>
<td>facet reflectivity (power) (R_1, R_2)</td>
<td>0.3</td>
</tr>
<tr>
<td>facet reflectivity (phase) phase(R1, R2)</td>
<td>0 rad</td>
</tr>
</tbody>
</table>

\(g = \text{optical gain}; \ z_a = \text{absorption and scattering losses. The group velocity} V_p\) in eqn. 9 equals the light velocity in vacuum divided by the group refractive index \(\mu_g\). For the index grating, which will be our case in all the studied laser structures, \(\kappa_{FR}\) equals the complex conjugate of \(\kappa_{PR}\).

The simulation programme discretises the laser section into elements, solves the above equations for each element after putting it into the following matrix form:

\[
\begin{bmatrix}
F_{n,k+1} \\
R_{n,k+1}
\end{bmatrix}
= \frac{1}{\gamma \cosh(\gamma \Delta z) + (i\delta - g + z) \sinh(\gamma \Delta z)}
\begin{bmatrix}
\gamma & ik_{FR} \sinh(\gamma \Delta z) \\
ik_{PR} \sinh(\gamma \Delta z) & \gamma
\end{bmatrix}
\begin{bmatrix}
F_{n,k} \\
R_{n-1,k}
\end{bmatrix}
\]  

(10)

\[
\gamma^2 = (i\delta - g + z_a)^2 + \kappa_{FR} \kappa_{PR}
\]  

(11)

where the index \(n\) represents the element number and the index \(k\) the temporal step. The detuning factor \(\delta\) is given by:

\[
\delta = \frac{2\alpha d \Delta N(z, t) \Delta z}{a}
\]  

(12)

where: \(a = \text{differential gain}; \ \Gamma = \text{confinement factor}; \ \Delta z = \text{length of one discretised laser element}; \ z_a = \text{Henry's line-width enhancement factor}; \ N(z, t) = \text{carrier density}.

The optical gain \(g\) in the above equations is represented by:

\[
g = \frac{a \Delta N(z, t) - N_0}{2(1 + e P)}
\]  

(13)

where \(\epsilon\) is the nonlinear gain coefficient, \(N_0\) is the carrier density at transparency and \(P\) represents the photon density, which is proportional to the sum of the square of the travelling forward \((F(z, t))\) and backward \((R(z, t))\) waves. The variation in gain with carrier density is taken into account using eqn. 13. The variation in gain with frequency is modelled using a digital filter technique. The digital filter results in an approximately parabolic gain profile, whose width and centre frequency does not vary with carrier density in the model. The changes in refractive index are taken into account in the model by introducing a separate phase factor represented by the detuning factor \(\delta\) (eqn. 12) in the wave equation (eqn. 9) [11, 12].

The carrier density is calculated using the carrier rate equation:

\[
\frac{dN(z)}{dt} = J(z) - \frac{N(z)}{\tau} - BN(z)^3 - CN(z)^3 - \frac{N(z) - N_0}{1 + e P(z)}
\]  

(14)

where: \(N(z) = \text{carrier density; } J(z) = \text{injection current density; } d = \text{active layer thickness; } V_p = \text{group velocity in the active layer; } \tau = \text{linear recombination on time; } B = \text{biomolecular recombination coefficient; } C = \text{Auger recombination rate.}

In eqn. 14, the first term on the right refers to the injected carriers, the second term represents the nonradiative recombination, the spontaneous radiative emission is given by the third term, the fourth term represents the Auger recombination. The last term on the right-hand side of the carrier rate equation accounts for the stimulated emission rate.
4 Numerical modelling results and discussion

We started with a conventional FP laser whose cavity length is equal to 640 µm which is the value required for InP-based lasers to get a 60 GHz mode separation frequency (see eqn. 15).

\[
\Delta f = \frac{c}{2\mu_0 L_r} \tag{15}
\]

If we progressively introduce DFB sections into the laser cavity, keeping the FP section length constant, we could expect, from the previous discussion in Section 3, to relatively filter all modes except two modes per reflection comb (see Fig. 3). A filter whose bandwidth between nulls lies around (100–110 GHz) is quite suitable for only selecting two modes separated by 60 GHz. To achieve this target, we started by introducing three 10 µm long DFB sections into the cavity. This leads to a small filling factor (≈ 3/67). With a DFB section coupling coefficient of 35 cm⁻¹, the equivalent coupling coefficient will be small, so the product effective coupling coefficient-laser length will be such that tanh(\kappa L_r) can be approximated to \kappa L_r; it turns out that the main mode separation will be roughly independent of \kappa and strongly dependent on 1/L_r. Since the small DFB sections can be considered as perturbations for the FP cavity, we can expect to get an optical spectrum close to the one of FP laser besides some mode filtration due to DFB inserted sections (see Fig. 4). Due to these three DFB sections inserted into the FP cavity, we started to see two main significant modifications in comparison with the FP spectrum:

(i) the existence of two main modes which are periodically repeated;
(ii) the appearance of side modes at a much lower level (< −30 dB).

The two central main modes, as expected, have a frequency separation close to that given by the FP one, as is the case for the side modes. The lower level of the side modes is explained by the filtering effect of the DFB sections. The periodicity of the two main modes is consistent with eqn. 6.

Increasing the number of DFB sections to 5, the spectral periodicity \(S_p\) increases, since the frequency separation between the two main modes does not significantly change because the filling factor is still too small to influence on the mode separation frequency. However, the side modes have a lower frequency separation. This can be explained by considering the total SGDFB laser length as an FP structure for the side modes. This consideration is quite reasonable as the side modes lie outside the reflection filter bandwidth, so that they do not see the DFB sections. These DFB sections are transparent to the side modes and these modes will follow the classical FP modes (eqn 13) with \(L_r\) designating here the total SGDFB laser length. Increasing the number of DFB sections up to seven (see Fig. 4) leads to an optical spectrum with a periodicity of the two main modes around 420 GHz, according to eqn. 6. In Fig. 5 we show the simulated millimetre wave spectrum generated by mixing optical components of a SGDFB laser with 7 DFB sections of 10 µm each on a photodetector. The main line appears near 60 GHz, resulting from the beating of the two main central modes. The side modes are shown at 32 dB lower and are related to multiple beating between main and side modes. The effect of the 7 DFB sections is seen in Fig. 5 as we only have a single line located close to 60 GHz with a SMSR of 32 dB over approximately a 400 GHz frequency range. Concerning the RF signal linewidth, it was shown that this linewidth could be highly reduced using RF subharmonic electrical injection [7].

If now we start increasing the length of the DFB section per period \(L_r\) while keeping the number of the DFB sections constant (7 sections) and keeping the total FP length (640 µm) constant too (so the total laser length increases), we observe (Fig. 6) that the side modes separation increases following the conventional law (eqn 13). However, the two main modes separation frequency increases with the increase of the DFB section length. Recalling eqn 8, we realise that increasing the DFB section length \(L_r\) increases the filling factor which will consequently increase the effective coupling coefficient. According to eqn. 1, this will result in an increase in the frequency separation between the two main modes.

Fig. 4 Simulated optical spectrum of SGDFB structure including 5 DFB sections of 10 µm long each inserted into FP section

Fig. 5 Simulated RF beating of SGDFB structure including 7 DFB sections of 10 µm long each inserted into FP section

Fig. 6 Mode separation against increase in DFB section length \(L_r\)
This structure, constituted with alternating DFB (10 µm) and FP (80 µm) sections (Fig. 1), is not the only design or the optimal one able to emit two main modes separated by 60 GHz and based on the SGDFB laser. As the 60 GHz spacing is mainly decided by two parameters, we can find other combinations of laser length \( L \), and filling factor \( h \) satisfying the same 60 GHz mode separation. The other main design parameter that might also be taken into consideration is the dual mode repetition period \( \gamma \), which must be as large as possible so as to get a pure dual mode in a broader spectral window. Designing a laser with the same length (710 pm) and keeping the same main design parameter that might also be taken into consideration (AR)-coated facets (Fig. 1) will give a dual mode repetition frequency of around 4300 GHz, which will be attenuated by the material optical gain curve (Fig. 7). With this period we succeeded in getting a 60 GHz dual mode laser with 30 dB of SMSR over a spectral window of roughly 9000 GHz centred around the 1.55 µm. The previous mentioned designs had ending FP sections (see Fig. 1 with zero facet phase reflectivity (see Table 1). However, this could not be controlled, even obtained in real devices. This problem could be avoided by sandwiching the above structure between two 40 µm DFB sections with antireflection (AR)-coated facets (Fig. 1) these design has the advantage of selecting the two central modes of order \( 0 \) and rejecting all other main and side modes of higher order filters (Fig. 8). This is due to the reflection characteristics of the two ending DFB sections, which is a single reflection peak centred around the Bragg frequency. This reflection peak will only coincide with the SGDFB one of order \( 0 \). Consequently, we will only get the two central modes at the output. In this way we have coupled the advantage of the low coupling coefficient necessary for the 60 GHz dual modes using a suitable laser length via a SGDFB structure to the filtering effect of the DFB sections with AR-coated facets. The latter will give a single reflectivity peak centred around the Bragg frequency, which will enhance the central reflectivity of order \( 0 \) of the SGDFB laser while rejecting all neighbouring main and side modes resulting from higher order Fourier filters.

5 Conclusion

In this paper, we have investigated the possibility of using the SGDFB laser as an efficient source for dual mode optical generation through a single electrode and a constant sampled grating period. The influence of design parameters such as filling factor (ratio of DFB section length to sampled grating period), sampled grating period, laser length and cavity ending reflectivity has been investigated. As an example, we succeeded in designing a 60 GHz dual mode laser with a structure constituted of 7 DFB sections of 10 µm each inserted into a 640 µm FP laser giving a filling factor of 1/9 and ended with two AR-coated DFB sections, showing a dual side mode suppression ratio (D-SMR) of more than 35 dB, which is quite adequate for microwave signal generation. One of the main advantages of this laser structure is having DFB sections with practical coupling coefficients and a quite reasonable total laser length. All of the above mentioned advantages will encourage us towards a future fabrication of this device.

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7 References


