Influence of Mach-Zehnder modulator bias point on chaotic dynamics in spin-wave optoelectronic oscillator

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Abstract. In this paper we investigate in details the scenario of a transition to chaos in the spin-wave optoelectronic oscillator. The feature of the investigated circuit is the presence of two nonlinearities with different nature – modulation instability of spin waves and nonlinearity of the transmission characteristic of the electro-optical modulator. The influence of a position of the modulator bias point on the scenario of chaos development is experimentally investigated.

1. Introduction

Investigation of nonlinear phenomena in various dynamic systems is a promising field of science. The dynamic chaos is an example of such phenomena [1]. Dynamical chaos could be used for development of secure telecommunication systems [2], radars [3], random number generators [4], etc. An analysis of scenarios of transition to chaos is an important part of this investigation. It is well known that scenario of transition to chaos depends on the nature of nonlinearity in the investigated system. The most common scenarios are the sequence of period doubling bifurcations, intermittency, and the sequence of birth of harmonics with irrational ratio of their frequencies.

For example, using of the spin-wave delay line as a nonlinear element could provide transition through sequence of period doublings or appearance of irrational harmonics [5-10] depending on the conditions of the chaos development. Another example is a broadband optoelectronic generator [11–14]. A nonlinear element of such generators is an electrooptical modulator of Mach–Zehnder.

This paper reports the study of transition to chaotic dynamics in the spin-wave optoelectronic oscillator (SWOEO). In our recent paper [13] we investigated analogous circuit. But observed chaotic dynamics was caused by the nonlinearity of the electrooptical modulator only. In contrast to the previous works, the nonlinear dynamics of the oscillator in the current paper is due to both optical and spin-wave nonlinearities.

2. Experimental set-up

Figure 1 (a) shows a block-diagram of the SWOEO. The oscillator circuit consists of two parts: (i) an optical path and (ii) a microwave path. The main components of the optical path are a laser with 1.55 µm wavelength of optical radiation and power of 15 mW, a Mach-Zehnder electrooptical modulator (MZM) with a frequency range of 10 GHz and a half-wave voltage of 3.3 V, a 100 m long single mode optical fiber with a core diameter of 8 µm, and a photodiode with microwave bandwidth 25 GHz. The microwave path includes a DC-block, a set of microwave amplifiers with an operating frequency range 2-8 GHz, a variable attenuator, a spin-wave delay line, a microwave directional coupler, and a bias-tee.
Figure 1(b) shows in details the construction of the spin-wave delay line. It is based on an yttrium-iron garnet (YIG) film epitaxially grown on a substrate of gallium–gadolinium garnet. The film length is 15 mm, its thickness - 6.9 μm. The film was magnetized transversely, which allowed the excitation of surface spin waves. The bias magnetic field was 1244 Oe. The input and output microstrip antennas with a width of 50 μm were used as the elements of excitation and reception of spin waves. The distance between the antennas was 3 mm. The bandwidth of the spin-wave delay line is the narrowest comparing to the other components of the oscillator. Therefore it limits the bandwidth of the oscillator in the range of 5.56 – 5.72 GHz.

The Principle of operation of the experimental prototype is as follows. The laser emits continuous optical radiation. The MZM modulates the amplitude of the optical radiation by a microwave signal coming from the microwave path of the oscillator. The modulated optical signal goes through the optical fiber to the photodiode which detects a microwave envelope. After that the envelope of the optical signal is amplified by the first microwave amplifier and enters the input of the spin-wave delay line. Then it propagates between antennae in form of spin wave. The signal from the output of the delay line comes to the attenuator, and then is amplified by the second microwave amplifier. The amplified signal transmits to the microwave port of MZM through the directional coupler and the bias-tee. The bias-tee allows to add a constant bias level to the microwave signal. A small part of the microwave signal is removed from the ring by the directional coupler with a coupling coefficient of 10 dB for its further investigation. Total losses of the microwave signal in considered optical path are quiet high as well as in the spin wave delay line. Therefore it is necessary to use the pair of microwave amplifiers to compensate these losses. The variable attenuator serves to control losses in microwave path. The signal removed from the ring goes to a microwave splitter, the first part of the signal is transmitted to spectrum analyzer for measurements of frequency characteristics, and the second part is transmitted through zero bias Schottky diode to fast oscilloscope for time domain analysis.

In the case of low amplification, the described circuit is a ring resonator. Its eigenmode frequencies depend on the delay time in the optic fiber and in the spin-wave delay line. In this particular oscillator, the eigenmodes were placed at the distance of approximately 1.8 MHz.

![Figure 1. Experimental prototype of oscillator (a), and spin-wave delay line construction (b).](image-url)
losses, the circuit starts to generate a microwave signal. Corresponding value of a ring gain coefficient $G$ is set to be zero. Further increase of the gain coefficient leads to an increase of the total power circulating in the ring and the parametrical instability of the spin-waves in the delay line emerges as well as modulation process in MZM becomes nonlinear due to high amplitude of the input microwave signal. This leads to changing of the generation regime. At this stage, a dependence of the generation regime on the value of the gain coefficient is being investigated. After this, the value of bias voltage is changed and the measurements are repeated.

3. Experimental results
Compensation of losses in the circuit leads to generation of a single harmonic with a frequency 5.597 GHz. The power of the harmonic is -21 dBm. At $G = 3.86$ dB spectrum enriches with additional harmonics. A sequence of grey pulses corresponds to the spectrum (see figure 2(a)). Generation of grey pulses is typical for parametrical processes in transversely magnetized ferrite films. The amplitude of the signal on the microwave port of MZM is smaller than half-wave voltage. Therefore this regime is caused only by the modulation instability of the surface spin waves.

![Figure 2. Oscillator dynamic regimes: waveforms (left-hand side) and spectra (right-hand side), insets show frequency spectra in narrow frequency range.](image-url)
Increase of the gain coefficient up to 4.31 dB leads to further enrichment of the spectrum. The frequencies of the generated harmonics are fixed, but power levels are nonstationary. Due to this the waveform becomes nonperiodic (see figure 2(b)). This regime is also caused by the nonlinearity of surface spin waves. Increase of gain up to 8.3 dB increases the amplitude of the signal on the input of MZM to threshold value which corresponds to nonlinear modulation regime. Nonlinearity of MZM provides generation of periodic sequence of rectangular pulses. Figure 3 (c) shows obtained signal. Period of the pulses is 0.5 µm, duration of pulse is 0.25 µm. Repetition rate of the pulses is defined by frequency between the harmonics shown by the insets in figure 3(c). The amplitude of the pulses is higher than the threshold of spin wave modulation instability. Thus, the high level of pulse is chaotically modulated. During a low amplitude half-period there are no modulation instability, and the level is constant. Further increase of the gain leads to decrease of the chaotic pulses duration.

After achieving of the gain $G = 10.6$ dB a monochromatic generation realizes again. The window of regular dynamics is limited by the gain of 12.45 dB. At this level oscillations abruptly become chaotic (see fig. 2 (d)). The feature of this regime is a presence of constant bias level in the waveform. After $G = 13.45$ dB the form of chaotic oscillations changes (see fig. 2 (e)). The bias level vanishes and a chaotic pulses emerges again. In this last regime chaotic dynamics corresponds not only to high level of the pulses, but to low levels also.

The observed transition scenario is not a “classical” scenario of the development of chaotic dynamics, but it demonstrates some features similar to both scenarios of the development of dynamical chaos in spin-wave ring generators and in optoelectronic generators without a spin-wave delay line. Thus, the development of periodic signal generation at relatively small values of the ring gain coefficient, which was not observed in the optoelectronic generator, indicates the development of modulation instability of the spin waves, the occurrence of which most often makes it possible to observe the Ruelle – Tackens scenario. At the same time, the shape of the observed chaotic pulses is typical for the nonlinearity of the electro-optical modulator, the development of which usually leads to the chaos generation through a sequence of period doubling bifurcations. Thus, an analysis of the scenario of the development of chaotic dynamics in a spin-wave optoelectronic ring oscillator indicates the simultaneous presence of two types of nonlinearity, which manifest themselves at different values of the signal power circulating in the generator circuit.

An estimation of a fractal dimension for all observed regimes is carried out using long waveforms obtained in experiment. First, phase portraits are reconstructed by the time delay method [16]. The form of the phase portrait is determined by an attractor. During the transition to chaos various attractors appear in the phase space. At the beginning, a stable point corresponding to generation of the monochromatic signal appears. Increase of gain coefficient leads to destruction of the stable point and emerging of a limit cycle. After transition to chaotic dynamic a strange attractor appears. A stable point again appears for the range of the gain coefficient corresponding to the window of regular dynamics. Destruction of this stable point leads to formation of a new strange attractor. The form of this strange attractor changes when chaotic pulses appears again.

A value of the fractal dimension characterizes the form of the attractors and complexity of the signals. The algorithm of Grassberger-Pracaccia [17] is used for calculation of the fractal dimension. Figure 3(a) shows the dependence of the fractal dimension on the ring gain coefficient.

![Figure 3](image_url)

**Figure 3.** Dependence of fractal dimension on gain coefficient (a) and a map of the generation regimes (b)
The fractal dimension for the regime of the monochromatic signal generation is zero. The limit cycle is characterized by the fractal dimension equal one. After the transition to the chaos generation the fractal dimension increases up to 2.4 and continue to rise with increase of gain coefficient. At $G = 8.3 \text{dB}$ the dimension of the strange attractor jumps up to 3.2. In the regime of chaotic pulses fractal dimension also increases with increase of gain coefficient. The maximum value is 3.7. After this, oscillator transits back to monochromatic regime and the fractal dimension decreases to zero. The following transition to chaos increases the fractal dimension. The increase of the fractal dimension is the same as before the window of the regular dynamics.

The conducted investigation of the bias voltage role in the generation process enables us making a map of the oscillation regimes on the coordinate plane of the gain coefficient vs. bias voltage. Figure 3(b) shows this map. The colours correspond to the different generation regimes. It is seen that an increase of the bias voltage in the beginning does not lead to significant decrease of the threshold gain coefficients. The weak dependence is caused by independence of the threshold value of spin-wave instability on the bias voltage. For $U_b > 0.8 \text{ V}$ thresholds of the oscillation regimes decrease because the bias point is placed close to the nonlinear region of the MZM transmission characteristic. For $U_b > 1.1 \text{ V}$, the oscillation of any type is not observed due to a lack of the total gain coefficient. When bias point increased to 1.3 V the generation again appears in the SWOEO. The peculiar feature of the dynamics in the oscillator is the appearance of the bistability. When the bias point is close to the maximum of the MZT transmission characteristic, the ring could transit to generation of either CW or quasiperiodic signal after the chaotic pulses generation regime.

4. Conclusion

In conclusion, the dynamical regimes of the spin wave optoelectronic oscillator was experimentally investigated. The peculiarity of the circuit was presence of two nonlinear elements with different origin of nonlinearity and different thresholds of its appearance. The scenario of transition to the chaos with increase of power of the signal in the oscillator witnesses that both nonlinearity work in several regimes simultaneously. It was shown that variation of the bias point of the electro-optical modulator influences on the thresholds of regimes and parameters of the generated signals.

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