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Synchronization and a secure communication scheme using optical star network

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ABSTRACT

This work aims to show the effect of synchronization phenomena in multi-nodal star optical network topology as well as to develop an efficient symmetric cryptosystem utilizing available parameters. The optical network is based on chaotic semiconductor laser (SL) systems described by dimensionless modified Lang–Kobayashi's (L–K) delay differential equations. The network nodes are mutually connected with a central semiconductor laser hub with bidirectional linear optical feedback. It has been observed that the laser output can be modulated using a star network setup. The laser intensity increases with the number of nodes and its much more higher than the same for solitary laser, keeping all other inputs as constant. So the network topology is an effective way to optimize the output power. The process by each nodes into the network is illustrated graphically for three, five and seven SLs, respectively. Also the whole network can be implemented as an optical communication system for transmission of signals. Each SL can act as a transceiver during communication. The communication process is examined using a chaotic signal as a plaintext connected with the SL hub and successfully provided a symmetrically secure mechanism upon the communication protocol. The result shows the optimization of output power with the increment of the number of nodes. Also the communication scheme can successfully decode the encrypted signal from SL Hub, at each other nodes.

1. Introduction

Semiconductor lasers [1–11] have been a potential area of research due to its rich chaotic phenomenon and optical communications [12–19]. Laser network based on optical injection can be considered as good transceiver for high speed optical communication. The optical injection locking can synchronize the nodes inside the laser network which has a broad applications in the coherent communications. Different network topologies implemented for optical communications, such as ring, star, fully connected etc. star network topology is useful as a communication model since each node is inherently isolated by the link that connects it to the central hub. This network configuration also keep the communication setup 'on' if there is any non or malfunctioning node. Also its easy to increase the network size by simply adding additional node to the network.

Chaotic optical communication [20] is a promising technique to improve both privacy and security in the communication networks. It employs synchronized chaotic nodes [21] to encode and decode information at the hardware level. The generated chaotic carrier at the central hub is used to encode information which can only be extracted when using the appropriate receiver.

High output power and broad bandwidth can be observed in super-luminescent light emitting diodes (SLEDs), which are useful for optical gyro sensors, optical coherence tomography, wavelength division multiplexing etc [22]. In all the cases, high output power plays an important role for SLEDs. The multi-mode interferometer (MMI) configuration has already been investigated as an effective way to optimize the output power for lasers. In this analysis, it has also been investigated as the optimization of output with various changes in the input parameters.

The work is organized as follows: in Section 2 an optical star network is constructed based on the modified L–K semiconductor laser models. It has been shown that the output power [23] is much higher inside the network than the solitary lasers. The chaotic properties inside the network are investigated by phase space diagram of the connected nodes. The numerical simulation done with 3, 5 and 7 star shaped connected SL networks. Section 3

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presents the phenomenon of synchronization inside the SL network. Network with n nodes can be synchronized with liner bidirectional feedback optical coupling. Some analytic conditions for synchronization are also stated for n laser nodes. The synchronization phenomenon is verified numerically by 3, 5 and 7 SL models. Section 4 contains the cryptographic scheme based on the star optical network. The encryption process is shown by a numerical example. It is interesting to observe that the electric fields are used as encryption keys, which is not transmitted through optical coupling. The network can be used for optical communication for any number of SL nodes. Section 5 is the conclusion.

2. Semiconductor laser star network

The semiconductor laser subjected to optical feedback can be described by the L–K model, which is a set of coupled delay differential equations. The dimensionless L–K model [19,25] can be written as

$$\frac{dE}{dt} = \frac{1}{2}(1+i\alpha)(n-1)E + \eta E(t-\tau)e^{-i\omega_0\tau} \quad (1)$$

$$\frac{T}{2}\frac{dn}{dt} = p - \frac{1}{2}(n-1) - n|E|^2 \quad (2)$$

where $E(t)$ is the intracavity complex electric field and $n(t)$ is the carrier population. Here α is the linewidth enhancement factor, ω_0 is the frequency of the solitary laser and η is the feedback rate. Also, $T=\tau_s/\tau_p$, where τ_p the photon lifetime, τ_s the carrier lifetime. p is proportional to the pumping rate above threshold. We denote $\overline{n}=1+2n(t)$.

The semiconductor lasers are extremely sensitive to back-reflections that arise in practical applications, potentially resulting in mode hopping, coherence collapse, strong excess noise and chaotic dynamics. The electric field amplitude E_0 and phase ϕ are defined by $E=E_0(t)e^{i\phi(t)}$, and obey

$$\frac{dE_0}{dt} = \frac{1}{2}E_0(\overline{n}-1) + \eta E_0(t-\tau)\cos(\phi-\phi(t-\tau)+\omega_0\tau)$$
$$\frac{d\phi}{dt} = \frac{1}{2}\alpha(\overline{n}-1) - \eta\frac{E_0(t-\tau)}{E_0(t)}\sin(\phi-\phi(t-\tau)+\omega_0\tau)$$
$$\frac{d\overline{n}}{dt} = \frac{2}{T}\left[p-\frac{1}{2}(\overline{n}-1)-\overline{n}E_0^2\right]$$

A complex network is set of interconnected nodes in which each node is considered like fundamental element with behavior depending of the nature of the network. We consider a complex dynamical network composes of N linearly and diffusively coupled identical nodes of laser dynamics, through the first state of each node. Each node constitutes a semiconductor laser dynamical system represented by $f(x)$ and the network is described as follows:

$$\dot{x}_i = f(x_i) + u_i, \quad i=1,2,\ldots,N \quad (3)$$

where $x_i=(E_{0i},\ \phi_i,\ n_i)$ is the state vector of dimensionless laser system, and u_i is the coupling between the elements of network defined as follows:

$$u_i = c\sum_{j=1}^{N}\gamma_{ij}\Gamma x_j, \quad i=1,2,\ldots,N.$$

The constant $c>0$ represents the coupling strength, and $\Gamma\in\mathbb{R}^{n\times n}$ is a constant 0–1 matrix linking coupled states. Assume that $\Gamma=diag(r_1,r_2,\ldots,r_n)$ is a diagonal matrix with $r_i=1$ for a particular i and $r_j=0$ for $j\neq i$. This means that two coupled nodes are linked through their i-th state. Let $G=(\gamma_{ij})_{N\times N}$ be the topological structures of a network satisfying the diffusive coupling connection: $G_{ij}\geq 0$, $i\neq j$, $\gamma_{ii}=-\sum_{j=1,j\neq i}^{N}\gamma_{ij}$. Thus we can write

$$G=\begin{bmatrix} -\sum_{i=2}^{N}\gamma_{1i} & \gamma_{12} & \cdots & \gamma_{1N} \\ \gamma_{21} & -\sum_{i=1,i\neq 2}^{N}\gamma_{2i} & \cdots & \gamma_{2N} \\ \vdots & \vdots & \ddots & \vdots \\ \gamma_{N1} & \gamma_{N2} & \cdots & -\sum_{i=1}^{N-1}\gamma_{Ni} \end{bmatrix}.$$

The matrix G is positive semidefinite since G is symmetric and all of its eigen values are real. Suppose that the dynamical network of lasers is connected in the sense that there are no isolated clusters. Then, G is a symmetric irreducible matrix. In this case, zero is an eigenvalue of A with multiplicity 1 and all the other eigenvalues of A are strictly negative. We consider the following laser network:

$$\frac{dE_{i0}}{dt} = \frac{1}{2}E_{i0}(\overline{n}_i-1) + \eta E_{i0}(t-\tau)\cos(\phi_i-\phi_i(t-\tau)+\omega_0\tau) + \sum_{j=1}^{N}\gamma_{ij}E_{j0} \quad (4)$$

$$\frac{d\phi_i}{dt} = \frac{1}{2}\alpha(\overline{n}_i-1) - \eta\frac{E_{i0}(t-\tau)}{E_{i0}(t)}\sin(\phi_i-\phi_i(t-\tau)+\omega_0\tau) \quad (5)$$

$$\frac{d\overline{n}_i}{dt} = \frac{2}{T}\left[p-\frac{1}{2}(\overline{n}_i-1)-\overline{n}_iE_{i0}^2\right] \quad (6)$$

under star network which is shown in Fig. 1. For this network the diffusive coupling configuration matrix is given by

$$G=\begin{bmatrix} -(N-1) & 1 & \cdots & 1 & 1 \\ 1 & -1 & \cdots & 0 & 0 \\ \vdots & \vdots & \ddots & \vdots & \vdots \\ 1 & 0 & 0 & -1 & 0 \\ 1 & 0 & 0 & 0 & -1 \end{bmatrix}.$$

In the following we study the numerical simulation of the network under considerations with the parameters, which are listed in Table 1. The Chaotic attractor formed by solitary L–K laser dynamics given in (4)–(6) is shown in Fig. 2(a). The attractors presented in phase space plots of E_0 vs n. The simplest form of star network with three nodes is a line network of three nodes. The corresponding attractor formed by a line network (simplest star configuration for 3 nodes) is considered to obtain the attractors presented in Fig. 2(b)–(d). Fig. 2(e)–(i) represents attractor formed

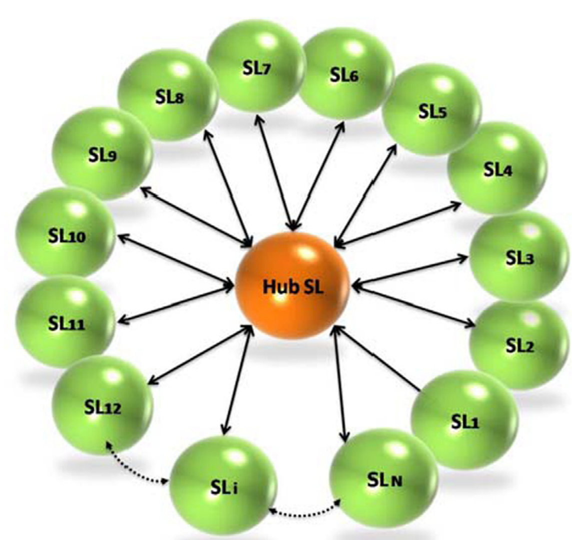

Fig. 1. The schematic diagram of laser network with (N+1) nodes. SL_i represents the ith node of the network under star network configuration.The central hub is the $(N+1)$th node.