Chaos Shift Orbit Modulation for Secret Communication

Senlin Yan
Department of Electronic Engineering, Nanjing Xiaozhuang University, Nanjing, China
Email: senlinyan@163.com

Abstract. A novel laser system of chaos shift parameter synchronization (CSPS) and dynamic chaos shift orbit synchronization (CSOS) is studied in depth when the parameters of transmitter shift in time, but the parameters of receiver do not change. We find that the system can obtain CSPS between the transmitter and receiver when the transmitter’s current is adjusted as chaos shift parameter (CSP) or an alterable parameter (AP). And CSOS still be achieved when the chaotic behavior and its trajectory of the emitter vary or jump in time with a real-time alterable current change in one laser. And our study proves that CSP and AP do not disturb to achieve the synchronizations. Based on CSPS and CSOS, a novel chaos shift orbit modulation (CSOM) coding scheme is studied via a real-time CSP change in the emitter for optics secret communications. The CSOM demodulation of an information is proved in two cases that a CSOM encoding technique is performed successfully. This system has real-time shift orbit performance, so it has high security and increases the difficulty for outside observers to break the information.

Keywords. Secure communication; chaos; synchronization; laser; encoding.

1. Introduction
Chaotic laser synchronization between two complex dynamical systems and its application in secure communication is a hot topic [1-3]. In this paper, we study on chaotic synchronization between two different complex dynamical laser systems and its encoding. Coupled lasers presented many types of nonlinear dynamic behaviors in both experiment and theory [4]. A coupled semiconductor laser system is used as some bistable devices and high-frequency generators, etc. [4]. At present, synchronization between coupled semiconductor lasers was widely reported [4]. However, very little work concerned on mutual coupling of different semiconductor laser emitter applying in secret communications. Traditionally, the transmitter’ parameters are encoded as secret keys in chaotic secret communications [5-8]. Decoding is achieved by the copied transmitter or when the transmitter’ parameters are identified. However, chaotic secret communications can be easily cracked because the transmitter’ parameters keep constant values. To increase security, we present a novel CSOM encoding based on CSPS and CSOS. The secrecy performance of the presented scheme is enhanced more than that of conventionalized chaotic communication schemes in regards to CSOS’s instant shifts in the transmitter’ parameters. The CSOM encoding is a valuable research direction in the chaotic encoding, so we must continue to study CSPS and CSOS in-depth [9, 10]. And our research is of a very high scientific value to the chaotic coding and chaotic synchronization applications.

In this paper, first, we study CSOS and CSPS model of the transmitter with the receiver laser in real-time by varying the current of one laser of the transmitter, where the transmitter’s current as CSP is dynamical adjusted or in real-time. Second, a CSOM encoding in two cases is performed. We find that instant shifts in the transmitter’ current can result in instant shifts of orbits of two chaotic lasers,
synchronization and its decoding can be obtained in the CSOM process. Last, we give our conclusion. For outside observers, we find that the variable CSOM increases a lot of difficulties for them to decipher the information from waveform. It will be important for private communications [5-10].

2. Model
A chaotic transmitter results from coupling semiconductor lasers with different parameters shown in figure 1 [1, 10], where coupling formation is made via interactions of the two fields of the space coupled lasers. The light beams $E_{t1}$ and $E_{t2}$ from the transmitter transmit to the receiver, where the laser $r$ of receiver has a feedback loop. We find that the transmitter laser $t2$ can synchronize with receiver laser $r$ no matter how the parameters of the transmitter laser $t1$ change. In general, we can still get the synchronization when the parameters of emitter $t1$ change. We define this synchronization as shift parameter synchronization. When the synchronization shows in chaotic states, we define this synchronization as CSPS. When the parameters of emitter laser $t1$ dynamical change, we define this synchronization as dynamic synchronization. When the parameters of emitter dynamical change and in real-time while the synchronization shows in chaotic states, we define this synchronization as CSOS, where the chaotic behavior and its trajectory vary or jump in real-time with the real-time CSP. The dynamic model is described by the following coupled equations [4-10]:

\[
\frac{dE_{t1}}{dt} = \frac{1}{2} (G_{t1} - \gamma_p) E_{t1} + \frac{k}{\tau_{t1}} E_{t2} \cos(\varphi_{t1} - \varphi_{t2})
\]

\[
\frac{d\varphi_{t1}}{dt} = \frac{1}{2} \beta (G_{t1} - \gamma_p) - \frac{k}{\tau_{t1}} E_{t1} \sin(\varphi_{t1} - \varphi_{t2}) - \Delta \omega
\]

\[
\frac{dN_{t1}}{dt} = \frac{I_{t1}}{q} - \gamma_{at1} N_{t1} - G_{t1} V_{p1} E_{t1}^2
\]

\[
\frac{dE_{t2}}{dt} = \frac{1}{2} (G_{t2} - \gamma_p) E_{t2} + \frac{k}{\tau_{t2}} E_{t1} \cos(\varphi_{t2} - \varphi_{t1})
\]

\[
\frac{d\varphi_{t2}}{dt} = \frac{1}{2} \beta (G_{t2} - \gamma_p) - \frac{k}{\tau_{t2}} E_{t1} \sin(\varphi_{t2} - \varphi_{t1}) + \Delta \omega
\]

\[
\frac{dN_{t2}}{dt} = \frac{I_{t2}}{q} - \gamma_{at2} N_{t2} - G_{t2} V_{p2} E_{t2}^2
\]

\[
\frac{dE_r}{dt} = \frac{1}{2} (G_r - \gamma_p) E_r + \frac{k}{\tau_{tr}} E_{t1} \cos(\varphi_r - \varphi_{t1}) + \frac{k_r}{\tau_{tr}} [E_{t2} \cos(\varphi_r - \varphi_{t2}) - E_r]
\]

\[
\frac{d\varphi_r}{dt} = \frac{1}{2} \beta_r (G_r - \gamma_p) - \frac{k_r}{\tau_{tr}} E_{t1} \sin(\varphi_r - \varphi_{t1}) - \frac{k_r}{\tau_{tr}} E_{t2} \sin(\varphi_r - \varphi_{t2}) + \Delta \omega
\]

\[
\frac{dN_r}{dt} = \frac{I_r}{q} - \gamma_{at} N_r - G_r V_p E_r^2
\]

where the “t1”, “t2” and “r” of the subscripts indicate lasers $t1$, and $t2$ and $r$, respectively. The variables $E$, $\varphi$ and $N$ indicate the amplitude and phase of the lasing and the carrier number, respectively. $k$ is the optical field coupling factor and optical injection factor of the laser $t1$, where they have the same level. $k_r$ is the optical injection-feedback factor, where the optical feedback and optical injection of the laser $t2$ have the same level. The other parameters are seen in reference [10].
3.1. CSOS
CSP $I_{t1}$ of transmitter change dynamical and in real-time results in the chaotic behavior and its trajectory vary or jump in real-time with the real-time CSP. In this case, synchronization can still achieve, so we define this synchronization as CSOS. We can use CSOS in real-time to secret communication because a real-time shift of transmitter’s parameter causes shifts in chaotic orbits, which will result in the great difficulty of deciphering the content. Next, we let CSP $I_{t1}$ vary real-time randomly in the chaotic regions to achieve a CSOS. And then based on CSOS, CSOM encoding can be achieved when the laser $t2$ current is modulated by an information signal. Then, we take the lasing $E_{t2}$ to transmit the information to the receiver.

In our work, the transmitter’s current $I_{t1}$ sets at a basic value and a random current value as CSP. In practical study, the base current set at 37.999 mA, and the random current varies between 0 mA and 0.5 mA. Thus, random variations of the current cause instant changes in dynamics orbit of transmitter. Figures 2 (a) and (b) show that a perfect synchronization and its CSOS are achieved between lasers $t2$ and $r$.

3.2. CSOM Encoding
Using the CSOS system, chaos modulation (CM) is operated to perform CSOM encoding, where the laser $t2$ current is modulated by an information signal, which means that the chaotic carrier contains
the information signal. And then the receiver can decode the information signal via CSOS technology while CSOM communication can be realized. We focus on both modulation and demodulation of CSOS between the lasers t2 and r.

Figure 3. CSOM communication. (a) chaotic carrier carrying an information signal; (b) a decoding process; (c) a filtered information signal; and (d) an information signal.

We take \( I_{t2} = I_{r} + \delta I = 37.999 \times (1 + 0.005 \times \sin 2\pi f_{M} t) \) mA, where the term \( \delta I = 37.999 \times 0.005 \times \sin (2\pi f_{M} t) \) mA indicates an information signal with a modulation frequency \( f_{M} = 0.1 \) GHz. CSP \( I_{t1} \) sets at 37.999 mA and a random current value varies between 0 mA and 0.5 mA. Figure 3 presents a CSOM process with \( k_{c} = 0.2 \). Figure 3 (a) gives chaos containing encoded information. Figure 3 (b) shows a CSOM decoding process using the CSOS. Figure 3 (c) shows a filtered information signal. Figure 3 (d) shows the information signal \( S = 0.005 I_{r} \times \sin (2\pi f_{M} t) \). The result shows that CSOM communication can be achieved perfectly. Our numerical result agrees with the CSOM decoding theory.

Figure 4. Another CSOM communication. (a) chaos carrying an encoded information; (b) a decoding process; (c) a filtered information signal; and (d) an information signal.

Another CSOM decoding process is discussed using another CSP variable method in figure 4, where CSP varies with different forms in time-domain. When \( t < 30 \) ns, \( I_{r} \) sets at 37.999 mA and \( \delta I \)
varies random between 0 mA and 0.3 mA. When 30<\gamma<60ns, we take \(I=0.25\times[1+\sin(0.2GHz\times\pi)]\) mA. When \(t>60ns\), we let \(\delta t\) vary at 0.1Gbit/s and its values vary between 0 mA and 0.2 mA. Figure 4 shows this CSOM decoding process. This CSOM encoding increases obviously the difficulty for outsiders to decipher the information.

3.3. Parameter Mismatch
We report briefly on the parameter mismatch of the system. Taking \(\Delta\omega=2\ GHz\), \(k=0.085\), \(I_1=38.33\) mA, \(I_2=I=25\) mA, and \(k_0=0\), we obtain
\[
\gamma = \langle |E_{12}^2-E_1^2|\rangle = 9\times10^{-3},
\]
and \(\langle \rangle \) is an average from 40ns to 80ns. When \(k_0=0.2\), \(I=24.96\) mA, we get the synchronous difference \(\langle |E_{12}^2-E_1^2|\rangle = 3.53\times10^{-5}<<\gamma\). When \(k_0=0.2\), the laser r gain set as 0.999a, obtained synchronous difference is \(\langle |E_{12}^2-E_2^2|\rangle = 1.71\times10^{-6}<<\gamma\). When \(k_0=0.2\), the laser r parameter set 0.999b, obtained synchronous difference is \(\langle |E_{12}^2-E_2^2|\rangle = 2.96\times10^{-8}<<\gamma\). So we find the system has the tolerance to parameter mismatch.

4. Conclusion
In conclusion, we have presented a CSOS laser system and its CSOM encoding. The transmitter results in instant changes in the chaotic movement orbit using the CSP and AP methods, but all kinds of dynamic synchronizations still is obtained between the transmitter and the receiver in dynamic regions and in real-time. We implement perfectly CSOM communications while our numerical result agrees with the decoding theory. The transmitter has the characteristics of instant variable orbit, which causes variables of the transmitter's parameter secret keys in real-time because of its multiple variables varying with CSP in different forms, so the system has the high security and added a lot of difficulties for deciphering the information. These results are important for CSOS applications in secure communications and the study of complex dynamic system synchronization.

References
[1] Ning J, Zhao A K, Liu S Q, Xue C P and Qiu K 2018 Chaos synchronization and communication in closed-loop semiconductor lasers subject to common chaotic phase-modulated feedback Optics Express 26 32404-32416.
[2] Fu Y D, Cheng M F, Jiang X X, Deng L, Ke C J, Fu S N, Tang M, Zhang M, Shum P and Liu D 2018 Wavelength division multiplexing secure communication scheme based on an optically coupled phase chaos system and PM-to-IM conversion mechanism Nonlinear Dynamics 94 1949-1959.
[3] Li Q L, Chen D W, Bao Q, Zeng R and Hu M 2019 Numerical investigations of synchronization and communication based on an electro-optic phase chaos system with concealment of time delay Applied Optics 58 1715-1722.
[4] Mulet J, Mirasso C, Heil T and Fischer I 2004 Synchronization scenario of two distant mutually coupled semiconductor lasers J. Opt. B: Quantum Semiclass. Opt. 6 97-105.
[5] Kang Z X, Sun J, Ma L, Qi Y H and Jian S S 2014 Multimode synchronization of chaotic semiconductor ring laser and its potential in chaos communication IEEE J. Quantum Electron. 50 148-157.
[6] Lawrance A J, Papamarkou T and Uchida A 2017 Synchronized laser chaos communication: Statistical investigation of an experimental system IEEE J. Quantum Electron. 53 8000210.
[7] Ning J, Xue C P, Liu D, Lv Y X and Qiu K 2017 Secure key distribution based on chaos synchronization of VCSELs subject to symmetric random-polarization optical injection Opt. Lett. 42 1055-1058.
[8] Troger J, Nicati P A, Thevenaz L and Rober P A 1999 Encoded Gbit/s digital communications with synchronized chaotic semiconductor lasers IEEE Quantum Electronics 35 32-297.
[9] Ke J, Yi L, Xia G and Hu W 2018 Chaotic optical communications over 100-km fiber transmission at 30-Gbit/s bit rate Optics Letters 43 1323-1326.
[10] Yan S L 2019 CSO secret communication Electronics Letters 55 1349-1352.