Simulation of synchronized laser radiation in bichromatic emitter

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Many problems in spectroscopy and remote sensing require the use of a bichromatic emitter – pulsed laser source of two-frequency radiation – with minimum time mismatch between pulses. The attempt is undertaken to reveal the influence of the parameters of a bichromatic emitter and their fluctuations on this mismatch and to find the ways to minimize it by means of computer simulation of generation evolution in the emitter.

Introduction

Some fields of laser spectroscopy, such as differential lidar absorption methods, CARS, delayed and multipulse interference, require the use of a double-pulse two-frequency laser source with a narrow spectrum and frequencies ν_1 and ν_2 tunable within the absorption line profiles of a substance under study. The efficiency can be sufficiently high, if pulses markedly overlap in time. At the same time, for activation of spin-orbital interaction in molecules by the field of optical biharmonic,[1] overlapping should be almost complete to ensure the constant, in time, ratio between radiation intensities at the two frequencies. This imposes far more strict restrictions on the laser emitter.

Such emitters are often controlled by electrooptical Q-switches with a photoelectric cross feedback.[2–4] Thus, generated pulses are "fixed," to a certain extent, to each other. At the same time, the attempts to obtain fully coincident pulses for sufficiently long time of laser operation (tens of minutes) fail, as a rule: pulses detune and the mean time ΔT between pulse peaks is from 1/3 to 1/4 of a pulse duration.

The aim of this paper is to develop computer programs for estimating, by numerical simulation, the influence of the instability of emitter parameters causing the time mismatch of laser pulses and to determine the conditions under which this mismatch can be minimized.

Model of emitter

We analyzed the operation of an emitter[4] (Fig. 1) consisting of two similar Nd:YAG lasers with 850-mm long cavities joined by a positive cross feedback. This feedback is intended for minimizing the interval ΔT between pulse peaks of these lasers. The cross feedback affects the processes in lasers by means of photoelectric control of the Q-switch transmittance in the first laser in response to changes in the output intensity of the second laser and vise versa. The transmittance S_i of the electrooptical Q-switch in the ith laser, as a function of the intensity q_j of radiation of the jth laser, achieves sequentially the threshold values, by which the control circuit of the Q-switch of the ith laser changes its state from P_{1i} to P_{2i}. This process is shown in Fig. 2 with the allowance made for the time lag inherent in control circuits *5* (see Fig. 1). The cross feedback provides acceleration of lasing evolution in the "lagging" laser and thus shortens the interval ΔT.

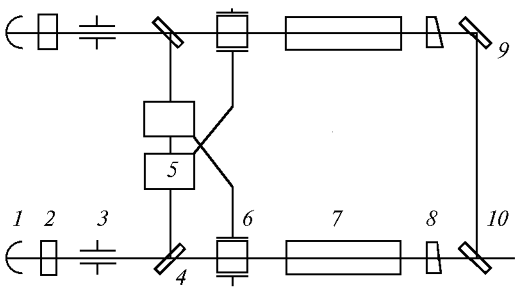

Fig. 1. Biharmonic laser: totally reflecting rear spherical mirrors *1* (F = 1000 mm), Fabry–Perot etalons for frequency tuning *2*, diaphragms for separating axial modes (1.75 mm) *3*, polarization mirrors for exiting the control radiation *4*, control circuits *5*, electrooptical lithium tantalate Q-switches *6*, laser active elements *7* (yttrium alumonate, λ_0 = 1064 nm), semitransparent plane mirrors *8*, plane mirrors *9* and *10* for bringing two beams together.

As the initial parameters (lengths of cavities and active elements, mirror reflection coefficients, and characteristics of electrooptical Q-switches), we used the corresponding values for an actual laser source from Ref. 4. So, the obtained results can be then experimentally tested and applied to optimization of the emitter. At the same time, it is obvious that the developed program has a wider application and can be used for analysis of other solid-state laser systems.

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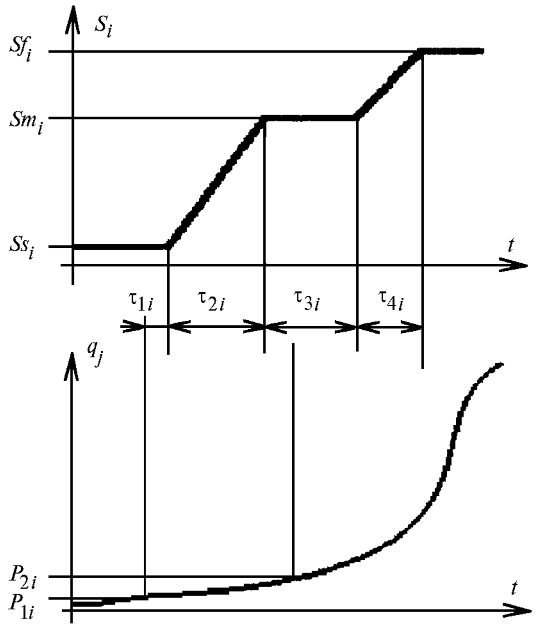

Fig. 2. Two-threshold cross feedback. Q-switch transmittance in the ith laser $S_i(t, P_{1i}, P_{2i}, q_j)$ is regulated by the jth laser radiation with the intensity q_j; τ_{1i} and τ_{3i} are the lags between the beginning of the Q-switch opening and the time when $q_j = P_{1i}$, P_{2i}; τ_{2i} and τ_{4i} are the times needed for the Q-switches to open.

We considered both single-step and (in contrast to Ref. 4) two-step switch regimes of the feedback. The latter regime allows the stage of lasing development to be elongated and the radiation spectrum to be markedly narrowed. The varied parameters of the ith (i = 1 and 2) channel of the system are the pump power Wp_i, reflection coefficients of the back and semitransparent mirrors of the cavity R_{1i} and R_{2i} (they determine the total cavity loss); two thresholds of the ith control scheme R_{1i} and R_{2i}, and three values of the Q-switch transmittance S_i: Ss_i at the start of its opening, when the Q-factor of the cavity is at its minimum, Sm_i at the intermediate stage, and Sf_i at the final stage.

The mathematical model used for the processes in the bichromatic emitter is based on the Stats – De Mars set of balance equations. The set was modified to take into account the control over Q-factors of two lasers joined by means of a positive cross feedback:

$$\begin{cases} \dfrac{dq_i}{dt} = (V_a B_i N_i - 1/\tau_c - 1/\tau_{ei})\,(q_i + Ran\, q_N), \\ \dfrac{dN_i}{dt_0} = Wp_i(N_T - N_i) - \beta B_i(q_i + Ran\, q_N)N_i - (N_T - N_i)/\tau. \end{cases} \quad (1)$$

Here $V_a = A_e\, l_a$, l_a is the length of the laser active element, $A_e = \pi w_0^2/4$ is the active element cross section determined by the caustic of the Gaussian beam w_0, (i, j) = (1, 2) and (2, 1), q_i is the photon volume density, q_N is the maximum volume density of noise photons, Ran is the random function varying between 0 and 1, β = 2 (for three-level scheme of the active center) and 1 (for the four-level scheme), $B_i = h\, \nu_i\, B_{21i}$, h is the Planck's constant, B_{21i} is the Einstein coefficient for stimulated transitions in the lasing channel, N_i is the population inversion, $\tau_{ei} = -c/(\ln\{R_{1i}\, R_{2i}\, S_i(t, P_{1i}, P_{2i}, q_j)\}\, l_r)$ is the photon lifetime in the cavity due to photon losses at the mirrors and in the Q-switch, c is the speed of light, l_r is the optical length of the laser cavity, $S_i(t, P_{1i}, P_{2i}, q_j)$ is the transmittance of the Q-switch *6* in Fig. 1 (see Fig. 2); τ_c is the photon lifetime in the cavity if ignoring the photon losses at the mirrors and in the Q-switch, τ is the time of longitudinal relaxation, and N_T is the total concentration of active centers. The coefficient B_i was calculated by the well known equation $B_i = 4\, \sigma_i\, c/(\pi\, w_0^2\, l_r)$, where σ_i is the cross section of transition at the frequency of the laser mode considered.

The simulating program has a modular structure and consists of two main parts: the computational part (the main program) and seven service units.[12]

The set of equations (1) was solved by the Euler method.[5] The central part of the algorithm is a cycle of step-by-step integration of Eq. (1) with automatic selection of the step. The cycle terminates either by user's command or when reaching the given value of the model time. The program provides for graphical output of the results during the computation; it allows a user to change the parameter values and to calculate both the behavior of the considered laser system in time and the dependence of the interval ΔT between pulses on an arbitrary parameter. The program language is Pascal with ASM applications.[6–8]

Results of simulation

The program simulating the processes in the bichromatic emitter was checked in two situations: with and without a feedback between lasers in the emitter. As the simulation showed, for the case of no feedback between lasers both operating in the regime of free lasing, the dynamics of processes in each of them corresponds to that known from the literature.[9]

As a test situation of a Q-factor modulation regime, the cross feedback was turned off, and each laser emitted independently, that is, the active positive feedback similar to the cross feedback took place. As the radiation intensity achieves the threshold values P_{1i} and P_{2i}, the Q-switches opened, and the volume density of photons grew sharply as is typical of the regime of generation of giant pulses.[9]

For the case of joined lasers, the program was also verified by analysis of characteristic changes in the intensity of radiation of a bichromatic laser. When varying the reflection coefficients of the laser mirrors and the pump pulse energy (with both on and off feedback), the general tendencies in the change of the radiation intensity corresponded to the physical concepts of the processes in lasers with the cross feedback.

Since the aim of this paper was to develop and test the mathematical model of the processes in the biharmonic emitter, we have been elucidating, first of all, (i) the influence of the feedback in the biharmonic emitter on the degree of synchronization of laser pulses and (ii) basic regularities of the effect of different parameters on synchronization in the presence of the cross feedback. The detailed study of the effects of some or other physical factors on the kinetics of the processes in the emitter is the subject of further investigations. Therefore, we assumed $B_{211} = B_{212}$; all the other parameters being taken close to the experimental values[4,9–11] or chosen from obvious physical reasoning. Based on the experience of laboratory experiments,[2–4] we have selected the following parameters to be used as varied ones: Wp_i, P_{1i} and P_{2i}, R_{1i} and R_{2i}, Ss_i, Sm_i, and Sf_i with the variations v equal to 3, 20, 1, and 2%, respectively.

To evaluate the influence of the varied parameters of the bichromatic emitter with the cross feedback on the value of ΔT, the "working points" of the laser emitter were determined at the first stage of simulation. In this context, a "working point" is a set of the parameter values, at which the radiation intensities of both lasers achieve maximum values $q_{\max i}$ at the same time (that is, $\Delta T = 0$). Then the value of some parameter was varied at the working point and the corresponding interval ΔT_p was found. The value ΔT_p was calculated by multiplying the steepness (of the ΔT dependence on the corresponding parameter, see Fig. 3) near the point $\Delta T = 0$ by the variation of the parameter v, therefore it is an upper bound. Since there are an unlimited number of working points, in the further consideration we analyzed the situation near three points with markedly different values of the parameters (see Table 1).

To estimate the influence of the feedback of some or other type on the interval ΔT between pulse peaks of the lasers, three regimes of operation of the bichromatic emitter were simulated:
free lasing of the independent lasers; Q-factor modulation in the presence of a feedback but without the cross feedback, when transmittance of the Q-switch in the ith channel is determined by the radiation intensity in it: $\tau_{ei} = - c / (\ln\{R_{1i} R_{2i} S_i(t, P_{1i}, P_{2i}, q_i)\} l_\text{r})$; and Q-factor modulation in the presence of the cross feedback, when $\tau_{ei} = - c / (\ln\{R_{1i} R_{2i} S_i(t, P_{1i}, P_{2i}, q_j)\} l_\text{r})$.

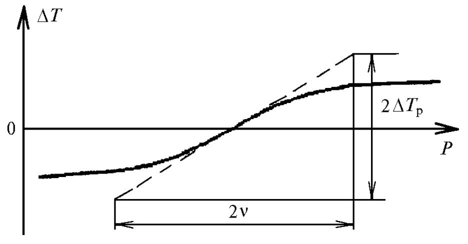

Fig. 3. Interval ΔT vs. varied parameter p (for example, Wp_1).

Table 1. Values of model parameters used in the computations

Parameter	Units	Value	Parameter	Units	Value
l_a	m	0.1	$P_{11} = P_{12}$	$1/\text{m}^3$	5×10^{10}
w_0	m	0.001	$P_{21} = P_{22}$	$1/\text{m}^3$	10^{15}
l_r	m	0.9	q_N	$1/\text{m}^{-3}$	8×10^{-6}
R_{11}	–	0.9	τ_c	s	9×10^{-8}
R_{21}	–	0.3	τ	s	2.5×10^{-4}
R_{12}	–	0.99	$\tau_{11} = \tau_{12} = = \tau_{31} = \tau_{32}$	s	0
R_{22}	–	0.35	$\tau_{21} = \tau_{22}$	s	10^{-9}
$Sf_1 = Sf_2$	–	0.8	$\tau_{41} = \tau_{42}$	s	2×10^{-9}
N_T	m^{-3}	5×10^{25}	σ	m^2	1.2×10^{-24}
First working point					
Wp_1	–	2.555×10^{-3}	$Ss_1 = Ss_2$	–	0.1
Wp_2	–	2.375×10^{-3}	$Sm_1 = Sm_2$	–	0.4
Second working point					
Wp_1	–	2.615×10^{-3}	$Ss_1 = Ss_2$	–	0.05
Wp_2	–	2.375×10^{-3}	$Sm_1 = Sm_2$	–	0.2
Third working point					
Wp_1	–	2.615×10^{-3}	$Ss_1 = Ss_2$	–	0.1
Wp_2	–	2.4325×10^{-3}	$Sm_1 = Sm_2$	–	0.2

The simulated results, which demonstrate the efficiency of the cross feedback as applied to minimization of the interval ΔT for the first working point, are given in Table 2. The pump parameter Wp_1 of the first channel of the bichromatic emitter was varied from 97 to 103% of its value at the working point, while the pump parameter Wp_2 of the second channel was unchanged. The values of ΔT corresponding to the maximum variations of Wp_1 (97% and 103%) are given in the column 2 and 3 of the Table 2, whereas column 4 gives the relative steepness of ΔT change at the working point (normalized to Wp_1).

Table 2. Comparison of the lasing regimes

Regime	ΔT_p, ns		$d\Delta T_\text{p}$	$q_{\max1}$, m^{-3}	$q_{\max2}$, m^{-3}
	$Wp_1 = 97\%$	$Wp_1 = 103\%$			
Free lasing	478.2	−1305.65	−291.83	$8.26\cdot10^{15}$	$9.65\cdot10^{15}$
Q-factor modulation (feedback)	1893.7	−1719.50	−609.67	$5.43\cdot10^{17}$	$5.96\cdot10^{17}$
Q-factor modulation (cross feedback)	5.10	−5.45	−2.17	$5.42\cdot10^{17}$	$5.89\cdot10^{17}$

One can see that the cross feedback improves the synchronization of the emitter channels by several orders of magnitude (as compared with the other considered regimes). Besides, analysis of the two last columns of Table 2 indicates that, first, the type of the positive feedback (cross or other) has no significant effect on the values of $q_{\max i}$. Second, the presence of the feedback increases the peak intensity of the optical radiation by several orders of magnitude, what would be expected for a Q-switched laser. Thus, the program correctly describes the behavior of lasers[2–4] with the cross feedback.

Table 3 demonstrates the contribution of variations of different parameters of the bichromatic emitter to the interval ΔT for the first working point as well. Column 3 of this table gives the values of $\Delta T_{\rm p}$ between the peaks of the laser pulses, as the corresponding parameter from column 1 increases by v% (the value of v is given in column 2). The final estimates Σ_* given in column 3 were obtained by summing the absolute values of $\Delta T_{\rm p}$. The ranges of variability of $\Delta T_{\rm p}$, when one parameter more decreases (within the limits given in column 2) along with the decrease of Wp_1 from 103 to 97%, are given in column 4. The same data, but for the increasing parameters are given in column 5.

Table 3. Joint influence of variations of different emitter parameters

Parameter	Parameter variation, %	$\Delta T_{\rm p}$, ns	$\Delta T_{\rm p}$, ns, with Wp_1 + 3% – 3% $+v\%\ldots-v\%$	$-v\%\ldots+v\%$
Wp_1	3	−6.2		
Wp_2	3	5.6	$\|\Delta T\| \le 0.34$	7.3–7.52
$\Sigma_{\rm W}$		11.8		
P_{11}	20	0.4	5.33 −5.59	4.79 −5.22
P_{12}	20	0.5	4.78 −5.08	5.29 −5.63
P_{21}	20	0.4	5.03 −5.34	5.03 −5.34
P_{22}	20	0.34	5.03 −5.34	5.04 −5.34
Σ_p		1.64		
R_{11}	1	0.69	5.19 −5.57	4.88 −4.79
R_{12}	1	0.74	4.79 −5.04	5.33 −5.71
R_{21}	1	0.62	5.19 −5.57	4.88 −5.18
R_{22}	1	0.57	4.79 −5.04	5.33 −5.71
Σ_R		2.62		
Ss_1	2	−0.72	5.03 −5.54	4.87 −4.84
Ss_2	2	0.86	4.76 −5.45	5.35 −5.37
Sm_1	2	−0.22	5.24 −5.47	4.84 −5.21
Sm_2	2	0.15	4.90 −5.14	5.16 −5.54
Sf_1	2	−0.13	5.15 −5.40	4.93 −5.28
Sf_2	2	0.16	4.98 −5.24	5.09 −5.45
Σ_s		2.24		
$\Sigma\Sigma$	–	18.3	–	–

It follows from Table 3 that different parameters of the bichromatic emitter influence differently the value of ΔT. Variations of the pump level Wp_i make the largest contribution to desynchronization of pulses. The contribution of other parameters (separately) is relatively low. However, the net contribution of all the 14 parameters (under the assumption that all the contributions have the same sign) is comparable with that given by the pump parameter. Note that such an agreed behavior of random independent variations of the parameters (believing that each of them can accept one of two values $\pm v$) has the probability as low as 2^{-14}. Consequently, under the assumption of independent variations of the parameters, the pump parameter makes the main contribution to ΔT. According to Table 3, the value of ΔT is about 12 ns. This agrees with the experiments, in which the values of ΔT close to 10 ns were observed at the pulse duration of 30–35 ns (Ref. 4).

Analysis of Table 3 also shows that as the pump parameters Wp_1 and Wp_2 vary in the same direction, desynchronization of pulses due to fluctuations of the pump parameters practically does not occur. This indicates the technically attractive capability of providing simultaneous generation of two pulses by placing the active elements inside a common laser head, since in this case fluctuations of the pump parameters affect them in practically the same degree.

The final values of ΔT caused by variations of both the pump and other parameters of the emitter are given in Table 4 for three working points.

Table 4. Pulse mismatch at three working points

Working point	$\Delta T_{\rm p}$, ns $\Sigma_{\rm W}$	$\Sigma\Sigma$
1	11.8	18.3
2	7.49	16.94
3	24.99	46.54

It is seen that changing working point, one can control the value of ΔT and, probably, reduce it almost to zero. Note also that the ratio of the effects of variations of the pump and other parameters depends on the working point.

Conclusion

The program developed for simulation of the processes in a bichromatic emitter sufficiently well describes the joint lasing in the coupled lasers and allows some conclusions to be drawn. In particular, it was found that the largest contribution to the pulse mismatch comes from the instability of the pump level, which can hardly be suppressed in an actual experiment. It was also shown that changing the working point could control synchronous operation of the emitter channels. As one of the ways to minimize ΔT, we propose the use of a common pump system for active elements of both channels. The alternative way may be updating the control principles of the Q-switches and introducing additional feedback loops.

In the future we plan to determine the influence of frequency mismatch between different laser channels (what manifests itself in different Einstein coefficients B_{21i}) and to study the promises and feasibility of optimizing control over the operation of a biharmonic laser.

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