RF-Interferences Generate Chaotic GHz FM—Carrier for Communications

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***Abstract*—Following the principle of a highly nonlinear delay oscillator, we demonstrate the generation of an RF chaotic frequency modulated carrier, which could be used in chaos based communication systems. The nonlinear process is provided by the transfer function of an RF interferometer, modulating the amplitude of an FM signal; for this purpose, the path difference required for the interference process, as well as a long delay required for complex chaotic oscillation, are designed through the use of optical fibers. The RF signal used to produce interferences is transposed in the optical domain by a direct laser modulation with the gigahertz chaotic FM signal. The interference is obtained at fiber outputs terminated by photodiodes for backconversion of the RF signal into the electrical domain. Experimental results reporting the particular dynamical behavior of the nonlinear delay RF oscillator are presented, and also discussed in terms of chaos communication applications.**

***Index Terms*—Chaos, dynamics, nonlinear oscillators, microwave radio communication, spread spectrum communication.**

I. Introduction

The early experimental setups dedicated to the demonstration of chaos communication were based on low frequency electronic circuits [1]. They were intended to generate experimentally chaotic oscillations belonging to a widespread nonlinear dynamics class, the ones described by nonlinear ordinary differential equations like the well known Lorenz system. Although the demonstration was successful, the system was lacking in terms of security in the context of cryptographic chaos-based applications [2], mainly due to its low dimensionality which allowed for a parameteric system identification. Later demonstrators employing Optics [5] then introduced much more complex dynamics through the use of nonlinear delay dynamics. This type of chaos generators allowed much higher attractor dimensions (greater than 100), which are believed to offer a much better confidentiality. The high dimension itself is not a sufficient condition for a high security level, but it makes cracking essentially more problematic. Recently, on the basis of the same dynamical principles, different groups demonstrated ultrahigh speed chaos encoding for optical communications [6], [7] at 3 Gb/s. In earlier work, we also explored the potential application of the same principles to the low frequency electrical domain [8]. We report here our latest results proposing a novel architecture for gigahertz (GHz) free space radio communications. The proposed hybrid optical and electrical architecture is also benefiting from the long [3] and still active [4] research on fiber-optics based microwave filtering.

The article is organized as follows. We first describe the chaos generator architecture producing a chaotic FM carrier in the GHz range. A dynamical model is then proposed according to a nonlinear delay differential process, and the dynamical model is also discussed with respect to different experimental parameter settings. This discussion will highlight some particular and unusual circumstances defining a new kind of dynamical modelling referred as dual delay time scales differential equation. Considering then the case of a single delay operating condition, some of the various possible dynamical behaviors are reported from numerics and experiments, in order to validate the model. Finally we conclude on the reported FM chaos generator, and discuss the application of this setup to chaos-based radio communication systems.

II. Operation Principles

A. Oscillator Architecture

Fig. 1 shows a schematic of the experimental setup used to perform a chaotic FM oscillation in the GHz range. It is organized in a feedback loop architecture comprising the following elements.

- A voltage controlled oscillator (VCO) is used to generate a GHz FM signal. It is driven by a base-band chaotic signal, thus generating at its output a chaotic FM carrier, with a conversion efficiency $S \simeq 29$ MHz/V. The output angular frequency $\omega(t)$ is assumed to be proportional to the input voltage $v(t)$. When message transmission is considered, the coding scheme makes the information-signal contributing to the chaos-generation process in the feedback loop. In that sense, the output signal is not a simple superposition of an independently generated chaotic carrier and a message.

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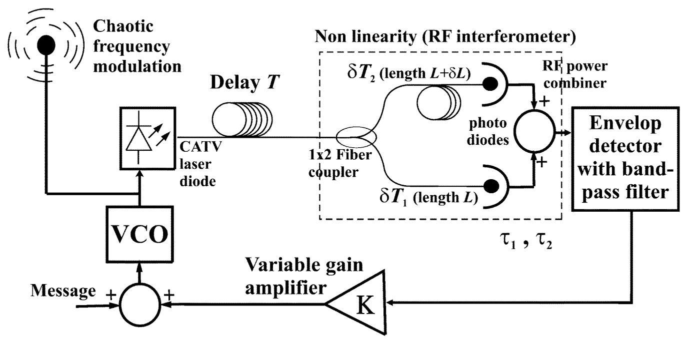

Fig. 1. Nonlinear delay optoelectronic FM oscillator.

The VCO output serves both as a complex chaotic FM signal masking the information to be transmitted, and as the drive of a nonlinear delayed feedback chain involving optoelectronic and electronic devices.

- The next component in the oscillator chain is a CATV laser diode (analog modulation semiconductor laser) generating an optical field beam which intensity is directly modulated by the VCO RF output. It performs the electrical (FM)-to-optical (IM) up-conversion of the signal.
- Next, different fiber lengths are used to generate various pure time delays T, T_1, and T_2, shifting in time all the different RF spectral components carried by the optical wave (with low dispersion and broad bandwidth due to the use of standard monomode fibers). The delay T allows for a high dimensionality of the chaotic oscillation [9], [10], as soon as it is sufficiently large compared to the characteristic time scales of the base-band oscillation signal (referred to as τ_1, of the order of 30 ns; T is about 100 ns corresponding to 20 m of fiber).
  The first fiber length is output on a fiber coupler, splitting the T-delayed signal into two nearly balanced parts. Each of the output port coupler is launched in fibers of different lengths, resulting in two additionnal delays T_1 and T_2. The latter are intended to perform a significative relative RF path difference for the RF modulation carried by the optical wave to get interference. Since the RF spectrum extends in the 1–2-GHz range, a differential delay of the order of tens of ns is required, corresponding to a fiber length difference of $\delta L = 5$ m. The fiber lengths are terminated by broadband amplified photodiodes, to recover the RF signal in the electrical domain.
- A power combiner followed by an envelop detector is then used to generate the RF interferences, and to detect its mean interference state, as a function of the instantaneous RF frequency delivered by the VCO. This output signal can be viewed as a nonlinear transformation $F[\omega(t)]$ of the instantaneous angular frequency delivered by the VCO. Note that any other spectral filtering with a more or less complex amplitude profile can be used to design a different nonlinear function $F[\omega]$. The envelop detector comprises as usual a base-band filter in order to suppress the GHz FM carrier frequencies, thus keeping only the low frequency amplitude modulation due to the RF-interference nonlinear profile; note that the spectral width of this filter can be tailored or adjusted according to specific technological constraint e.g., channel spectral width for communication applications. Here, this filter is of a band-pass kind, and is modeled by a simple second order band-pass filter; its low and high cut-off frequencies f_{c2} and f_{c1} have been arbitrarily fixed in the experiment to 100 kHz and 5 MHz; they correspond in the time domain to characteristic times $\tau_2 = 1.6\ \mu$s and $\tau_1 = 32$ ns, respectively.
- A variable gain amplifier is necessary to deliver a large amplitude feedback signal to the VCO input, so that the frequency excursion of $\omega(t)$ can be large enough to cover the nonlinear operating range of the function $F[\cdot]$ as much as possible. This condition is required because the complexity of a nonlinear delay dynamics is related to the number of extrema located in the operating range [10].

B. Dynamic Modeling

This section is devoted to more detailed qualitative and quantitative modeling of the individual elements of the oscillator, as well as to the global modeling of the oscillator itself in terms of a differential equation.

1) Optoelectronic RF-Interferences: An important originality of the setup, with respect to the work reported in [8], concerns the preferred solution to perform a nonlinear function through an RF interference phenomenon. In this previous work, the nonlinear transformation was corresponding to the filtering profile of a set of different parallel *RLC* resonant filters, operating in the frequency range of a "long wave" VCO (output frequency of a few hundreds of kilohertz). However, when GHz carrier are involved as in the present case, OP Amp filters based on discrete components cannot be implemented reliably. Following the initial idea developped in optics [11], [5], we are performing a nonlinear RF filter profile through a two wave interference. However, due to large quantitative differences between optical and electronic waves (even in the microwave range of concern at GHz frequencies), particular attention is required in the choice of the physical parameters. More precisely, we will underline the fact that these quantitative differences might lead in some cases to novel delay dynamical processes.

In order to achieve a high chaos complexity or entropy with delay differential dynamic, it is known [10] that the nonlinear transformation should exhibit multiple extrema within the amplitude range of the dynamical variable. Such a feature is directly related in our experiment to the RF path difference i.e., to the delay difference $\delta T = (T_1 - T_2) = n\delta L/c$ involved in the interferometer (where c/n is the velocity of light in fibers, and δL is the physical length difference between the interferometer arms). Fig. 2 shows typically how the free spectral range (FSR) of the RF-interference, can be changed with respect to the fiber length difference δL. The fiber length differences we use are of the order of a few meters (instead of of a few millimeters for the optical setup in [11]). This kind of length is easily achievable experimentally when using an optical carrier for delaying FM signal; furthermore, no critical temporal coherence problem is involved since the interference occurs in the electrical domain and not in the optical one. Each situation reported in that

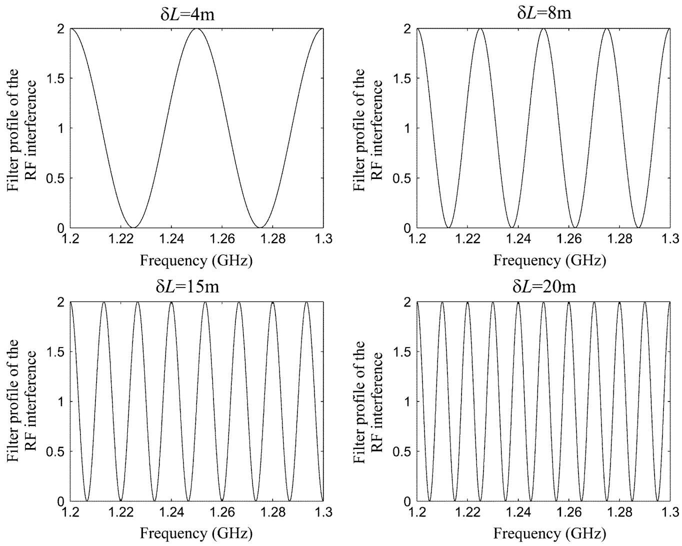

Fig. 2. Nonlinear function $F[\nu = \omega/2\pi]$ for different fiber length difference between the interferometer arms.

figure would lead experimentally to a different chaos generator, with more or less entropy capability when operating in chaotic regime, but with nearly similar qualitative statistical properties. As soon as more than a few extrema can be scanned, the chaotic regime exhibits a standard Gaussian noise distribution. Such an experimental flexibility in choosing this physical parameter corresponds to a wide set of parameter values that can enter in the definition of a chaotic key characterizing the deterministic nature of the chaotic carrier.

Modeling this simple "two waves" interference is straightforward, the nonlinear transformation being described by the following equation:

$$F[\omega] = F_0 \cdot \left\{ 1 + \cos\left[\frac{2n\,\delta L}{c} \cdot \delta\omega + \phi \right] \right\} \qquad (1)$$

where F_0 is a static weight of the nonlinear function, depending on various physical parameters such as the VCO output RF amplitude, the laser modulation efficiency, the photodiode sensitivity, and the envelop detector gain; δL is the fiber length difference, $\delta\omega(t)$ is the instantaneous angular RF frequency at the VCO output, and $\phi = 2n\delta L\omega_0/c$ is a static phase for the nonlinear function, depending on the VCO central oscillation frequency. Note that more complicated interferometers can be performed, e.g., with multiple arms (>2) and unbalanced amplitudes in each arm. This would result in a more complex nonlinear shape of the RF filter profile, resulting in different chaotic solutions.

2) Band-Pass Filter: In this subsection, we emphasize another particular experimental detail not yet underlined, as far as we know, in any reference treating of nonlinear delay differential dynamics. This unusual dynamical feature arises from both the particular situation of a GHz wave interference, and also from the rate at which the corresponding wave frequency is modulated, relatively to the time delay difference involved in the interferometer arms. In usual optical interference processes, the rate of change of the interference condition occurs typically on time scales much longer than the propagation time difference along the two intereference paths by about five orders of magnitude (see [6] and [11]). The consequence is that from a dynamical point of view, the nonlinear interference transfer function is considered as an instantaneous transformation. In the present case using RF waves, the interference paths might be long enough (up to tens or hundreds of meters corresponding to tens or hundreds of nanoseconds), that the interference effect can not be viewed as intantaneous compared to the modulation speed of the interfering wave: if the VCO input modulation signal extends over a few megahertz, significant frequency changes on tens of nanoseconds timescale can be observed, which occur on faster time scales than the one involved in the interferometer path difference. The interferences result thus in the superposition of significantly different RF frequency carrier, for which beating phenomena are involved within the bandwidth of the oscillator. Taking this phenomenon into account, the nonlinear transformation performed by the interference becomes dynamical and can be described as follows:

$$F[t] = F_0 \cdot \left\{ 1 + \cos\left[\delta T\,\omega_0 + \int_{t-\delta T}^{t} \delta\omega(\theta)\,dt \right] \right\} \qquad (2)$$

where ω_0 is the mean angular frequency of the VCO output, leading to a static phase shift $\phi = \delta T\omega_0$ of the cosine interference function in $F[\cdot]$. The second phase argument of this cosine function is an integral term depending not only on the actual instantaneous pulsation deviation, as is the case for (1), but also on the time fluctuations of the frequency deviation, at time t, and over the whole integration time δT (the differential delay between the two interferometer arm s). This results in a time-dependent nonlinear process, which introduces significant differences in the dynamical behavior. Introducing the instantaneous RF phase modulation (the integral of the angular frequency modulation), one might rewrite the previous equation in terms of a *dual delay time, i.e., 2-D, nonlinear function*

$$F[t, t-\delta t] = F_0 \cdot \{1 + \cos[\phi + \varphi(t) - \varphi(t-\delta t)]\}$$

with

$$\varphi(t) = \int_{t_0}^{t} \omega(\theta)d\theta. \qquad (3)$$

This unusual situation in delay dynamical systems is underlined here as a particular operating condition of the experimental setup, which was initially developed for unrelated issues (wireless chaos communication system). It might however have more fundamental repercussion in the future, e.g., for stability analysis of this particular kind of nonlinear multiple delays differential process, which is of concern in other fields of science well known to exhibit delay effects such as life sciences (population dynamics, cell production in living bodies, dynamics of information transmission in neural networks, etc.). Such fundamental aspects are of no concern in the present article and will not be investigated further here. Indeed in practice, when the relation $\delta T < \tau_1$ is verified, a behavior corresponding to (1) is observed instead of that described in (2), thus justifying neglection of the time-dependent part. The previous inequality can be illustrated graphically as shown in Fig. 3, where the operating point of the actual setup is indicated. This point corresponds to

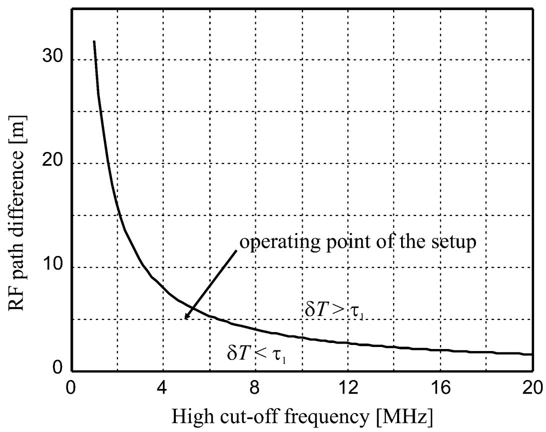

Fig. 3. Separation in parameter space ($\delta L, f_{c1} = 1/2\pi\tau_1$) for a time-independent (usual case) or a time-dependent (unusual case) nonlinear process $F[\cdot]$

$\delta T = 25$ ns ($\delta L = 5$ m), and a high cut-off frequency f_{c1} of 5 MHz ($\tau_1 = 32$ ns).

3) Time Delay: From a dynamical point of view, the time delay T is a key parameter allowing for a high-dimensional behavior of the generated chaos. Indeed, the phase space dimension is infinite due to the existence of this delay, and the chaotic attractor dimension is large, but finite [9], [10], [12]. A typical condition usually observed in high dimensional delay dynamics is $T > 2\tau_1$. In our experiment $T = 100$ ns, obtained through a fiber length of $L = 20$ m. Much longer delays can be easily reached experimentally (up to tens of kilometers), thanks to the use of an optical carrier for the FM GHz signal. The dimensionality of the chaotic dynamic that can be obtained, is known to vary as a linear function of T/τ_1; with the reported setup, this factor can thus range from a few units, to several thousands. In terms of oscillator theory, the delay is a linear phase shifter versus oscillating frequency, which allows more and more delay modes to oscillate in phase, as the time delay is increased. The principle of a chaotic regime in delay dynamical systems is based on a strong nonlinear mixing of many delay modes. The frequency spacing of the delay modes is $1/T$, which has to be large enough for chaotic operation, compared to the bandwidth of the oscillator ($\Delta f = f_{c1} - f_{c2}$). The chaos complexity increases with the number of modes, as well as with the strength of the nonlinear mixing (i.e., the number of extrema actually participating in the dynamics, and depending on the interferometer arms difference as illustrated in Fig. 2).

4) Amplification: As usual in oscillators, the feedback gain is of great importance in the actual oscillation that can be observed. Varying that gain from low values to higher ones in a nonlinear delayed oscillator, allows generally to observe numerous different dynamical regimes, from fixed points to chaos through periodic and pseudo-periodic oscillations. The amplifier gain K in Fig. 1 can be varied in practice between 0 and 40 dB, thus allowing the observation of many different regimes (see the bifurcation diagrams below), among which chaos can be found above an easily reachable gain threshold. A high gain provides a large frequency swing at the VCO output, and thus a strong nonlinear operation of the nonlinear transformation performed by the two wave interferometer.

5) Global Dynamical Model: According to the previous setup description, we can consider that the oscillator dynamic is ruled by linear filtering in the base-band frequency domain, which is the limiting dynamic of the oscillator loop, applied to a nonlinear delayed feedback forcing term:

$$\frac{\Omega(s)}{\mathrm{LT}\{F[\omega(t-T)]\}} = \frac{\tau_2\, s}{(1+\tau_2\, s)(1+\tau_1\, s)} \tag{4}$$

where s is the Laplace variable, LT stands for Laplace Transform, and hence $\Omega(s) = \mathrm{LT}[\omega(t)]$. The right-hand side is representative of the assumed second order band-pass filter limiting the oscillation in the frequency domain through the low and high cut-off characteristic times τ_2 and τ_1. Following the conversion rules of Laplace polynomial operators into differential terms in the time domain, we obtain the following second order delay differential equation:

$$\tau_1\tau_2\,\frac{d^2\omega}{dt^2}(t) + (\tau_1+\tau_2)\frac{d\omega}{dt}(t) + \omega(t) - \omega_0 = \beta\,\tau_1\,\frac{dF[\omega]}{dt}(t-T) \tag{5}$$

where β is the normalized feedback gain defined as $\beta = K\,V_0\,S\,\kappa/2$, depending on the electronic feedback gain K, the tuning rate of the VCO S, and the optoelectronic gain κ involving the slope efficiency of the laser, the fiber losses, and the photodiode sensitivity. The parameter ω_0 is determined by the VCO central frequency, which is used to adjust the operating point on the nonlinear function $F[\omega]$, determining the constant phase shift $\phi = 2n\,\delta L\,\omega_0/c = \omega_0\delta T$ in (1). It is important to notice from (5) that a significantly different dynamical process is concerned, as compared to those usually seen in the delay dynamics litterature (e.g., in [13] and [14], the linear filter at the origin of the differential process is always of low pass type). Due to the band-pass character of the oscillator filtering loop, the delayed nonlinear function in the right-hand side of (5) appears with a differentiation. As far as we know, this situation was studied only recently in the literature [6], [15]–[18] in the context of chaos communication, and may have important consequences in the explanation of the different dynamical regimes specifically observed in this "band-pass" delay dynamics (see [19] for a recent specific stability analysis of such band-pass delay dynamics, or [20] for the report of chaotic breathers). Most of delay dynamics reported in the literature are indeed dc-preserving oscillation loops, which case could be also obtained with our setup if using a low-pass base band filter instead of a band-pass one. Out of the fundamental interest from the dynamical system point of view, the band-pass feature in our setup was motivated by the communication application perspective, for which bandwidth limited informations are of concern; the aim was here to match at the oscillator level, the chaos spectrum to that of the bandwidth limited information.

Equation (5) was used to simulate the oscillator behavior after integration with a fourth-order Runge–Kutta algorithm. We also calculated from this theoretical model different dynamical properties that can be expected from the nonlinear delay dynamics, such as the probability distribution of the dynamical variable

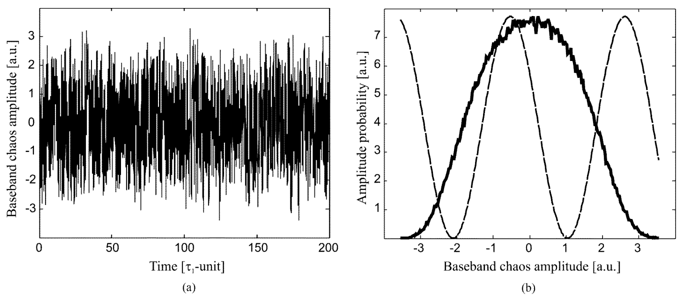

Fig. 4. Temporal and statistic behavior of the VCO output frequency deviation ($\beta = 8$, $\phi = 2.1$ rad, $\delta L = 5$ m). (a) Time series. (b) PDF on the background of $F(\omega)$.

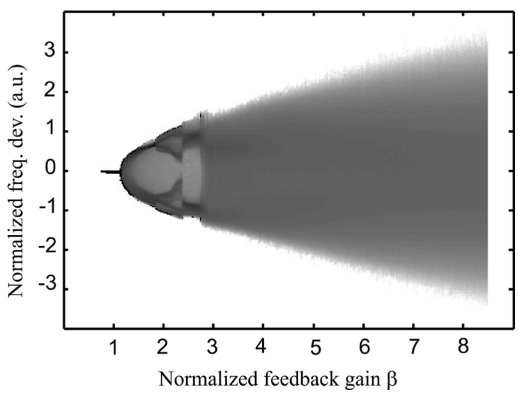

Fig. 5. Bifurcation diagram ($\phi = 2.1$ rad, $\delta L = 5$ m).

$\omega(t)$ for different regimes, or the Lyapunov dimension in chaotic regime (according to a modified Farmer method for delay equations [9]). The corresponding results are reported in the next section.

III. Numerical Simulation Results

A. Time Evolution and Statistical Properties

Fig. 4(a) represent a typical chaotic waveform obtained from the numerical simulation of (5). The amplitude corresponds to the frequency deviation from the central frequency ω_0. Such a noise-like waveform is typically used in a chaos-based communication system. The probability density function (PDF) is depicted in Fig. 4(b) for the same chaotic regime, for which the typical bell-shape of a Gaussian process is observed. This statistical feature is intended to exhibit neutral statiscal properties, thus making the chaotic carrier similarly to the superposition of numerous independent random processes according to the central limit theorem. Note that such feature is obtained for only three scanned extrema of the nonlinear function $F(\omega)$,as it can be seen in Fig. 4(b).

B. Bifurcation Diagram

The bifurcation diagram in Fig. 5 is obtained numerically when increasing the feedback loop gain (horizontal axis, parameter β). The vertical axis corresponds to the centered dynamical variable i.e., the VCO input or its instantaneous output frequency deviation $\omega - \omega_0$. The PDF amplitude is encoded in grayscale (dark color corresponding to a high probability, and white to a null one).

For small β-values, the dynamic is in a stable fixed point state (no oscillation). At $\beta \simeq 1.25$, a crisis is observed as a nonzero amplitude periodic oscillation suddenly appears, with a typical frequency related to $1/2T$. While further increasing β, the temporal trajectories evolve through more or less complex periodic oscillations, which always reveal the characteristic time scale of the delay T. The expected chaotic regimes start from $\beta > 2.7$, with a "2-maxima" broadly distributed PDF. This PDF evolves smoothly and asymptotically to a single maximum PDF at $\beta \simeq 5$ and higher, showing a nice bell-shape ($\beta > 8$). Although the global bifurcation route to chaos resembles the ones already described in the litterature for low-pass delay dynamics, significantly different behavior can be observed with band-pass delay dynamics, especially when varying the phase parameter ϕ. More specifically, there is no clear period doubling in the bifurcation cascade, although the general shape of the bifurcation diagram follows this well known "route-to-chaos" scenario. We also noticed that the chaotic regimes seem to start abruptly in a nearly crisis fashion at $\beta \simeq 2.7$, as a small discontinuous amplitude jump is observed at the bifurcation point, both experimentally and numerically; this fact might be related to a subcritical nature of the Hopf bifurcation due to the band-pass nature of the feedback filtering process, which reason is to be confirmed by further theoretical investigations. An exhaustive analysis of the different bifurcation scenarios with respect to all possible parameter settings is, however, not the purpose here.

C. Lyapunov Exponents

From the dynamical model in (5), we adapted to the band-pass situation a numerical method initially proposed by Farmer [9] to calculate the Lyapunov spectrum, and estimate from it the corresponding Lyapunov dimension. The Farmer's method has been mainly used for the conventional situation of a low-pass nonlinear delay dynamics, and it is considered as one of the only few numerical tools available for the estimation of the dynamic complexity in the case of delay dynamics. The modified method we used for the band-pass situation, did give convergent results, which can be considered as a rough estimate of the actual chaotic attractor dimension, as stated by the Kaplan–Yorke conjecture. Though the actual experimental chaotic regime corresponds to an intermediate complexity (for a moderate gain $\beta = 4.5$ and a moderate delay $T/\tau_1 = 3.1$), a Lyapunov dimension as high as $D_\lambda \approx 25.7$ has been found. This indicates that much higher complexity can indeed easily be obtained with the setup. Such high-complexity dimension could, however, not be confirmed from experimental data, due to the high sensitivity of the computation method with respect to noise level.

IV. Experimental Results

With the setup depicted in Fig. 1, different experimental measurements have been done in order to confirm or discuss some of the theoretical and numerical results previously reported.

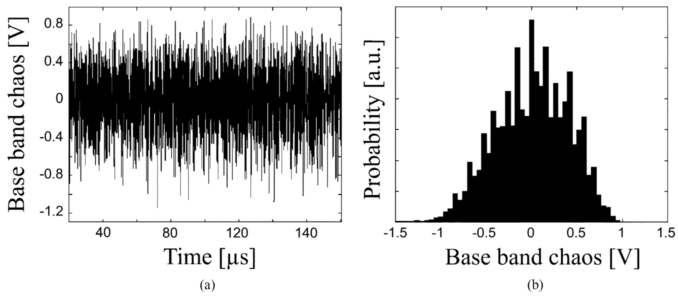

Fig. 6. Experimental chaotic regime. (a) Time trace of the base-band chaos (VCO input). (b) PDF.

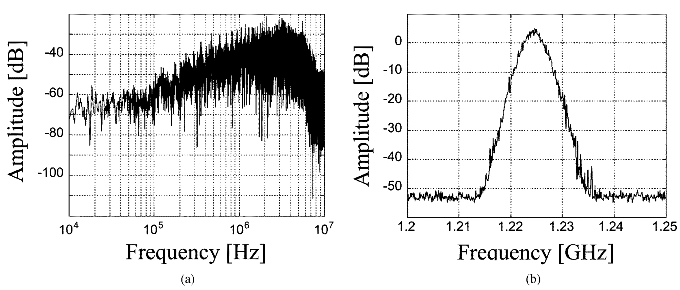

Fig. 7. Experimental chaotic spectra. (a) Base-band spectrum. (b) FM spectrum.

A. Temporal Evolution

The signal actually recorded in the experiment corresponds to the VCO input; it is captured with a digital oscilloscope (Lecroy 5-GHz analog bandwidth). Fig. 6(a) shows a time series of this base-band signal, which corresponds to a chaotic regime obtained numerically with the normalized parameter $\beta = 8$ and $\phi = 2.1$. The corresponding spectrum is depicted in Fig. 7(a), and the resulting chaotic FM spectrum measured while replacing the emission antenna by an oscilloscope input channel, is reported in Fig. 7(b).

As calculated with the numerical integration of the nonlinear delayed band-pass dynamics, the time series in chaotic regime ressembles a noisy signal with characteristic time scale fluctuations related to the high and low cut-off characteristic times. The statistical distribution is also closely Gaussian. The spectrum of the time series reveals an expected broadband spectral signature, which extends within the frequency limit of the band-pass filter. The corresponding FM spectrum shows a spectral spreading of a few tens of megahertz around the RF carrier at 1.225 GHz.

B. Bifurcation Diagram

When slowly varying the oscillator feedback gain, it is possible to observe experimentally the different qualitative changes of the dynamical regime, from the stable steady state observed for low gain, to the chaotic regime for higher feedback gain. The resulting bifurcation diagram is depicted in Fig. 8, for a normalized offset phase approximately adjusted to $\phi = 2.1$, in order to compare with the diagram shape of the numerics. Clear qualitative similarities are noticed with the numerical result in Fig. 5 i.e., the global shape of the bifurcation diagram is kept. Also the relative positions of the bifurcation points along the horizontal axis appear quantitatively well matched.

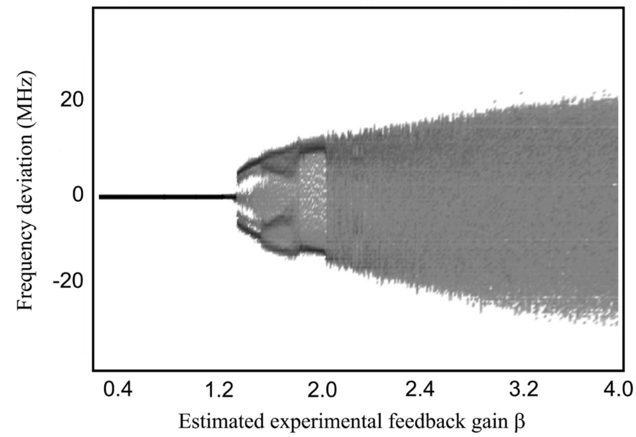

Fig. 8. Experimental bifurcation diagram ($\phi = 2.1$ rad, $\delta L = 5$ m).

The good qualitative and quantitative agreement between experiments and numerical predictions indicate that the adopted theoretical model of a nonlinear delayed band-pass dynamics is valid. Further exhaustive investigations of the numerous dynamic regimes exhibited by the setup with various parameter setting are in progress.

V. Conclusions and Perspectives

We demonstrate an experimental nonlinear oscillator based on a delay band-pass dynamics, capable of generating a large variety of dynamical behaviors, from the stable steady state to the high complexity chaotic regimes, through periodic or pseudo periodic oscillations. Very good agreement between experiments and numerical predictions have been found, thus indicating that the experimental setup and its characteristic parameters and features can be accurately controlled, though a potentially high complexity behavior. Such a complexity can be achieved practically at GHz electronic frequency, through an original and novel optoelectronic architecture. This architecture involves an FM radio-frequency signal allowing for a nonlinear transformation obtained through a microwave Mach–Zehnder interferometer performed with optoelectronic devices. New specific dynamical features have been found with the setup, for particular operating condition; for example, an original dual delay time nonlinear dynamics can be obtained when the interferometer arms exhibit relative delays larger than the characteristic response time of the feedback.

From a more applied perspective, the frequency range of concern in the experiment might be of relevant interest for practical application to chaos communication in free space transmission. Following a master-slave chaos synchronization scheme, and an in-loop additive chaos modulation with an information message $m(t)$ at the emitter (see Fig. 1), an operational wireless chaos-based commmunication scheme can be conceived. A possible architecture for the decoding receiver is proposed in Fig. 9, which involves an open loop receiver. The phase-locked loop (PLL) at the input radio detection, allows for the processing of two parallel branches that are required for message decoding. First, the base-band signal of the PLL recovers the signal *chaos* + *message* $(v(t) + m(t))$ as it exists at the VCO input of the emitter. Second, the FM locked output of the PLL allows for

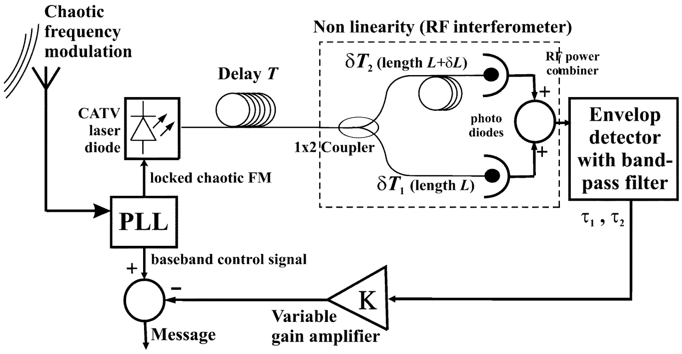

Fig. 9. Receiver setup intended to recover an information masked within the chaotic FM carrier.

the regeneration of the chaotic FM signal $(\omega_r(t))$, and serves as an input for the local replication process of the base-band chaotic signal alone (without message part). This locally replicated signal $v_r(t)$ thus obeys the following differential equation:

$$\tau_{1r}\tau_{2r}\,\frac{d^2v_r}{dt^2}(t)+(\tau_{1r}+\tau_{2r})\frac{dv_r}{dt}(t)+v_r(t)-v_{0r} = \beta_r\,\tau_{1r}\,\frac{dF[\omega_r]}{dt}(t-T_r) \quad (6)$$

where the subscript r is attached to receiver parameter or variables. Assuming emitter and receiver parameter are properly matched, comparing (6) with (5), and setting $v(t) = \omega(t)/(2\pi S)$, it is obvious (see [5] which reports the same replication principle) that the receiver signal $v_r(t)$ is able to replicate the corresponding one at the emitter $v(t)$. Subtracting this replicated base-band chaos to the base-band output of the PLL enables the recovery of the information message $m(t)$.

Work is in progress to demonstrate experimentally the validity of such a wireless chaos communication scheme, and to show the possibility for accurate parameter matching between emitter and receiver, so that efficient decoding can be obtained at the receiver. The parameters need in principle to be first transmitted as a secret key from the emitter to the receiver. A typical experimental procedure is then used to adjust those parameters according to the one defined by the secret key; this procedure consists of a measure of these parameters in an open loop configuration (similarly as described in [5]).

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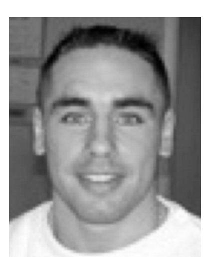

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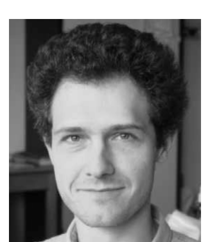

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