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Time Domain Dynamic Analysis of a 1550 nm Monolithic Two-section Mode Locked MQW Laser

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Abstract

In this study, time domain dynamic model of a mode locked two-section DBR laser was presented. Short duration and high power optical pulse generation from a semiconductor laser was obtained by using this model. For this aim, one of the laser sections acting saturable absorber was reverse biased while the other section called gain section was forward biased with a DC current. This method is called passive mode locking. A semiconductor laser biased in this way can produce mode locked pulses by adjusting reverse and forward bias.

Simulation results demonstrate that the mode locked semiconductor laser used in this study can produce optical pulses with picosecond duration.

Keywords: Semiconductor Lasers, Passive Mode Locking, Laser Time Domain Dynamic Model, DBR Mirror, Short Duration Optical Pulse Generation.

1. Introduction

Semiconductor lasers are the lasers in which a p-n junction forms gain medium and population inversion is obtained by forward biasing of this p-n junction.

Semiconductor lasers (diode lasers) are widely used in the fields such as optical communication systems, optical recorder and reading systems (like CD, DVD etc.), medical applications, defense systems, solid state laser drivers, luminous pointers and scientific measurement systems. In optical communication systems, semiconductor lasers with low power and threshold current about 20-80 mA are used. Low power lasers of which threshold current is between 20-80 mA are generally used for optical communication.

Nowadays mostly used wavelengths for optical communication systems are about 1300 nm and 1550 nm (D, S, C, L bands) (GRAY 1994; RABLAU 2010).

With increasing information traffic, faster, more efficient and higher capacity communication systems are needed. Because of this, for developing high capacity optical systems with low cost and low energy consumption, semiconductor lasers which can work at high temperatures, high speeds and low threshold currents without cooling are required (NAKAMURA *et al.* 2005).

Various multisection semiconductor laser configurations were proposed for different purposes. Gain and absorption in a semiconductor are dependent on carrier concentration non-linearly. By applying various voltages to the sections of a semiconductor laser, different carrier concentrations are created and thus, gain and absorbance can be controlled easily. Reverse biased laser sections act as absorber and fulfill the mission of saturable absorber used in solid state, gas and dye lasers (VASIL'EV 1995).

Short duration and high power optical pulses are required for various applications like low loss fiber optical communication, integrated optical circuits, optical switches, free space communication, LIDAR applications, sensing, spectroscopy. Optical pulse durations can be shortened by reducing dispersion generated in the laser cavity. Bragg and chirped mirrors forming negative dispersion can be used for this purpose. Due to high reflectivity of these mirrors, optical feedback in the laser cavity is improved that leads to enhancement of the laser performance.

With mode locking technique, the shortest optical pulses are generated from semiconductor lasers. As known, a typical laser cavity can support multiple modes simultaneously. All modes in the laser spectrum are made co-phased with mode locking technique.

In active mode locking, loss and gain of the laser cavity are modulated at frequency equal to frequency difference between two neighboring modes. In this

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method, duration of the laser driving current is chosen equal to round trip time of the light in the cavity to create gain for very short time. In this way, carrier concentration in the cavity can exceed necessary threshold value for a very short time and short duration optical pulses are generated.

Passive mode locking technique can be applied on multisection semiconductor lasers. In passive mode locking, one or more sections of the laser are reverse biased. Owing to these sections, saturable absorbers are created. Recovery time of these saturable absorbers are very fast and due to this, loss in the cavity is made bigger than the gain except peak point of the optical pulse. Thus, only peak of the optical pulses are amplified and other parts of the pulses are attenuated. There are several theoretical and experimental studies examining mode locking in the literature.

Traveling wave model were used to model various lasers. In a study, stability, pulse duration and limits of the pulse repetition rate of a monolithic mode locked laser were investigated using traveling wave model (WILLIAMS *et al.* 2004). In the study maden by HASLER (HASLER *et al.* 2005), a distributed Bragg reflector (DBR) laser with a saturable absorber produced better optical pulses with a laser configuration in which saturable absorber was formed on the front side of the laser. AVRUTIN AND PORTNOI (2008)'s theoretical study showed that carrier transport time was increased by increasing thickness of the confinement layer and thus, shorter duration and more stable optical pulses can be generated.

Several experimental studies were carried out to obtain short duration optical pulses with mode locking. SCHWERTFEGER *et al.* (2007) fabricated a 10 mm length, 920 nm DBR heterostructure laser and obtained optical pulses with 7 ps full width at half maximum (FWHM) and 3.6 W peak power at 4.1 GHz repetition rate. Larson *et al.* (2007) generated 3.7 ps duration and 10 mW average power optical pulses from a DBR AlGaInAs-InP laser by using mode locking. MALDONADO-BASILIO *et al.* (2010) compared various mode locked semiconductor laser cavities and showed that output power of passive mode locked laser can be increased with increasing longitudinal mode number. Many studies were performed to generate short duration and high power optical pulses with mode locking. AKBAR *et al.* (2011) achieved to generate 4 ps duration and over 550 mW peak power optical pulses from a 1.55 μm AlGaInAs/InP laser with an integrated optical amplifier by using passive mode locking technique. HOU *et al.* (2013) generated 3.19 ps duration pulses at 40 GHz repetition rate and 155 mW average power by using a 1.55 μm AlGaInAs/InP laser with DBR mirrors formed monolithically by surface etching.

In this study, simulation of a 1550 nm monolithic two-section DBR multi quantum well (MQW) laser was performed and output of the laser dependent on various parameters were investigated. Coupled traveling wave equations were used for the simulation of the laser. Studies achieved for similar structures were utilized to determine laser parameters. Besides, the effects of wavelength and reverse voltage on laser parameters and on laser output were taken into account (ZHANG *et al.* 1994; YU and BIMBERG 1995; CAKMAK 2006).

In the first two sections of this study, coupled traveling wave equations and laser structure used for the simulation were discussed in detail. Parameters used in the simulations were explained in the third section. The fourth section presents the simulation results obtained. Finally, the paper concludes with conclusion section.

2. Time Domain Dynamic Model of the Mode Locked Laser

Time and position dependent modeling techniques may be needed to analyze short duration optical pulses generated from semiconductor lasers with mode locking. For this purpose, traveling wave equation, in which optical mode in a cavity is combination of forward and backward propagating waves, can be used (WILLIAMS *et al.* 2004). If envelopes of back and forth propagating waves are changing slowly, time and position dependent traveling wave equations,

$$\frac{1}{v_g}\frac{\partial F(t,z)}{\partial t}+\frac{\partial F(t,z)}{\partial z}=(g-i\delta-\alpha_i)F(t,z)+i\kappa R(t,z)+s_f \qquad (1-a)$$

$$\frac{1}{v_g}\frac{\partial R(t,z)}{\partial t}-\frac{\partial R(t,z)}{\partial z}=(g-i\delta-\alpha_i)R(t,z)+i\kappa F(t,z)+s_r \qquad (1-b)$$

where F and R are the slowly varying complex envelope amplitudes for the forward and reverse optical fields (AVRUTIN *et al.* 2000). In these equations, v_g, g, α_i, δ, κ and s_f and s_r are the group velocity of optical pulse, the local gain, the local loss, the detuning factor, the coupling parameter and the spontaneous emission noise, respectively. These equations take into account only waves in propagation direction and neglect waves in other directions (WILLIAMS *et al.* 2004).

For absorber section $-g$ is used instead of g in Equation 1a and 1b. Also, κ is only included in the solution for the grating sections or the absorber section of colliding mode locking lasers if dynamic grating effect is taken into account.

Equations 2a and 2b refer gain and absorbance dependent on carrier and photon densities at gain and absorber sections of the laser, respectively.

$$g(N) = \frac{\Gamma g_G[n_t - N(t,z)]}{2(1+\varepsilon_G P(t,z))} \qquad (2-\mathrm{a})$$

$$g(N) = \frac{\Gamma g_A[N(t,z) - n_t]}{2(1+\varepsilon_A P(t,z))} \qquad (2-\mathrm{b})$$

In these equations, Γ, $g_{G/A}$, n_t, $\varepsilon_{G/A}$, N and P are the confinement factor, the differential gain constant in gain and absorber sections, the transparency carrier density, the gain compression factors in gain and absorber sections and the carrier and photon densities, respectively. Photon density can be calculated by Equation 3.

$$P(t,z)\ |F(t,z)|^2 + |R(t,z)|^2 \qquad (3)$$

Detuning factor is calculated by Equation 4.

$$\delta\ \frac{2\pi}{\lambda_0}\left(\eta_{eff}(t,z) - \eta_0\right) \qquad (4)$$

λ_0 and η_{eff} represent lasing wavelength and effective refractive index, respectively. η_0 is the refractive index at $N(t,z)=n_t$. Relation between lasing wavelength and period of the grating shown by Λ is

$$\Lambda = \frac{p\lambda_0}{2\eta_0} \qquad (5)$$

where p is an integer indicating degree of the grating. Effective refractive index can be calculated by Equation 6.

$$\eta_{eff}(t,z) = \eta_0 - \frac{\lambda_0}{4\pi}\Gamma\alpha_H g_G[N(t,z) - n_t] \qquad (6)$$

In equation 6, α_H shows linewidth enhancement factor. Spontaneous emission noises used in Equations 1a and 1b should be random. Gaussian distributed complex expressions providing following equations can be used as noise terms.

$$\langle s(t,z)s(t,z')\rangle = 0 \qquad (7-\mathrm{a})$$

$$\langle s(t,z)s^*(t,z')\rangle = \sqrt{\beta KBN^2 / v_g L} \qquad (7-\mathrm{b})$$

Noise terms for forward and backward propagating wave equations can be considered as equal. In these equations, β, K, B and L are the spontaneous emission, the Petermann factor, the Bimoleculer radiative recombination coefficient and the cavity length, respectively.

Laser model is completed by adding following equations to traveling wave equations given by Equations 1a and 1b. Equations 8a and 8b show carrier rate equation for gain and absorber sections, respectively.

$$\frac{\partial N(t,z)}{\partial t} = \frac{I}{eV} - \frac{N(t,z)}{\tau_G} - \frac{2v_g P(t,z)g}{\Gamma} \qquad (8-\mathrm{a})$$

$$\frac{\partial N(t,z)}{\partial t} = -\frac{N(t,z)}{\tau_A} + \frac{2v_g P(t,z)g}{\Gamma} \qquad (8-\mathrm{b})$$

In these equations, I, e, V and $\tau_{G/A}$ are the laser driving current, the electron charge, the active layer volume and the carrier lifetime at the gain and absorber sections. The carrier lifetime at the gain section is

$$\tau_G = (A + BN(t,z) + CN(t,z)^2)^{-1} \qquad (9)$$

where A and C refer nonradiative and Auger recombination coefficients, respectively (ADAMS *et al.* 1987; ZHANG *et al.* 1994; ZHU *et al.* 1997; AVRUTIN *et al.* 2000; WILLIAMS *et al.* 2004; ZATNI *et al.* 2004).

3. *Laser Structure*

Simulated laser structure is shown in Figure 1, absorber and gain sections are created by reverse and forward biasing of the absorber and gain contacts, respectively. DBR mirror in front of the ridge waveguide generates negative dispersion and increases feedback to enhance laser output.

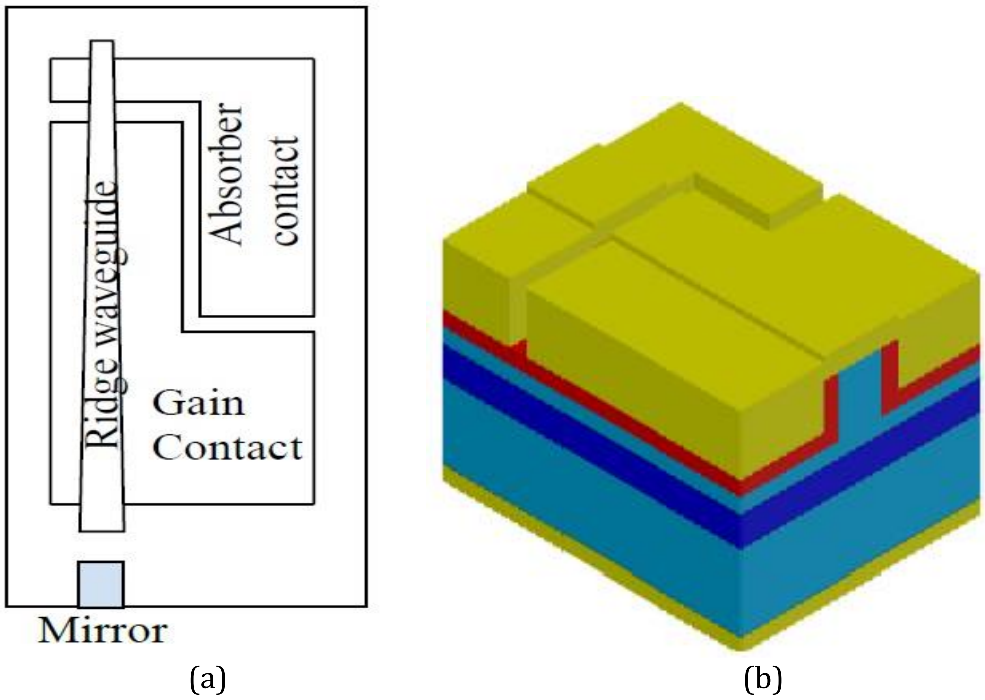


Figure 1. Schematic (a) and 3D (b) view of the multisection laser.

4. Simulation

The relatively slow temporal variation in the carrier density rate equation permits integration by either first-order Newton-Raphson or Runge–Kutta techniques (WILLIAMS *et al.* 2004).

Parameters used in the simulation of the mode locked semiconductor laser were taken from some studies using similar semiconductor laser structures (ZHANG *et al.* 1994; YU and BIMBERG 1995; CAKMAK 2006).

A logarithmic relationship was used for the carrier lifetime at the absorber section dependent on the applied reverse bias. Also g_G/ε ratio was considered roughly constant for the absorber and gain sections thus the gain compression factor in the gain section was used to calculate gain compression factor in the absorber section

Some of the parameters used in the simulation are listed in Table 1 (KARIN *et al.* 1994; JONES *et al*. 1995). Experimental results obtained from a similar material structure were used to calculate effective refractive index and linewidth enhancement factor dependent on the wavelength and reverse bias (FELLS 1995; ZHU *et al.* 1997).

The parameters listed at Table 1 were used to model gain, absorber and DBR sections of the laser, separately. In the model, the gain and absorber sections were considered forward and reverse biased, respectively and DBR section was considered unbiased. The simulation results using this model show that the mode locked semiconductor laser can produce self-generated ultra-short optical pulses. Full width at half maximum (FWHM) of these pulses were measured and the effects of some parameters on the optical pulses were examined.

Firstly, laser driving current was changed and it was seen that FWHM value decreased with increasing driving current. In Figure 2, FWHM values with increasing laser driving currents are shown while absorber reverse bias is kept at 0.8V.

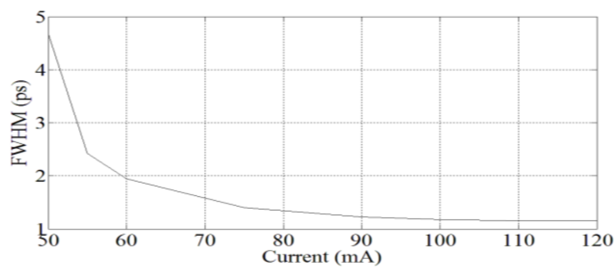
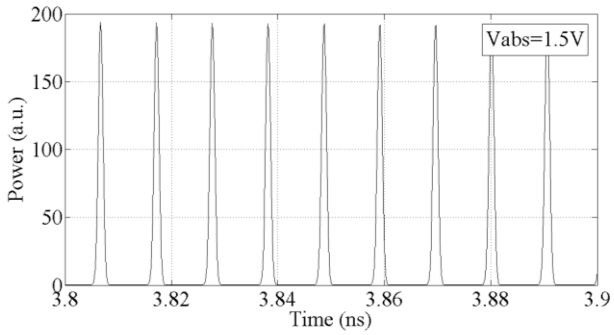


Figure 2. Variation of FWHM value with laser driving current

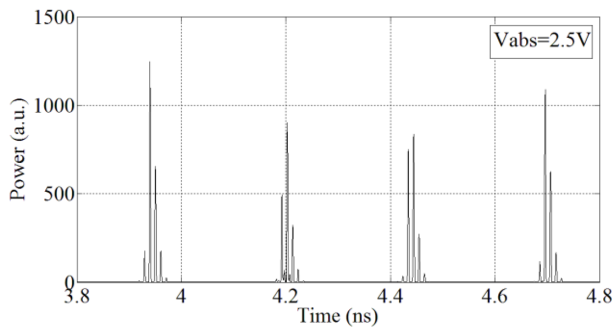
Table 1. Some parameters used for simulating semiconductor laser.

Parameter	Symbol	Value
Length of gain section	L_G	372μm
Length of absorber section	L_A	30μm
Length of DBR mirror	L_M	30μm
Width of active layer	W	4μm
Thickness of active layer	d	0.18μm
Lasing wavelength	λ_0	1.55μm
Refractive index at transparency	η_0	3.283
Petermann factor	K	1
Confinement factor	Γ	0.35
Spontaneous emission factor	β	10^{-4}
Carrier density at transparency	n_t	$1.2\text{x}10^{-24}$ m^{-3}
Differential gain constant	g_G	$2.5\text{x}10^{-20}m^{-1}$
Gain compression factor	ε_G	$3\text{x}10^{-23}$ m^3
Local loss	α_i	$4000m^{-1}$
Nonradiative carrier recombination coefficient	A	$1\text{x}108s^{-1}$
Bimoleculer radiative recombination coefficient	B	$1\text{x}10^{-16}m^3s^{-1}$
Auger recombination coefficient	C	$3\text{x}10^{-41}m^6s^{-1}$
Coupling parameter	κ	7400

Subsequently, absorber parameters dependent on the reverse biased voltage applied to the absorber section were investigated. It was seen that carrier lifetime at the absorber section decreased with increasing reverse bias voltage. After the carrier lifetime fell under a critical value, optical pulse train starts to self-modulate and laser output exhibited an unstable characteristic. The instability is shown in Figure 3. It was also observed that linewidth enhancement factor of the optical pulses was dependent on this bias voltage. FWHM value of the optical pulses varies parallel to the variations of the linewidth enhancement factor.



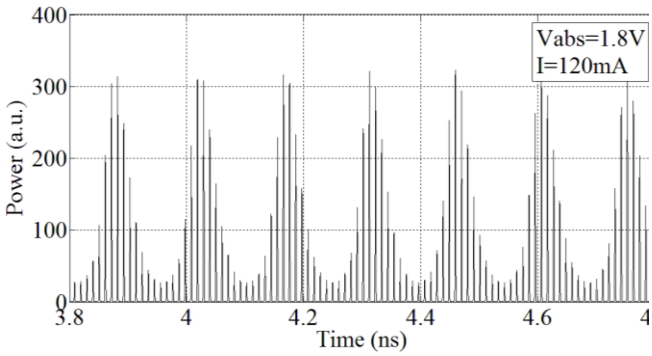
(a)



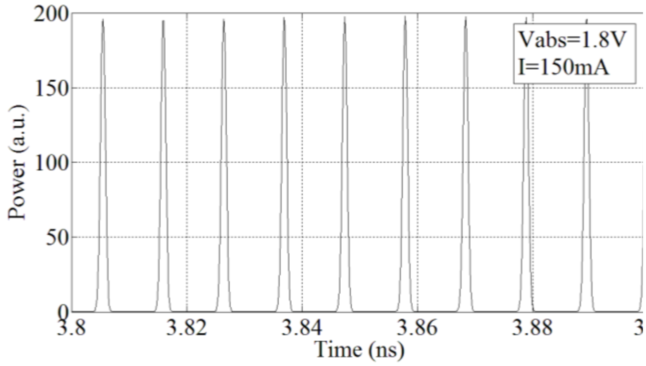
(b)

Figure 3. Variation of optical pulses with reverse bias voltage applied to absorber section (a) V_{abs}=1.5V (b) V_{abs}=2.5V

By increasing laser driving current applied to the laser gain section, this instability can be prevented. In Fig 4, transition from instability to stability by increasing the laser driving current is shown.



(a)



(b)

Figure 4. Transition from instability to stability by increasing the laser driving current (a) I=120mA (b) I=150mA

6. *Conclusion*

In this study, time domain dynamic model of a mode locked two-section DBR laser was obtained. Simulation results showed semiconductor laser used in this study can produce picosecond duration optical pulse train by using passive mode locking.

It was seen that FWHM values of the pulses decreased with increasing laser driving current. It was also observed that the reverse voltage applied to laser absorber section similarly influences on linewidth enhancement factor at this section and FWHM values of the pulses. Simulation results showed a reduction in the carrier lifetime in the absorber section with increasing reverse bias voltage applied to the absorber section. After the carrier lifetime fell under a critical value, optical pulse train started to self-modulate and thus, laser output exhibited an unstable characteristics. The instability was prevented by increasing laser driving current.

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