Investigation of self-generation of broadband microwave chaotic and noise signals in microwave photonic ring oscillator

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Abstract. Nonlinear dynamics of a microwave optoelectronic oscillator was investigated for the first time with the use of time series analysis. The detailed study of the generated microwave waveforms showed a route from stable monochromatic oscillations to noise through a series of bifurcations. The oscillator demonstrated the periodic and chaotic dynamics in the intermediate regimes of self-generation. Peculiarities of the signals and their spectra for the chaotic and noise regimes were found. The chaotic and noise dynamics were proven with the Grassberger-Procaccia method.

1. Introduction
During the past decades a special interest of researchers is devoted to the development of the microwave (MW) generators of dynamic chaos. It is caused by the possibility of using chaotic signals in telecommunications [1], radar systems [2], and in random number generators [3]. Special attention is paid to the frequency spectrum bandwidth of the generated chaotic signal. An increase of the spectrum width allows to increase speed of the communication system or to achieve better resolution of the radar.

In recent papers the microwave generators of the broadband chaotic signals based on different physical principles were described. For example, in [4] the microwave generator, which uses an interaction of semiconductor superlattices with a bulk or microstrip resonator, was investigated. In [5] the generator of chaotic oscillations based on a bipolar MW transistor was elaborated. In [6-9] the electronically tunable ring oscillators based on magnetic films were studied. In the ring oscillators the
ferromagnetic films and ferrite-ferroelectric structures played a role of nonlinear elements. These generators allow controlling parameters of self-generated dynamic chaos by varying the magnetic or electric field applied to the nonlinear element.

Nowadays the microwave photonic devices are under extensive investigation [10-12]. Particular attention is given to the optoelectronic oscillators (OEO) for microwave signal generation [13-18]. The microwave photonics technology provides a vast advantage for microwave signal processing and generation in comparison with conventional microelectronics. One of the advantages of the optoelectronic components is their broad frequency bandwidth. Thus, it is relatively simple to create a broadband optoelectronic generator of microwave dynamic chaos [19].

The aim of this work is a detailed investigation on the nonlinear dynamics of the microwave optoelectronic oscillator. In contrast to work [19] we show, for the first time, that the optoelectronic oscillator demonstrates both chaotic and noise dynamics.

2. Experimental setup
A block-diagram of the oscillator is shown in Fig. 1. The main components of the oscillator are a laser diode, an electro-optic modulator (EOM) of Mach-Zehnder type, an optical fiber, a photodetector, a DC-block, microwave amplifiers, an isolator, a variable attenuator, a high pass filter (HPF), and a directional coupler. Coaxial cables connect components of the microwave path. Optical radiation wavelength of the laser was 1.55 μm. Its power was 10 mW. Bandwidth of the EOM was 10 GHz. Half-wave voltage of the EOM was 3.3 V. The optical fiber had a length of 100 m and a diameter of 8 μm. Upper operating frequency of the photodetector was 25 GHz. The amplifiers bandwidth was 2-8 GHz. The HPF cut-off frequency was 3.5 GHz.

A principle of operation of the oscillator is as follows. The laser emits a continuous wave optical radiation, which is used as a carrier signal. The electro-optical modulator modulates the optical radiation by a microwave signal coming from the MW path. The modulated optical signal propagates through the optical fiber and is delayed by a time of about 521 ns. The photodetector demodulates the optical signal and transmits its envelope to the MW path. The DC-block removes the direct current level from the output photocurrent. The resulting alternative current signal is amplified by the microwave amplifiers and supplied to the driving port of the electro-optic modulator, closing the ring circuit. A pair of the microwave amplifiers compensates total propagation losses of the microwave signal in the ring. The variable attenuator is used for control of these losses. A small portion of the microwave signal is extracted from the ring by the directional coupler for monitoring the generated waveforms. The monitoring was carried out by means of a fast microwave diode detector connected to a digital oscilloscope and a microwave spectrum analyzer.

It is worth mentioning that the frequency band of the generated chaotic oscillations is determined by the bandwidth of the microwave path. In the described circuit, the lower cut-off frequency of the chaotic generation is determined by the HPF characteristics. The higher cut-off frequency is determined by the microwave amplifiers. Therefore, the frequency spectrum of the chaotic signal is in the range of 3.5-8 GHz.

The electro-optic modulator was the nonlinear element of the generator. Its cosine transmission characteristic causes the nonlinearity of conversion of the microwave signal to an envelope of the optical signal.

3. Experimental results
The experimental study of the route to the noise signal self-generation was carried during a smooth increase of the ring gain coefficient G. The increase of G was caused by reducing the attenuation of the microwave signal in the variable attenuator. The value of G = 0 dB was chosen as the reference point at the threshold of the microwave signal self-generation. An increase of the ring gain led to a change of the self-generation regime. Nonlinear dynamics of the optoelectronic oscillator was caused by the nonlinear transmission characteristic of the EOM. All the other components, including microwave amplifiers, operated during the measurements in a linear regime.
Generation of a monochromatic microwave signal started at the self-generation threshold. The frequency of the generated harmonic was 3.676 GHz and its power was 0.3 mW. A number of small frequency peaks around the generated harmonic was observed. They were due to noise amplification of the frequencies corresponding to eigen-modes of the ring. These harmonics were weakened for about 40-50 dB. Since these harmonics were not phase correlated, the self-generation of signal with a constant level of microwave power was observed.

With increasing the ring gain $G$ above 7.3 dB, the power of the microwave signal supplied to the electro-optical modulator exceeds 55 mW. A bistability occurred above this power level. The single-frequency spectrum was replaced by a frequency-comb spectrum, and the center frequency changed to 3.652 GHz. The observed spectrum consisted of harmonics with two values of detuning frequencies, approximately equal to 1.92 and 178.6 MHz.

In this regime, the fast oscillations of different duration appeared. We will call them the trains of fast oscillation. The period of the fast oscillations $T_1$ was approximately 5.6 ns. The duration of the trains periodically varied and repeated after the formation of a number of the trains. In the observed sequence of the trains it was easy to identify a certain period $T_2 = 520.8$ ns (we will call it as a period of slow oscillations), which did not depend on $G$. Thus, each period of the slow oscillations contained several trains of the fast oscillations. The frequencies of the generated harmonics were multiples of each other. The microwave signal had an amplitude modulation of period $T_2$. Therefore, the generation regime was a periodic one. The duration and profile of the trains appearing during one period were changed with an increase of the ring gain.

Further increase of the ring gain above 11.7 dB led to stochastization of the oscillations and the spectrum became broadband. On the left side of Fig. 2 the spectrum and fragment of the chaotic waveform measured at $G = 15.1$ dB are shown. It can be seen that the spectrum of the microwave

![Fig. 2. Spectra (a), their fragments (b), and waveforms (c), measured in the chaotic generation regime for $G = 15.1$ dB (left panel) and in the noise generation regime for $G = 22.9$ dB (right panel).]
signal consisted of the broadband noise pedestal with separate harmonics. Frequencies of these harmonics corresponded to ring eigen-modes. The envelope of the generated microwave signal had a form of a sequence of well-defined chaotic pulses.

A change of the generation regime occurred above $G = 18.7$ dB. The separated harmonics disappeared. The frequency spectrum of the microwave signal became broadband. The waveform in time domain took non-periodic form. The frequency spectra and oscillograms recorded for $G = 22.9$ dB are shown on the right side in Fig. 2.

4. Analysis of the nonlinear dynamics from time series

Analysis of the waveforms allowed us to determine, whether the generated non-periodic signal is a quasi-periodic signal, dynamic chaos or random noise [20]. The waveforms with duration of 10 μs and the resolution between points of 100 ps were recorded for analysis of the generation regime.

At the first stage phase portraits of the observed generation regimes were constructed by the time delay method. Fig. 3 (a) demonstrates the phase portrait corresponding to the periodic generation regime for $G = 9.4$ dB. The dynamics of the optoelectronic system was defined as evolving of the system state in time yielding two orbits. One of them was in the form of a closed loop, and another was in the form of a point. The shape of the loop was determined by the shape of the fast oscillation pulses. The point on the phase portrait corresponded to the constant power level of the waveform. For $G = 9.4$ dB, this point had coordinates $(10 \text{ mV}, 10 \text{ mV})$. The jumps were periodic. The phase portrait had a similar form for the other values of the ring gain, corresponded to a periodic generation regime. The time, during which system state was following the loop, was growing with an increase of the gain coefficient. In contrast, time, during which system state was staying in the point, was decreasing.

The form of the attractor was changed significantly above $G = 11.7$ dB due to stochastization of oscillations. Fig. 3 (b) illustrates the phase portrait obtained for $G = 15.1$ dB. In this regime, the chaotic pulses with the base level near 0 mV were observed. Thus the phase portrait extends to the origin of coordinates. The bifurcation occurring at $G = 18.7$ dB changed the waveform and led to changes of the phase portrait form. The phase trajectories start to rotate around a certain point of the phase space (see Fig. 3 (c)).

Unstructured phase portraits, shown in Fig. 3 (b,c), are typical for systems, which generate a chaotic signal with a high fractal dimension or a noise signal with infinite fractal dimension [16]. To clarify the origin of the generated signals, the values of correlation dimension, fractal dimension, minimum embedding dimension, and largest Lyapunov exponent of the obtained attractors were
The results show that for $G = 15.1 \, \text{dB}$ the minimum embedding dimension was equal to 28; the fractal dimension was equal to 11.5. The largest Lyapunov exponent was equal to $2.8 \, \mu\text{s}^{-1}$. These values characterize observed signal as a dynamical chaos.

Analysis of the phase portraits for $G > 18.7 \, \text{dB}$ demonstrated that increase of phase portraits dimension up to 55 leads to increase of correlation dimension. Thus, the value of fractal dimension for these values of ring gain coefficient is infinite. This specifies observed signals as a noise. Therefore, increase of the ring gain coefficient above 18.7 dB leads to bifurcation during which chaotic generation is changing by the noise generation.

5. Conclusion

The complex nonlinear dynamics of the microwave optoelectronic oscillator was investigated. The oscillator demonstrated periodic, chaotic, and noise dynamics. A bifurcation leading from chaotic to noise dynamics was found. The chaotic and noise origins of the generated microwave signals were confirmed with the time series analysis.

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