10Gb/s field experiment chaos communication
with nonlinear delay electro-optic phase dynamics

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Abstract—We report on very recent achievements in optical chaos communications. Electro-optic phase modulation principles have been used to design a new chaos generator based on nonlinear delay dynamics. A multiple delay (both short and long) architecture allowed for an enhanced chaotic complexity, as well as a more accurate synchronization capability, over the full bandwidth of a typical 10 Gb/s binary message. The setup is also flexible to allow for the definition of a hardware key defining the physical parameters ruling the dynamics.

1. Introduction

Investigations of optical nonlinear delay dynamics was first motivated by fundamental interests for the understanding of the numerous dynamical behaviors that were observed both numerically and experimentally [1]. Later, this kind of experimental setups met an even growing interest in the scientific community, through their potential use for a novel approach to security for optical telecommunications at the physical layer: high speed optical data encryption by chaotic motion of light, and decryption of the corresponding stream cipher through the principle of chaos synchronization [2, 3]. Among the various setups proposed in the literature, our work is referring to the electro-optic and optoelectronic architectures [4], which dynamics are ruled by filtered delayed nonlinear feedback loop, instead of other ones corresponding to delayed feedback rate equations of lasers [5]. The recent electro-optic setup we report on, introduces a specific feature in the sense that the delayed feedback is temporally nonlocal. These features are obtained thanks to the use of principles initially developed for optical differential phase shift keying (DPSK). The principle of operation and the dynamical modeling of the setup [6] will be first described. We will then report on the capability of this experimental approach to establish a new state of the art in optical chaos communications, with a field experiment at a record bit rate of 10 Gb/s [7]. We will conclude with future works and other issues related to phase chaos dynamics.

2. Principles for phase chaos generation

The experimental setup designed for the generation of a dynamics of the physical variable "optical differential phase" is depicted in Fig.1. We describe here the principle of operation of the emitter, which is intended for broadband chaos generation.

It consists of a standard DFB telecom semiconductor laser, which is seeding an integrated optics LiNbO$_3$ electro-optic phase modulator (PM). The phase of the light-beam is linearly modulated according to the RF drive voltage, with a conversion sensitivity $V_\pi \simeq 4.5$ V, and with a modulation bandwidth BW spanning over 15 GHz. The nonlinear transformation required for any possible chaotic operation, is obtained by the phase-to-intensity nonlinear transfer function performed by an imbalanced passive interferometer (temporal imbalancing δT), a so called DPSK (differential phase shift keying) demodulator in optical telecommunications. A nonlinear operation regime is practically achieved if the electro-optic phase modulation is large enough, and if it can be operated faster than the imbalancing (BW$\times\delta T \gg 1$, a condition which is at the origin of the temporal non-locality). The resulting nonlinear optical intensity fluctuations is then converted into the electrical domain through a broadband telecom amplified photodiode. Before being fed back onto the PM electrodes, the electrical signal is amplified by an RF driver, so that the total feedback loop gain allows for a strong enough nonlinear operation (the voltage applied on the PM has to be capable of modulating over more than V_π; the driver involved in the setup can operate up to 26 dBm, which is corresponding to 12 V$_{pp}$, thus ca. 2-3 times more than the V_π). The various fiber lengths connecting the different pigtail telecom devices, are leading to a total feedback loop delay significantly greater than the other time scales, $T \gg \delta T \gg (\text{BW})^{-1}$. A variable optical attenuator is also used to control the total feedback loop gain, which is proportional to the optical power in the optical path of the loop. A fiber coupler at the PM output extract the phase modulated lightbeam, to be analyzed or to be transmitted to a receiver for synchronization experiments.

According to the previous setup description, one can derive a dynamical model for the nonlocal nonlinear delay oscillator as follows: the oscillation loop can be considered as

a sequential signal processing chain, which output serves as the input. Starting from the phase modulation $\varphi(t)$, the nonlinear nonlocal phase-to-intensity conversion obeys the following instantaneous transformation (it is an imbalance two wave interferometer, which interference condition is dynamically modulated by the PM):

$$P_t(\varphi) = P_0\{1 + \cos[\varphi(t) - \varphi(t - \delta T) + \phi_0]\}, \qquad (1)$$

where $\varphi(t) = \pi v(t)/V_\pi$. This optical signal is then delayed in time by T, and converted into the electrical domain by a fast photodiode of sensitivity S. This photodiode also has practically the most restrictive bandwidth of the whole oscillator feedback loop, the driver and PM having a broader bandwidth. For sake of simplicity we adopt a linear band-pass filtering of the second order for the photodiode filtering effect, with low and high cut-off frequencies f_{cl} and f_{ch} respectively, and a constant gain G. This leads to the following integro-differential temporal dynamics of the electrical signal v_t driving the modulator:

$$2\pi f_{cl} \int_{t_0}^{t} v_\xi d\xi + v_t + \frac{1}{2\pi f_{ch}}\left[\frac{dv}{dt}\right]_t = G \cdot S \cdot P_{(t-T)}, \qquad (2)$$

where we have assumed $f_{ch} \gg f_{cl}$, which is easily fulfilled for telecom devices, since they typically have ca. 6 orders of magnitude bandwidth from the low to the high cut-off frequencies (from a few 10s of kHz, up to more than 10 GHz). The previous model was successfully used to simulate the dynamical behavior, and most of the features observed experimentally have been recovered numerically [6], among which the chaotic motions of interest here.

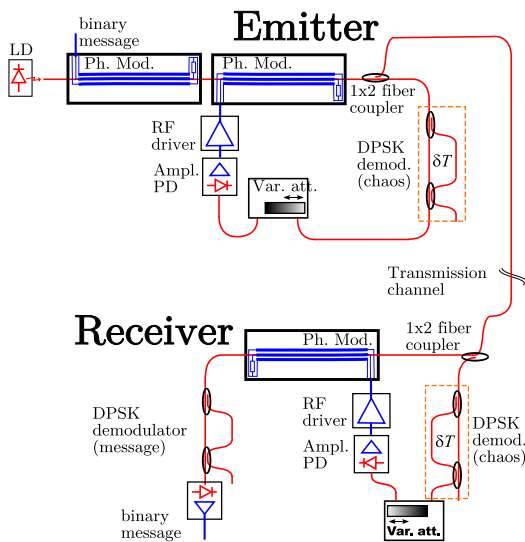## 3. Application to chaos communications

Figure 1: Optical transmission for chaotic masking of DPSK data.

The principle of operation of the emitter-receiver setup can be described as follows. At the emitter side, a first PM is used to perform a DPSK encoding on the CW laser beam. This beam seeds then the second PM, which is subjected to the nonlinear nonlocal delayed feedback in order to add a chaotic phase onto the DPSK modulation. It is worth noting that the message contributes to the nonlinear dynamics, as an additional drive signal in the emitter closed loop. In Eq.(1), which is the feedback driving term in the right hand side of the dynamics in Eq.(2), the phase modulation has to be changed into $\varphi + \varphi_m$, where $\varphi = \pi v/V_\pi$ as already previously stated, and the second term φ_m comes directly from the binary message modulation. At the output of the second emitter PM, a fiber coupler splits the lightbeam with the phase $\varphi + \varphi_m$ into two parts, one for the nonlinear nonlocal delayed feedback at the emitter, and one for the transmission channel (the phase-chaos-masked data).

At the receiver side, the incoming lightbeam is also split into two parts. One is seeding the receiver PM intended for an all-optical removal of the chaotic phase masking the message, and one is used for the replication of the nonlinear nonlocal delayed processing path. The latter path is intended to replicate the processing occurring at the emitter in order to generate the masking chaos; however a minus sign in the processing path is required for phase chaos cancellation by the receiver PM. The opposite sign was practically implemented using the complementary output of the DPSK demodulator with respect to the one used at the emitter. Following this, the electrical signal applied to the receiver PM, is expected to be the opposite one compared to the signal at the emitter, as long as the parameters at the receiver are closely matched to the ones of the emitter. The output of the receiver PM, when the chaos compound is properly canceled, exhibits the phase modulation of the DPSK message only. Then a simple DPSK demodulator, with an imbalancing matched with the data bit rate, allows to recover the original data. Notice here that the nonlinear nonlocal feedback performed also by a DPSK demodulator for chaos generation, has in principle an imbalancing which is not related to that of the data rate to be masked by the chaos. As we will see later, this DPSK demodulator required for chaos generation, can be replaced by any kind of multiple wave imbalanced interferometer, whereas the binary message DPSK demodulator is a standard one, as used in conventional DPSK optical transmissions. Figure 2 shows the typical results obtained when a 10 Gb/s transmission was first experimented on a 22 km long installed fiber network, the "Lumière" brothers ring fiber network in our city of Besançon, France (see the bottom in Fig.2 the satellite view of our area, and the geographic localization of the Lumière network; the Lumière brothers, which are the inventor of the cinema, are born in our city). The clear eye diagrams are corresponding to the data properly recovered by the authorized decoder described in Fig.1. The blurred eye diagram are the typical ones obtained by an unauthorized eavesdropper, which does not have the physical in-
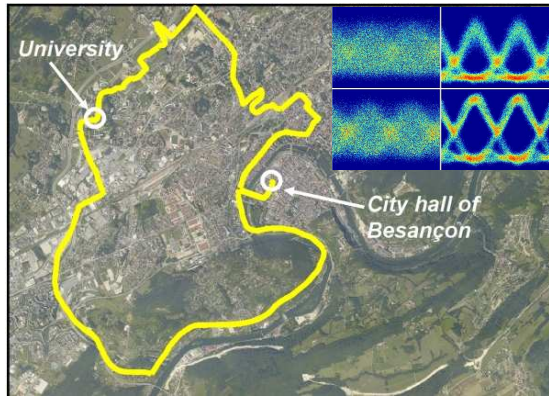
Figure 2: Satellite view of the area of first field experiment at 10 Gb/s were demonstrated ("Lumière" brothers ring network, city of Besançon, France); inset: recorded eye diagrams; left: unauthorized receiver; right: authorized receiver; up: $\beta = 4$; low: $\beta = 2.5$. .

formations allowing for the chaos cancellation path in its receiver. The upper traces are obtained with $\beta = 4$, corresponding to a high masking level, but a lower signal quality recovery (authorized bit error rate, BER, of ca. 10^{-4}, but still error free recoverable with the use of standard error correction codes). The lower traces are leading to a lower masking efficiency, but a much greater data recovery quality (BER of 10^{-8}, for which error correction codes are not needed).

A second field experiment in the city of Athens, confirmed that a longer transmission, up to 120 km with two fiber amplifiers and two dispersion compensation modules, can achieve comparable performances at 10 Gb/s, and error free transmission at 3 Gb/s. It is worth mentioning here that, although the spectral spreading performed by the ultra-fast chaotic optical phase motion is extremely large, standard dispersion compensation techniques can be efficiently used in order to counter-balance the dramatic dispersion actually experienced with long standard single mode fibers. A small and negligeable channel–induced distortion is however observed, mainly originating from the fiber channel nonlinear propagation effects [9].

4. Security issues

In this last section, we will try to show how far the proposed phase chaos electro-optic architecture can offer also attractive solutions for future implementations of highly secure optical transmission via chaotic masking, benefiting from the architecture flexibility offered by the delayed electro-optic feedback loop.

In the setup configuration as reported in Fig.1, it is clear that security is *a priori* relatively low, since any eavesdropper can use commercially available devices, and then he can try to find the right physical parameter settings (even if this task, for an exhaustive non-digital parameter search,

might be already time and efforts consuming). Nevertheless, we will show next that slight modifications of the original setup can lead to significantly improved security in the sense of this exhaustive search.

Figure 3 shows how the previously underlined channel dispersion sensitivity can be positively used, when extra dispersive components are added inside the phase-chaos electro-optic feedback loop. It is here proposed that a dispersion compensation module can emulate the dispersion of any arbitrary length of fiber (from 0 km to ca. 80 km), the resulting dispersion effect being part of an additional new tunable physical key parameter to be also know by the authorized receiver. To show the sensitivity of the decoding with respect to the in-loop added dispersion, we have measured the decrease of the inter-correlation coefficient between the received chaos from the emitter, and the replicated one at the receiver, versus the in-loop dispersion mismatch between emitter and receiver. Knowing that correlation between original and replicated chaos needs to be higher than 0.95 in order to be able to extract properly the masked binary data, we can easily conclude that in-loop dispersion is an interesting physical parameters in order to enhance security of chaos-based optical communications using electro-optic phase chaos. Another architecture
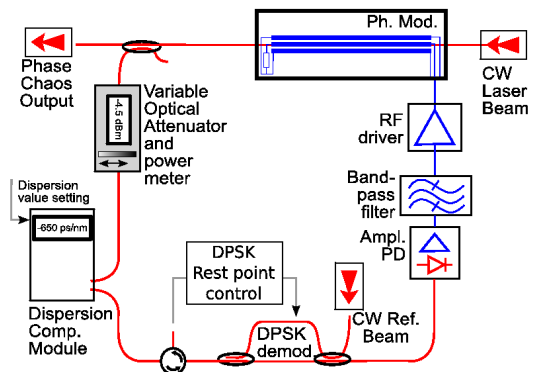
Figure 3: Demonstration of the in-loop dispersion sensitivity on the synchronization quality.

modification has been investigated experimentally, which consists in adding a second optoelectronic delayed feedback. Multiple delayed feedback loop is known to exhibit improved chaos complexity through the increased number of positive Lyapunov exponents. In the phase chaos setup in Fig.1, a straightforward manner for adding a second delayed feedback loop is to use the second complementary output of DPSK demodulator (see Fig.4 upper). The influence of this second loop on the synchronization quality was simply measured again through the inter-correlation coefficient between the emitter and the receiver chaos, versus the attenuation of the second feedback. The result is Again, one can notice that as soon as the second loop has a relative weight above -5dB with respect to the main loop, synchronization is sufficiently degraded so that decoding

Figure 4: Dual loop phase chaos. Emitter setup with variable weight of the second loop.

quality does not allow a proper binary message recovery. In an even more flexible and efficient security enhanced configuration, one could implemented both of the previously suggested architecture modifications, together with a digital-key control of the physical parameters (as suggested in [7]). The corresponding optical chaos communication scheme could fulfill both real time high bit rate encryption at the physical level, as well as a high security level through a high dimensional analogue and digital key for the definition of the masking chaos operating conditions.

5. Conclusion

We reported on a recently developed electro-optic oscillator. Its dynamics is ruled by a nonlinear nonlocal delayed integro-differential equation, which is featuring various solutions from the stable steady state to high complexity chaotic waveform, through periodic and pseudo-periodic oscillations. We have described how such ultra-fast and broadband chaos generator can be successfully used for the masking at the physical layer of a 10 Gb/s DPSK optical link. The unmasking at the receiver is involving chaos synchronization principle, which efficiency is crucial for a high quality of the recovered data stream. Two field experiments have demonstrated the capability of the approach to be practically operational over installed fiber optic networks.

Recent development have dealt with architecture modifications in order to provide a higher security level for this kind of physical layer encryption approach. This could be even further enhanced through the use of digitally and dynamically switchable physical parameters at the chaos generator, as well as through the definition of specific encryption protocols for the switching rule. We also anticipate that the setup might be also of interest for other emerging applications of complex systems, such as high speed random number generation [8], or a novel kind of analogue computer mimicking the behavior of the brain and referred as

"Reservoir Computing" [10].

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