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Communications using multi-mode laser system based on chaotic synchronization *

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The communication using chaotic synchronization between two multi-mode Nd:YAG lasers has been investigated numerically. The digital communication using multi-mode chaotic lasers is quite different from that using single mode lasers. By introducing a short break between two adjacent bits in the communication scheme, the digital signals can be successfully encoded into the spiky pulses and decoded through the subtraction of receiver output from the transmitted. Even when the two multi-mode lasers are not synchronized perfectly with certain deviations, the encoded digits can still be decoded correctly.

Keywords: digital communication, multi-mode laser system, chaotic synchronization
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1. Introduction

The investigations of encoding and decoding messages in real time using chaotic synchronization have attracted much attention both theoretically and experimentally in recent years.[1−19] Some groups have demonstrated the practical feasibility of communication using synchronized chaos in an electronic circuit system.[1−7] The transmission of messages with electronic circuit has typically bandwidths of tens of kilohertz or less. If the chaotic optical system is used in the communications, signals can be masked at bandwidths of hundreds of megahertz or higher.

Encouraging progresses in the study of communications using chaotic optical system have been reported.[8−12] The scheme is to communicate from the carrier laser to the receiver laser. As the receiver output synchronizes to the carrier output rather than to the transmitted (carrier with message), the message can be recovered in real time by subtracting the receiver output from the transmitted (i.e., the receiver input). In most of the numerical simulations carried out, the laser model is assumed to be operating in a single cavity mode. Although the experimental observations are in good agreement with the results utilizing the single-mode laser model, the importance of synchronization and communication in multi-mode laser systems should still be considered.[20−23]

For most practical purposes, either multi-mode laser system or multi-mode optical fibre is used. If a single-mode laser system is used in optical communication, the efficiency is reduced greatly by selecting a single mode out of the multiple modes. For optical fibre, the fabrication quality will affect the process of coding and decoding if synchronization of chaotic intensity is used.[24,25] Also, it is difficult to keep the fibre in single mode operation over long distances. If the communication using chaotic synchronization in a multi-mode laser system can be achieved, the requirement of a single-mode operation in either multi-mode laser system or multi-mode fibre can be loosened considerably. The digital communication using chaotic synchronization in multi-mode fibre can be put in practice.

In this paper, the scheme of communications between a pair of multi-mode chaotic Nd:YAG lasers is numerically investigated. In Section II, the multi-mode loss modulated Nd:YAG laser model is presented for encoding and decoding messages. In section III, the technique of inserting a small break between two adjacent signals of bits with either "1" or "0" is introduced for successful communications using chaotic multi-mode lasers. The results of numerical simulations are presented. A discussion and summary of the results conclude the paper.

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2. Communication using multi-mode lasers

The scheme of communicating signals *via* chaotic synchronized lasers is composed of a pair of loss-modulated Nd:YAG lasers operating in the chaotic regime. If the two lasers are of multi-mode, the equations describing the multi-mode transmitting laser and receiving laser are given by:

$$\frac{\mathrm{d}E_T^j}{\mathrm{d}t} = \gamma_c(G_T^j - \alpha_T^j)E_T^j + \mathrm{i}\omega_T^j E_T^j + \sqrt{\varepsilon_T^j}\eta_T^j, \quad (1a)$$

$$\frac{\mathrm{d}G_T^j}{\mathrm{d}t} = \gamma_F\left[P_T^j - G_T^j\left(1 + |E_T^j|^2 + \sum_{\substack{k\neq j\\ k=1}}^{N}\beta_{jk}|E_T^k|^2\right)\right], \quad (1b)$$

$$\frac{\mathrm{d}E_R^j}{\mathrm{d}t} = \gamma_c(G_R^j - \alpha_R^j)E_R^j + \mathrm{i}\omega_R^j E_R^j + \sqrt{\varepsilon_R^j}\eta_R^j - \kappa A_b\gamma_c\left(E_R^j - \frac{A_s}{A_b}\right)E_T^j, \quad (2a)$$

$$\frac{\mathrm{d}G_R^j}{\mathrm{d}t} = \gamma_F\left[P_R^j - G_R^j\left(1 + |E_R^j|^2 + \sum_{\substack{k\neq j\\ k=1}}^{N}\beta_{jk}|E_R^k|^2\right)\right], \quad (j = 1, 2, \cdots, N), \quad (2b)$$

where the superscript j denotes the jth mode, the subscript T denotes the transmitting laser while R denotes the receiving laser. There are N modes in each laser. The total electric field E and gain G of the transmitter and receiver are given by

$$E_T = \sum_{j=1}^{N} E_T^j, \quad E_R = \sum_{j=1}^{N} E_R^j, \quad (3a)$$

$$G_T = \sum_{j=1}^{N} G_T^j, \quad G_R = \sum_{j=1}^{N} G_R^j. \quad (3b)$$

In the above equations, E denotes the complex, slowly varying amplitude of the electric field, G is the gain of the active medium, $\tau_c = \dfrac{1}{\gamma_c}$ is the cavity round-trip time, $\tau_F = \dfrac{1}{\gamma_F}$ is the decay time of the upper lasing level, ω is the detuning of the laser frequency from the nearest empty cavity mode, P is the pump parameter, ε is the spontaneous emission noise strength, and η is a complex Gaussian white noise term of zero mean and correlation $\langle\eta^j(t)\eta^{k*}(t')\rangle = 2\delta_{jk}\delta(t-t')$. The sinusoidal loss modulation in the laser system is given by $\alpha^j = \alpha_0^j - \alpha_1^j\cos\Omega t$ where $\alpha_1^j \ll \alpha_0^j$. The final term on the right-hand side in equation (2a) is responsible for the coupling between the transmitting and receiving laser, which also accounts for any losses in the transmission process. To achieve the synchronization, it is assumed that $\alpha_{0R}^j = \alpha_{0T}^j + \kappa A_b$, where κ is the coupling coefficient, through which the message is brought into the output of the transmitter. When there is no signal encoded, $A_s = A_b$; while sending a signal, $A_s = (1 \pm v)A_b$, where v is the signal strength. The sign "+" corresponds to signal bit "1" while "–" corresponds to signal "0".

In Eqs.(1) and (2), it is reasonable to assume that the coupling between different longitudinal modes washes out if the beat frequency with which different modes oscillate is much faster than the time scale of the laser fluctuations. This is definitely the case for the Nd:YAG lasers under consideration. In addition, Eqs.(1) and (2) do not directly couple the gain of one laser to the field of the other. This simplification relies on the fact that the inversions of one laser do not overlap with the other. So they are independent with each other. If the total number of the modes in the laser system equals to one, i.e., N=1, Eqs.(1) and (2) are exactly the single mode laser system in the scheme of optical communication described in Ref.[8].

The total output intensity of the chaotic laser is a series of irregularly spaced pulses with a spiky appearance, as shown in Fig.1. It is clear that the total intensities of transmitter and receiver lasers show very good synchronization. In general, the encoded signal can be extracted as the integrated intensity difference:[8]

$$M = \int_{\text{pulse}} (|A_s E_T|^2 - (|A_b E_R|^2)\mathrm{d}t. \quad (4)$$

For bits "1", the value of $M > 200$. While for bits "0", $M < -200$. In the region of $-200 \leq M \leq 200$, there is no bit at all.

At first glance, it seems that the optical communications using multi-mode laser system is the same as that using single mode laser system. It is trivial to extend the communication scheme from single mode to multi-mode laser system. However, the value of M calculated numerically from Eq.(4) and presented in Fig.2 shows that it is not the case. In the numerically simulations, 100 stochastic bits are produced for the transmitted message and repeatedly by changing the seed of the pseudo-random number generator. Three modes in each laser of the multi-mode lasers are considered.

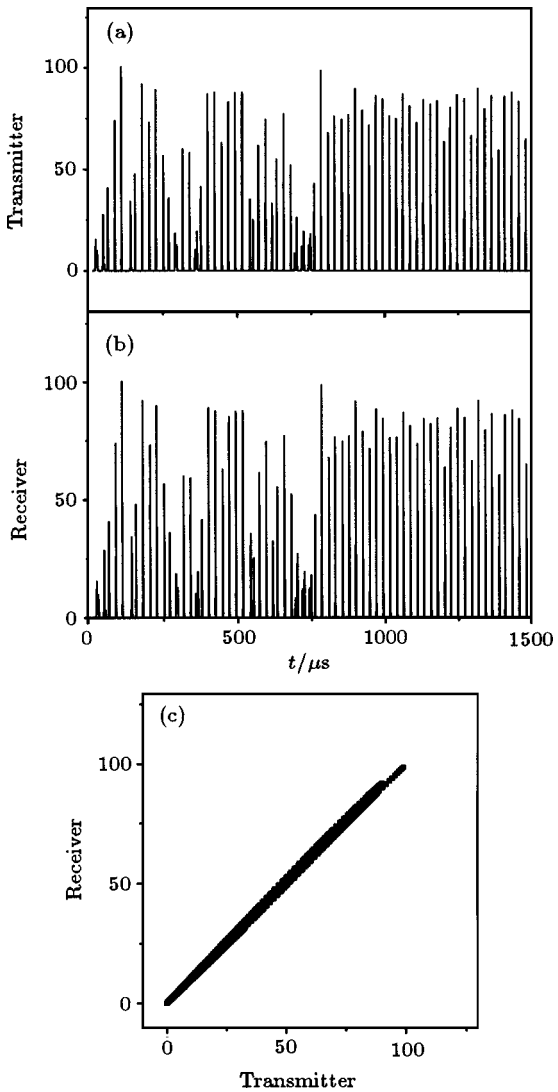


Fig.1. Total intensity of the loss-modulated three-mode Nd:YAG lasers operated in the chaotic regime. $\alpha_{0T} = \alpha_{0R}$=0.01, α_1=2.0×10^{-4}, Ω=541.6(1/ms), $P_T = P_R$=0.03, $\varepsilon_T = \varepsilon_R = 8.33 \times 10^{-9}$(1/s), $\omega_R - \omega_T$=50000 (rad/s). The intensity output is irregularly spaced spiky pulses.

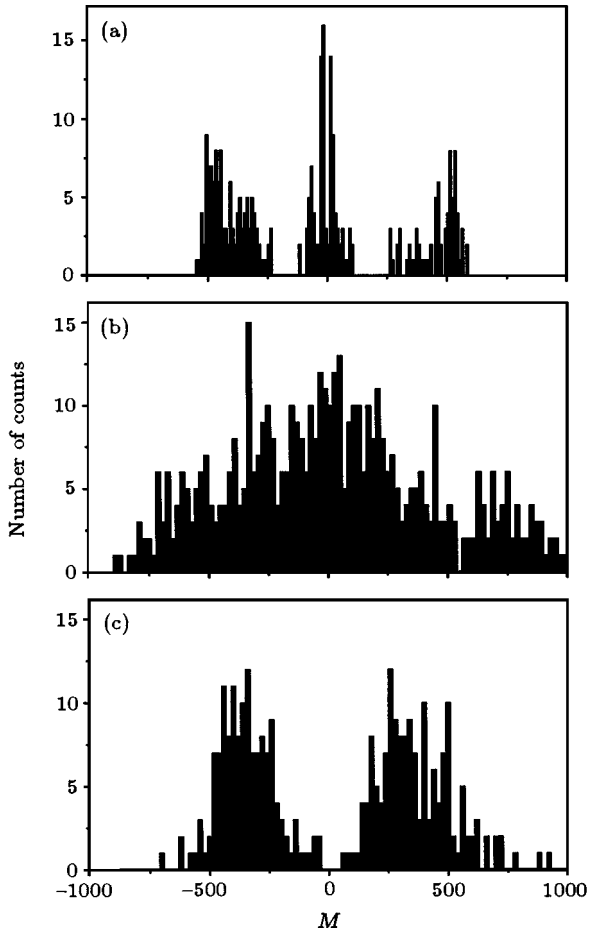


Fig.2. The distribution of M for a large number of bits. (a) When using single-mode lasers, large separation between "0" bits on the left and "1" bits on the right can be found. In the middle of the diagram there is a peak due to the unused pulses. (b) When using three-mode lasers with filtering out fake bits caused by the unused pulses, the two kinds of bits are mixed entirely. Thus the messages cannot be transferred correctly. (c) When using three-mode lasers with a short time break between two adjacent bits, the two kinds of bits can be clearly separated. Thus the messages can be transferred successfully.

The communication process is the same as that using single mode laser system in Ref.[8]. From Fig.2(a), it is seen that the digital communication using single mode laser system is quite successful. Though there is a region of no bits, the bits "1" and "0 " can be clearly distinguished since the peak value of M is separated at two sides of either greater than 200 or less than −200. From Fig.2(b), it is clear that both bits "1" and "0" are mixed when multi-mode laser system is used in digital communications. The peak value of M is located around M=0 with long tail at either side of M.

Figure 3 illustrates the numerical simulations of the whole process for communication using three-mode lasers when the method of digital communication for single mode lasers is employed. The signals are encoded on the total intensity of the carrier. After the transmitted is subtracted from the output of the receiver, the signals can be decoded. If the maxima of the pulses are lower than the threshold, these pulses cannot convey any signals. They become unused pulses. When the fake bits caused by these unused pulses are filtered out, the correct messages can be obtained. Though all the bits are extracted correctly, whether the extracted bit is "0" or "1" cannot be decided yet. If the bit "1" is determined with

$M > 0$ and bit "0" with $M < 0$, there will be many mistakes as shown by the arrows in Fig.3. The "1" bit indicated by the arrow in Fig.3(a) is transmitted. When it is decoded by the receiver laser, it becomes a "0" bit as indicated by the arrow in Fig.3(d). This is exactly shown in Fig.2(b). It shows that the scheme of digital communication using single mode lasers has to be modified when multi-mode laser system is used.

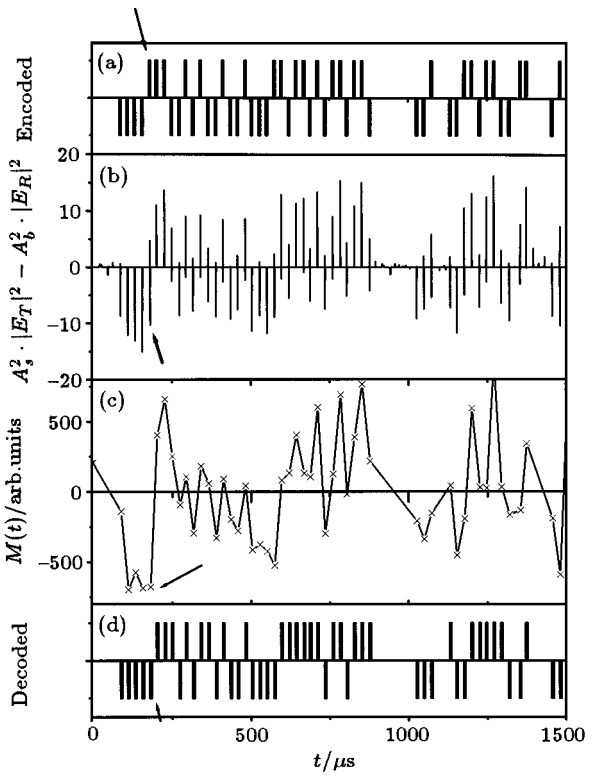


Fig.3. Numerical simulations of the whole process for communication using three-mode lasers by the usual method. Signal strength is v=10.0%. The transmission has a very low success rate. The signal indicated by an arrow is a bit "1" in (a), but its value of M is very small at about –700 in (c), so it is decoded as a bit of "0" in (d).

3. Modification of the communication scheme

When a multi-mode laser system is employed in digital communications the effect of interference between two adjacent bits appears. If the first signal is a "0" bit, this "0" bit will result in decreasing the curve of $(A_s^2 \cdot |E_T^2| - A_b^2 \cdot |E_R^2|)$. If the second signal is a "1" bit, it should bring an increase in the curve of $(A_s^2 \cdot |E_T^2| - A_b^2 \cdot |E_R^2|)$. However, the interference effect of the first signal will cause a decrease in the curve. The second bit decoded may be a wrong one. If the first signal is a "1" bit, this "1" bit will result in increasing the curve of $(A_s^2 \cdot |E_T^2| - A_b^2 \cdot |E_R^2|)$. If the second signal is a "0" bit, it should bring a decrease in the curve of $(A_s^2 \cdot |E_T^2| - A_b^2 \cdot |E_R^2|)$. However, due the interference effect of the first bit, the curve of $(A_s^2 \cdot |E_T^2| - A_b^2 \cdot |E_R^2|)$ may increase. The second bit decoded may also be a wrong one. In the process of digital communications, even the third and the fourth bit may be affected by the interference effect of the first one. This interference effect can be clearly seen in Figs.3(b) and 3(c). It seems that the interference effect is mainly due the coupling between modes in the multi-mode laser system.

The interference effect depends on the time interval between the two nearest bits. If the time interval between two bits is long enough, the interference effect will die out. In order to eliminate the mistakes and improve the success rate of decoding signals, the digital communication scheme needs to be modified to extend from single mode laser system to multi-mode laser system. The modification is to insert a time break between two nearest bits. The time break should be long enough to let the interference effect to die out and short enough to encode more digits. When a pulse used as carriers for encoding bits go beyond the fixed threshold, a bit is encoded. Then the transmission is broken for a short period, and then go on to transfer the next bit. Now the "1" bits and "0" bits are no longer mixed. From Fig.2(c), it can be seen that there is a wide gap between two kinds of bits. Thus the bit "1" and "0" bit can be decided correctly.

Figure 4 illustrates the numerical simulations of whole process for communication using three-mode lasers by the new method for first 3.0 ms. There are 100 stochastic bits produced for the transmitted message and repeatedly by changing the seed of the pseudo-random number generator. All the bits can be decoded at the receiver correctly. In the numerical simulations, it is not necessary to utilize an additional filter to remove the fake bits, as that described in Section II. In encoding digits, a break is inserted between two adjacent bits, it is the same for decoding bits. After a bit is extracted, the extraction should be broken for a short time too, and then go on to find the next bit. The period of the break here should be equal to the period of the break when the bit is encoded. By this requirement, the digits can be encoded and decoded correctly when a multi-mode laser system is employed in the communications. From Fig.4, it is clearly seen that the bits of both "1" and "0" can be transmitted correctly.

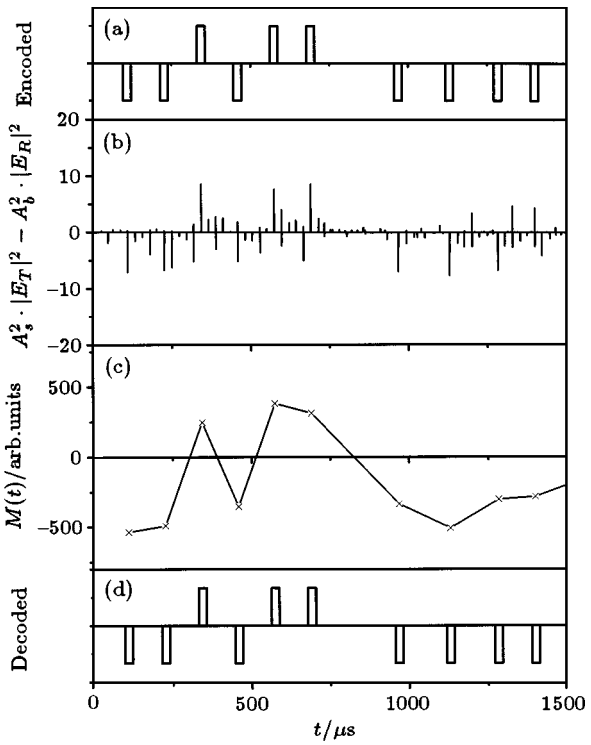


Fig.4. Numerical simulations of the whole process for communication using three-mode lasers by inserting a short time period between two adjacent bits. Signal strength is v=10.0%. It can be seen that the stochastic bits injected can be extracted and decoded correctly.

4. Conclusion

The digital communications using a multi-mode laser system is investigated. The communication scheme that is very effective for single-mode lasers cannot be simply extended to multi-mode lasers. In a multi-mode laser system, there is strong interference effect between two nearest bits. The interference effect depends on the time interval between the two bits. If multi-mode lasers are used in digital communications, a short time period between two adjacent bits should be inserted. The time period should be long enough to let the interference effect of the first bit die out and short enough to encode more bits on the carrier. After the modification, a multi-mode laser system can be successfully used in digital communications. Even the synchronization between two multi-mode lasers is not perfect with certain deviations, the digits can still be encoded and decoded correctly. This shows that the method introduced in this paper can be widely used in different systems for digital communications.

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