Control of the Chaotic Dynamics of Delayed Feedback Klystron Oscillator and its Application in Chaotic Communications

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Abstract — The paper deals with the control of complex nonlinear dynamics of a delayed feedback microwave klystron oscillator as well as with its application to the problem of chaotic communications. Basic features of nonlinear dynamics such as the types of chaotic attractors and transition to chaos scenarios are shortly reviewed. The possibility of the control of nonlinear dynamics is studied with the purpose of an application of the oscillator in direct chaotic communications (DCC). Further, an information transmission using chaotic shift keying (CSK) modulation and coherent reception is demonstrated via numerical simulation. The driving by an external signal is used to control the chaotic states of the transmitter oscillator for the purpose of generation of CSK basis functions.

I. INTRODUCTION

Numerous applications such as chaotic communications and information processing [1]–[4], noise radar technology [5], electronic countermeasure, and microwave plasma heating require powerful sources of spread spectrum chaotic microwave radiation. Both solid-state and vacuum electron devices can produce chaotic radiation at microwave frequencies. Recently, successful operation of an L-band chaotic communication scheme using a bipolar transistor chaotic generator has been reported [4], [6]. However, at centimeter and millimeter wavelengths only vacuum devices are capable to produce chaotic radiation with several watts output power. Among the vacuum devices, a klystron delayed feedback oscillator seems to be one of the most promising candidates for development of chaotic microwave generators because klystron amplifiers are able to obtain high efficiency and high output power. In our previous works, we have studied nonstationary and chaotic dynamics of klystron oscillators numerically [7]–[10] and experimentally [7], [11]. A wide variety of regular and chaotic self-modulation regimes has been revealed, which is favorable for application in chaos-based communication systems. On the other hand, klystrons are narrowband devices, compared with traveling wave tubes (TWTs). Recently, application of a chaotic TWT oscillator to satellite communication has been considered [12], and first experimental demonstration of information transmission has been reported [13]. However, controlling chaotic regimes in a wideband TWT oscillator is difficult. For that purpose, a tunable band-pass filter is usually embedded in a feedback circuit [13]–[15]. However, embedding the filter in the TWT oscillator dramatically reduces the bandwidth of output chaotic radiation, which becomes comparable to that of the klystron oscillator. Also, the driving of the TWT oscillator by an external signal might be required to obtain stable and controllable robust chaotic oscillations [13].

In this article, we discuss the possibility of the control of chaotic states by an external driving signal, and its application in a chaotic communication scheme. In Sec. II, we describe the schematic of the two-cavity oscillator along with basic equations and briefly summarize the results of numerical analysis. In Sec. III, we propose a direct chaotic communications (DCC) scheme with the chaos shift keying (CSK) digital modulation technique using the klystron oscillator and present results of numerical modeling of information transmission. On the purpose of switching between chaotic regimes that is prerequisite of a CSK scheme, an external driving harmonic signal was applied to klystron oscillator.

II. NUMERICAL MODEL OF THE DELAYED FEEDBACK KLYSTRON OSCILLATOR

Consider two-cavity klystron oscillator with an output connected to input via a dispersionless feedback transmission line (coaxial cable) containing variable attenuator and phase shifter (Fig. 1). A numerical model of the oscillator described by the system of delayed differential equations has been developed in [7]:

\[
\frac{dF_1}{d\tau} + \gamma_1 F_1 = \gamma_1 F_2 (\tau - 1),
\]

\[
\frac{dF_2}{d\tau} + \gamma_2 F_2 = -2i\alpha e^{i\omega_0 \tau} J_1(|F_1|) \frac{F_1}{|F_1|}.
\]

(1)

First equation stands for an excitation of the input cavity by the signal from delayed feedback line, it contains a delayed term. Delay time is normalized to unity. Second equation is responsible for the output cavity excitation by the bunched electron beam. In (1), \( F_{1,2} \) are the slowly varying dimensionless envelopes of oscillations in the input and output cavities respectively, \( \tau = \omega_0 t / \psi \) is the normalized time, \( \omega_0 \) is the resonant frequency of the cavities, \( \psi \) is the phase shift during propagation along the feedback loop, \( J_1 \) is a Bessel function of the 1st kind, \( \gamma_{1,2} = \psi / Q_{1,2} \) are the parameters of losses inversely proportional to the cavity loaded Q-factors, and

\[
\alpha = \frac{\rho KM^2}{4V_0 \sqrt{2}}
\]

(2)
is a self-excitation parameter proportional to the gain of the amplifier and the amount of feedback \( \rho \) [7], [10]. In (2), \( I_0 \) and \( V_0 \) are the beam current and voltage respectively, \( K \) is the characteristic impedance of the output cavity, \( M \) is the gap modulation factor, and \( \theta_0 \) is the unperturbed electron transit angle in the drift space. In the following, it is assumed that the cavities are identical, their Q-factors and resonant frequencies are the same, and hence \( \gamma_1 = \gamma_2 = \gamma \). It is also supposed that the cavities are perfectly matched with the feedback transmission line.

Simulation of non-stationary processes reveals a complex sequence of bifurcations produced by the increase of the self-excitation parameter, \( D \) [7]–[10]. Transition to chaos via a period doubling (Feigenbaum) scenario, which is typical for many other delayed feedback systems (compare [8], [16]) dominates in this system as well. However, in general, the dynamics of the system is much more complicated than the classical Feigenbaum scenario. Quasiperiodic self-modulation and the Ruelle–Takens scenario of transition to chaos were also observed in distinct regions of the phase space. In the chaos domain, there exist many windows of periodic self-modulation where attractors are represented by limit cycles of different shapes. Increasing \( \alpha \) beyond the chaos threshold gives rise to a continuous complication of shapes of limit cycles accompanied by numerous transitions between chaotic and periodic regimes. Chaotic regimes emerge either via period doublings or via hard transition, while periodic ones emerge either via intermittency or via hard transition.

Complex dynamics of the klystron oscillator is characterized by existence of various types of chaotic regimes with different spectra and attractor topologies that is favorable for designing CSK systems.

III. CONTROLLING CHAOTIC STATES BY AN EXTERNAL SIGNAL AND CHAOTIC SHIFT KEYING

Several basic approaches to communication systems using chaotic signals have already been developed [1]–[4]. For example, in the recent work [13] a chaotic masking modulation/demodulation scheme was realized, in which an information signal is fed into the feedback circuit of the chaotic TWT oscillator. In [12], a more complicated way of information transmission was described. It uses control of a chaotic phase trajectory of a TWT oscillator in a Poincare section. In this work we focus on another communication scheme based on digital transmission of information using CSK. In particular, we use a direct chaotic communications (DCC) approach [2], [4]: a CSK scheme in which the information-carrying chaotic signal is generated directly in RF or microwave band. Since the klystron oscillator exhibits several chaotic states [7]–[11], one can digitally transmit information by assigning different symbols to signals generated on different attractors. However, to realize this scheme, one should know how to solve the problem of controlling chaos, i.e. how to switch between the attractors. For example, this switching can be achieved by proper modulation of parameters of the oscillator, such as beam current or amount of feedback. In this paper, we consider a more simple way of control: driving an oscillator with an external harmonic signal.

![Fig. 1. Schematic of the klystron delayed feedback oscillator.](image)

It was found that the external signal can effectively control the operating state of the oscillator. Fig 2 represents spectra and phase portraits of two chaotic regimes that build up the basis functions of a CSK scheme. The following values of parameters are chosen for the simulation: \( \alpha = 11.28 \), \( \gamma = 1.0 \), \( \psi = 0.99\pi \), \( F_{\text{ext}} = 2.0 \), and \( \omega_{\text{ext}} = 0.0 \) (i.e. the driv-
ing frequency is equal to the resonant frequency). From Fig. 2, one can clearly see that the adding of the external signal significantly changes the output chaotic signal. Namely, one can switch between chaotic regimes of the oscillator by turning the external signal of constant amplitude and frequency on and off. This makes it possible to use the klystron generator as the transmitter in a CSK communication system.

Consider a transmitter based on the klystron oscillator with an external signal added in the feedback line (Fig. 3(a)). Equations (1) become

\[
\begin{align*}
\frac{dF^{\text{tx}}_1}{d\tau} + \gamma F^{\text{tx}}_1 &= \gamma \left(F^{\text{tx}}_2 (\tau - 1) + I \cdot F_{\text{in}} \exp(i\omega_0 \tau')\right), \\
\frac{dF^{\text{tx}}_2}{d\tau} + \gamma F^{\text{tx}}_2 &= -2i\alpha e^{-i\phi} J_i \left| F^{\text{tx}}_1 \right| \frac{F^{\text{tx}}_1}{F^{\text{tx}}_2},
\end{align*}
\]

where \( I \in \{0,1\} \) represents bit information flow and the term \( F_{\text{in}} \exp[i\omega_0 \tau'] \) serves as high-frequency carrier.

\[ F(t) \]

\[ \text{Klystron} \]

\[ \text{Delay} \]

\[ F(t-1) \]

\[ \hat{F}(t) \]

\[ F(t) \]

\[ \text{Klystron} \]

\[ \text{Delay} \]

\[ \hat{F}(t-1) \]

\[ F(t) \]

Fig. 3. Schematics of the proposed DCC transmitter (a) and receiver (b). Operator \( L \) denotes transformation of the signal by the klystron amplifier.

For the information decoding, we consider a coherent receiver, in which a replica or synchronous chaotic response of the chaotic signal of the free-running transmitter oscillator is recovered [4]. In the receiver, the signal is split in two parts. One of them passes through a klystron and a delay line which are supposed to be identical to those of the transmitter (Fig. 3(b)). The klystron amplifier in receiver can be described by the following equations:

\[
\begin{align*}
\frac{dF^{\text{rx}}_1}{d\tau} + \gamma F^{\text{rx}}_1 &= \gamma F^{\text{rx}}_2, \\
\frac{dF^{\text{rx}}_2}{d\tau} + \gamma F^{\text{rx}}_2 &= -2i\alpha e^{-i\phi} J_i \left| F^{\text{rx}}_1 \right| \frac{F^{\text{rx}}_1}{F^{\text{rx}}_2}.
\end{align*}
\]

Decoding of information is made by comparing output from the channel \( F^{\text{rx}}_n (\tau) \) with the delayed response of the receiver’s klystron \( F^{\text{rx}}_n (\tau - 1) \). From Fig. 3 one can realize that in the case when there is no external driving signal in the transmitter (“zero” symbols) we have equal or close (depending on channel distortion) values of \( F^{\text{rx}}_n \) and \( F^{\text{rx}}_n' \), while they are completely different for the symbol “one”.

\[ F(t) \]

\[ \text{Klystron} \]

\[ \text{Delay} \]

\[ \hat{F}(t-1) \]

\[ F(t) \]

\[ \text{Klystron} \]

\[ \text{Delay} \]

\[ \hat{F}(t-1) \]

\[ F(t) \]

Fig. 4. Illustration of coding-decoding process in the proposed DCC scheme without distortion in the channel: (a) — information to be transmitted; (b) — output signal of the transmitter; (c) — input signal of the receiver; (d) — difference signal \( \delta F^{\text{rx}} \); (e) — estimation of the transmitted bits.

First of all, consider the case when there is no signal distortion in the channel. Basic stages of information transmission are represented in Fig. 4. The information signal depicted in Fig. 4(a) forms the modulated output signal of the transmitter, \( F^{\text{tx}}_n \) of Eqs. (3), shown in Fig. 4(b). Fig. 4(c) depicts the input signal in the receiver, \( F^{\text{rx}}_n \), which is identical to \( F^{\text{tx}}_n \). Fig. 4(d) depicts the behavior of the difference signal \( \delta F^{\text{rx}} = F^{\text{rx}}_2 - F^{\text{rx}}_n \). One can clearly see that for “zero” symbols \( \delta F^{\text{rx}} = 0 \), while for “one” symbols \( \delta F^{\text{rx}} \neq 0 \). This allows errorless recover of the transmitted signal (Fig. 4(e)).

Fig. 5 illustrates information transmission affected by channel distortion. An additive white Gaussian noise (AWGN) channel is considered, i.e. noise signal \( F^{\text{ns}}(\tau) \) with zero expectation is added to transmitter’s output, i.e. \( F^{\text{tx}} = F^{\text{tx}} + F^{\text{ns}} \). Signal-to-noise ratio (SNR) of 10 dB is chosen. Comparing Fig. 5(b) and 5(c) one can see that those signals are different. Although the difference between \( \delta F^{\text{ns}} \) corresponding to “zero” and “one” is not as obvious as at
Fig. 4 at the chosen level of SNR, difference in per-bit energies allows detection of what symbol was transmitted by means of a threshold decision on per-bit energy of $\delta F''$.

Low SNR level (1 dB) causes errors in recovered signal (Fig. 6). However, BER remains on an acceptable level which is sufficient for information transmission using redundant channel coding (see e.g. [17]).

Although a coherent receiver provides better noise performance than a noncoherent one (i.e. less error probability in case of equal signal-to-noise ratio), usually it demonstrates significantly higher sensitivity to parameter mismatch of the corresponding elements of transmitter and receiver [2], [4]. Concerning the studied system, this issue is the topic of ongoing studies, as well as the issue of the reduction of bit error rate at lower SNR and higher bit rates. However, CSK schemes are known to be less sensitive to parameter mismatch than other chaotic modulation schemes such as chaotic masking [4].

### IV. CONCLUSION

One of the main features of complex nonlinear dynamics of the klystron oscillator with delayed feedback concludes in the possibility of formation of different types of chaotic attractors. This makes the klystron oscillator an attractive device for use in a direct chaotic communication system. Corresponding results of numerical simulations are presented showing a possibility of information transmission by a CSK method with a coherent receiver. Driving by an external harmonic signal was used to control the chaotic states of the oscillator, i.e. to switch between the attractors of different types. The suggested DCC scheme appears to be robust to noise in the channel. This is a first demonstration of a chaotic communication system using a klystron, a device that is widely used in conventional communications.

Finally, we wish to note that the CSK scheme has relatively poor masking properties. However, our motivation is not the secrecy of communication, but the advantages of a broadband chaotic carrier over a conventional single or multifrequency ones, which might result in improved efficiency and device compactness, electromagnetic compatibility, jamming and interference immunity, etc. [2],[4],[5],[12].

### REFERENCES


