Phase noise management of spin-wave delay-line oscillators

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Abstract. A phase noise of microwave oscillators having an active ring circuitry with a spin-wave delay line is theoretically and experimentally investigated. The delay line was made with yttrium iron garnet (YIG) film epitaxially grown on gadolinium gallium garnet substrate. Obtained results demonstrate a management of the oscillator phase noise with a variation of the distance between antennas used for excitation and reception of spin waves in the YIG film.

1. Introduction
It is well known, that active ring circuits containing a spin-wave delay line based on yttrium iron garnet (YIG) film and a microwave amplifier can generate microwave signals of various types. Thus, it is possible to generate highly monochromatic signals [1-3], periodic sequence of nonlinear pulses, in particular, solitons [4-8], and chaotic signals [9-13]. Carrier frequency of the generated stationary signals can be tuned by magnetic field. Phase noise of delay-line oscillators can be reduced with an increase in delay time or, in other words, with an increase in slope of phase-frequency characteristic of the delay line. This is one of the advantages of the YIG-film delay-line oscillators in comparison with oscillators based on YIG-sphere resonators. Therefore, delay-line oscillators have potentially lower phase noise in comparison with resonator oscillators.

Physically clear that, an increase in time delay of spin-wave delay line increases its insertion loss also. It requires to increase the ring gain $G$ required for beginning a self-generation. It could increase the phase noise of the oscillator. The aim of this work was is experimental and theoretical investigation of the influence of the time delay on the phase noise spectrum of the spin-wave delay-line oscillator.

2. Design of the spin-wave delay-line oscillator
A schematic diagram of the experimental oscillator is shown in figure 1. Meander-type microstrip antennas were used for excitation and reception of the spin waves in the YIG film. The width of the microstrip and the distance between the antenna elements are 50 $\mu$m and 260 $\mu$m, respectively. The distance between the antennas $d$ was able to be varied in the range of 4-10 mm. The YIG-film waveguide was positioned on the microstrip antennas. The film was grown on a gadolinium gallium garnet substrate by a method of liquid phase epitaxy. The film had a thickness of 13 $\mu$m and a saturation magnetization of 1950 Gs. A half of ferromagnetic resonance line-width $\Delta H$ measured for frequency of 5300 MHz was 0.5 Oe. The film demonstrated unpinned surface spins. To avoid possible influence of reflected waves on the experimental results, the ends of the film were acute. The spin-wave delay line was placed between the poles of an electromagnet created a uniform magnetic field of...
Figure 1. Schematic diagram of the oscillator. The units are designated as follows: (1) meander-type antennas; (2) YIG film; (3) electromagnet; (4) microwave amplifier; (5) variable attenuator; (6) directional coupler.

1150 Oe. Such mutual orientation of the field and the propagation direction of spin waves corresponds to the excitation of surface spin waves in the YIG film.

The experimental oscillator also included the microwave amplifier Mini-Circuits ZXL0-8080E-S+. The total length of the ring circuit was less than 1 m. Variable attenuator was used to control the net gain of the ring. The directional coupler led out small portion of self-generated microwave signal for analysis. Spectrum analyzer Tectronix RSA6114B was utilized for measurements of the spectrum and phase noise of the generated continuous wave signal.

3. Results and discussion

It is well known, that microwave generation begins in the active ring if two following conditions are satisfied. The first condition is for the ring gain $G$:

$$G \geq \exp(\omega r_d) + M,$$

where $\omega = 2\pi |\gamma| \Delta H$, $\Delta H$ is a ferromagnetic resonance linewidth, $|\gamma|$ is a module of gyromagnetic ratio, $\tau_d$ is a time of one circulation of the signal in the ring (we will call it "a ring delay time"), $M$ is a total loss caused by excitation and reception of spin waves and attenuation of microwave signal in passive components. The second condition is for phase:

$$\phi_e(\omega) + 2\pi n,$$

where $\phi_e$ is a phase shift accumulated in electrical part of the ring, $\phi_m$ is a phase shift accumulated by spin waves in the delay line, $n$ is any integer.

An example of experimentally obtained transmission characteristic of the spin-wave delay line for $d = 4$ mm is shown in figure 2. The arrow on the graph shows the frequency at which the above described conditions were satisfied and continuous wave (CW) generation was observed. This frequency equals 5390 MHz.
The ring delay time $\tau_d$ depends mainly on the delay time of the spin-wave delay line. Delay time of the spin-wave delay line is determined by a distance between the excitation and reception antennas as $\tau_d = d/V_{gr}(\omega)$, where $V_{gr}(\omega)$ is a group velocity of the spin waves. The experimental dependence of delay time versus spin wave propagation distance for carrier frequency $f_0 = 5390 \text{ MHz}$ is shown in figure 3. As the distance $d$ increases the losses in the spin-wave delay line increases exponentially as $\exp(\omega_r \tau_d)$. The spin wave losses as a function of the distance $d$ for $f_0 = 5390 \text{ MHz}$ is shown in figure 4. To compensate the increase of insertion loss the variable attenuator was used.

![Figure 2. The spin-wave delay line insertion loss.](image)

![Figure 3. Delay time as a function of distance for $f_0 = 5390 \text{ MHz}$.](image)

![Figure 4. Insertion loss as a function of distance for $f_0 = 5390 \text{ MHz}$.](image)

The measurements of the phase noise were carried out for three values of $d$ of 4 mm, 7 mm, and 10 mm corresponding to the delay time $\tau_d$ of 80 ns, 140 ns, and 200 ns. Phase noise spectrum of the generated CW microwave signal is shown in figure 5. The measured value of the phase noise at 10 kHz offset was of -100 dBC/Hz.
Consider briefly factors influencing on the phase noise spectrum of the oscillator. An equation describing the spectrum of phase noise in single sideband above the carrier frequency and taking into account the thermal noise can be written as [14]

\[
L(f_m) = 10 \log_{10} \left( \frac{G F k T}{2 P} \left[ \frac{1}{4 \pi^2 \tau_d^2} \left( \frac{f_a}{f_m} + \frac{1}{f_m} \right) + \frac{f_a}{f_m} + 1 \right] \right),
\]

(3)

where \(f_m\) is the offset frequency from the carrier frequency; \(G\) is a gain of the amplifier; \(F\) is a noise figure of the amplifier; \(k\) is Boltzmann constant; \(T\) is temperature; \(P\) is signal power; \(f_0\) is a carrier frequency; \(\tau_d\) is delay time of the microwave signal in the active ring; \(f_a\) is an offset frequency at which the flicker noise of the active element (amplifier) emerges. It is seen from equation (3), that the minimum value of the phase noise is determined by delay time of microwave signal in the active ring, temperature of the device and the frequency at which the flicker noise of the active element occurs. The term \(G F k T / 2 P\) in equation (3) determines the threshold of the thermal noise of the generated signal and theoretically can be reduced with reduction of the required gain and noise figure of the amplifier [15].

Numerical simulation of phase noise spectra was carried out for parameters of the experimental oscillator. The results are shown in figure 6. The spectra were calculated for three experimental values of \(d\). They were in a good agreement with measured spectra. Thermal noise level obtained in the calculations was much less than experimental one. Relatively large experimental thermal noise of -120 dBc/Hz was due to intrinsic noise of spectrum analyzer. Theoretical analysis predicted a phase noise reduction with an increase in \(d\). It was confirmed by analysis of the experimental spectra (see figure 7). The experimental data demonstrate that an increase in \(d\) from 4 mm to 10 mm reduces the phase noise at 10 kHz offset from -100 to -104.5 dBc/Hz.
4. Conclusions
The influence of the time delay of the spin-wave delay line on the phase noise spectrum of the microwave oscillator is investigated. It is demonstrated that an increase in the distance between the excitation and reception spin-wave antennas leads to a reduction of the phase noise of the oscillator. A good agreement between theory and experiment is shown.

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