Two-channel laser system with stabilization of time mismatch between pulses: simulation results

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A lot of problems in spectroscopy and remote sensing of the atmosphere demand the use of two-channel systems, which generate pulses with different wavelengths and minimum mismatch ΔT between pulses. To attain to this end, it is suggested to control the Q-factors of laser cavities using smooth positive cross feedback. According to the results of computer simulation, this feedback provides ΔT about a fraction of nanosecond. The degree of influence of laser system parameters on ΔT is determined.

Introduction

This paper continues investigation into the ways of improving synchronism of pulse generation by a two-channel laser system (TLS) using computer simulation. The measure of pulse desynchronization is the mismatch ΔT between the times, at which pulses reach the maximum intensity.

As known, the operation of such systems and, in particular, a bichromatic laser is usually controlled by electrooptic Q-switching with photoelectric cross feedback, which relates generation of pulses. However, the attempts to achieve complete coincidence of pulses at a rather long operating period (tens of minutes) usually fail: pulses lose synchronism, and the mean time interval between their maxima becomes from 1/3 to 1/4 of their duration.

Computer experiments conducted earlier suggested, in particular, the conclusion that the largest contribution to pulse mismatch is caused by instability of the pump level. It was also shown that it is possible to control synchronism of laser channels by changing the working point. As one of the ways to diminish ΔT, it was proposed to improve the principles and systems of control over electrooptic switches of a biharmonic laser.[1] The results obtained from analysis of new ways to control the system operation are considered below.

Model of two-channel laser system

As in Ref. 2, in this paper we study the operation of a two-channel bichromatic emitter, whose two channels are identical yttrium aluminate lasers with 850 mm long cavities and the positive cross feedback (PCF), see Fig. 1.

The feedback serves for minimizing the interval ΔT between the maxima of pulses from these lasers. The effect of the cross feedback on the processes in the lasers is provided for by photoelectric control of a switch transmittance in the first laser depending on the intensity of the second laser radiation and vice versa.

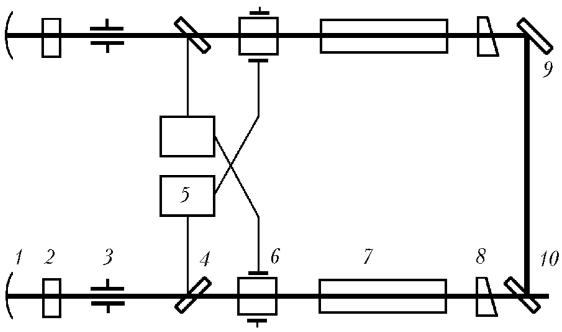

Fig. 1. Schematic of bichromatic emitter: spherical end mirrors (F = 1000 mm) *1*; Fabry–Perot etalons for wavelength tuning *2*; diaphragms for separation of axial modes (1.75 mm in diameter) *3*; polarization mirrors for removal of control radiation *4*; control systems *5*; lithium tantalite electrooptic Q-switches *6*; active laser elements (yttrium aluminate, λ_0 = 1064 nm) *7*; plane semitransparent mirrors *8*; plane mirrors for converging two beams in one *9* and *10*.

Earlier we approximated variation of the transmittance S_i of the electrooptic switch in the ith laser as a function of the intensity q_j of the jth laser radiation that sequentially achieves two threshold values P_{1i} and P_{2i}, at which the system of control over the switch of the ith laser changes its state, by a piecewise-linear function (see Fig. 2 in Ref. 1) accounting for the lag effect in operation of the control systems *5* (see Fig. 1). Due to the PCF, generation in the lagging laser was accelerated, and thus the interval ΔT was decreased. This two-stage system of control over the switch transmittance has two peculiarities. First, the laser radiation intensity affects the S_i value no more than four times during the cycle of generation of a pair of pulses and this effect has a character of short switching. Second, it is impossible to control the shutter opening rate in the process of generation. In our opinion, the possibilities of minimizing ΔT can be extended due to the increase in the number of stages in the control system. Therefore, a system of continuous control over the switches *6* (see Fig. 1) is proposed as an alternative

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to the two-stage system. The system of continuous control obviously corresponds to the case of an unlimited number of stages.

To implement the Q-switch mode, it is needed, at least, to guarantee shutter opening, for example, excluding the possibility of decreasing in their transmittance, that is, to create the *positive* feedback. At the same time, to synchronize laser pulses, it is necessary to provide for regulation of the switch opening rate, since the possibility of shutter closing is deliberately excluded. The system of continuous shutter control, whose schematic is shown in Fig. 2, meets these minimum requirements. Its efficiency was to be analyzed in the computer experiment.

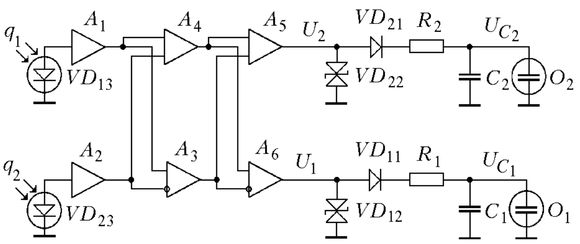

Fig. 2. Equivalent schematic of continuous control over electrooptic shutters in bichromatic laser: amplifiers A_i; diodes VD_{i1}; bi-directional stabilitrons VD_{i2}; receiving photodiodes VD_{i3}; resistors R_i; capacitors C_i; electrooptic shutters O_i.

Laser radiation, whose intensity is determined by the number of photons q_i in the mode volume, is converted by the photodetectors VD_{13} and VD_{23} into the electric signal. It is amplified by the preamplifiers A_1 and A_2 with the gain factors K_1 and K_2 and then the signals from their outputs are entered into the summing A_4 and differential A_3 amplifiers with the gain factors K_4 and K_3, respectively. Then the sum signal from the output of A_4 comes to the adder A_5 and to the noninverting input of the differential amplifier A_6 with the gain factors K_5 and K_6, respectively. The difference signal from the output of A_3 comes to A_5 and the inverting input of A_6. Then the voltage U_1 (U_2) from A_6 (A_5) through the rectifying diode VD_{11} (VD_{21}) and the resistor R_1 (R_2) charges the capacitor C_1 (C_2), the voltage U_{C_1} (U_{C_2}) across which just controls the transmittance (S_2) of the switches in the first (second) laser.

Bidirectional stabilitrons VD_{i2} with the stabilization voltage $U_{C_{\max}}$ symbolize restriction of the gain factors in the amplifiers A_5 and A_6 at high signal amplitudes due to, for example, the limitedness (from above) of the supply voltage. In all other respects, the amplifiers A_i are believed ideal. The values of R_iC_i characterize the total lag of the system of control over the switches transmittance, and C_i accounts also for the permittance of the switches themselves. It is assumed that S_i linearly depends on U_{C_i}, and before the beginning of the generation cycle $U_{C_i} = 0$, $S_i = Ss_i$, that is,

$$S_i(t) = Ss_i + (Sf_i - Ss_i)\ U_{C_i}(t)/U_{C_{\max}}, \qquad (1)$$

where Sf_i is the transmittance when switches are completely open, which is achieved at $U_{C_i}(t) = U_{C_{\max}}$.

The dynamics of voltages $U_{C_i}(t)$ across the capacitors that determines, according to Eq. (1), variation of the switch transmittance $S_i(t)$ is described by the following equations and the equations for voltages U'_i at the output of ideal unloaded amplifiers A_5 and A_6 and for the voltages U_i at the output of the same amplifiers, whose nonideality is accounted for by the presence of stabilitrons:

$$U'_1 = K_6\ [K_4\ (K_1q_1 + K_2q_2) - K_3\ (K_1q_1 - K_2q_2)],$$

$$U'_2 = K_5\ [K_4\ (K_1q_1 + K_2q_2) + K_3\ (K_1q_1 - K_2q_2)],$$

$$U_i = U'_i \ \text{ at } |\ U'_i\ | < U_{C_{\max}},$$

$$U_i = \mathrm{sign}(U'_i)U_{C_{\max}} \ \text{ at } |\ U'_i\ | \geq U_{C_{\max}},$$

$$\mathrm{d}U_{C_i}(t)/\mathrm{d}t = [U_i - U_{C_i}(t)]/R_iC_i \ \text{ at } U_i > U_{C_i},$$

$$\mathrm{d}U_{C_i}(t)/\mathrm{d}t = 0 \ \text{ at } U_i \leq U_{C_i}. \qquad (2a)$$

The idea of smooth positive cross feedback (SPCF) was considered above and implemented in the system shown in Fig. 2, the processes in which are described by Eqs. (1) and (2a). According to it, the total signal $K_4(K_1q_1 + K_2q_2)$ from the output of A_4 provides for some initial switch opening rate. And this rate is the same for both channels, when $K_5 = K_6$ and $R_1C_1 = R_2C_2$. Obviously, the signal $K_4(K_1q_1 + K_2q_2)$ from the A_4 output includes the terms $K_4K_1q_1$ ($K_4K_2q_2$) and $K_4K_2q_2$ ($K_4K_1q_1$) corresponding to the *positive* and *cross positive* feedback with respect to the first (second) TLS channel.

The difference signal $K_3(K_1q_1 - K_2q_2)$ from the A_3 output is capable of increasing this rate in one of the lasers and decreasing down to zero in the other. The switch opening in this case is guaranteed by the fact that the diodes VD_{11} and VD_{21} provide the possibility of excluding the decrease in the shutter transmittance (capacitor discharge). Regulation of the shutter opening rate, in its turn, should provide for pulse synchronization. This regulation decreases the switch opening rate in that laser, whose radiation *intensity* is *higher*. Therefore, as applied to such a laser, it is correct to speak about the *negative* feedback, but against the background of the total positive feedback. However, as applied to the laser, whose radiation intensity is *lower*, we can speak about the *extra positive* feedback.

This classification of the terms in the first two equations (2a) is rather conditional. Indeed, if we write the equations for the voltages U'_i at the output of the ideal unloaded amplifiers A_5 and A_6 as

$$U'_1 = K_6\ [K_1(K_4 - K_3)q_1 + K_2(K_4 + K_3)q_2],$$

$$U'_2 = K_5\ [K_1(K_4 + K_3)q_1 + K_2(K_4 - K_3)q_2], \qquad (2b)$$

then it becomes obvious that the term $K_2(K_4 + K_3)q_2$ ($K_1(K_4 + K_3)q_1$) corresponds to the *cross positive* feedback with respect to the first (second) TLS channel. And the term $K_1(K_4 - K_3)q_1$ $(K_2(K_4 - K_3)q_2)$ at $K_4 - K_3 < 0$ corresponds to the *negative* feedback with respect to the first (second) TLS channel.

As was already mentioned, the control system in Fig. 2 is characterized by that the opening rate for each switch is caused by the weighted sum $K_1q_1 + K_2q_2$ of the radiation intensities in both channels. The *cross positive* feedback is thus implemented. Are there other versions possible of the control system? In our opinion, it may be as is shown in Fig. 3. This version differs by that the switch opening rate in the first (second) channel is determined by the value of $K_7K_1q_1$ $(K_8K_2q_2)$, that is, the radiation intensity q_1 (q_2). The *positive* (but not *cross*!) feedback is thus implemented.

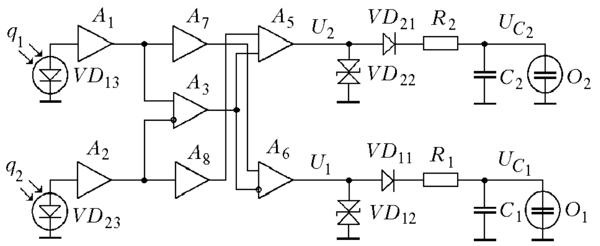

Fig. 3. Equivalent schematic of an alternative system for continuous control over electrooptic switches in a bichromatic laser. Designations are the same as in Fig. 2.

To simplify comparison of the results of system simulation, the gain factors of the amplifiers A_7 and A_8 are assumed equal to $2K_4$. This is connected with the fact that in the first version of the system (see Fig. 2) two signals come to the adder K_4, which sums them. In the second version (see Fig. 3) A_7 and A_8 have only one input, and the signal at this input corresponds to the signal at *each* of the inputs of the A_4 amplifier in the first version of the control system. The corresponding equations for the voltages U'_i at the output of ideal unloaded amplifiers A_5 and A_6 are given below:

$$U'_1 = K_6\,[2K_4K_1q_1 - K_3\,(K_1q_1 - K_2q_2)] = K_6\,[K_1(2K_4 - K_3)q_1 + K_3K_2q_2],$$

$$U'_2 = K_5\,[2K_4K_2q_2 + K_3\,(K_1q_1 - K_2q_2)] = K_5\,[K_2(2K_4 - K_3)q_2 + K_3K_1q_1].$$

Let us take into account the dependence of the switch transmittance $S_i(t)$ on the voltage U_{C_i} that is expressed by Eq. (1), as well as by Eq. (2a) describing the U_{C_i} dynamics. Then it is easy to obtain the model of variation of the switch transmittance:

$$R_iC_i\,\mathrm{d}S_i(t)/\mathrm{d}t = U_i(Sf_i - Ss_i)/U_{C_{\max}} + Ss_i - S_i(t) \quad \text{at} \quad U_i > U_{C_i},$$
$$\mathrm{d}S_i(t)/\mathrm{d}t = 0 \quad \text{at} \quad U_i \le U_{C_i}. \qquad (3)$$

To reveal the effect of instability of the bichromatic emitter parameters on the time mismatch ΔT in the two shutter control systems considered above, we have conducted a cycle of computer experiments. For this purpose, we varied the following parameters of the *i*th ($i = 1$ and 2) channel: pump power Wp_i; reflection coefficients of the cavity end and semitransparent mirrors R_{1i} and R_{2i}; two values of the switch transmittance S_i: at the initial stage of opening (Ss_i, when the Q-factor of the *i*th laser cavity is minimal) and the final (Sf_i) stage; and the products R_iC_i.

As a basis for the mathematical model of the processes in a bichromatic emitter, we have chosen the Statz–DeMars system of balance equations in the single-mode approximation modernized with allowance for Q-factor control in two cavities related by a SPCF[1]:

$$\begin{cases} \dfrac{\mathrm{d}q_i}{\mathrm{d}t} = (V_\mathrm{a}\,B_i\,N_i - 1/\tau_\mathrm{c} - 1/\tau_{ei})\,(q_i + \mathrm{Ran}\,q_\mathrm{N}), \\ \dfrac{\mathrm{d}N_i}{\mathrm{d}t} = Wp_i(N_\mathrm{T} - N_i) - \beta B_i \times \\ \times\,(q_i + \mathrm{Ran}\,q_\mathrm{N})N_i - (N_\mathrm{T} + N_i)/\tau. \end{cases} \qquad (4)$$

Here $V_\mathrm{a} = A_\mathrm{e}\,l_\mathrm{a}$, l_a is the length of the laser active element, $A_\mathrm{e} = \pi\,w_0^2/4$ is the active element cross section area determined by the waist size of the Gaussian beam w_0; $(i, j) = (1, 2)$ and $(2, 1)$; q_j is the number of photons in the laser mode; q_N is the maximum number of noise photons in the laser mode; Ran is a random function varying from 0 to 1; $\beta = 2$ (for the 3-level scheme of an active center) and 1 (for the 4-level one); $B_i = h\nu_iB_{21i}$; h is the Planck constant, B_{21i} is the Einstein coefficient for stimulated transitions in the lasing channel; N_i is the population inversion; $\tau_{ei} = -\,c/(\ln\{R_{1i}\,R_{2i}\,S_i(t)\}\,l_\mathrm{r})$ is the lifetime of photons in the cavity due to their loss at the mirrors and switch; c is the speed of light; l_r is the optical length of the laser cavity; τ_c is the lifetime of photons in the cavity neglecting their loss at the mirrors and in the shutter; τ is the longitudinal relaxation time; N_T is the total concentration of active centers. In computer experiments, the coefficients B_i were calculated by the known equation: $B_i = 4\sigma_i\,c/(\pi w_0^2\,l_\mathrm{r})$, where σ_i is the cross section of the transition at the frequency of the laser mode considered; for simplicity it was assumed that $\sigma_1 = \sigma_2 = \sigma$ and $B_1 = B_2$.

Simulation results and discussion

Verification of the computer model of processes in the bichromatic emitter that was conducted in Ref. 1 showed that the model is suitable for describing the dynamics of radiation from the lasers coupled as shown in Fig. 1.

To estimate the effect of the variable parameters of the bichromatic emitter with SPCF on the value of ΔT, at the first stage of simulation (as in Ref. 1) we determined working points (WP). The term “working point” of the bichromatic emitter means a set of parameter values, at which the intensities of radiation from the two lasers achieve maximum values $q_{\max\,i}$

simultaneously (that is, $\Delta T = 0$). Then some parameter was varied at a working point, and the mismatch ΔT of laser pulses corresponding to this variation was determined. For correct comparison with the previous results, the working points with SPCF implemented in accordance with the systems shown in Figs. 2 and 3 were taken maximum close to those in Ref. 1. The basic parameters of the biharmonic laser model (2)–(4) at these working points are tabulated in Table 1 (unfortunately, Table 1 in Ref. 1 gives, by our oversight, only the co-factor Wp_i instead of the product τWp_i, the dimensionality of q_N should be given in phot, and the value should be $8 \cdot 10^6$).

Table 1. Model parameters used in computer experiments

Parameter	Value	Parameter	Value
l_a, m	0.1	$R_1C_1 = R_2C_2$, ns	1
w_0, m	0.001	q_N, phot	$8{\cdot}10^6$
l_r, m	0.9	τ_c, s	$9{\cdot}10^{-8}$
R_{11}	0.9	τ, s	$2.5{\cdot}10^{-4}$
R_{21}	0.3	σ, m^2	$1.2{\cdot}10^{-24}$
R_{12}	0.99	N_T, m^{-3}	$5{\cdot}10^{25}$
R_{22}	0.35	$K_5 = K_6$	1
$Sf_1 = Sf_2$	0.8	K_3	$1{\cdot}10^{-12}$
K_1	1.0000544	K_4	$1{\cdot}10^{-13}$
K_2	1		
First working point			
τWp_1	0.0025375	$Ss_1 = Ss_2$	0.1
τWp_2	0.002375		
Second working point			
τWp_1	0.0025775	$Ss_1 = Ss_2$	0.05
τWp_2	0.002375		
Third working point			
τWp_1	0.0025975	$Ss_1 = Ss_2$	0.1
τWp_2	0.0024325		

For the proposed versions of the SPCF (see Figs. 2 and 3), according to the results of our computer experiments given in Tables 2 and 3, the time mismatch ΔT at separate variation of any parameter of the model (2)–(4) does not exceed fractions of nanosecond ($|\Delta T| \le \Delta T_{max} \approx 0.74$ ns) with the laser pulse duration of about 6 ns. In this case, the pulse amplitude $q_{max\ i}$ not only does not decrease, but increases by 0.3–2.6% (and even 11% at the first working point for q_1 when simulating processes in TLS including the system shown in Fig. 2) with respect to the results obtained in Ref. 1.

Note that $q_{max\ i} \sim 5 \cdot 10^{17}$ photons. At $\lambda = 1064$ nm, $w_0 = 1$ mm and the pulse duration of 6 ns, this corresponds to the peak power of radiation propagating in the cavity $P = h\nu c q_{max}/(2l_r) \sim 15$ MW, its waist peak intensity 1.5 GW/cm^2 and the pulse energy of about 46 mJ.

As before, instability of the pump parameter Wp_i is responsible for the largest contribution to ΔT (only at the third working point the sum Σ_S of the contributions due to the transmittances Ss_i and Sf_i is comparable with the sum Σ_W of the contributions due to Wp_i). However, the results systematized in Table 3 indicate that the proposed switch control systems and modes (with the properly selected parameters) improve the synchronization between laser pulses by roughly an order of magnitude as compared to the case of the two-stage positive cross feedback considered in Ref. 1.

Analysis of the data from Tables 2 and 3 leads to the conclusion that the character of TLS functioning in the case of SPCF implemented in accordance with the schemes shown in Figs. 2 and 3 is almost identical. This is likely caused by the fact that the design of the negative feedback in both cases is the same, and from the viewpoint of the effect on ΔT and the radiation power (the value of $q_{max\ i}$) the method of implementation (structure scheme) of the positive feedback is not so important.

Table 2. Effect of variations of different emitter parameters on the value of ΔT

Parameter	Parameter variation v, in %	ΔT, ns (Fig. 2)			ΔT, ns (Fig. 3)		
		WP 1	WP 2	WP 3	WP 1	WP 2	WP 3
Wp_1	3	−0.593	0.393	−0.610	−0.573	0.472	−0.590
Wp_2	3	−0.609	0.442	−0.620	−0.589	0.447	−0.600
Σ_W		1.202	0.835	1.23	1.162	0.919	1.19
R_1C_1	3	0.0629	−0.0259	0.0817	0.0845	0.0119	0.105
R_2C_2	3	−0.0703	−0.0274	0.0761	0.0783	−0.0862	0.234
R_1C_1	50	−0.129	−0.093	0.18	0.142	0.107	0.214
R_2C_2	50	−0.144	0.0847	0.168	−0.136	0.0967	0.157
Σ_{RC}		0.273	0.1777	0.348	0.278	0.2037	0.361
R_{11}	1	0.220	0.125	0.210	0.220	0.149	0.200
R_{12}	1	0.211	0.149	0.223	0.223	0.173	0.237
R_{21}	1	0.230	0.130	0.213	0.220	0.153	0.203
R_{22}	1	0.201	0.144	0.220	0.223	0.169	0.234
Σ_R		0.862	0.548	0.866	0.886	0.644	0.874
Ss_1	2	0.152	0.124	−0.737	0.133	0.149	−0.726
Ss_2	2	0.126	0.109	0.124	0.107	0.134	0.145
Sf_1	2	−0.141	−0.0988	0.119	−0.133	0.0967	0.140
Sf_2	2	−0.169	−0.0723	0.187	−0.146	0.0665	0.210
Σ_S		0.588	0.4041	1.167	0.519	0.4462	1.221
$\Sigma\Sigma$		2.925	1.9648	3.611	2.845	2.2129	3.646

Table 3. Pulse mismatch at three working points

WP	ΔT, ns (Ref. 1)		ΔT, ns (Fig. 2)		ΔT, ns (Fig. 3)	
	Σ_W	$\Sigma\Sigma$	Σ_W	$\Sigma\Sigma$	Σ_W	$\Sigma\Sigma$
1	11.8	18.3	1.202	2.925	1.162	2.845
2	7.49	16.94	0.835	1.9648	0.919	2.2129
3	24.99	46.54	1.23	3.611	1.19	3.646

We have conducted many (40) calculations corresponding to the same set of parameters in the vicinity of a working point and imitating the presence of white noise affecting the number of photons in the mode. In spite of the low noise level ($0 \le q_N(t)/q_{max} \le 1.6 \cdot 10^{-11}$), variations ΔT_N of ΔT due to noise in our model have the value about 0.06–0.17 ns (Table 4). These values are very close to the effect of the overwhelming majority of the variable parameters (see Table 2). If the noise is increased, its effect will possibly exceed the effect caused by each parameter separately, that is, the variation ΔT_N will become larger than the mismatch ΔT_{max} arising at the most unfavorable variations of the laser parameters. If we assume that the noise imitated in the model is adequate to the noise in the actual system, then we can likely conclude that the proposed control systems (see Figs. 2 and 3) provide for the limiting possible (in the presence of noise) minimization of ΔT.

Table 4. Effect of noise on ΔT

ΔT, ns (Fig. 2)			ΔT, ns (Fig. 3)		
WP 1	WP 2	WP 3	WP 1	WP 2	WP 3
0.06	0.13	0.15	0.078	0.16	0.17

Conclusion

In this paper it is proposed to use the smooth positive cross feedback in the system of control over Q-factors of laser cavities for minimization of the interval ΔT between the peaks of the pulses of two lasers. Two versions of the electronic systems implementing SPCF are suggested. As applied to these systems, we can speak about the extra negative and positive feedbacks against the background of the total positive feedback.

The cycle of computer experiments has been conducted, and it allowed us to find the degree of influence of the two-channel laser system parameters on the mismatch ΔT. Comparison of the results obtained (see Tables 2 and 3) demonstrates the possibility of significant (by more than an order of magnitude) decrease in the time mismatch ΔT between laser pulses without deterioration of the laser power characteristics due to the application of SPCF. Therefore, in practice it is worth controlling the processes in TLS using the control systems shown in Figs. 2 and 3 or similar.

It has been assumed that the control systems developed (see Figs. 2 and 3) provide for the limiting possible (in the presence of noise) minimization of the time mismatch between laser pulses.

References

1. I.V. Izmailov, M.M. Makogon, B.N. Poizner, and V.O. Ravodin, Atmos. Oceanic Opt. **12**, No. 4, 384–387 (2000).
2. K.V. Gurkov, G.E. Kulikov, and V.P. Lopasov, Atmos. Oceanic Opt. **8**, No. 6, 475–476 (1995).