Biological Cell Imaging Using Coupled Laser Diode

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Abstract: The significance of this work is to exploit the advantage of longitudinal mode selectivity with asymmetrical construction of two laser cavities. Yet, the mode selectivity results from two sections laser structure can be used in biological cell imaging application where the cell can be detected if passed through. Therefore, a simulation is carried out to model coupled cavity laser for biological cell applications. As a result, wavelength resonance, gain threshold as well as mode life time are calculated. Moreover, the biological cell is considered in the modelling and the results are also presented. Such application can be extended for not only two section laser but also for M-section.

Key words: Laser diode · Biological cells · Coupled cavity · Coupled laser diode

INTRODUCTION

In the literature, there have been extensive studies of groove-coupled M-section lasers particularly; two sections laser [1-3]. It has been shown that such physical structure provides high spectral mode selectivity leading to single longitudinal mode operation of semiconductor laser. Single longitudinal mode operation of semiconductor laser is likely to be used in wavelength division multiplexing techniques [4, 5]. Moreover, single longitudinal mode laser produces high optical power which makes it suitable for long-haul fibre optical communication systems. It also minimizes the pulse broadening due to fiber dispersion.

The difference between simple Fabry-Perot laser and multisession laser is by adding a gap (or narrow groove) between the two successive sections. Insertion of the groove offers electrical (but not optical) isolation [6].

A laser is a powerful tool for large numbers of biomedical applications. In this paper, coupling of two optical laser diodes will be used to emit laser beams which will interact with a biological cell. The interaction of laser beam and biological cell exists in many forms. Thus, the effect of a biological cell on laser beam will be investigated by placing enucleated cell between the two laser beams.

The purpose of this paper is to develop a model incorporates modifications of coupled lasers by a biological cell as they pass through. The modifications are quite enough to determine biological changes accompanied with cell function and enough to be used as detection method. However, the study will mainly focus on the effect of cell and laser types on the two beams interaction with the biological material. After this investigation, the model will hopefully contribute in developing biological cell imaging. The stationary modes of a semiconductor laser will be investigated theoretically and the cavity modes will be calculated.

This paper is organized as follows. Following this introduction, the analysis of Coupled-Cavities Lasers is described and explained in detail in Section II. Then, the use of biological cell image detection is presented in Section III. Simulation results are presented and discussed. Conclusions are then presented.

Coupled-Cavities Lasers: The coupled cavity laser consists of at least two optical cavities each with a particular length (Z). Those cavities are isolated by the air gaps as shown in the Figure (1). The significance of the air gap is the mode selectivity. The number of laser modes (longitudinal modes) can be evaluated within a spectral region (wavelength range) where the optical cavity gain...
becomes larger than the losses [7]. Each mode has its own resonance wavelength and threshold gain which needs to be calculated. However, unlike Fabry-Perot cavities, the threshold gains and mirror life time of the coupled cavity laser are not constant and the mode spacing are not equal as will be shown from the results [8].

**Analysis of Two Section Lasers:** Starting from a Fabry-Perot resonator \((M=1)\) plane wave complex \(A_m\) and \(B_m\) \([4, 9, 10]\)

\[
E(z) = A_m \exp(-ik_mz) + B_m \exp(ik_mz) \tag{1}
\]

Similarly, the expression for the magnetic field is \([4, 9]\):

\[
H_m(z) = -\frac{k_m c}{\omega} A_m \exp(-ik_mz) + \frac{k_m c}{\omega} B_m \exp(ik_mz) \tag{2}
\]

where \(\omega\) is the light angular frequency and \(c\) the speed of light in vacuum.

The refractive index \(\eta_m\) describes phase propagation as follows:

\[
K_m = \frac{\omega}{c} (\eta_m + ik_m) \tag{3}
\]

where, \(c\) is the velocity of the light. The gain constant \(k_m\) accounts for amplifications and attenuation. It is positive for lossy media and negative for gain media. The amount of pumping controls the value of \(k_m\).

It has been assumed that the attenuation or gain in each section of the laser is homogeneous.

The resonance wavelength \(\lambda_n\) is related to the resonance frequency \(\omega_{mode}\) via this relation

\[
\omega_{mode} = \frac{2\pi c}{\lambda_n} = \frac{c}{\eta_l} \text{Re}\{K_1\} \tag{4}
\]

In order to achieve the lasing condition, the threshold gain that is needed to overcome the losses inside the cavity is described as

\[
K_1 = \frac{c \ln R}{\omega L} \tag{5}
\]

\(R\) denotes the intensity reflection coefficient

\[
R = \frac{(\eta_l - 1)^2}{(\eta_l + 1)^2} \tag{6}
\]
L is the cavity length and $n_1$ is the refractive index of cavity one

$$g_{th} = -2 \text{Im} \{ K_1 \}$$  \hspace{1cm} (7)

The lifetime of each optical mode can be evaluated using the following relation [4, 9]:

$$\frac{1}{\tau_l} = \frac{1}{\tau_{mir}} + \frac{1}{\tau_{abs}}$$  \hspace{1cm} (8)

where $\tau_{abs}$ is the scattering losses and are assumed to be equal for all mode, $\tau_{mir}$ is the mirror life time which will be calculated as follows

$$\tau_{mir} = \frac{\sum_{m=1}^{M} \int_{z_m}^{z_{m+1}} \langle U_m(z) \rangle \, dz}{\langle I \rangle}$$  \hspace{1cm} (9)

where $U_m$ is the energy densities and $\langle I \rangle$ is the time averaged energy flux density defined as

$$\langle I \rangle = \frac{2}{\epsilon_0} \frac{\mu_0}{\eta_0} \left( \eta_0 |A_0|^2 + \eta_{M+1} |A_{M+1}|^2 \right)$$  \hspace{1cm} (10)

where $\epsilon_0$ is the permittivity in free space and $\mu_0$ is the permeability in free space.

At the boundaries $z = z_m$. The boundary condition can be given as a matrix notation [9]:

$$\begin{pmatrix} A_{m+1} \\ B_{m+1} \end{pmatrix} = Q(z_m) \begin{pmatrix} A_m \\ B_m \end{pmatrix}$$  \hspace{1cm} (11)

where the transition matrix $Q(z_m)$ is given by [4, 9]:

$$q(z_m) = \begin{pmatrix} \frac{k_{m+1} + k_m e^{i(k_{m+1} - k_m)z_m}}{2k_{m+1}} & \frac{k_{m+1} - k_m e^{i(k_{m+1} - k_m)z_m}}{2k_{m+1}} \\ \frac{k_{m+1} - k_m e^{-i(k_{m+1} - k_m)z_m}}{2k_{m+1}} & \frac{k_{m+1} + k_m e^{-i(k_{m+1} - k_m)z_m}}{2k_{m+1}} \end{pmatrix}$$  \hspace{1cm} (12)

It has been assumed that no incoming waves existed. Therefore, for M boundaries [4, 9]

$$A_{m+1} = h_0 = 0$$

The transcendental matrix equation that governs a system with M element is generated as follows [4, 9]:

$$\begin{pmatrix} 0 \\ B_{m+1} \end{pmatrix} = Q(z_m)Q(z_{m-1})...Q(z_0)\begin{pmatrix} A_0 \\ 0 \end{pmatrix}$$  \hspace{1cm} (13)

Giving a discrete set of complex propagation constants $k_m$ (that characterise the modes), the solutions of this matrix equation can then be found [4, 11]. For each possible laser mode, the imaginary part of $k_m$ represents the threshold gain $g_m$ whilst the real part represents the mode spacing or the resonance frequency $\omega_m$. It is expected that for two sections and more the spacing between adjacent modes and the threshold gain varies from mode to mode.

**Method Description:** The presented model to discuss the laser action in two-section laser makes use of linear theory to obtain resonance frequencies and threshold gains for the modes of the two-section laser structure. It should be mentioned that the linear model describes the steady state behaviour only. The threshold wavelengths are first calculated by using bisection method without considering

![Fig. 3: Threshold and resonance wavelength for semiconductor laser with one section, $Z_1 = 308 \mu m$.](image-url)
gain or losses. Then, the gain threshold for each mode is calculated after adding absorption in the second cavity (or section two). The calculations of threshold gain are accomplished to give $B_i$ zero value.

The field amplitude density and the threshold gain for laser with only one section are depicted in Figure (3) and Figure (4), respectively. The results are taken in the wavelength range (1.3-1.35) µm. It shows that the equal gain threshold is exhibited for $Z_i=308$ µm.

**RESULTS**

The field amplitude density and the threshold gain for laser with section one are depicted in Figure (3) and Figure (4) in the wavelength range (1.3-1.35) µm, respectively. It shows that the equal gain threshold is exhibited for $Z_i=308$ µm.

The gain threshold and the resonance wavelength are depicted in Figure (5) with no absorption in cavity two is taken into account. It can be observed that the resonance wavelength spacing is not equal and the gain threshold differs from mode to mode. However, adding absorption in cavity two will alter the peak gain threshold as shown in Figure (6) and Figure (7). The values for $k_i$ are chosen as $-3.55 \times 10^{-3}$ and $-5 \times 10^{-3}$, respectively. It can be noted that the peak gain threshold reduces when $k_i$ varies from $-3.55 \times 10^{-3}$ to $-5 \times 10^{-3}$ which means that increasing the amount of absorption in cavity two results in decreasing the peak gain threshold.

In biological cell imaging, the tissue can be characterised by spatially dependent refractive index ($\eta$), where the imaginary part represents the absorption, as example for mitochondria (rat liver) the absorption is around (10-15) mm$^{-1}$ [12] and this value is considered to

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Fig. 4: Field intensity of semiconductor laser with one section, $Z_i=308$ µm.

Fig. 5: Gain threshold and resonance wavelength for two section laser, $k_i=0$
Fig. 6: Gain threshold and resonance wavelength for two section laser, $k = -3.55 \times 10^{-3}$

Fig. 7: Gain threshold and resonance wavelength for two section lasers, $k = -5 \times 10^{-3}$

Fig. 8: Gain threshold versus wavelength for $Z_1 = 1 \mu m$, $Z_2 = 10 \mu m$ and $k = -2.042 \times 10^{-3}$
Fig. 9: Life time versus wavelength for $Z_2 = 10 \mu m$, $Z_3 = 1 \mu m$ and $k = -2.042 \times 10^{-3}$

Fig. 10: Gain threshold versus wavelength for $Z_1 = 3 \mu m$, $Z_2 = 10 \mu m$ and $k = -2.042 \times 10^{-3}$

Fig. 11: Life time versus wavelength for $Z_1 = 3 \mu m$, $Z_2 = 10 \mu m$ and $k = -2.042 \times 10^{-3}$
be the imaginary part of the refractive index. In coupled cavity laser, the parameters in section two have been modified to describe a biological cell. Therefore, \( \eta_1 \) and \( k_3 \) are modified as \( \eta_1 = 1.38 \) and \( k_3 = 2.042 \times 10^{-3} \) which is equivalent to absorption constant 10 mm\(^{-1}\) for mitochondria (rat liver). After modifying the system parameters, the physical parameters such as \( Z_3 \) (cavity two length) needs to be adjusted to be comparable to the tissue dimensions. Consequently, \( Z_3 \) is varied from 1\( \mu m \) to 5\( \mu m \) and \( Z_2 \) is fixed at 10\( \mu m \) [12, 13].

The physical parameters of the two sections laser that have been used in the simulation are included in Table 2.

In Figures (8 – 12), the gain threshold and its corresponding life time are given for three different values of \( Z_2 \) with the same absorption. It can be observed from Figures 8, 10 and 12 that as the cavity length increases, the gain threshold increases. Also, the peak of the gain threshold is shifted to the right when \( Z_2 \) increased.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>value</th>
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</thead>
<tbody>
<tr>
<td>( Z_0 )</td>
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</tr>
<tr>
<td>( Z_1 )</td>
<td>308 ( \mu m )</td>
</tr>
<tr>
<td>( Z_2 )</td>
<td>50 ( \mu m )</td>
</tr>
<tr>
<td>( Z_3 )</td>
<td>70 ( \mu m )</td>
</tr>
<tr>
<td>( \eta_1 )</td>
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</tr>
<tr>
<td>( \eta_2 )</td>
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</tr>
<tr>
<td>( \eta_3 )</td>
<td>1</td>
</tr>
<tr>
<td>( \eta_4 )</td>
<td>3.5</td>
</tr>
<tr>
<td>( \eta_5 )</td>
<td>1</td>
</tr>
<tr>
<td>( k_3 )</td>
<td>-2.3 \times 10^{-4}, -3.55 \times 10^{-4} \text{ and } -5.3 \times 10^{-4}</td>
</tr>
</tbody>
</table>

On the other hand, Figures 9, 11 and 13 show that the life time difference between modes decreases with increasing \( Z_2 \), particularly when \( Z_2 \) exceeds 5\( \mu m \).

It should be pointed out that increasing the absorption losses into cavity two requires higher threshold gain to overcome these losses which, in turn, necessitates an increase in the laser threshold current. Thus, the laser can then be used as a detection of biological cells.
CONCLUSIONS

The focus of this paper has been the study of the biological cell detection using coupled cavity semiconductor laser. The proposed model incorporates modifications of coupled lasers by a biological cell as they pass through. The coupled cavity laser has been analyzed and presented. Then biological cell imaging is characterized by its own absorption coefficient has been tested and the resultant resonance wavelength and its corresponding threshold gain have been investigated. The proposed model is not restricted to two-section semiconductor laser; it can be extended and well applied to cope with multi-sections laser.

REFERENCES