High bit rate optical communication systems based on chaotic carriers

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Abstract. In this thesis, the potential of using chaotic optical carriers generated by non-linear optical oscillators as an encryption medium of high bit rate pseudorandom sequences - and therefore their application in the development of an innovative platform of secure optical communications - is studied. The operation of chaotic semiconductor laser emitters capable of hiding data and their application within an emitter-receiver system is simulated, underlying the decoding process that leads to a successful message recovery. A complete high bit rate optical communication system based on chaotic carriers is developed, followed by a successful encoding and decoding process. We confirm that the insertion of 100 km conventional optical fiber for telecommunication applications, as the transmission medium, has a minimal effect for bit rates of the order of 1 Gb/s. For the very first time, this experiment is also performed in real-world conditions, using an installed optical network of 120 km within the metropolitan area of Athens. The successful results are presented in a recent publication of the popular Nature magazine.

1 Introduction

Optical communication systems are now well established in the infrastructure of the global communication nest, providing a huge bandwidth potential for demanding future applications. In order to assure the uppermost possible privacy and security of the interconnected users various approaches have been essayed over the last decade, including quantum cryptography and chaotic digital, electrical and optical systems. Especially chaotic optical communications is a flourishing contemporary research field, very promising in shielding the security aspects of the future optical networks. The potential of synchronizing coupled non-linear generators has been proved to a great extend [1], including semiconductor laser emitters that operate in the telecommunication wavelengths and that exhibit chaotic dynamics of high complexity [2]. Optical feedback [3], optical injection [4] or optoelectronic feedback [5] are some of the typical configurations used to generate a high-dimensional chaotic laser output. The bandwidth of such chaotic carriers may extend even up to tens of gigahertz, making them ideal candidates for high bit-rate message encryption. Experimental observation of chaos synchronization has been reported for all the above systems [6,7].

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In recent experiments that involve data communications in chaotic optical systems, encoding and decoding of sinusoidal signals with frequencies up to a few gigahertz has been demonstrated [8]. A 2.5 Gb/s non-return-to-zero (NRZ) pseudorandom bit sequence has been referred to be masked in a chaotic carrier, produced by a 1.3 μm DFB diode laser subjected to optoelectronic feedback, and partially recovered [9]. Also, a similar system was developed by Larger et al. at 1,55 μm, who successfully encrypted a 3 Gb/s pseudorandom message into a chaotic carrier, while the system's decoding efficiency was characterized by low BER values of the order of 10^{-9} [10]; however the non-linear medium in that case was a Mach-Zehnder modulator. Finally, a 1,55μm all-optical communication system with chaotic carriers has been successfully developed and characterized by the authors, with BER measurements at gigabit rates that exhibited promising results [11]. All the above communication systems have been studied in an in-situ transmitter-receiver configuration, in absence of any transmission medium.

In this work we demonstrate the feasibility of the implementation of a secure all-optical gigabit communication transmission system based on chaos cryptography. Pseudorandom bit sequences that are effectively encrypted into optical chaotic carriers are transmitted over a length of 100km single-mode fiber and are successfully decrypted at the receiver side. BER measurements are presented for different message bit-rates in order to characterize the system's performance and to identify the extent of the transmission effects induced by the fiber link, assuming various configurations of dispersion management in the transmission path. This is the first report to our knowledge of a chaotic communication system that contains a long transmission fiber-link and thus includes the effects of transmission in the recorded final performance [12]. Additionally, and for the very first time, this experiment is also performed in real-world conditions, using an installed optical network of 120 km within the metropolitan area of Athens [13]. The successful results are presented in a publication of the popular Nature magazine [14].

2 Experimental configuration

A. Transmitter

The experimental setup of an all-optical open-loop chaotic communication system is shown in Fig.1. Two DFB lasers from the same wafer with almost identical characteristics have been selected as the transmitter and the receiver lasers. Both lasers operate at current values of 9.6mA and 9.1mA respectively (with threshold current at 8mA) and with proper temperature controlling they emit at 1552.1nm. Their relaxation frequency oscillation is at 3GHz. The chaotic carrier is generated in a 6m optical external cavity formed between the master laser and a digital variable reflector that determines the amount of optical feedback that is sent into the master laser – set in our setup to around 2%. A polarization controller inside the cavity is used to adjust the polarization state of the light reflected back from the reflector. A non-return-to-zero pseudorandom message with small amplitude and code length of 2^7-1 is encrypted into the chaotic carrier of the external cavity's output by externally modulating a LiNbO3 modulator.

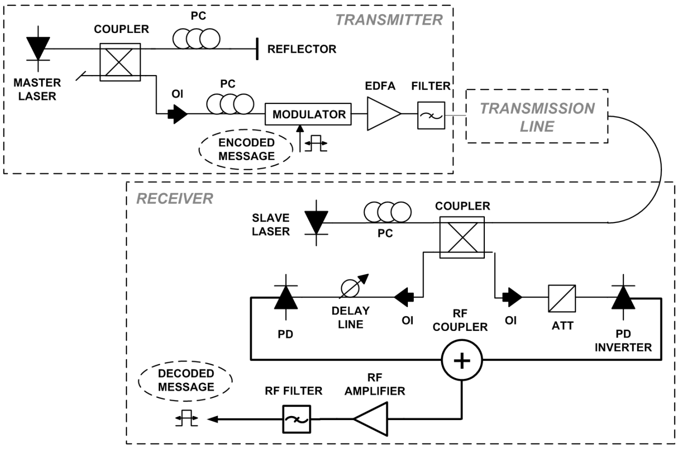


Fig.1. Experimental setup of an all-optical communication transmission system based on chaotic carriers. PC: polarization controller, OI: optical isolator, PD: photoreceiver, ATT: attenuator.

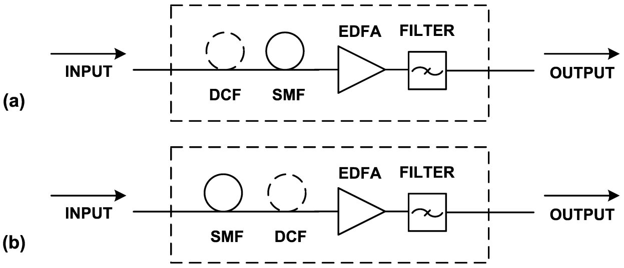
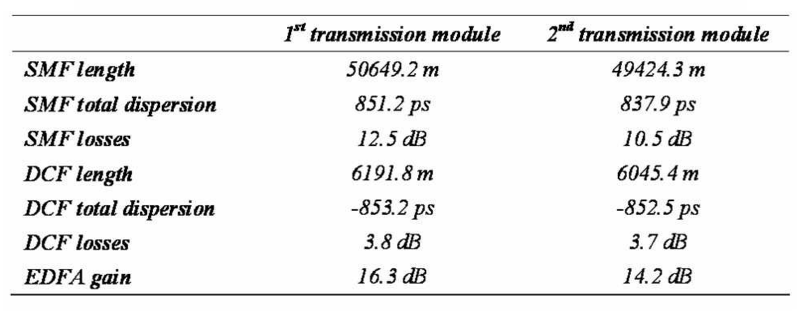


Fig.2. Optical transmission modules: a) pre-compensation and b) post-compensation dispersion configurations. SMF: Single-mode fiber, DCF: Dispersion-compensation fiber, EDFA: Erbnium-doped fiber amplifier.

B. Transmission path

The chaotic carrier with the encrypted message is amplified to gain enough optical power (4mW) and is transmitted through a total length of 100km fiber span, formed by two transmission modules. Each of them consists of 50km single mode fiber (type G.652), a dispersion compensation fiber module that is used to eliminate the chromatic dispersion, an erbium-doped fiber amplifier (EDFA) that is used to compensate the transmission losses and an optical filter that rejects most of the amplified spontaneous emission (ASE) noise of the EDFA. The transmission characteristics of the two modules are presented in detail in table I. Depending on the sequence of the transmission components used in the transmission modules, different dispersion management techniques can be evaluated: the pre-compensation technique, in which the DCF precedes the SMF (fig.2a) and the post-compensation technique, in which the DCF follows the SMF (fig.2b).

Table I. Transmission parameters



	1st transmission module	*2nd transmission module*
SMF length	*50649.2 m*	*49424.3 m*
SMF total dispersion	*851.2 ps*	*837.9 ps*
SMF losses	*12.5 dB*	*10.5 dB*
DCF length	*6191.8 m*	*6045.4 m*
DCF total dispersion	*-853.2 ps*	*-852.5 ps*
DCF losses	*3.8 dB*	*3.7 dB*
EDFA gain	*16.3 dB*	*14.2 dB*

C. Receiver

At the receiver's side, the transmitted output is unidirectionally injected into the slave laser, in order to force the latter to reproduce the chaotic waveform. The optical power of the injected signal into the receiver's laser diode is set to around 0.4mW. Lower values of optical injection power prove to be insufficient to force the receiver to synchronize satisfactorily, while higher values of injection power lead to reproduction not only of the chaotic carrier but of the message also. The use of a polarization controller in the injection path is critical, since the most efficient reproduction of the chaotic carrier by the receiver can be achieved only for an appropriate polarization state. The chaotic waveforms of the transmitter and the receiver are driven through a 50/50 coupler to two fast photodetectors that convert the optical input into electronic signal. The photoreceiver used to collect the optical signal emitted by the receiver adds a π-phase shift to the electrical output related to the optical one. Consequently, by combining with a microwave coupler the two electrical chaotic signals – the transmitter's output and the inverted receiver's output – an effective subtraction is actually carried out. In the transmitter's optical path an optical variable attenuator is used to achieve equal optical power between the two outputs, while a variable optical delay line in the receiver's optical path determines temporal alignment of both signal waveforms. The subtraction product is the amplified message, along with the residual frequency components of chaotic carrier which are finally rejected by an electrical filter of the appropriate bandwidth.

3 Results and discussion

A. Back-to-back system performance

By applying the conditions analyzed above in the proposed communication system and by optically injecting 0.4 mW of the transmitter s output into the receiver, the best BER curve achieved for different message bit-rates is shown in fig.3. The code length of the pseudorandom message is 2^7-1, however, almost the same results were obtained by using a code length of 2^{23}-1. The message amplitude, determined by the applied modulation voltage V_{mod}, is set at such levels so that the filtered encrypted message that arrives at the receiver has a BER value of no less than $6 \cdot 10^{-2}$. For each bit-rate studied, electrical filters of different bandwidth have been tested in order to ensure an optimized BER performance of the recovered message. The filter bandwidth (B_f) selection is crucial and is not only determined by the message bandwidth B but it is associated to the chaotic carrier cancellation that is achieved at the receiver. For example, at the decoding process stage, if the chaos cancellation is not significant the residual spectral components of the chaotic carriers will probably cover the largest part of the decoded message spectrum. In this case, the lowest BER value will emerge by using a filter that rejects the chaotic components, even if it rejects simultaneously part of the message itself (B_f<B). On the contrary, for a very good decoding performance, the lowest BER value may emerge by using a filter with B_f >B.

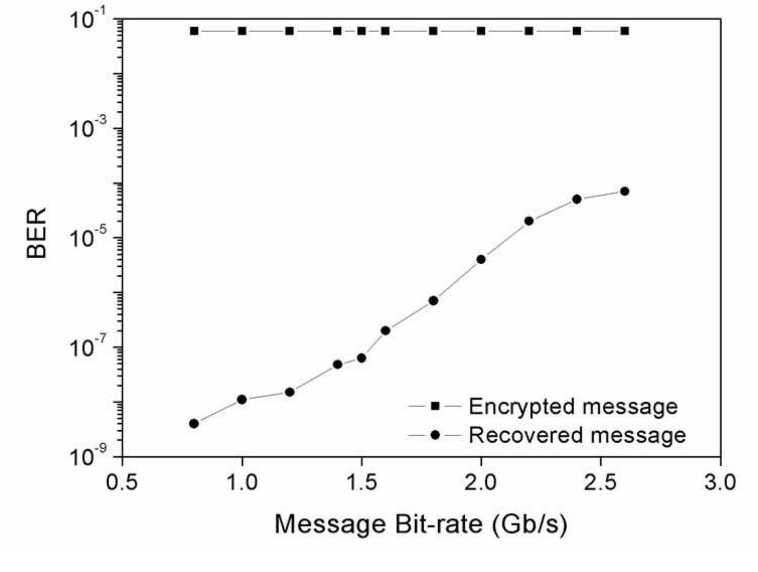


Fig.3. BER measurements of the encrypted and the recovered message in a back-to-back configuration for different message repetition rates.

The lowest BER value measured for the recovered message was $4 \cdot 10^{-9}$, for message bit-rate of 0.8 Gb/s. As the bit-rate is increased to a multi-Gb/s scale, the BER values are also increased monotonically. This is mainly attributed to the filtering properties of the message at the receiver. The message filtering effect has been confirmed to be larger for lower frequencies and decreases as message spectral components approach the relaxation oscillation frequency of the laser in the gigahertz regime, similar to the response of steady-state injection-locked lasers to small-signal modulation. The above observation is consistent with the results of fig.4. As the message rate approaches the relaxation frequency of the receiver s laser (~3GHz) the deteriorated message filtering leads to decrypted signal BER values higher than 10^{-4}.

B. Transmission system performance

When intercepting the optical transmission path of 100km the BER values are slightly increased, when compared with the back-to-back configuration. Specifically, when no compensation of the chromatic dispersion is included in the transmission path i.e. absence of the dispersion compensation fiber (DCF) in fig.2 - the BER values are increased over an order of magnitude (fig.4, circles). For a 0.8Gb/s message the best attained BER value is now 10^{-7}. This increase is attributed to the amplified spontaneous emission noise from the amplifiers, as well as to the non-linear self-phase modulation effects induced by the 4mW transmitted signal.

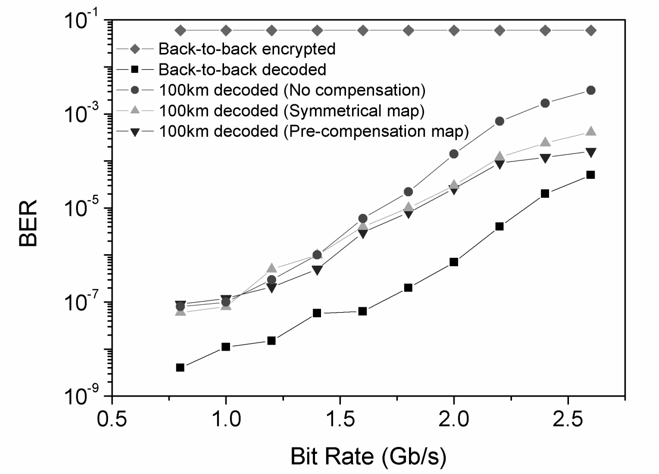


Fig.4. BER measurements of the encrypted, the back-to-back decoded and the decoded message after 100km of transmission, for different compensation management techniques (no compensation, symmetrical map, pre-compensation map), in respect to the message repetition rate.

When dispersion compensation is applied by including into the transmission modules the appropriate dispersion compensation fibers, the BER curves reveal a slightly better system performance in respect to the case without dispersion compensation as the message rate increases. Two different dispersion compensation configurations that are commonly used in optical communication transmission systems have been employed. The first named symmetrical map consists of the transmission module of fig.2a followed by the transmission module of fig.2b. The second named pre-compensation map consists of two transmission modules that correspond to fig.2b. The corresponding BER values of these two configurations, for the different message rates, are presented in fig.4 (up and down triangles, respectively). For message bit-rates up to 1.5Gb/s, the decryption performance is practically comparable to the case where dispersion compensation is not included. By increasing the message rates, chromatic dispersion plays a more important role in the final decoding performance, so by including different dispersion compensation maps a slight improvement can be achieved. In fact, the pre-compensation configuration shows a very small advantage over the symmetrical map for high bit-rates, up to 2.5GHz.

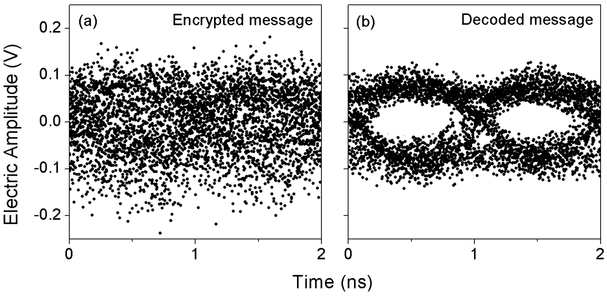


Fig.5. Typical eye diagrams of 1Gb/s (a) encrypted message and (b) decrypted message after 100km transmission.

4 Field demonstrator

Extending the above experimental work to the real-world, for the first time, a chaos encrypted optical transmission system is implemented, utilizing an installed optical network infrastructure of approximately 120 km that covers the metropolitan area of Athens. Successful encryption of gigabit pseudorandom sequences, transmission over the above span and decryption at the receiver side is demonstrated. The transmission infrastructure is an installed optical network of single mode fiber that covers the wider metropolitan area of Athens, has a total length of 120km and is provided by Attika Telecom SA. The topology of the link is shown in the map of fig.6. It consists of three fiber rings, linked together at specific cross-connect points. A dispersion compensation fiber (DCF) module, set at the beginning of the link (pre-compensation technique), cancels the chromatic dispersion induced by the single mode fiber transmission. A number of erbium-doped fiber amplifiers and optical filters are used along the optical link for compensation of the optical losses and amplified spontaneous emission noise filtering, respectively.

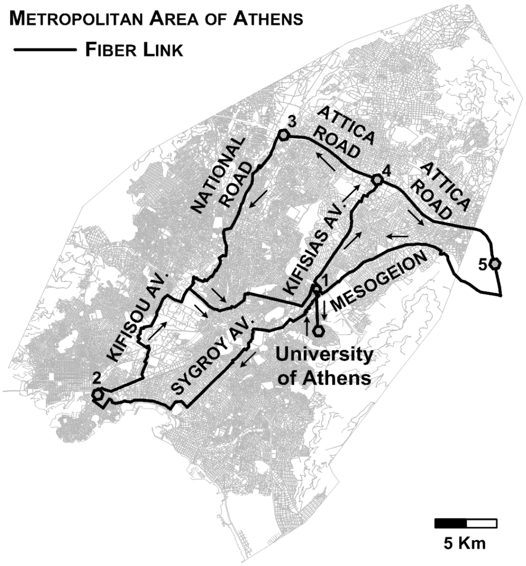


Fig.6. Topology of the 120km total transmission link in the metropolitan area of Athens.

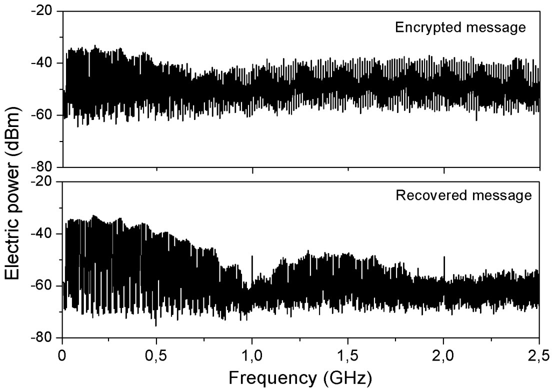


Fig. 7. RF spectra of the encrypted and the recovered 1 Gb/s message.

The system s efficiency on the encryption and decryption performance is studied by bit-error rate (BER) analysis of the encrypted/decoded message. The message amplitude is attuned so that the BER values of the filtered encrypted message do not exceed in any case the value $6 \cdot 10^{-2}$. In fig.7, spectra of the encrypted (upper trace) and the decrypted - after the transmission link - (lower trace), 2^7-1 length, 1 Gb/s message are shown. The good synchronization performance of the transmitter-receiver setup leads to an efficient chaotic carrier cancellation and hence to a satisfactory decoding process. The performance of the chaotic transmission system has been studied for different message bit rates up to 2.4 Gb/s and for 2 different code lengths: 2^7-1 and 2^{23}-1 (fig.8). All BER values have been measured after filtering the electric subtraction signal, by using low-pass filters with bandwidth adjusted each time to the message bit rate. For sub-gigahertz bit-rates the recovered message exhibits BER values lower than 10^{-7}, while for higher bit-rates a relatively high increase is observed. This behavior characterizes the back-to-back and the transmission setup, with relatively small differences in the BER values, revealing only a slight degradation of the system performance due to the transmission link.

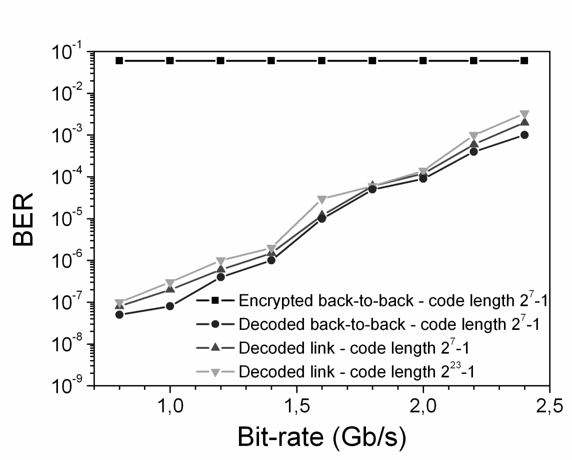


Fig. 7. BER performance of encrypted (squares), back-to-back decoded (circles) and after transmission link decoded (triangles) message.

5 Conclusions

The results reported here provide a convincing proof-of-practical concept for optical chaos communications technology. Building on this, it should be possible to develop reliable cost-effective secure communications systems that exploit deeper properties of chaotic dynamics. Opportunities for such technological advances have emerged from the substantial theoretical and experimental advances accomplished within the OCCULT project (**http://nova.uib.es/project/**occult) and in other laboratories around the world. A complete high bit rate optical communication system based on chaotic carriers is developed, followed by a successful encoding and decoding process. We confirm that the insertion of 100 km conventional optical fiber for telecommunication applications, as the transmission medium, has a minimal effect for bit rates of the order of 1 Gb/s. For the very first time, this experiment is also performed in real-world conditions, using an installed optical network of 120 km within the metropolitan area of Athens.

The prototype technology that has been developed would benefit from added intelligence features. It will be essential to develop a meaningful measure of the security provided by any proposed secure communications technology one capable of useful comparison with other technologies. Beyond that, we envisage opportunities for effecting fundamental advances in chaos synchronization techniques, using smart encryption techniques, developing active eavesdropper-evasion strategies, designing compact transmitter/receiver modules, as well as implementing robust technology for bidirectional chaotic communications, chaotic message broadcasting, parallel communications with spatiotemporal chaos, and frequency multiplexing through sharing of the chaotic broadband spectrum. In addition, chaos communication systems are fully compatible with the widely used wavelength division multiplexing (WDM), provided the chaotic carrier bandwidth is much smaller than the WDM channel spacing. In combination, such advances should enable the delivery of practical systems for intelligent chaotic optical data encoding and lead to deeper fundamental insight into communication between systems with irregular or even adaptive signals.

References

1. L. M. Pecora and T. L. Carroll, Synchronization in chaotic systems, Phys. Rev. Lett., vol. 64, pp. 821 824, 1990.
2. P. Colet and R. Roy, Digital communication with synchronized chaotic lasers, Opt. Lett., vol. 19, pp. 2056 2058, 1994.
3. R. Lang, K. Kobayashi, External optical feedback effects on semiconductor injection laser properties , IEEE J. Quantum Electr., vol. QE-16, pp. 347-355, 1980.
4. V. Annovazzi-Lodi, S. Donati, M. Manna, Chaos and locking in a semiconductor laser due to external injection, IEEE J. Quantum Electron., vol. 30, pp. 1537-1541, 1994.
5. H. D. I. Abarbanel, M. B. Kennel, L. Illing, S. Tang, and J. M. Liu, Synchronization and communication using semiconductor lasers with optoelectronic feedback, IEEE J. Quantum Electron., vol. 37, pp. 1301 1311, 2001.
6. J.-P. Goedgebuer, P. Levy, L. Larger, C.-C. Chen, and W. T. Rhodes, Optical communication with synchronized hyperchaos generated electooptically, IEEE J. Quantum Electron., vol. 38, pp. 1178 1183, 2002.
7. A. Argyris, D. Kanakidis, A. Bogris, and D. Syvridis, Spectral Synchronization in Chaotic Optical Communication Systems, IEEE J. Quantum Electron., vol. 41, pp. 892-897, 2005.
8. J. Paul, M.W. Lee and K.A. Shore, 3.5-GHz Signal Transmission in an All-Optical Chaotic Communication Scheme Using 1550-nm Diode Lasers, IEEE Photon. Technol. Lett., vol. 17, pp. 920-922, 2005.
9. J.-M. Liu, H.-F. Chen, S. Tang, Synchronized chaotic optical communications at high bit-rates , IEEE J. Quantum Electron., vol. 38, pp. 1184-1196, Sep. 2002.
10. L. Larger, J.-P. Goedgebuer and V. Udaltsov, Ikeda-based nonlinear delayed dynamics for application to secure optical transmission systems using chaos , C. R. Physique, vol. 5, pp. 669 681, 2004.
11. A. Argyris, D. Kanakidis, A. Bogris, and D. Syvridis, Experimental evaluation of an open-loop all-optical chaotic communication system, IEEE J. Sel. Topics Quantum Electron., vol. 10, pp. 927 935, 2004.
12. A. Argyris, D. Kanakidis, A. Bogris, D. Syvridis, First Experimental Demonstration of an All-Optical Chaos Encrypted Transmission System , 30th European Conference of Optical Communications 2004, Sweden, Tu 4.5.1, September 2004.
13. A. Argyris, A. Bogris, D. Syvridis, Field Demonstrator of a Chaos Encrypted Optical Transmission System , 31st European Conference of Optical Communications 2005, Glasgow, Scotlannd, Th 3.1.2, September 2005.
14. Apostolos Argyris, Dimitris Syvridis, Laurent Larger, Valerio Annovazzi-Lodi, Pere Colet, Ingo Fischer, Jordi Garcia-Ojalvo, Claudio R. Mirasso, Luis Pesquera and K. Alan Shore, Chaos-based communications at high bit rates using commercial fibre-optic links , Nature, vol. 438, n. 7066, pp. 343-346, November 2005.