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OPTICAL DATA COMMUNICATION

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On data communication in two-level schemes of optically coupled chaotic lasers

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***Abstract*.** **Two-level schemes for data communication are proposed in which the upper level consists of phase-matched chaotic lasers synchronously perturbing the generation dynamics of a transmitter and receiver at the lower level and forming the communication link. For four schemes (with radiation injection from the controlling level to the controlled level, with mutual radiation injection between the two levels, and with a random synchronous perturbation of the pump-period modulation of lasers at the controlled level in each of the above schemes), the signal recovery errors are studied numerically depending on the coupling coefficients between the levels. It is shown that the recovery errors are minimal only for controlled receivers and the code functions reconstructed on them are close to the specified function.**

Keywords: *dynamic chaos, data communication, external signal injection.*

Communication links based on phase-matched generation regimes of optically coupled chaotic lasers are being extensively developed in the last decade [1 – 5]. The communication link coding one data bit in a single pulse from a chaotic carrier was first proposed in paper [1]. Such a link provides the maximum data transfer rate with the successive data access. Another scheme for coding a chaotic carrier, in which the coding function is not coupled to randomly propagating pulses, was proposed in [2]. This scheme is more convenient for the parallel data access. Communication links [1, 2] have a small bit-rate capacity (~ 1 Mbit s^{-1}), which is limited by Nd : YAG [1] and CO_2 lasers [2] used in them. Because the communication link using CO_2 lasers [2] can find applications especially for communications in a free space, the problem of increasing its bit-rate capacity is still topical. The high bit-rate capacity (~ 10 Gbit s^{-1}) of communication links can be provided by using semiconductor lasers [3 – 5].

It is accepted that communication links [1 – 5] have operation advantages and increase the data transfer security [4 – 6]. Note, however, that the protection of the communication link [1 – 5] can be violated if the parameters of a transmitter proved to be known. It is desirable to have the protection that would successfully operate even when the parameters of the radiation source are known. In this paper, we consider one of the possibilities of increasing the data protection in the communication link and increasing its bit-rate capacity by using a more complicated channel scheme and nonstationary pumping.

Consider a two-level communication link (Fig. 1) consisting of the upper controlling (lasers T′ and R′) and lower controlled (lasers T and R) levels. We assume that radiation generated in the receiver R′ is synchronised by radiation from the transmitter T′, while radiation generated in the receiver R is synchronised by radiation from the transmitter T. In the general case, the pump periods of lasers T′ and R′ can differ from those of lasers T and R, which results in a different temporal behaviour of their fields. If radiation from lasers T′ and R′ is injected into lasers T and R, respectively, the temporal behaviour of their fields proves to

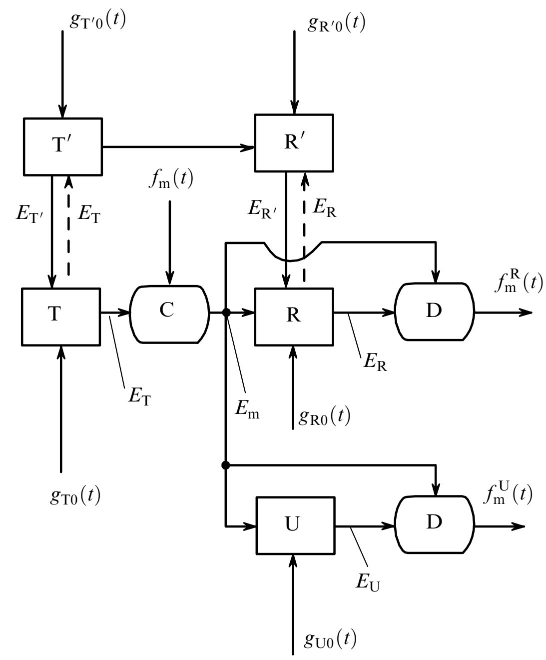

Figure 1. Two-level schemes of optically coupled lasers: T′, T: transmitters; R′, R: receivers; C: coder; D: decoders; E_L, $g_{L0}(t)$: laser fields and pump rates, respectively (L = T′, T, R′, R, U); T′, R′: controlling level; T, R: controlled level; U: independent receiver; E_m: injected signal; $f_m(t)$: coding function; $f_m^{R,U}(t)$: coding functions reconstructed using (11).

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be perturbed. We also assume that the pump periods of lasers T and R can be synchronously perturbed by the same random function. In addition, we assume that there is a duplicate U of the receiver at the lower level, to which a signal from the transmitter R comes, but no control is delivered from the upper level, i.e., from the receiver R, and whose pumping is not perturbed. We can assume that the coding function in such a two-level system is reconstructed in the receiver R and is not reconstructed in the duplicate U. If this assumption is fulfilled, the two-level scheme of data transfer has a stronger protection because, to get access to the scheme, one should to reconstruct the parameters of two lasers and the perturbation function of the pump period (if it was perturbed). Note also that an increase in the number of communication links at the controlled level can increase the bit-rate capacity of the channel without the reduction of the data protection.

We considered four two-level schemes: scheme 1 with radiation injection only from the controlling level to the controlled level (E_T and E_R are not injected into T$'$ and R$'$) and without perturbation of the pump period; scheme 2 with radiation injection only from the controlling level to the controlled level (E_T and E_R are not injected into T$'$ and R$'$) and with perturbation of the pump period; scheme 3 with the mutual injection of radiation between the controlling and controlled levels (E_T and E_R are injected into T$'$ and R$'$) and without perturbation of the pump period; and scheme with the mutual injection of radiation between the controlling and controlled levels (E_T and E_R are injected into T$'$ and R$'$) and with perturbation of the pump period.

We assumed in our calculations that the communication channel is based on CO_2 lasers. The behaviour of an individual laser was described in the fixed-pump approximation using one effective relaxation time and the coding method from [2]. In this case, the equations describing the temporal behaviour of lasers have the form

$$\tau \frac{dg_{L1}(t)}{dt} = g_{L0}(t) - g_{L1}(t)\left(1 + |E_L|^2\right), \quad (1)$$

$$g_{L0}(t) = A_L\left[1 + \sin\frac{2\pi t}{T_L(t)}\right], \quad (2)$$

$$\frac{dE_L}{dt} = \frac{1}{2}(g_{L1} - g_{th\,L}) + Z_L, \quad (3)$$

$$Z_{T'} = M(E_T - E_{T'}) + M_{TR}(E_{R'} - E_{T'}), \quad (4)$$

$$Z_{R'} = M(E_R - E_{R'}) + M_{TR}(E_{T'} - E_{R'}), \quad (5)$$

$$Z_T = M(E_{T'} - E_T), \quad (6)$$

$$Z_R = M(E_{R'} - E_R) + M_{TR}(E_m - E_R), \quad (7)$$

$$Z_U = M_{TR}(E_m - E_U), \quad (8)$$

$$E_m = [1 + f_T(t)]E_T, \quad (9)$$

$$f_m(t) = 2A_c\theta\left[\mathrm{sign}\left(\sin\frac{2\pi t}{T_c}\right)\right] - 1. \quad (10)$$

Here, E_L the complex amplitudes of the fields; $g_{L1}(t)$ are the radiation gains; $g_{L0}(t)$ are the pump rates; A_L are the laser-pump-modulation amplitudes (L = T$'$,R$'$, T,R,U); Z_L is the function describing the action of radiation injected into laser L on lasing. The ratios of pump modulation periods of lasers T$'$ and R to those of lasers T and R were $T_{T,R,U}/T_{T',R'} = 0.75$, 1.0, and 1.25. The lasing thresholds were identical for all the lasers. The coupling coefficients M_{TR} between lasers T$'$ and R$'$ and lasers T and R were identical and constant, while the coupling coefficients M between lasers T and T$'$ and lasers R and R$'$ were changed in the range from 0 to 0.05. For the convenience of comparison of the results, we used in equations (1)–(10) the same normalisation as in [2], i.e., the gain was normalised by multiplying by the doubled resonator length $2L$, the field amplitudes at the saturation intensity were equal to unity, and the time was normalised to the round-trip transit time of radiation in the resonator $\tau_r = 2L/c$. The injection signal E_m was modulated in the amplitude scheme by a meander with parameters $A_c = 0.04$ and $T_c/T_T = 16$; $f_m(t)$ is the coding function; and $\theta(x)$ is the Heaviside function. According to Fig. 1, to reconstruct the coding function by lasers R or U, we used the values of fields at the receiving ends of the communication link:

$$f_m^{R,U}(t) = (|E_m| - |E_{R,U}|)/|E_{R,U}|, \quad |E_{R,U}| \neq 0. \quad (11)$$

The error E_f of the coding function f_m was determined as

$$E_f = \left\{\frac{1}{\Delta t}\int_{t_0}^{t_1}\left[f_m^{R,U}(t) - f_T(t)\right]^2 dt\right\}^{1/2}, \quad (12)$$

where $\Delta t = t_1 - t_0$; t_0 and t_1 are the instants of the beginning and end of the study, respectively. In the absence of radiation modulation and perturbations in the communication channel, the parameter E_f characterises the deviation of the field of the laser R or U from the field of the laser T (the deviation appears due to different pumping of lasers R or T and T or due to injection of radiation from lasers T$'$ and R$'$ into lasers T and R). If the pumps of the lasers depend identically on time and the injected radiation is modulated, criterion (12) gives the error of the coding function reconstruction.

The time dependences of the pump periods $T_{T,R}(t)$ of lasers T and R for schemes 2 and 4 were determined from expressions

$$T_{T,R}(t) = T_{T,R} + \sigma_{T_{T,R}} T_{ran}(t). \quad (13)$$

Here, $T_{T,R}$ is the unperturbed pump period and $\sigma_{T_{T,R}}$ is the corresponding root-mean-square deviation. As the function T_{ran}, we used a random sequence with a Gaussian correlation function between the elements and correlation time equal to $\frac{1}{3}$ of the average interval between pulses generated by the laser T at the given pump amplitude (in this case, the correlation time of the random sequence proved to be approximately twice the mean pulse duration). The sequences were modulated using the algorithm of moving summation [7] for $\sigma_{T_{T,R}}/T_{T',R'} = 0.25$. System of equations (1)–(10) was solved by the fourth-order Runge–

Kutta method with a small constant integration step in time for the convenient use of the discrete sequence $T_{\text{ran}}(t)$ in calculations.

Dependences of the errors E_{f} of the coding-function reconstruction on the coupling coefficient M for lasers R and U are shown in Fig. 2 for the four schemes studied and three pump modulation periods. Consider first schemes 1 and 3. If the pump periods of lasers T, R, and U are equal to those of lasers T$'$ and R$'$, the signal can be decoded at any coefficients M [coinciding curves (*1*) and (*3*) in Figs 2a,c). Deviations of $T_{\text{T,R,U}}$ from $T_{\text{T}',\text{R}'}$ violate matching of the time dependences of fields of lasers T, R and U and T$'$, R$'$. As a result, a synchronous perturbation of the fields of lasers T and R appears, which, however, does not prevent the signal decoding by the laser R (Figs 3a, c) at any value of M. The independent receiver U is not subjected to the same perturbations as the receiver R, the signal is not decoded on it (Figs. 4a, c) and decoding errors for $M > 0.01$ are large [curves (*2*) and (*4*) in Figs 2a,c]. For $M = 0$, a perturbing signal does not come to the controlled level, so that all the dependences in Figs 2a, c converge at the same point.

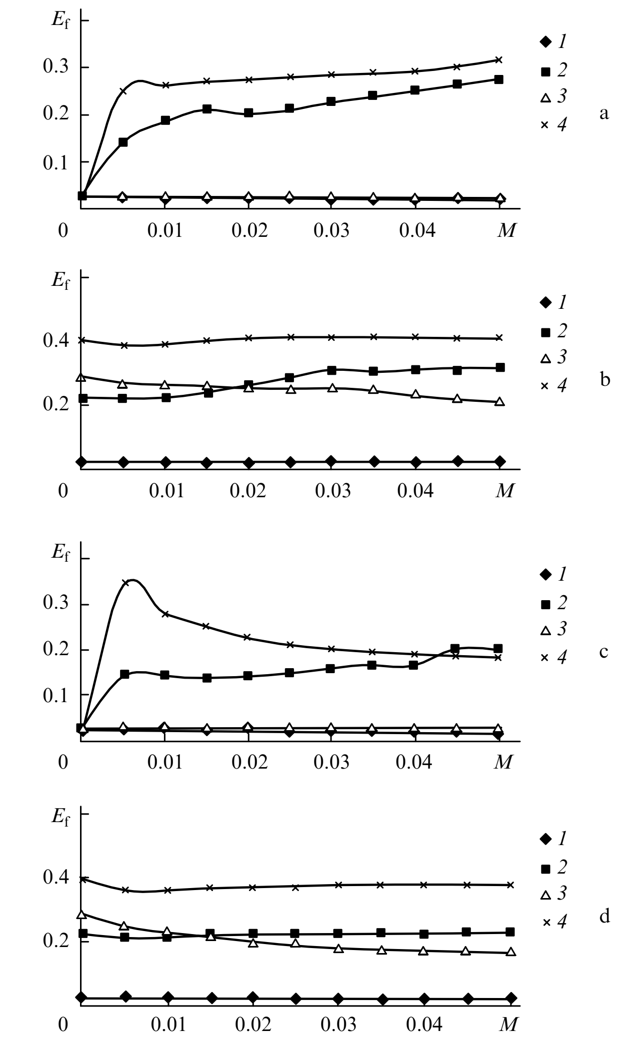

Figure 2. Dependences of the recovery errors E_{f} of the coding function on the coupling coefficient M between lasers T$'$ and T, R$'$ and R (hereafter, Figs a–d correspond to schemes 1–4); (*1*) E_{f} for the laser R ($T_{\text{T,R}}/T_{\text{T}',\text{R}'} = 0.75$); (*2–4*) E_{f} for the laser U ($T_{\text{T,R,U}}/T_{\text{T}',\text{R}'} = 0.75$, 1.0, 1.25).

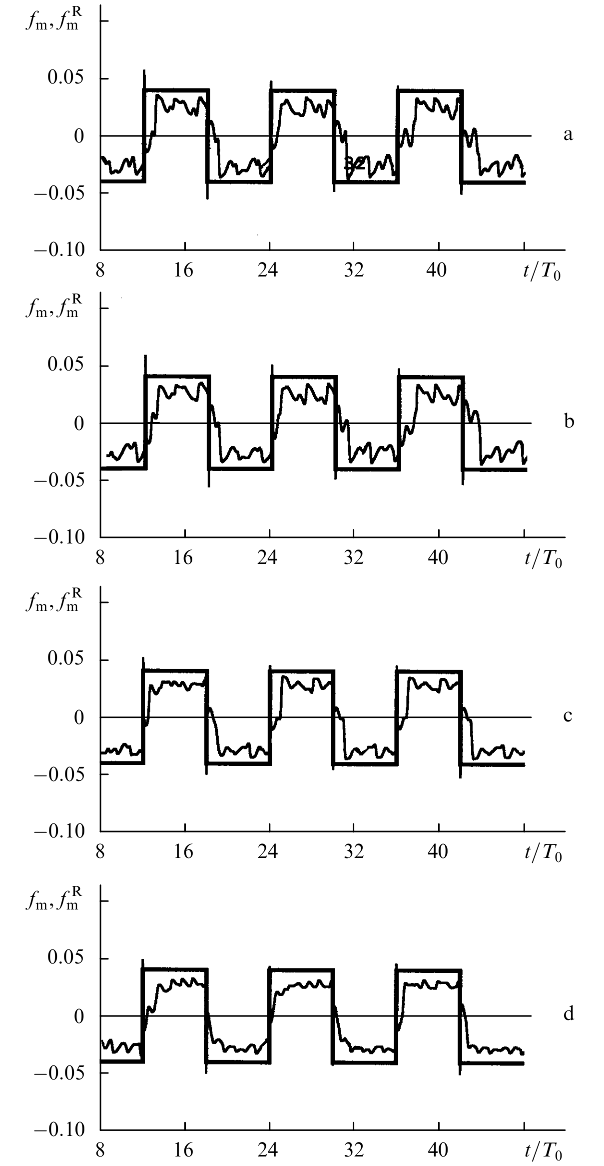

Figure 3. Time dependences of the meander f_{m} and the signal f_{m}^{R} on the laser R recovered using (11) ($T_{\text{T,R,U}}/T_{\text{T}',\text{R}'} = 0.75$) for $M = 0.05$; T_0 is the unperturbed pump period.

Perturbations of the modulation periods of lasers T and R lead to the mismatch between the behaviour of the fields of lasers T, R and T$'$, R$'$ U even when the mean values of periods $T_{\text{T,R}}(t)$ and $T_{\text{T}',\text{R}',\text{U}}$ coincide. For this reason, curves (*3*) and (*1*) in Figs 2b,d do not coincide. In addition, because the pumps of lasers T and R forming the communication channel are perturbed, while the pump of the laser U is not perturbed, decoding errors in this laser appear at $M = 0$ as well. Therefore, in this case, the coding function is successfully reconstructed for any value of M by the laser R subjected to two perturbations (Figs. 3b, d) rather than the laser U (Figs 4b,d).

Our study has shown that two-level systems preserve the synchronisation of the transmitting and receiving ends of the communication link in a broad range of coupling coefficients between levels and provide signal decoding. An independent receiver, which is not subjected to control signals, does not provide decoding. The coupling coefficient between the levels $M \sim 0.01$ is quite sufficient for suppress-

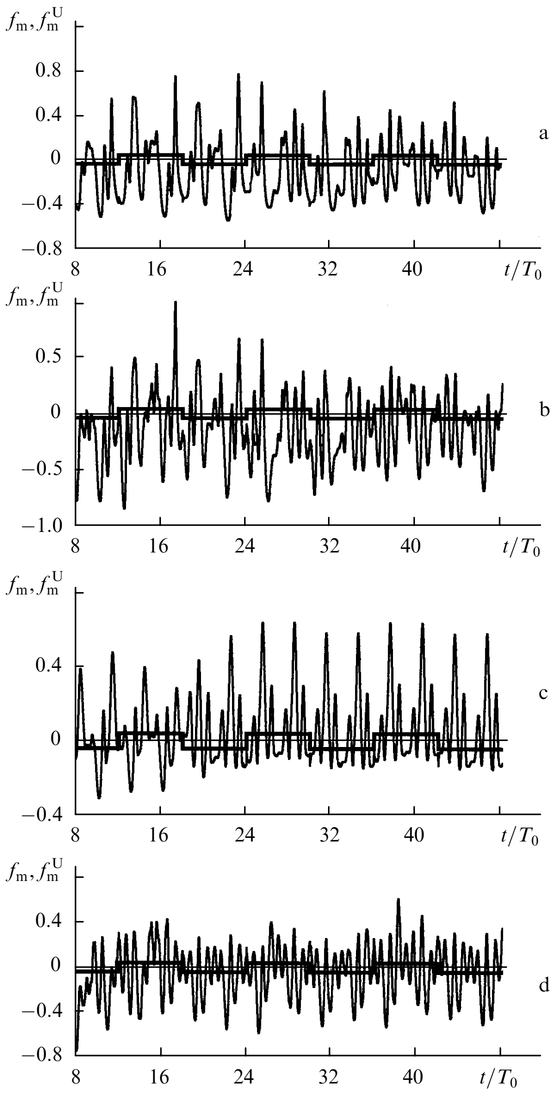

Figure 4. Time dependences of the meander f_m and the signal f_m^U on the laser U recovered using (11) ($T_{T,R,U}/T_{T',R'} = 0.75$) for $M = 0.05$.

ing the recovery of the coding function by the independent receiver. The requirements for data transfer involve the increase in the bit-rate capacity of the communication link and the improvement of its protection. These requirements can be satisfied using multilevel schemes in which the protection of the entire system is determined by the protection of the control level (for example, by means of a quantum communication link), while the bit-rate capacity is determined by a great number of links at the controlled level.

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