



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

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

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,  $\alpha_i$  is the local loss,  $\delta$  is the detuning factor,  $\kappa$  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,

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

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

In the given equations,  $I$ ,  $e$ ,  $\Gamma$ ,  $P$ ,  $V$  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.

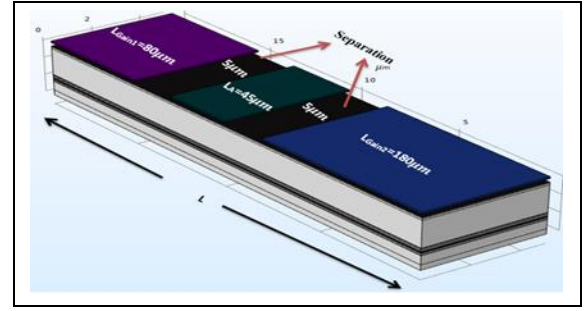
### 3 Numerical results of diode lasers

The constants and laser parameters determined in the modeling in our study are shown in Table 1, [16].

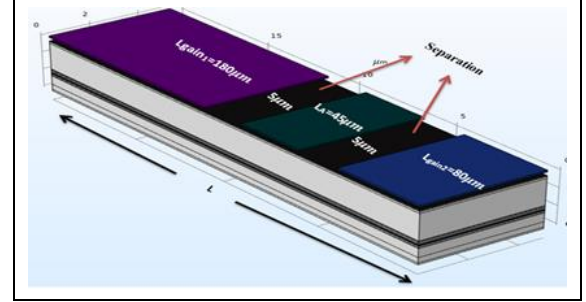
Table 1. Constants and laser parameters used for modelling.

Parameter	Symbol	Value
Spontaneous emission factor	$\beta_{sp}$	$10^{-3}$
Length of gain <sub>1</sub> section	$L_{G1}$	80 $\mu\text{m}$
Length of gain <sub>2</sub> section	$L_{G2}$	180 $\mu\text{m}$
Length of absorber section	$L_A$	45 $\mu\text{m}$
Active-region width	$w$	5 $\mu\text{m}$
Active-layer thickness	$d$	0.2 $\mu\text{m}$
Confinement factor	$\Gamma$	0.3
Effective mode index	$\mu$	3.4
Group refractive index	$\mu_g$	4
Linewidth enhancement factor	$\beta_c$	5
Facet loss	$\alpha_m$	45 $\text{cm}^{-1}$
Internal loss	$\alpha_{int}$	40 $\text{cm}^{-1}$
Gain constant	$a$	$2.5 \times 10^{16} \text{ cm}^2$
Carrier density at transparency	$n_o$	$10^{18} \text{ cm}^{-3}$
Nonradiative recombination rate	$A_{nr}$	$10^8 \text{ s}^{-1}$
Radiative recombination coefficient	$B$	$10^{-10} \text{ cm}^3/\text{s}$
Auger recombination coefficient	$C$	$3 \times 10^{-29} \text{ cm}^6/\text{s}$
Wavelength	$\lambda$	1550 nm

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  $\mu\text{m}$ . The total cavity lengths for all modeling includes a separation length of 10  $\mu\text{m}$ . The cavity lengths are kept constant at 315  $\mu\text{m}$ . Variations of the power versus time are shown in Figure 2.

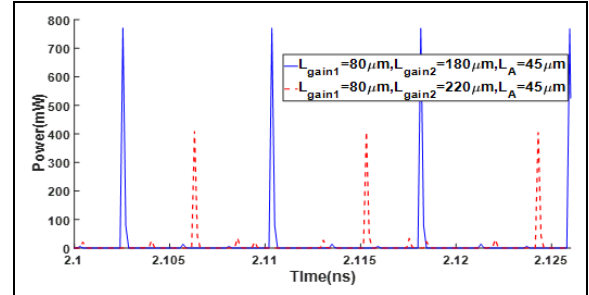


(a)

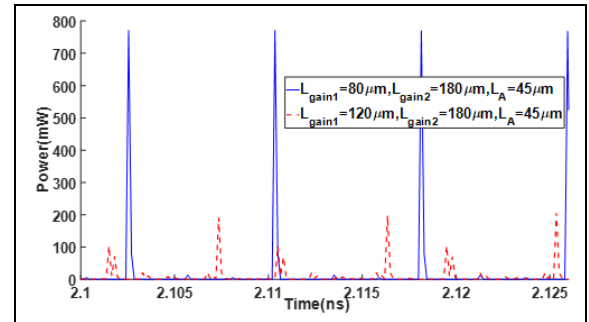


(b)

Figure 1. Different forms of modeled passively mode-locked diode lasers. (a):  $L_{\text{gain}1} = 80 \mu\text{m}$ ,  $L_{\text{gain}2} = 180 \mu\text{m}$  and  $L_A = 45 \mu\text{m}$ , (b):  $L_{\text{gain}1} = 180 \mu\text{m}$ ,  $L_{\text{gain}2} = 80 \mu\text{m}$ ,  $L_A = 45 \mu\text{m}$ . Cavity length  $L$  is 315  $\mu\text{m}$  for both cases.



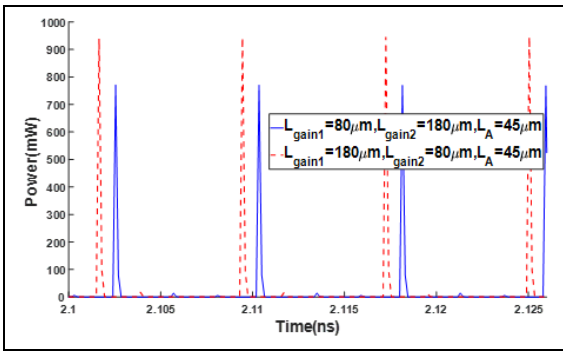
(a)



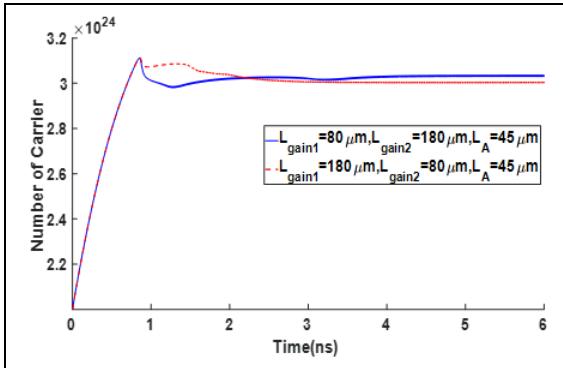
(b)

Figure 2(a): Variation of power versus time for  $L_{\text{gain}1} = 80 \mu\text{m}$ ,  $L_{\text{gain}2} = 180 \mu\text{m}$ ,  $L_A = 45 \mu\text{m}$  (blue solid line, cavity length  $L = 315 \mu\text{m}$ ) and  $L_{\text{gain}1} = 80 \mu\text{m}$ ,  $L_{\text{gain}2} = 220 \mu\text{m}$ ,  $L_A = 45 \mu\text{m}$  (red dashed line, cavity length  $L = 355 \mu\text{m}$ ), b) variation of power versus time for  $L_{\text{gain}1} = 80 \mu\text{m}$ ,  $L_{\text{gain}2} = 180 \mu\text{m}$ ,  $L_A = 45 \mu\text{m}$  (blue solid line, cavity length  $L = 315 \mu\text{m}$ ) and  $L_{\text{gain}1} = 120 \mu\text{m}$ ,  $L_{\text{gain}2} = 180 \mu\text{m}$ ,  $L_A = 45 \mu\text{m}$  (red dashed line, cavity length  $L = 355 \mu\text{m}$ ).  $I = 120 \text{ mA}$  and  $V = -0.5 \text{ V}$  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  $\mu\text{m}$ , 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)

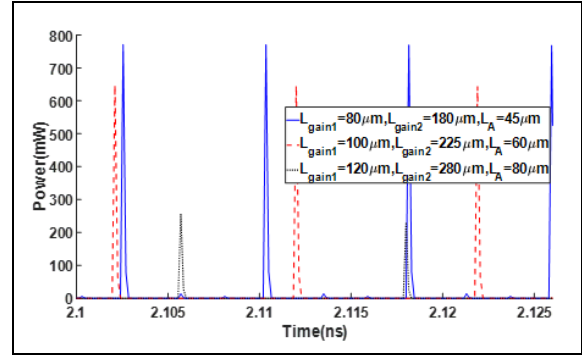


(b)

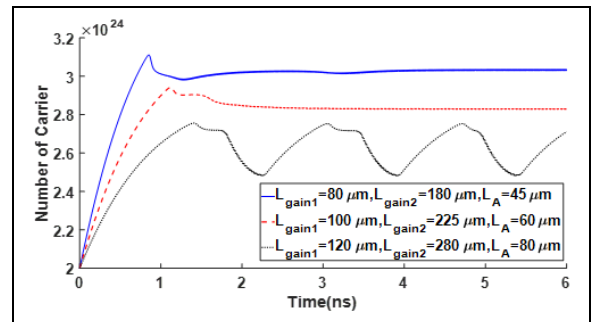
Figure 3(a): Variation of power versus time for  $L_{\text{gain1}}=80 \mu\text{m}$ ,  $L_{\text{gain2}}=180 \mu\text{m}$ ,  $L_A=45 \mu\text{m}$  (blue solid line, cavity length  $L=315 \mu\text{m}$ ) and  $L_{\text{gain1}}=180 \mu\text{m}$ ,  $L_{\text{gain2}}=80 \mu\text{m}$ ,  $L_A=45 \mu\text{m}$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

Figure 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 ( $L_{\text{gain1}}=80 \mu\text{m}$ ,  $L_{\text{gain2}}=180 \mu\text{m}$ ,  $L_A=45 \mu\text{m}$ ,  $L=315 \mu\text{m}$ ) has higher output power of 800 mW than that of the other configurations.

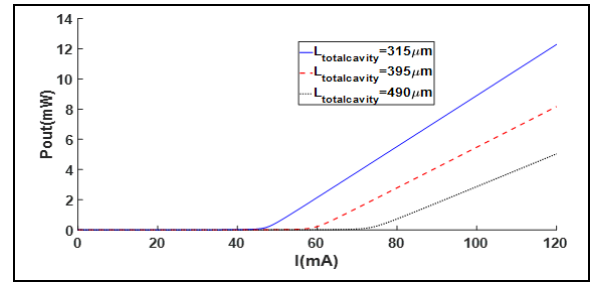
For  $L_{\text{gain1}}=100 \mu\text{m}$ ,  $L_{\text{gain2}}=225 \mu\text{m}$  and  $L_A=60 \mu\text{m}$ , the output power is obtained to be approximately 600 mW at  $L=395 \mu\text{m}$ .



(a)



(b)



(c)

Figure 4(a): Variation of power versus time for  $L_{\text{gain1}}=80 \mu\text{m}$ ,  $L_{\text{gain2}}=180 \mu\text{m}$ ,  $L_A=45 \mu\text{m}$  (blue solid line, cavity length  $L=315 \mu\text{m}$ ) and  $L_{\text{gain1}}=100 \mu\text{m}$ ,  $L_{\text{gain2}}=225 \mu\text{m}$  and  $L_A=60 \mu\text{m}$  (red dashed line, cavity length  $L=395 \mu\text{m}$ ) and  $L_{\text{gain1}}=120 \mu\text{m}$ ,  $L_{\text{gain2}}=280 \mu\text{m}$  and  $L_A=80 \mu\text{m}$  (black dashed line, cavity length  $L=490 \mu\text{m}$ ), (b): The number of carriers versus current in which the section lengths are the same as that of (a):  $I=120 \text{mA}$  and  $V=-0.5 \text{V}$  for all, (c): Variation of L-I characteristics for cavity length  $L=315 \mu\text{m}$  (blue solid line), cavity length  $L=395 \mu\text{m}$  (red dashed line) and cavity length  $L=490 \mu\text{m}$  (black dashed line).

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  $\mu\text{m}$ . However, as seen in Figure 5(a) and (b), the three-sections laser with  $L_{\text{gain1}}=180 \mu\text{m}$ ,  $L_{\text{gain2}}=80 \mu\text{m}$  and  $L_A=45 \mu\text{m}$  has a higher output power and the electric field is also obtained to be higher.

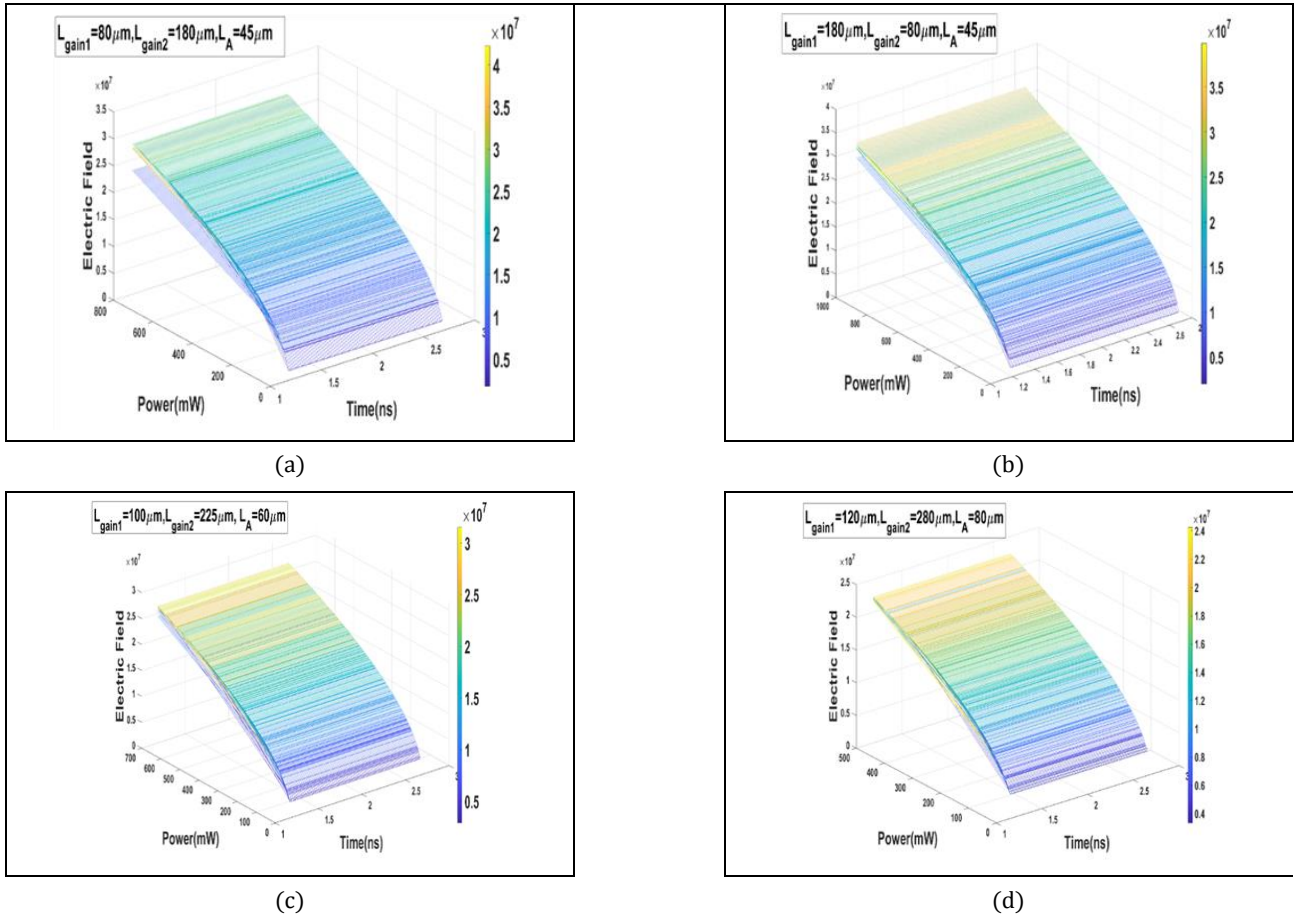


Figure 5. Variation of power and electric field versus time. (a):  $L_{\text{gain1}}=80\mu\text{m}$ ,  $L_{\text{gain2}}=180\mu\text{m}$  and  $L_A=45\mu\text{m}$  at a cavity length of 315  $\mu\text{m}$ . (b):  $L_{\text{gain1}}=180\mu\text{m}$ ,  $L_{\text{gain2}}=80\mu\text{m}$  and  $L_A=45\mu\text{m}$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

#### 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

Rukiye AKSAKAL performed the analysis, and Rukiye AKSAKAL and Bülent ÇAKMAK 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

"Ethics committee permission is not required for the article prepared".

"There is no conflict of interest with any person/institution in the article prepared".

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