Vol 17 No 9, September 2008
1674-1056/2008/17(09)/3264-06

Chinese Physics B

© 2008 Chin. Phys. Soc.
and IOP Publishing Ltd

Improving performance of optical fibre chaotic communication by dispersion compensation techniques*

Zhang Jian-Zhong(张建忠), Wang Yun-Cai(王云才)†, and Wang An-Bang(王安帮)

Department of Physics, College of Science, Taiyuan University of Technology, Taiyuan 030024, *China*

(Received 23 November 2007; revised manuscript received 26 January 2008)

This paper numerically investigates the effects of dispersion on optical fibre chaotic communication, and proposes a dispersion compensation scheme to improve the performance of optical fibre chaotic communication system. The obtained results show that the transmitter–receiver synchronization progressively degrades and the signal-to-noise ratio of the recovered message deteriorates as the fibre length increases due to the dispersion accumulation. Two segments of 2.5-km dispersion-compensating fibres are symmetrically placed at both ends of a segment of 245-km nonzero dispersion-shifted fibre with low dispersion in one compensation period. The numerical results show that the signal-to-noise ratio of the extracted 1 GHz sinusoidal message is improved from –2.92 dB to 15.38 dB by this dispersion compensation for the transmission distance of 500 km.

Keywords: chaotic communication, fibre propagation, chaotic synchronization, message extraction, semiconductor laser, dispersion compensation.

PACC: 0545, 4281D, 4260

1. Introduction

Data security is one of the most important issues in communication networks. Owing to higher dimension and broader bandwidth of optical chaos generated from laser, optical chaotic communication has shown the better security and attracted increasingly extensive attention. Many systems for optical chaotic communication based on either fibre lasers[1,2] or semiconductor lasers[3−6] have been proposed and successfully demonstrated in free space. Theoretical investigations[7,8] indicated that optical chaotic communication had potential application in optical fibre transmission, and could achieve optical fibre chaotic secure communication by combining with the existing optical fibre links. Similar to that of conventional optical communication network, the loss and dispersion are two of the most important factors to limit the transmission distances and rates of optical fibre chaotic communication. The loss of optical power can be easily solved by optical amplifiers, but dispersion is a more challenging problem, especially for high bit rate communication system. For example, a field optical chaotic communication system was successfully realized in 120-km commercial fibre-optic channel for 1-Gb/s transmission rate. However, its bit-error rates were only 10^{-7} mainly due to the dispersion.[9] Therefore, compensating the dispersion can effectively improve the system's performance of fibre chaotic communication.

A little research has already been devoted to the dispersion effects in optical fibre chaotic communication system. Reference [10] numerically investigated the effects of dispersion on the recovered message of fibre chaotic communication system in which fibre nonlinearity and amplifier noise were together taken into account. Reference [11] further theoretically investigated the effects of dispersion on chaotic carrier, synchronization quality and the recovered message of fibre chaotic communication system in which fibre nonlinearity and amplifier noise were together included. However, both Refs.[10] and [11] did not carry out the dispersion compensation. Reference [12] suggested that the symmetrical dispersion compensation map was more efficient than the pre- and post-dispersion compensation maps and the maps utilizing nonzero dispersion-shifted fibre (NZ-DSF) were superior to that employing other types of fibre for optimizing the transmission properties of fibre chaotic communication system by a numerical simulation. In this

*Project supported by the National Natural Science Foundation of China (Grant Nos 60777041 and 60577019) and the International Cooperation Project of Shanxi Province, China (Grant No 2007081019).

†Corresponding author. E-mail: wangyc@tyut.edu.cn

paper, by combining the advances of the symmetrical map and the maps utilizing NZ-DSF, we especially propose a dispersion compensation scheme to overcome the downgrading of the system performance and improve the quality of the recovered message. Meanwhile, we numerically study the effects of dispersion on chaotic carrier, synchronization performance and the retrieved message of fibre chaotic communication system.

2. Theoretical model

2.1. Transmitter and receiver lasers

The closed-loop scheme in our study is shown in Fig.1. Both transmitter (LD_T) and receiver (LD_R) have the same configuration, which are composed of a semiconductor laser with an external reflector. The message is superposed on the chaotic carrier by injection-current modulation. The output from the transmitter is injected into the fibre for long-distance transmission where the optical isolator (ISO) is used to ensure unidirectional transmission. At the end of the fibre an erbium-doped fibre amplifier (EDFA) is placed to restore the fibre loss. The restored chaotic carrier encoded by the message is divided into two beams by beam splitter (BS). One beam is injected into the receiver laser. The other beam, as well as the output from the receiver laser, is separately detected by two identical photodiodes (PDs). The message can be recovered from the subtracting of the two detected signals.

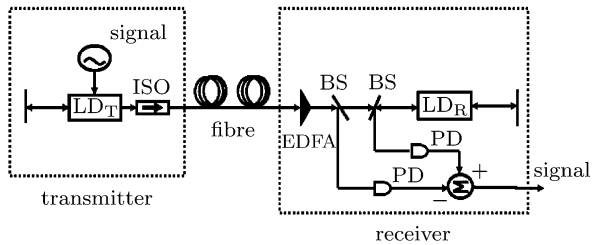


Fig.1. Schematic diagram for fibre chaotic communication system.

We use the Lang–Kobayashi rate equations which consider the semiconductor laser with optical feedback and optical injection to describe the dynamics of the transmitter and the receiver. The rate equations are described as follows:[12]

$$\frac{\mathrm{d}E_{\mathrm{T,R}}(t)}{\mathrm{d}t} = \frac{1}{2}(1+\mathrm{i}\alpha)\left[G_{\mathrm{T,R}}(t) - \frac{1}{\tau_{\mathrm{P}}}\right]E_{\mathrm{T,R}}(t) + k_{\mathrm{T,R}}E_{\mathrm{T,R}}(t-\tau)\exp(-\mathrm{i}\omega\tau) + k_{\mathrm{inj}}E_{\mathrm{ext}}(t), \tag{1}$$

$$\frac{\mathrm{d}N_{\mathrm{T,R}}(t)}{\mathrm{d}t} = \frac{I_{\mathrm{T,R}}}{qV} - \frac{1}{\tau_n}N_{\mathrm{T,R}}(t) - G_{\mathrm{T,R}}(t)\left|E_{\mathrm{T,R}}(t)\right|^2, \tag{2}$$

$$G_{\mathrm{T,R}}(t) = \frac{G[N_{\mathrm{T,R}}(t) - N_0]}{1+\varepsilon\left|E_{\mathrm{T,R}}(t)\right|^2}. \tag{3}$$

Where E and N are the slowly varying complex electrical field amplitude and the carrier density in the laser cavity respectively, subscripts T and R represent the transmitter and receiver respectively. $\omega\tau$ is the round-trip phase shift induced by the external feedback, where ω is the angular frequency of the free-running laser. The field E_{ext} is the input signal at the receiver and I is the pump current density of the semiconductor laser. We define the feedback coefficient of semiconductor laser with optical feedback $k_{\mathrm{T,R}}$ and the injection coefficient from the transmitter to the receiver k_{inj} as follows:

$$k_{\mathrm{T,R}} = \frac{1}{\tau_{\mathrm{in}}}\frac{(1-r_0^2)r_{\mathrm{T,R}}}{r_0}, \tag{4}$$

$$k_{\mathrm{inj}} = \frac{1}{\tau_{\mathrm{in}}}\frac{(1-r_0^2)r_{\mathrm{inj}}}{r_0}, \tag{5}$$

where τ_{in} is the round-trip time in the laser cavity, r_0 and $r_{\mathrm{T,R}}$ represent amplitude reflectivity of the laser exit facet and the external reflector respectively, r_{inj} represents the percentage of the transmitter's output electrical field amplitude injected into the receiver laser cavity. All the involved laser parameters and their values used in our numerical model are from Ref.[13].

2.2. Fibre channel

The light propagation along the fibre connecting the transmitter and the receiver is described in terms of the well-known nonlinear Schrödinger equation.[14]

$$\mathrm{j}\frac{\partial E}{\partial z} = -\frac{\mathrm{j}}{2}\alpha E + \frac{1}{2}\beta_2\frac{\partial^2 E}{\partial T^2} - \gamma\left|E\right|^2 E, \tag{6}$$

where $E(z,T)$ is the complex slowly varying amplitude field, z is the propagation distance, and T is the time measured in a reference frame moving at the group velocity. α is the fibre attenuation coefficient,

β_2 is the second-order dispersion parameter, and γ is the nonlinear coefficient. In this paper, we only investigate the effects of fibre dispersion on the system of fibre chaotic communication, and do not take into account such subordinate factors as fibre nonlinearity and amplifier noise when the optical power injected into the fibre is appropriate. So we set γ=0 here. In our numerical simulation, we consider NZ-DSF (1550nm) with typical values of α=0.2 dB/km and β_2=1 ps^2/km as transmission channel. Two ideal EDFAs whose amplified spontaneous emission noise is neglected are utilized in each 250-km-long span of fibre channel and placed at the beginning and at the end of the link. Their gain value is set to G=exp(αL) in order to compensate for the fibre loss in an amplification period.

3. Dispersion influences

3.1. The effects of dispersion on chaotic carrier

The correlation dimension of the chaos generated by the transmitter is 6.37 according to Grassberger–Procaccia (G–P) algorithm,[15] and the largest Lyapunov exponent is 3.6 ns^{-1}. Therefore, the output waveform of the transmitter is high-dimensional chaos. We use the chaotic output of transmitter as the carrier whose bandwidth is about 4.18 GHz. The mean optical power of the chaotic carrier is about 5.6 mW. Chaotic carrier is injected into fibre channel, and after the long propagation distance, its output is shown in Fig.2. Figure 2 shows that the irregular pulses of chaotic carrier generated by transmitter laser and the outputs of chaotic carrier through optical fibre of length 100, and 300 km. From Fig.2, we see that chaotic carrier is widened due to the accumulated dispersion as the length of fibre increases. Meanwhile, at the end of 100, and 300-km-long fibres an EDFA is placed to compensate for the fibre loss.

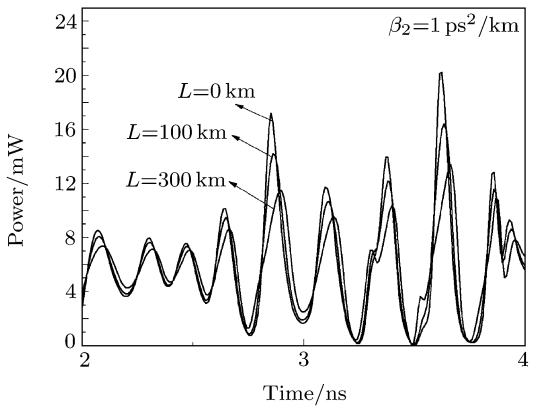


Fig.2. Chaotic evolution of the transmitter and the fibre, 100, and 300 km.

3.2. The effects of dispersion on synchronization

The synchronization error σ is a criterion of the synchronization quality of fibre chaotic communication system, with a small value of σ indicating a high synchronization quality. The synchronization error is defined as $\sigma = \langle |P_{\rm T} - P_{\rm R}| \rangle / \langle P_{\rm T} \rangle$, where $\langle \cdot \rangle$ denotes averaging over time. Figure 3 shows the synchronization correlation plots of two chaotic waves of transmitter and receiver for different lengths of fibre. The ideal synchronization scenario would correspond to a straight line. For short propagation distances, the distortion induced by the fibre is very small and the synchronization diagram fits very well to a straight line. In fact, even in the absence of a fibre, the synchronization will never be perfect because both lasers are not operating in exactly the same regime and the receiver laser has an injected signal. It is clear that the synchronization progressively degrades as the fibre length increases. The main reason is that as the fibre length increases, the accumulation of fibre dispersion leads to the widening of chaotic carrier shown in Fig.2. From Fig.4, we also find that when the length of fibre is less than 100 km, the accumulated dispersion is very small and the synchronization error σ is almost kept constant, and when the length of fibre is greater than 100 km, synchronization error σ linearly increases with the propagation length.

3.3. The dispersion versus SNR

We use the signal-to-noise ratio (SNR) to evaluate the quality of the extracted message of the system. The SNR is defined as SNR=10log$_{10}$($P_{\rm S}/P_{\rm N}$), where $P_{\rm S}$ and $P_{\rm N}$ represent the power of the signal and noise, respectively. The message is encoded in the chaotic carrier through direct current modulation of the transmitter. We define the modulation current as $I = I_{\rm b} + I_{\rm m}\sin(2\pi ft)$. Where $I_{\rm b}$=18 mA is the bias current; $I_{\rm m}$=3.6 mA is the current amplitude of the modulated message; and f=1 GHz is the modulation frequency. When the receiver synchronizes with the transmitter, the message can be recovered by sub-

tracting the receiver output from the transmitted signal. The decoded messages are shown in Fig.5. Figure 5(a) is the encoded 1GHz sinusoidal message. Figure 5(b)–5(d) are the recovered messages for the lengths of fibre, 100, 300, and 500 km, respectively. The quality of the recovered message obviously degrades with the propagation distance. When the length of fibre reaches 500 km, the decoded message is almost submerged in the noise.

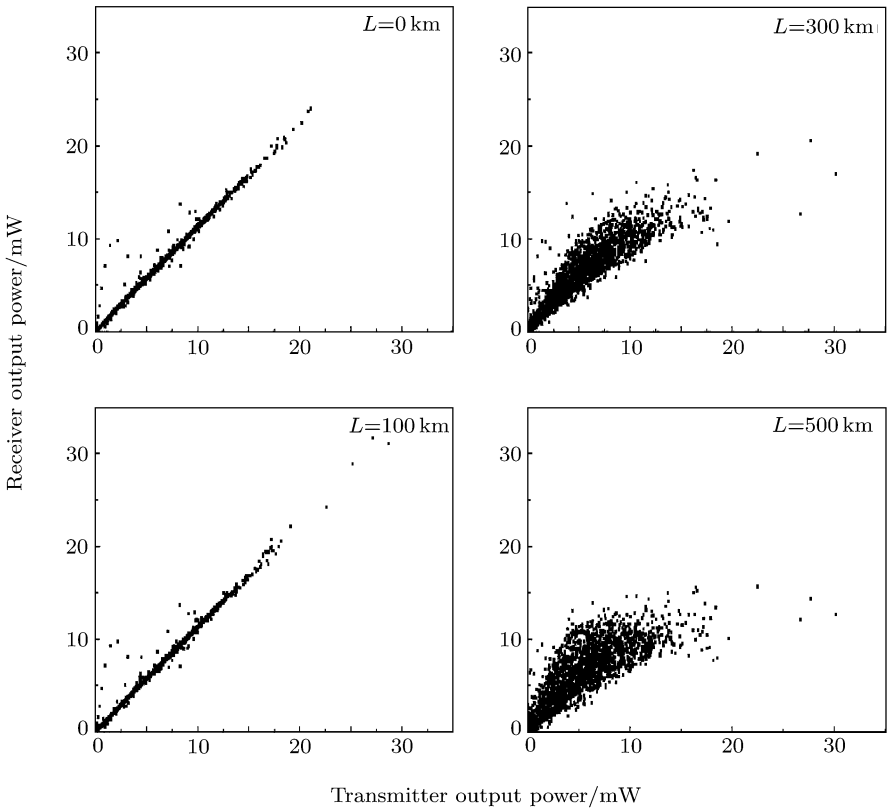


Fig.3. Synchronization plots of receiver output power versus transmitter output power for the fibre 0, 100, 300, and 500 km.

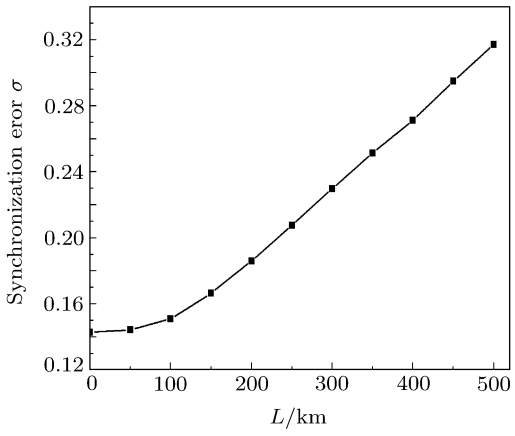


Fig.4. Synchronization error σ as a function of the propagation distance.

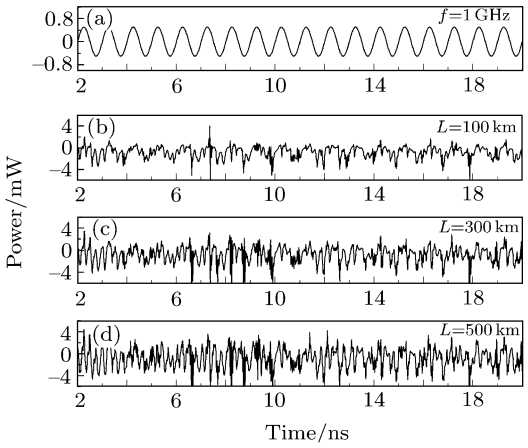


Fig.5. Encoded and decoded messages. (a) encoded 1GHz sinusoidal message, (b)–(d) decoded messages for fibre lengths of 100, 300, and 500 km, respectively.

Figure 6 shows that the SNR of the recovered message decreases with the increase of the length of fibre. For fibre chaotic communication system encoding 1 GHz sinusoidal message, the SNR of the recovered message is 14.63 dB when the length of fibre is 50 km. However, the SNR of the recovered message degrades to –2.92 dB when the length of fibre is 500 km. In addition, we also find that the SNR does depend on the message frequency and it is degraded as the frequency increases.

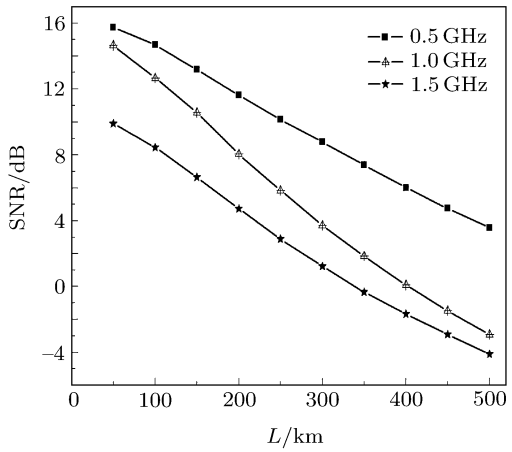


Fig.6. SNR versus the propagation distance for the message frequency of 0.5, 1, and 1.5 GHz, respectively.

4. Dispersion compensation

As mentioned above, we can find that the dispersion plays an important role in fibre chaotic communication system. The symmetrical dispersion compensation map was more efficient than the pre- and post-dispersion compensation maps and the maps utilizing NZ-DSF were superior to that employing other types of fibre.[12] By combining the advances of the symmetrical map and the maps utilizing NZ-DSF, we propose a new dispersion compensation scheme to compensate the dispersion in fibre chaotic communication system. The proposed dispersion compensation map is shown in Fig.7, which consists of a segment of 245-km-long NZ-DSF with β_2=1 ps^2/km, two segments of 2.5-km-long DCFs with β_2=–49 ps^2/km symmetrically placed before and after the NZ-DSF, and two EDFAs in one compensation map. Thus the value of the average dispersion of fibre between two optical amplifiers closes to zero in a dispersion compensation period.

After dispersion compensation is carried out, the performance of fibre chaotic communication system is significantly improved. Figure 8 shows the comparison between the synchronization plots and the recovered messages with and without dispersion compensation

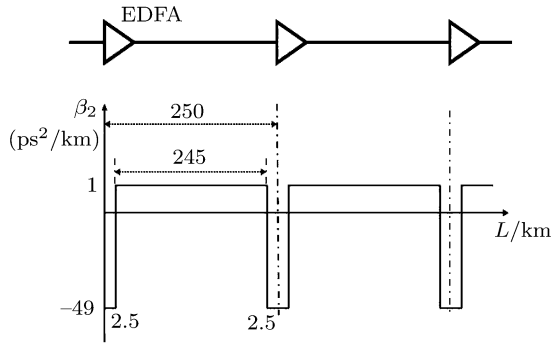


Fig.7. Schematic diagram of dispersion map.

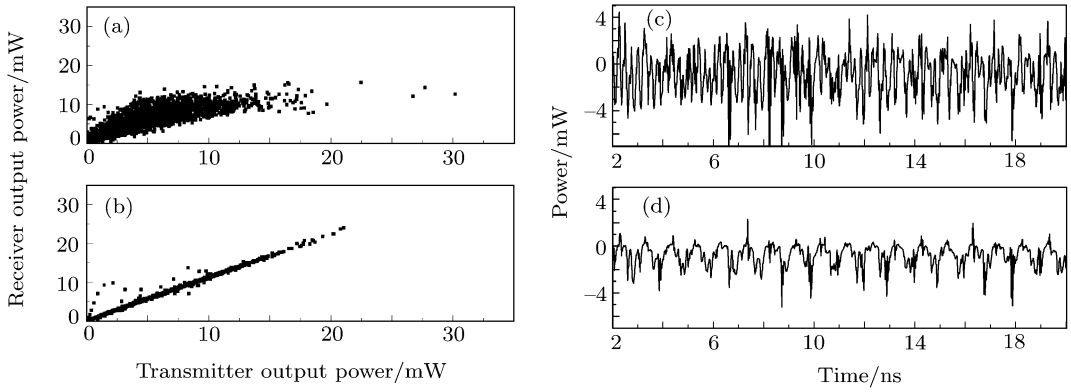


Fig.8. Comparison between the synchronization plots and the recovered messages with and without dispersion compensation. (a), (c) the synchronization plot and the recovered message without dispersion compensation for the length of fibre, 500 km; (b), (d) the synchronization plot and the recovered message with dispersion compensation for the length of fibre, 500 km.

when the length of fibre is set to 500 km From Figs.8(a) and 8(b), an evident synchronization improvement of the transmitter and receiver system is observed after dispersion compensation. Furthermore, the synchronization error decreases from 0.32 to 0.14 via dispersion compensation for the transmission distance of 500 km. From Figs.8(c) and 8(d), it is obvious that the quality of the recovered message with dispersion compensation is better than that without dispersion compensation. For 1GHz sinusoidal message encoded through 500-km-long fibre, the SNR of the recovered message increases from –2.92 dB to 15.38 dB via dispersion compensation.

After the dispersion in fibre chaotic communication system is compensated, not only the transmission distances are significantly extended but also higher transmission rates can be achieved. Figure 9 shows

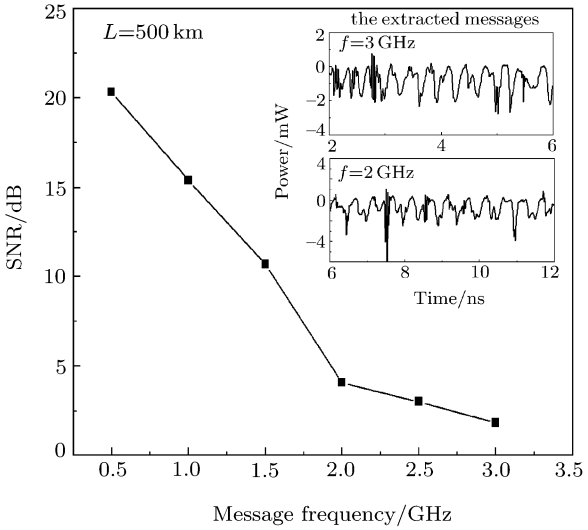


Fig.9. SNR of the extracted message as a function of the message frequency for the transmission distance of 500 km in fibre chaotic communication system with dispersion compensation.

that the SNR of the extracted message is plotted as a function of the message frequency for the dispersion-compensated system. Although the SNR of the extracted message decreases with the increase of the message frequency for the transmission distance of 500 km, the SNR of the extracted 3 GHz sinusoidal message can still reach 1.82. This indicates that when the frequency of the transmitted sinusoidal message is as high as 3 GHz, the message extraction of the dispersion-compensated system is possible. However, as mentioned in the preceding section, even if 1 GHz sinusoidal message is encoded, the message recovery cannot be achieved without the dispersion compensation for the transmission distance of 500 km.

5. Conclusions

In this paper, a theoretical model to characterize long-distance fibre chaotic communication system is described. The effects of dispersion on synchronization quality and the recovered message of the system are qualitatively and quantitatively investigated. The dispersion accumulation degrades the system's synchronization and deteriorates the recovered message as the length of fibre increases. We present a symmetrical dispersion compensation scheme to compensate the effects of dispersion on fibre chaotic communication system. The synchronization error decreases from 0.32 to 0.14 when the length of fibre is 500 km. The SNR of the recovered 1GHz sinusoidal message increases from –2.92 dB to 15.38 dB for the transmission distance of 500 km.

References

[1] van Wiggeren G D and Roy R 1998 *Science* **279** 1198
[2] Luo P M, Chu P L and Liu H F 2000 *IEEE. Photon. Tech. Lett.* **12** 269
[3] Sivaprakasam S and Shore K A 2000 *IEEE J. Quantum Electron.* **36** 35
[4] Liu J M, Chen H F and Tang S 2001 *IEEE Trans. Circuits Syst.* I **48** 1475
[5] Kusumoto K and Ohstsubo J 2002 *Opt. Lett.* **27** 989
[6] Kanakidis D, Argyris A and Syvridis D 2003 *J. Lightwave Technol.* **21** 750
[7] Mirasso C R, Colet P and García-Fernábdez P 1996 *IEEE. Photon. Tech. Lett.* **8** 299
[8] Sánchez-Diaz A, Mirasso C R, Colet P and García-Fernández P 1999 *IEEE J. Quantum Electron.* **35** 292
[9] Argyris A, Syvridis D, Larger L, Annovazzi-Lodi V, Colet P, Fischer I, Garcia-Ojalvo J, Mirasso C R, Pesquera L and Shore K A 2005 *Nature* **437** 343
[10] Zhang F and Chu P L 2003 *J. Lightwave Technol.* **21** 3334
[11] Bogris A, Kanakidis D, Argyris A and Syvridis D 2004 *IEEE J. Quantum Electron.* **40** 1326
[12] Kanakidis D, Bogris A, Argyris A and Syvridis D 2004 *J. Lightwave Technol.* **22** 2256
[13] Wang Y C, Li Y L, Wang A B, Wang B J, Zhang G W and Guo P 2007 *Acta Phys. Sin.* **56** 4686 (in Chinese)
[14] Agrawal G P 2001 *Nonlinear Fibre Optics* 3rd Edition (San Diego, CA: Academic) p50
[15] Grassberger P and Procaccia I 1983 *Physica* D **9** 189