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Chaotic optical phase generated by electro-optic and optoelectronic nonlinear and nonlocal delayed feedback: successful field experiment at 10 Gb/s

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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. Laboratory and field experiments proved the efficiency of the setup at that bit rate, demonstrating the superiority of the proposed original approach for practical high speed optical communications secured at the physical layer. The setup is also flexible to allow for the definition of hardware key defining the physical parameters ruling the dynamics, and which knowledge is conditional to the proper decoding. Additional variations of the setup is proposed in order to offer a higher security degree through the increase of the analogue processing occurring in the chaos generation process.

I. 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 of optical telecommunications at the physical layer: high speed optical data encryption by chaotic motion of light, and decryption of the corresponding stream cypher 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], [5], which dynamics are ruled by filtered delayed nonlinear feedback loop, instead of other ones corresponding to delayed feedback rate equations of lasers[6]. The recent electro-optic setup we report on, introduces a specific features 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). We will first describe the principle of operation, and the dynamical modeling of the setup[7]. Dynamics, bifurcations, as well as route to chaos will be reported, while varying the gain parameter of the nonlinear oscillator. Finally, we

will demonstrate the interest of the setup for a particular application, optical chaos communications, successfully demonstrated during a field experiment at a record bit rate of 10 Gb/s, over two installed fiber optic metropolitan networks[8]. We will conclude with future works and other issues related to phase chaos dynamics.

II. 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. It consists of a standard DFB telecom semiconductor laser, which is seeding an LiNbO₃ electro-optic phase modulator (PM). The phase of the lightbeam 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 modulation performed by an imbalanced interferometer. The temporal imbalancing δT between the two arms of a fiber based Mach-Zehnder demodulator is δT .

Fig. 1. Setup performing a nonlocal nonlinear delay dynamics.

We achieve a nonlinear modulation if the electro-optic phase modulation can be operated faster than the imbalancing ($BW \times \delta T \gg 1$, condition at the origine 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 RF electrode,

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}). The various fiber lengths 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, we derive a dynamical modeling of 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:

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

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 the most restrictive bandwidth for all the oscillator loop, the driver and PM having a broader bandwidth. For sake of simplicity we adopt a linear bandpass filtering of the second order for the photodiode 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:

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

where we have assumed $f_{ch} \gg f_{cl}$, which is easily fulfilled for telecom devices, since they have typically ca. 6 orders of magnitude bandwidth from the low to the high cut-off frequencies. The previous model was successfully used to simulate the dynamical behavior, and most of the features observed experimentally have been recovered numerically [7]. These behaviors will be briefly described in the next section.

III. DYNAMICS AND BIFURCATIONS

A usual bifurcation parameter corresponds to the weight of the non linearity in the dynamical process. As it can be noticed from Eqs.(1) and (2), the weight of the nonlinear transformation in the dynamics is scaled through the normalized quantity $\beta = \pi G S P_0 / V_\pi$, and thus a very straightforward experimental way for tuning this weight is to adjust the optical power level P_0 via a variable optical attenuator inside the oscillator loop. The accessible tuning range for the parameter β spans from 0 to ca. 5.

Experimental amplitude (statistics of v_t) and spectral (modulus of the spectrum $|\text{FT}[v_t]|$) bifurcation diagrams are represented in Fig.2.

Fig. 2. Experimental bifurcation diagram recorded as a function of the normalized oscillator feedback gain β ($\phi_0 = \pi/4$).

The trivial stable steady loses its stability around $\beta = 0.5$, and a periodic oscillation close to half of the free spectral range $(2\delta T)^{-1}$ is observed. A bifurcation similar to a period doubling is observed at $\beta = 1$, but as β is increased, the oscillation becomes more and more complex as expected. Complex periodic waveforms, or even pseudo periodic ones are arising progressively as β is increased, and broad spectrum dynamics already appear around $\beta = 1.8$. A strong enough nonlinear mixing flattens the spectrum above $\beta = 4$, where we could consider that the chaotic regime is fully developed, spanning its spectrum over the whole bandwidth of the oscillator, which fits the one of high speed telecommunication signals. Such chaotic regime are thus nicely matched when masking of 10 Gb/s optical transmission are expected, or any other ultra fast analogue optical signal processing (another recent application dedicated to high speed random number generation [9] could also advantageously make use of our broadband phase chaos generator). The next section is devoted to the particular application we developed for our phase chaos generator, and which we also tested over installed fiber optic network: the chaotic masking of optical DPSK transmissions.

IV. APPLICATION TO CHAOS COMMUNICATIONS

Figure 3 shows the basic architecture of an emitter-receiver systems performing standard DPSK modulation and demodulation at the very beginning and at the very end of the link, as well as chaotic masking before transmission, and chaos cancelation before DPSK demodulation. The receiver is built so that its input is split into two paths. The direct path is seeding a phase modulation aimed at all optical chaos cancelation of the incoming phase modulated lightbeam. The second path is following a similar nonlinear delayed processing as the one involved at the receiver for chaos generation. This nonlinear delayed processing forms the physical key of the encryption/masking process.

The principle of operation of the emitter-receiver setup can be described as follows. At the, 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

Fig. 3. Optical transmission for chaotic masking of DPSK data.

noting that with a message added as in Fig.3, the chaotic notion is not the same as the ones observed and described in the previous section. Indeed, the message contributes to the nonlinear dynamics, as an additional drive signal. In Eq.(1), the right hand side of the dynamics in Eq.(2), the phase modulation has to be changed into $\varphi + \varphi_m$, where $\varphi = \pi v/V_\pi$, and the second term φ_m comes directly from the binary message modulation. At the output of the second PM, a fiber coupler split the lightbeam with the phase $\varphi + \varphi_m$ into two part, one for the nonlinear nonlocal delayed feedback at the emitter, and one for the transmission channel.

At the receiver side, the incoming lightbeam is also split into two parts. One is seeding the receiver PM intended to remove all optically the chaotic masking part of the phase modulation, one for the replicated nonlinear non-local delayed processing path. The latter path is intended to replicated the one at the emitter, however with a minus sign. The opposite sign was 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 the opposite signal compared to the one at the emitter, as long as the parameter of the receiver are closely matched with the one of the emitter (see [10] for parameter mismatch sensitivity of our open loop receiver architecture). The output of the receiver PM, when the chaos compound is properly canceled, only have the phase modulation of the DPSK message. A simple DPSK demodulator, with an imbalancing matched with the data bit rate, allows to recover the original data.

Figure 4 shows the typical results obtained when a 10 Gb/s transmission was first experimented on a 22 km long installed fiber network, the “Lumière” ring fiber network in our city of Besançon, France (see the bottom in Fig.4 the satellite view of our area, and the geographic localization of the Lumière network; the brothers Lumière are, the inventor of the cinema, are born in Besançon). The

Fig. 4. Eye diagrams of the first optical chaos communications at 10 Gb/s; left: unauthorized receiver; right: authorized receiver; up: $\beta = 4$; low: $\beta = 2.5$. Satellite view of the area of first field experiment at that bit rate, over the “Lumière” ring network in the city of Besançon, France.

clear eye diagrams are corresponding to the data properly recovered by the authorized decoder described in Fig.3. The blurred eyes are the ones obtained by an unauthorized eavesdropper, which does not have the chaos cancelation path in its receiver. The upper traces are obtained with $\beta = 4$, corresponding to a high masking, but a lower signal quality recovery (bit error rate, BER, of ca. 10^{-4}). The lower traces are leading to a lower masking efficiency, but a much greater data recovery quality (BER of 10^{-8}).

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, could achieve comparable performances at 10 Gb/s, and error free transmission at 3 Gb/s.

V. 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.

Further development are concerned by architecture modifications in order to provide a higher security level for this kind of physical layer encryption approach. This should be achievable 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 random number generation, as well as Reservoir Computing and Liquid State Machines [11].

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