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Multi-user bidirectional communication using isochronal synchronisation of array of chaotic directly modulated semiconductor lasers

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ABSTRACT

Isochronal synchronisation between the elements of an array of three mutually coupled directly modulated semiconductor lasers is utilized for the purpose of simultaneous bidirectional secure communication. Chaotic synchronisation is achieved by adding the coupling signal to the self feedback signal provided to each element of the array. A symmetric coupling is effective in inducing synchronisation between the elements of the array. This coupling scheme provides a direct link between every pair of elements thus making the method suitable for simultaneous bidirectional communication between them. Both analog and digital messages are successfully encrypted and decrypted simultaneously by each element of the array.

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1. Introduction

Chaotic synchronisation has emerged as an important topic of research in diverse fields like physical [1], chemical [2] and biological systems [3]. Synchronisation of chaotic lasers has attracted much attention in the recent years for its potential application in single as well as multi-channel secure communication [4–10]. Recently, secure high speed long distance communication is achieved using synchronisation of chaotic lasers [11]. Long wavelength directly modulated semiconductor lasers are the most preferred light source in the fiber-optic communication links due to the appropriateness of its output wavelength which falls in the minimum loss and dispersion window of optical fibers. This has attracted much attention to the study of its chaotic dynamics and synchronisation [12–16]. Dynamics of semiconductor lasers with direct current modulation is also widely investigated [17–21]. A positive delayed optoelectronic feedback combined with strong current modulation suppresses chaotic dynamics and bistability in semiconductor lasers [22,23]. For InGaAsP lasers used in optical communication systems, the gain reduction occurring due to nonlinear processes is very strong and its effect is the suppression of chaotic dynamics [12]. It is recently reported that a negative delayed optoelectronic feedback is efficient in producing chaotic outputs from directly modulated semiconductor lasers with optimum value of nonlinear gain suppression factor [16].

Synchronization of two chaotic semiconductor lasers can be achieved using many different coupling schemes like unidirectional coupling [24,25], bidirectional coupling [26,27] which can be either optical or optoelectronic, direct or delayed [28,29]. Even though bidirectional coupling is effective in synchronizing chaotic oscillators, all the secure communication systems devised until very recently were mainly based on unidirectional coupling. Message transmission in both directions is the general approach in commercial communication systems. This naturally demands a bidirectional coupling between the oscillators. Also, channel delay is one of the most critical factors that affect the performance efficiency of secure communication systems using coupled chaotic systems. These realizations have enhanced the importance of research on synchronisation of bidirectional delay coupled oscillators [30–38].

Most of the methods proposed for the isochronous (zero-lag) synchronisation of delay coupled systems depend on the introduction of a third relay element coupled bidirectionally to the two oscillators [30–32], where the relay element can even be different from the outer systems [30]. As there is no direct link between the oscillators which are isochronally synchronized, this method has limited applicability for the purpose of bidirectional secure communication. Recent studies have shown that using the third element as a drive element rather than as a relay element [37] can provide isochronal synchronisation between the oscillators and

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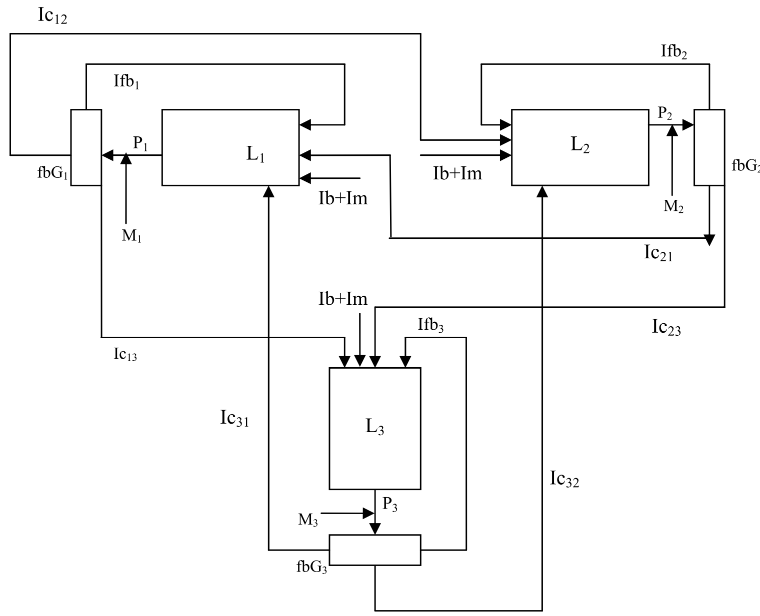

Fig. 1. Schematic of array of three mutually delay coupled directly modulated semiconductor lasers with negative optoelectronic feedback. The laser diodes L_1, L_2 and L_3 are driven by bias current I_b and a GHz modulation current I_m. fbG_1, fbG_2 and fbG_3 are feedback generators which splits the light outputs P_1, P_2, P_3 into required fractions for self feedback and coupling signals delayed by appropriate times and generates proportional feedback signals Ifb_1, Ifb_2, Ifb_3 and coupling signal Ic_{12}, Ic_{13}, Ic_{21}, Ic_{23}, Ic_{31}, Ic_{32} respectively. M_1, M_2 and M_3 are message signals which are encoded onto the outputs of L_1, L_2 and L_3 by the chaotic masking scheme.

is effective for bidirectional communication. A method of using face to face coupling added with self feedback is also effective in achieving isochronous synchronisation between two chaotic semiconductor lasers [34,35] and has better stability performance when compared to the scheme without self feedback. A performance comparison of unidirectional and bidirectional coupling between chaotic semiconductor lasers with self feedback demonstrating the high tolerance of bidirectional coupling towards parameter mismatch is reported recently [38].

Here we investigate the possibility of bidirectional secure communication in an array of three mutually delay coupled chaotic directly modulated semiconductor lasers. Individual array elements are long wavelength directly modulated semiconductor lasers with optimum values of nonlinear gain reduction factor and delayed optoelectronic self feedback. The method of adding coupling signal to the self feedback signal is used for synchronizing the array elements. Analog and digital messages are successfully encoded and decoded simultaneously at each element. The results show that the method is effective for simultaneous multi-user secure communication in optical communication networks.

2. Laser array model

Schematic diagram of the array of mutually coupled directly modulated semiconductor lasers with a delayed negative optoelectronic feedback is shown in Fig. 1. Laser diodes L_1, L_2 and L_3 are driven with their bias currents which are modulated using a sinusoidal GHz current and are mutually coupled to each other. A fraction of the light output from each element is delayed by the required time, converted into electronic signal and is fed back to its own input as self feedback signal. Two other fractions are sent to the other two elements as coupling signals. Thus each element receives a total of three delayed feedback signals comprising of the self feedback signal and two coupling signals received from the other two elements. The total feedback signal of every element is kept equal to the optimum value required for producing chaotic outputs [16]. Dynamics of each of the array elements can be represented by rate equations for the photon density (P), carrier density (N), and driving current (I) as follows

$$\frac{dN_{1,2,3}}{dt} = \frac{1}{\tau_e}\left\{\left(\frac{I_{1,2,3}}{I_{th}}\right) - N_{1,2,3} - \left[\frac{N_{1,2,3}-\delta}{1-\delta}\right]P_{1,2,3}\right\} \tag{1}$$

$$\frac{dP_{1,2,3}}{dt} = \frac{1}{\tau_p}\left\{\left[\frac{N_{1,2,3}-\delta}{1-\delta}\right](1-\varepsilon P_{1,2,3})P_{1,2,3} - P_{1,2,3} + \beta N_{1,2,3}\right\} \tag{2}$$

$$I_{1,2,3}(t) = I_b + I_m \operatorname{Sin}(2\pi f_m t) - r_s \times \left(P_{1,2,3}(t-\tau_s)\right) - r_{c_{2,3,1}} \times \left(P_{2,3,1}(t-\tau_c)\right) - r_{c_{3,1,2}} \times \left(P_{3,1,2}(t-\tau_c)\right) \tag{3}$$

The subscripts 1, 2, 3 represent the array element address, N and P are the carrier and photon densities, I is the driving current, τ_e and τ_p are the electron and photon lifetimes, $\delta = n_0/n_{th}$, $\varepsilon = \varepsilon_{NL} S_0$ are dimensionless parameters where n_0 is the carrier density required for transparency, $n_{th} = (\tau_e I_{th}/eV)$ is the threshold carrier density, ε_{NL} is the factor governing the nonlinear gain reduction occurring with an increase in S, $S_0 = \Gamma(\tau_p/\tau_e)n_{th}$, I_{th} is the threshold current, e is the electron charge, V is the active volume, Γ is the confinement factor and β is the spontaneous emission factor. $I_b = b \times I_{th}$ is the bias current where b is the bias strength, $I_m = m \times I_{th}$ is the modulation current where m is the modulation depth and f_m is the modulation frequency [12]. The parameters r_s and r_c are the self feedback and coupling strengths and τ_s and τ_c are the feedback and coupling delay times. The total strength of the signal comprising of the self feedback and coupling signals is kept within the optimum value of delayed feedback for producing chaotic outputs [16]. The delay times of coupling and self feedback signals are also fixed at their optimum values. The above equations are numerically simulated using fourth order Runge–Kutta method with parameter values as given in Table 1. For investigating the message encoding/decoding characteristics of the scheme shown in Fig. 1, three message signals M_1, M_2 and M_3 are encoded onto the outputs P_1, P_2 and P_3 of lasers L_1, L_2 and L_3 respectively. These messages are received and decoded simultaneously at the other two lasers.

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