Materials Physics and Mechanics 29 (2016) 71-75 Received: October 26, 2016

INFLUENCE OF ABSORBER CHARACTERISTICS ON OPERATION REGIMES OF PASSIVE MODE LOCKED LASERS BASED ON InGaAlAs/InGaAs/InP HETEROSTRUCTURES

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Abstract. Using developed theoretical model of mode synchronization in semiconductor passively mode locked laser (PMLL) we have calculated influence of length and relaxation rate of saturable absorber (SA) on operation regimes of PMLL. We included in consideration the influence of emission rate of free carriers from the levels of dimensional quantization in the SA and found out the optimum operating voltage for PMLL in the fundamental synchronization mode (one harmonic component) as -1.5 – -2 V with optimal length of the SA as 0.637 mm.

1. Introduction

Passively mode locked lasers (PMLLs) provide the generation of the picosecond optical pulses and can be used as optical clock for transmitting signals in fiber-optic systems. PMLLs are also utilized in photonic analog-to-digital (PADC) converters for sampling of microwave signals. The main advantage of PMLL is high stability of the pulse repetition rate providing a small aperture jitter error in PADC [1]. Semiconductor lasers allow to make PMLL with small size, low power consumption and low threshold current. To realize passive mode locking (PML) semiconductor laser should have a nonlinear optical element which cuts off a laser modes and absorbs the light. This nonlinear element calls saturable absorber (SA) and can be fabricated by a controlled input of saturable defects into the laser cavity, for example, using ion implantation [2], or by applying a negative bias voltage on part of laser [3]. In our work semiconductor PMLL consisted of two sections i.e. gain section and negatively biased SA, both made of the same material (Fig. 1). SA plays a critical role in PML because duration and shape of output optical pulses strongly depend on energy relaxation rate and parameters of SA. The aim of this work was to study the characteristic of PMLLs based on InGaAlAs/InGaAs/InP heterostructure varying length and relaxation rate of the SA.

2. Theoretical model, structure description

Recently we have suggested and developed a model of PML for laser with quantum wells (QWs) as active region. The model was described in detail in [4]. The model described the change of electromagnetic field in time and space was based on the traveling wave equations with proper boundary and initial conditions. Using approximation of slowly varying amplitudes of the electromagnetic field the model determined the density of photons and electrons in SA and gain section at any given time. The model showed the dynamics of the laser output during setting of PML as well. Within the framework of the developed model, we examined saturation and relaxation processes of SA by varying length and negative bias. The simulated stripe laser based on heterostructure consisted of 5 InGaAs QWs with 3.47 nm thickness and InGaAlAs barriers with 10 nm thickness grown on InP substrate [5, 6]. As stated earlier, the PMLL consisted of two sections - SA $0 \le z \le l_a$, where l_a was the length of SA and gain section $l_a \le z \le L$, where L was the total cavity length (TCL) equaled to 4.55 mm what is corresponds to pulse repetition rate of 10 GHz.

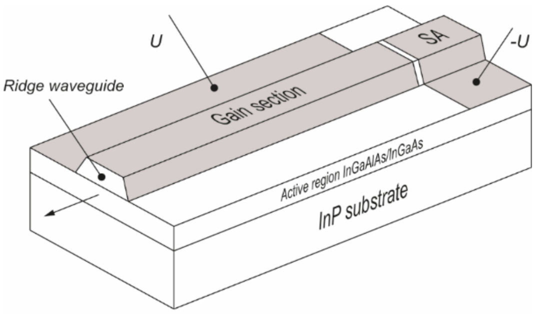

Fig. 1. Layout view of PMLL.

Rate equations are presented below and taking into account the injection of carriers in the ground state of QW, recombination losses and the interaction with the optical field through the induced transitions:

$$\frac{\partial n(z,t)}{\partial t} = \frac{I}{eV} - An - Bn^2 - Cn^3 - v_g \sigma_g (n - n_t)(\left|E^+(z,t)\right|^2 + \left|E^-(z,t)\right|^2); \tag{1}$$

$$\frac{\partial n(z,t)}{\partial t} = -Dn - v_g \sigma_a (n - n_t)(\left|E^+(z,t)\right|^2 + \left|E^-(z,t)\right|^2), \tag{2}$$

where n is injected carrier density, e is electronic charge, V is volume of active region, σ_a, σ_g are the differential absorption and gain, A is nonradiative recombination ratio, B is radiative recombination ratio, C is Auger recombination coefficient, D is SA relaxation rate, I is pumping current, n_t is transparency carrier density, v_g is group velocity, $E^+(z,t)$ и $E^-(z,t)$ are amplitudes of wave moving in opposite directions. Equation (1) was related to the gain section where injection of free carriers took place. Equation (2) was written for the SA under negative bias. It should be noted that the free carrier density in the gain section is always higher than the transparency carrier density 10^{18} cm^{-3} and is always lower in the SA and only in the case when the free carrier density reached the transparency carrier density the SA becomes fully transparent and we get a ultrashort laser pulse at the output.

The relaxation time of the SA is well described by formula (3) in the framework of the theory of thermionic emission [7, 8]:

$$\tau_a = \sqrt{\frac{2\pi m^* L_w{}^2}{k_B T}} \exp\left(\frac{E_b - \dfrac{L_w e(\left|U\right| + V_{bi})}{2d}}{k_B T}\right), \tag{3}$$

where m^* is effective mass, L_w is QW thickness, k_B is Boltzmann's constant, T is temperature, E_b is energy barrier for electron, V_{bi} is the built-in potential, d is thickness of depletion region, U is negative bias on the SA. The relaxation rate of the SA entering the equation (2) is equal to the reciprocal of relaxation time: $D = \tau_a^{-1}$. The parameters of the simulated structure are presented in the Table 1.

Table 1. The parameters of the simulated structure.

№	Name	Notation	Value	Dimension
1	Effective mass	m^*	$0,035m_0$	g
2	Total cavity length (TCL)	L	0,455	cm
3	SA length	l_a	3…20% L	cm
4	QW thickness	L_w	$3,47\ 10^{-7}$	cm
5	Energy barrier for electron	E_b	0,28	eV
6	Built-in potential	V_{bi}	0,8	eV
7	Depletion region thickness	d	$60\ 10^{-17}$	cm
8	Transparency carrier density	n_t	10^{18}	cm^{-3}
9	Differential gain	σ_g	$4\ 10^{-16}$	cm^2
10	Differential absorption	σ_a	$2\ 10^{-15}$	cm^2
11	Nonradiative recombination ratio [9]	A	$2\ 10^8$	s^{-1}
12	Radiative recombination ratio [9]	B	$0,96\ 10^{-10}$	cm^3/s
13	Auger recombination coefficient [9]	C	$7\ 10^{-29}$	cm^6/s
14	Bias voltage on the SA	U	-0,5…-4	V
15	Volume of active region	V	$1,7\ 10^{-10}$	cm^{-3}
16	Pumping current	I	0,2	A

3. Results and discussion

At the first stage, we varied the length of the SA in a wide range from 3 to 20 % of the TCL. The simulation results are shown in Fig. 2. We observed a multimode laser operation regime in the case of small lengths of the SA between 3 to 10 % of the TCL. For practical use it was crucial for PMLL to have a single ultrashort pulse at the output, so having two or even four (in case of 3-5 % of the TCL) pulses is a negative effect. This regime was realized due to incompetence of insertion losses (internal absorption) of the SA. In proper regime the SA should absorb the modes with small amplitude and thus formed a single ultrashort pulse in the cavity. When all of the QWs in the SA section became exited there was a single ultrashort laser pulse at the output. In the case of a short SA length the amount of free levels were not enough to absorb all longitudinal modes except one and at the output there were more than one pulse (Fig. 2a,b). The optimum SA length for the simulated structure was found to be 12-14 % of the TCL when laser generates one ultrashort pulse (Fig. 2c). Further increasing the SA length leads to high insertion losses and there was no any ultrashort pulse in the laser cavity (Fig. 2d).

At the second stage we calculated the SA relaxation rate and time in depending on the value of negative bias. Negative bias was varied from 0.5 V to -4 V and the SA relaxation rate was calculated using formula (3) and was in the range of $10^{10} – 10^{14}$ cm^{-1}. The simulation results are presented in Figs. 3 and 4.

Negative bias increased the SA relaxation rate and leaded to increasing of escape rate of free carriers from the levels of dimensional quantization in the SA. When value of negative bias was not large enough (higher -1V) the ultrashort pulses were not generated (Fig. 3a) because it was impossible to achieve a transparency carrier density in the SA section (Fig. 4a). Upon reaching -1V the escape rate of free carriers from levels of dimensional quantization in QWs in the SA was not fast enough that is leading to formation of 2 ultrashort (about 2 ps) laser pulses in the cavity (Fig. 3).

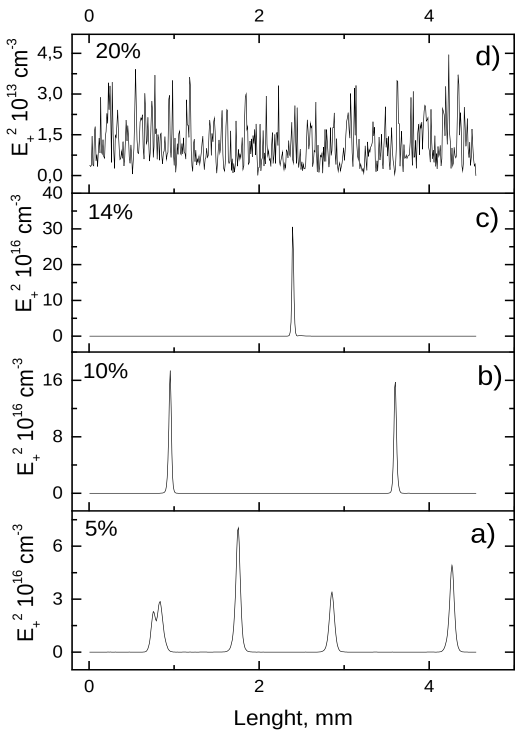

Fig. 2. The dependence of the photon density in the cavity on the SA length expressed in percentage of the TCL when the negative bias on the SA was - 1.5 V.

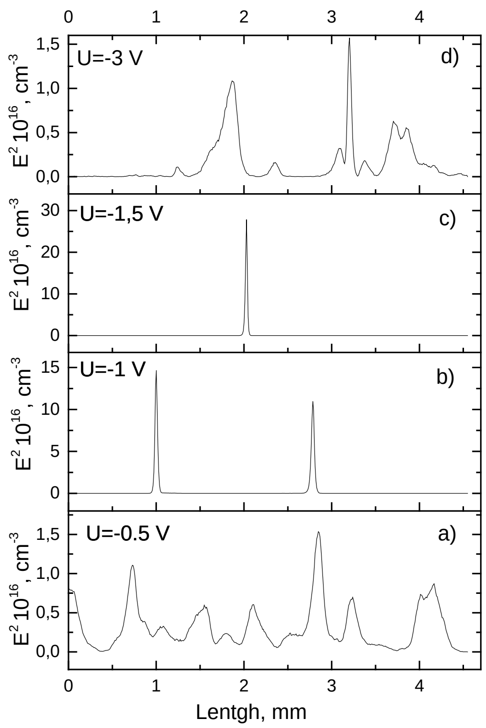

Fig. 3. The dependence of the photon density in the cavity on negative bias on the SA when its length is equal to 14 % of the TCL

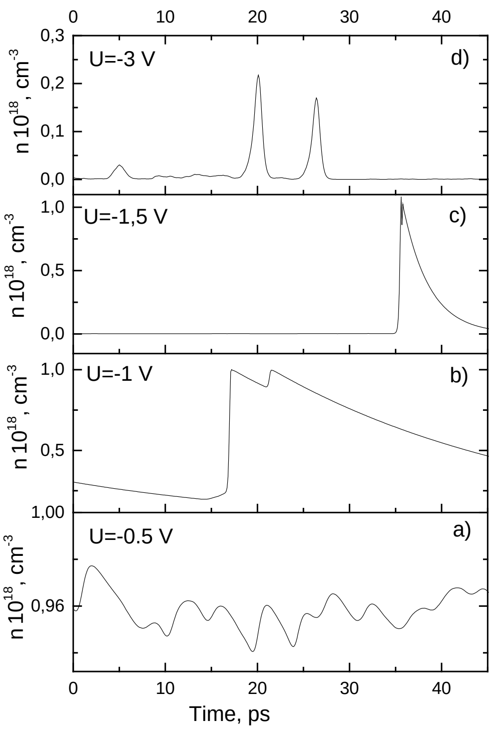

Fig. 4. Dynamics of electron density relaxation in the SA on various negative bias on the SA when its length is equal to 14 % of the TCL

In the bias values from -1.5 V to -2.5 V the SA relaxed fast enough and there was only one ultrashort pulse in the cavity (see Fig. 3c) forming and the SA saturated up to a transparency threshold density (Fig. 4c) in this case. When the bias values was lower -3 V the escape speed of free carriers from the SA was too large and the SA had no time enough to saturate (Fig. 3d).

Thus optimum length of the SA was 12-14 % of TCL (4.55 mm) or 0,546 - 0,637 mm. Optimum operating voltage at the SA lied in the range of -1,5 to -2 V.

The results of the work were obtained using computational resources Peter the Great Sainte-Petersburg Polytechnic University Supercomputing Center.

4. Conclusions

We numerically simulated influence of the SA parameters on characteristics of PMLL based on InGaAlAs/InGaAs/InP heterostructure. It was found that for the simulated structure the optimum length of the SA is 0,546 - 0,637 mm. We have shown that the PML fundamental regime can be achieved when bias voltage on the SA is from -1,5 to -2 V.

Acknowledgment

This work was supported by the Ministry of Education and Science of the Russian Federation in the framework of the Federal Target Program "Research and development on priority directions of scientific-technological complex of Russia for 2014-2020", the code 2015-14-582-0038, agreement № 14.581.21.0013 of August 4, 2015, unique ID RFMEFI58115X0013.

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