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Comparative theoretical investigation of passively mode-locked diode lasers with different cavity configurations

Farklı kavite konfigürasyonlarına sahip pasif mod kilitli diyot lazerlerin karşılaştırmalı teorik incelenmesi

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Abstract

In this study, modelling results of 1550 nm AlGaInAs/InP passively mode-locked semiconductor lasers with two gain sections and one absorber section are reported using propagation wave equations according to different lengths and positions of the these sections. Comparative results of output power, carrier number and pulse width of three section semiconductor lasers are obtained using different cavity lengths. It has been found that three-section lasers with a longer first gain section have higher output power of 920 mW and shorter pulse durations of approximately 1.57 ps. When the current and voltage are kept constant, higher output power and higher electric field are obtained as the cavity length gets shorter.

Keywords: Multisection laser diode, Modeling, Passively mode locking

Öz

Bu çalışmada, iki kazanç bölümü ve bir soğurucu bölümü olan 1550 nm AlGaInAs/InP pasif mod kilitli yarı iletken lazerlerin modelleme sonuçları, bu bölümlerinin farklı uzunluk ve konumlarına göre ilerleyen dalga denklemleri kullanılarak raporlanmaktadır. Üç bölümlü yarı iletken lazerlerin çıkış gücü, taşıyıcı sayısı ve darbe genişliğinin karşılaştırmalı sonuçları, farklı kavite uzunlukları kullanılarak elde edildi. Birinci kazanç bölümü daha uzun olan üç bölümlü lazerlerin, 920 mW'lık daha yüksek çıkış gücüne ve yaklaşık 1,57 ps'lik daha kısa darbe sürelerine sahip olduğu bulunmuştur. Akım ve gerilim sabit tutulduğunda kavite uzunluğu kısaldıkça daha yüksek çıkış gücü ve elektrik alan elde edilir.

Anahtar kelimeler: Çok bölmeli lazer diyot, Modelleme, Pasif kip kilitleme

1 Introduction

Semiconductor lasers are extremely small photonic devices emitting lasing radiation [1]. Mode-locked diode lasers have been recognized as potentially favorable for a wide variety of applications that offer technically stable and cost-effective ultrashort pulse sources with high repetition rates which are well-suited for telecommunications and optical sampling [2–5]. For telecommunication applications, threshold current of InGa(Al)As(P)/InP 1300–1550 nm lasers have been suitable for many years [6]. Mode-locking is a technique used in optics by which a laser generates ultra-short duration pulses in picoseconds or less by inducing a constant phase relationship between the modes of the cavity [7]. Passively mode-locked lasers, one of the mode-locking techniques have often been used to produce pulses of very short durations of the order of picosecond [8]. The design of ultrashort pulse lasers is quite complex and generally exhibit low average power levels [9]. However, in passively mode-locked technique, the gain section of the laser is biased with forward current, while the absorber is biased with the reverse voltage [10]. Multisection mode-locked semiconductor lasers are often preferred because they provide higher output power than single-section lasers. Passively mode-locked diode lasers may be integrated into photonic circuits, thereby obtaining on chip sources of multiple phase-locked optical wavelengths. These which achieve repetition rates (RR) in terahertz frequency ranges and high pulse energy, are important in fields such as microwave photonics [11], optical fiber communications [12], optical division multiple access systems [13]. The advantage of passively mode-locked diode lasers is that they basically require only fixed current and voltage sources for the device to generate the pulsed signal [14]. Passively mode-locked diode lasers can generate low output powers of a few milliwatts. To increase the output power, lengths of the gain or absorber regions and the cavity length can be manipulated.

In our study, we presented variations of output power and pulse width of a 1550 nm AlGaInAs/InP passive mode-locked diode laser depending on different cavity lengths. We also compared the pulse widths by examining the effect of the output power and the number of carrier according to the different lengths of the gain and absorber regions.

2 Theoretical analyses

2.1 Travelling wave equations

Modelling of mode-locked ultra-short optical pulses requires the use of time and location-dependent travelling wave equations (equations 1 and 2). Travelling wave equations, in which consist of forward (F) and reverse (R) traveling waves in a cavity, can be defined as [15],

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

$$+s_f(z,t)$$

$$\frac{1}{v_g}\frac{\partial R(t,z)}{\partial t}-\frac{\partial R(t,z)}{\partial z}=(g-i\delta-\alpha_i)R(t,z)+i\kappa\,F(t,z) \qquad (2)$$

$$+s_r(z,t)$$

where v_g is the group velocity of the optical pulse which is described as the velocity with which the envelope of an optical pulse propagates in a medium, g is the local gain, α_i is the local loss, δ is the detuning factor, κ is the coupling parameter and $s_{r,f}$ is the spontaneous emission noise [16]. Carrier rate (N) equations for absorber and gain sections are defined as,

$$\frac{\partial N(t,z)}{\partial t}=\frac{I}{eV}-\frac{N(t,z)}{\tau_G}-\frac{2v_gP(t,z)\,g}{\Gamma} \qquad (3)$$

$$\frac{\partial N(t,z)}{\partial t}=-\frac{N(t,z)}{\tau_A}+\frac{2v_gP(t,z)\,g}{\Gamma} \qquad (4)$$

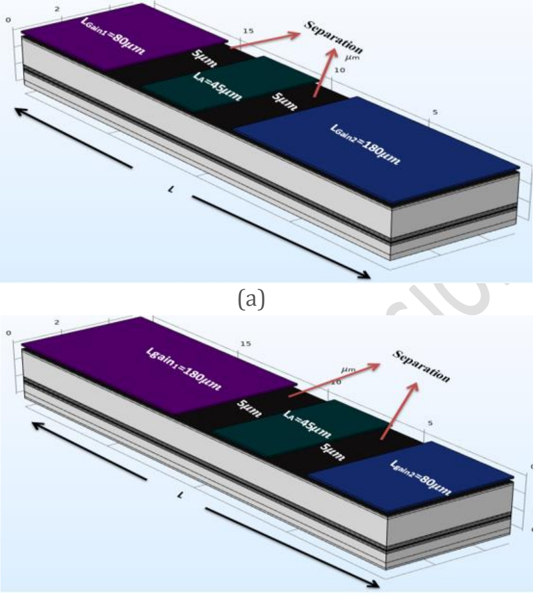
In the given equations, I, e, Γ, P, V and $\tau_{(G/A)}$ are the laser driving current, the electron charge, the confinement factor, the photon density, the active layer volume and the carrier lifetime at the gain and absorber sections, respectively.

Table 1. Constants and laser parameters used for modelling

PARAMETER	SYMBOL	VALUE
Spontaneous emission factor	β_{sp}	10^{-3}
Length of $gain_1$ section	L_{G1}	80 μm
Length of $gain_2$ section	L_{G2}	180 μm
Length of absorber section	L_A	45 μm
Active-region width	w	5 μm
Active-layer thickness	d	0.2 μm
Confinement factor	Γ	0.3
Effective mode index	$\overline{\mu}$	3.4
Group refractive index	μ_g	4
Linewidth enhancement factor	β_c	5
Facet loss	α_m	45 cm^{-1}
Internal loss	α_{int}	40 cm^{-1}
Gain constant	a	$2.5x10^{16}cm^2$
Carrier density at transparency	n_o	10^{18} cm^3
Nonradiative recombination rate	A_{nr}	10^8 s^{-1}
Radiative recombination coefficient	B	10^{-10} cm^3/s
Auger recombination coefficient	C	$3x10^{-29}$ cm^6/s
Wavelength	λ	1550 nm

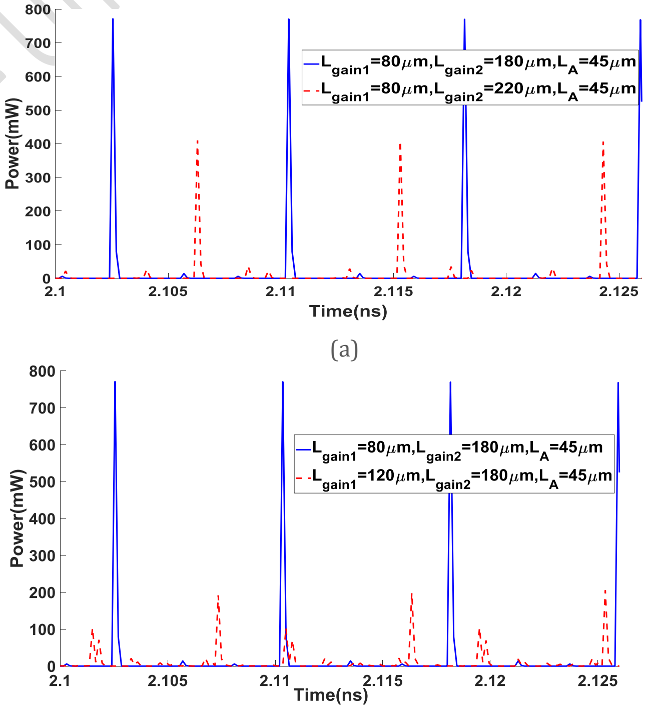
3 **Numerical** results of diode lasers

The constants and laser parameters determined in the modeling in our study are shown in Table 1 [16]. Two different configurations were used in modeling as seen in Figure 1 in which gain sections have different lengths while the absorber section has the same length of 45 μm. The total cavity lengths for all modeling includes a separation length of 10 μm. The cavity lengths are kept constant at 315 μm. Variations of the power versus time are shown in Figure 2.



(b)

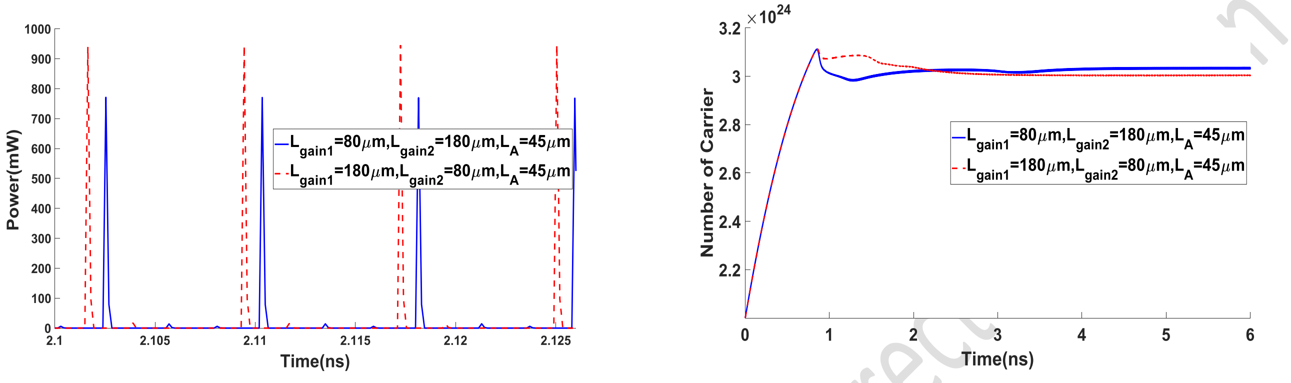
Figure 1. Different forms of modeled passively mode-locked diode lasers: (a) L_{gain1}= 80μm, L_{gain2}= 180μm and L_A = 45μm, (b) L_{gain1}=180μm, L_{gain2}=80μm, L_A=45μm. Cavity length L is 315μm for both cases.



(b)

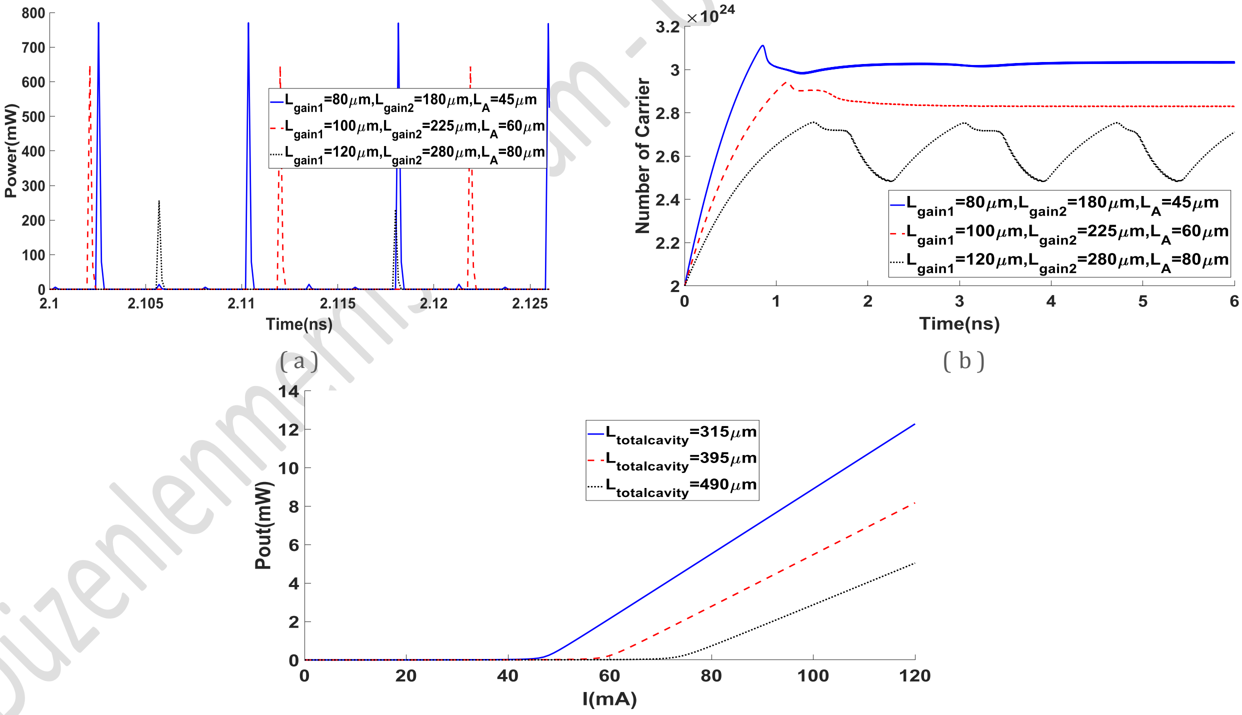
Figure 2. a) Variation of power versus time for L_{gain1}=80μm, L_{gain2}=180μm, L_A=45μm (blue solid line, cavity length L=315 μm) and L_{gain1}=80 μm, L_{gain2}=220 μm, L_A=45μm (red dashed line, cavity length=355 μm), b) variation of power versus time for L_{gain1}=80 μm, L_{gain2}=180 μm, L_A=45μm (blue solid line, cavity length L=315 μm) and L_{gain1}=120 μm, L_{gain2}=180 μm, L_A=45μm (red dashed line, cavity length L=355 μm). I=120 mA and V=-0.5 V for all.

In Figure 2(a), it is seen that the output power decreases if the length of the second gain section is increased while keeping fixed the length of the first gain section and the absorber region, without changing the cavity length in which the current applied is 120 mA and the reverse voltage is -0.5 V in both cases. However, as seen in Figure 2 (b), when the current, voltage and cavity lengths are kept constant, the output power dramatically decreases if the length of the first gain region is increased without changing the length of the second gain and absorber regions. Thus, it turns out that to increase the output power, it is required to increase the length of the first gain section while decreasing second gain region. While the cavity length is fixed at 315 µm, passively mode-locked diode laser with the first gain section longer than the second one has higher output power (Figure 3 (a)). The same pulse width of 1.57 ps is obtained for both cases. This could be because more carriers are formed initially, as seen in Figure 3(b).



(a) (b)

Figure 3. a) Variation of power versus time for L_{gain1}=80 µm, L_{gain2}=180 µm, L_A=45µm (blue solid line, cavity length L =315 µm) and L_{gain1}=180 µm, L_{gain2}=80 µm, L_A=45µm (red dashed line, cavity length L=315 µm), b) the number of carriers versus time for L_{gain1}= 80µm, L_{gain2}= 180µm, L_A=45µm (blue solid line) and L_{gain1}= 180µm, L_{gain2}=80µm, L_A=45µm (red dashed line). I=120mA and V=-0.5 V for all.

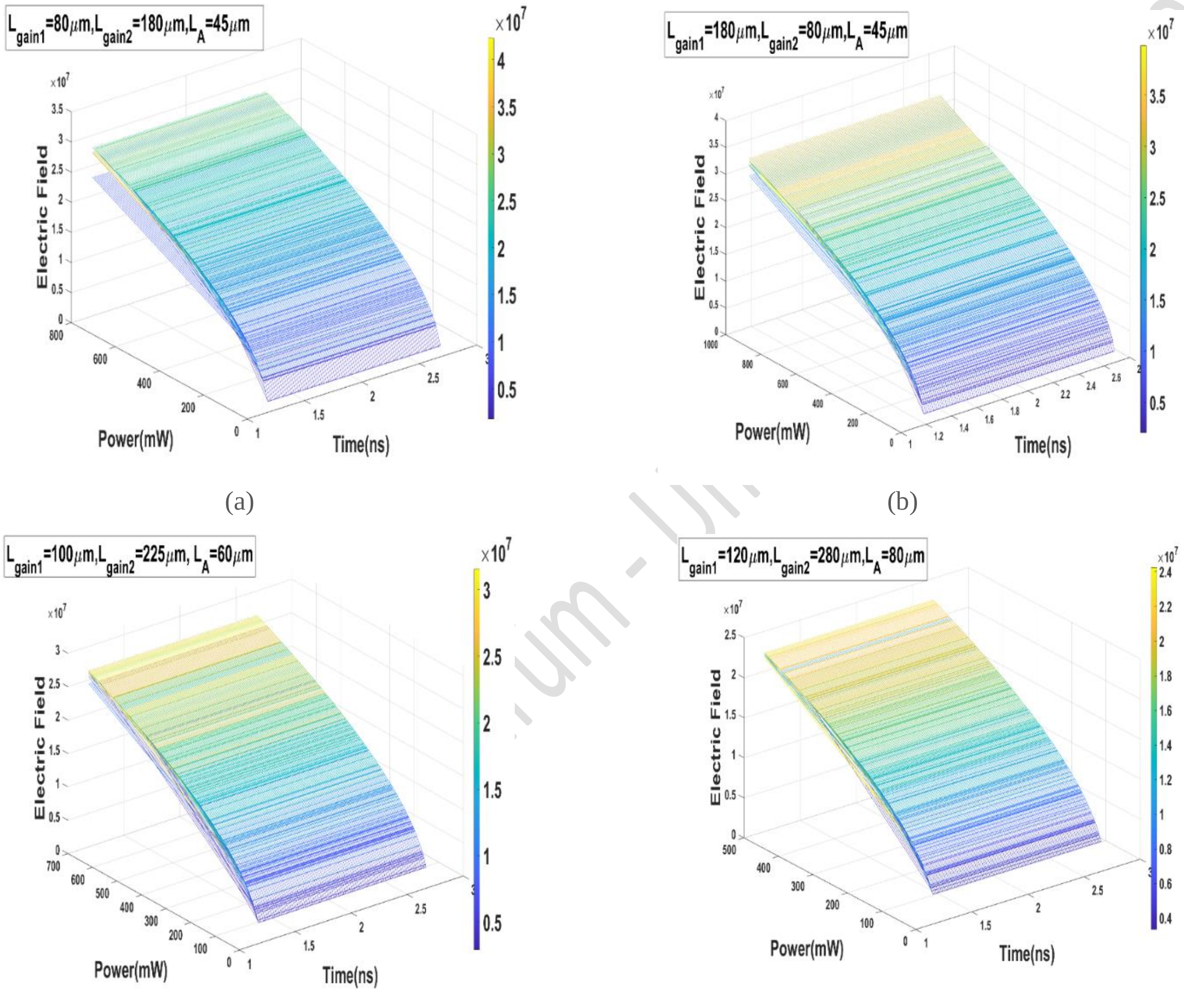


(a) (b)

(c)

Figure 4. a) Variation of power versus time for $L_{gain\,1}$= 80µm, $L_{gain\,2}$= 180µm, L_A =45µm (blue solid line, cavity length L=315 µm) and L_{gain1}=100µm , $L_{gain\,2}$=225µm and L_A = 60µm (red dashed line, cavity length=395 µm) and L_{gain1}=120µm, $L_{gain\,2}$ = 280µm and L_A = 80µm (black dashed line, cavity length L=490 µm), (b) the number of carriers versus current in which the section lengths are the same as that of (a). I=120 mA and V=-0.5 V for all, (c) Variation of L–I characteristics for cavity length L=315 µm (blue solid line), cavity length L=395µm(red dashed line) and cavity length L= 490µm (black dashed line).

Fİgure 4 demonstrates the variation of output power and carrier density versus time for different cavity lengths of laser with different gain and absorber section lengths. As seen in Figure 4, when the lengths of the gain and absorber regions are increased up to one and a half times for all cases, the output power decreases while no change is observed in the pulse width. It should be noted that it is advantageous to keep the overall cavity length shorter to produce ultrashort duration pulses. In Figure 4(a), the laser with the shortest cavity length (L_{gain1}=80µm, L_{gain2}=180µm, L_A=45µm, L=315 µm) has higher output power of 800 mW than that of the other configurations. For L_{gain1}=100 µm, L_{gain2}=225 µm and L_A=60 µm, the output power is obtained to be approximately 600 mW at L=395 µm.



(a) (b)

(c) (d)

Figure 5. Variation of power and electric field versus time, (a) L_{gain1}= 80µm, L_{gain2}=180µm and L_A =45µm at a cavity length of 315 µm, b) L_{gain1}=180µm, L_{gain2} =80 µm and L_A= 45µm at cavity length of 315 µm, c) L_{gain1}=100µm , L_{gain2}=225µm and L_A = 60 µm at a cavity length of 395 µm, (d) L_{gain1}=120µm , L_{gain2} =280 µm and L_A =80µm at a cavity length of 490 µm. I = 120mA and V = - 0.5V for all.

In Figure 5, power and electric field versus time values are obtained depending on the different cavity lengths, while the applied current and voltage are kept constant. It was observed that the electric field and power decrease as the cavity length increases. As seen in Figure 5(a) and (b), the electric field and power are higher in the device with the shortest cavity length of 315 µm. However, as seen in Figure 5(a) and (b), the three-sections laser with L_{gain1} = 180µm , L_{gain2} = 80µm and L_A = 45 µm has a higher output power and the electric field is also obtained to be higher.

4 Conclusions

In this study, a three-section passively mode-locked diode laser consisting of two gain and one absorber regions is studied theoretically using traveling wave equations.

Depending on the various lengths of the gain and absorber regions, variation of the output power, density and pulse width versus time was obtained by varying the cavity lengths. When the applied voltage and current are kept constant and, lengths of the these regions are increased, it is observed that the output power decreases while the pulse width does not change. It implies that it is advantageous to keep the cavity length shorter to generate high power, high electric field and ultrashort pulses. When the current and reverse voltage are kept constant at 120 mA and -0.5 V respectively, the lasers with a longer first gain section than the second one have higher initial number of carriers that lead to higher output power with about 920 mW and pulse durations of 1.57 ps. To conclude, our model demonstrates that the lasers with longer first gain section can be preferred to obtain higher output powers and shorter pulse durations.

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6 Author contribution statements

Author 1 performed the analysis, and Author 1 and Author 2 contributed to the evaluation of the results of this analysis and to the editing of the text.

7 Ethics committee approval and conflict of interest statement

There is no ethical committee approval and no conflict of interest with any person/institution for the submitted publication.

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