Theoretical analysis of phase noise spectrum of active ring microwave oscillators based on spin-wave delay lines

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Abstract. A phase noise of the microwave oscillators based on spin-wave delay lines is theoretically investigated. Theoretical results show that spin-wave damping in the delay line limits a phase reduction with increasing time delay. It is possible to find an optimum value of the time delay for each particular value of damping decrement in order to provide minimum phase noise of the generated microwave signal.

1. Introduction
Microwave signal oscillators are widely used in microwave electronics. The simplest oscillator with a carrier frequency in the microwave band typically consists of a microwave amplifier, directional coupler, and a passive circuit with feedback frequency control element. Resonators are usually used for the frequency control. Short-term stability of the generated microwave signal for dielectric resonator oscillators is usually determined from the analysis of phase noise spectrum and by the design of the generator [1]. The frequency tuning of oscillators is performed by tuning the resonance frequency of the resonator [2]. Generation occurs as a result of excitation of the system by noise existing in the components of the oscillator. The main disadvantage of dielectric resonators is their limited tuning range. Any tuning of the resonator adversely affects its quality factor even for phase-locked loop oscillator. Thus, tuning and phase noise are competing parameters. Typically, generators with low phase noise demonstrate relatively small frequency tuning and vice versa.

Another approach to design oscillators is based on the use of delay lines. The delay line operates as a frequency selective element. In this case whole active ring acts as a resonator. Active ring oscillators based on acoustic [3-5] and optical [6,7] delay lines are known for a long time. Their main disadvantages are the difficulty of the fabrication and complexity of analogue tuning over a wide frequency range. Additionally, optical oscillators have large size.

Microwave active ring oscillators based on the spin-wave delay lines are free from these disadvantages [8]. The spin-wave delay line has small sizes (from millimetres to several centimetres) and can be tuned by changing the external magnetic field. A typical range of frequency tuning is 1-20 GHz. Note also that the spin-wave devices can be easily made with conventional photolithography and surface mounted electronic components. It is possible to create miniature tunable low-noise microwave signal generators based on the spin-wave technology. In particular, the possibility for creation of tunable spin-wave delay-line oscillators with low phase noise (on the order of $-130$ dBC/Hz at 10 kHz offset) was demonstrated [9-13]. Although the first working models of spin-wave
microwave generators were built and demonstrated a long time ago, an interest for study and development of microwave oscillators is unabated so far [14].

The aim of this work is detailed study of the influence of spin-wave oscillator design on the phase noise spectrum of generated signal.

2. Theoretical investigation

Figure 1 presents the simplest circuitry of the spin-wave generator which consists of a microwave amplifier (1), a spin-wave delay line (2), and a directional coupler (3). The coupler serves for coupling a small part of microwave signal out of the ring. This ring circuit allows one to generate pulsed and monochromatic microwave signals with different parameters [15]. Generation begins at the resonant frequencies of the active ring. The theoretical description of the resonance properties for more general case of multiferroic delay line is described in details in ref. [16].

Consider briefly the main factors determining a phase noise spectrum of the generator. The simplest spin-wave generator have a ring circuitry consisting of the spin-wave delay line and the microwave amplifier. An equation describing the spectrum of phase noise in single sideband (SSB) above the carrier frequency, taking into account the thermal noise can be written as [17]

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

where \(f_m\) is an 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 (i.e. this is the time of one circulation of the signal in the ring); \(f_a\) is an offset frequency at which the flicker noise of the active element (amplifier) emerges. It is seen from equation (1), 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 (1) 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 [18]. In addition, the amplifier as any active element generates its own noise on the order of \(1 / f_m\) which could increase the overall phase noise at frequencies of less than detuning frequency \(f_a\), i.e. flicker noise frequency.

Figure 2 shows influence of \(f_a\) on phase noise spectrum of the spin-wave delay-line oscillator. The calculations were done for \(\tau_d = 100\) ns. As can be seen from the figure, this influence is relatively small. For example, if \(f_a\) increases from 0 Hz (the ideal case) up to 100 kHz, the phase noise at offset 10 kHz increases from −105 dBC/Hz to −95 dBC/Hz. The main contribution to the phase noise spectrum is introduced with the time delay of microwave signal travelling around the active ring. The phase noise produced by the mechanism of the time delay is on the order of \(1 / f_m^2\). As is seen from figure 3, an increase in the delay time \(\tau_d\) up to 10 \(\mu\)s reduces significantly the level of the phase noise.
Thus, the time delay of the active ring is the most effective tool to control the phase noise spectrum of the ring oscillators.

Figure 2. The phase noise spectra calculated for different values of the flicker noise frequency $f_a$.

Figure 3. The phase noise spectra calculated for different values of the delay time $\tau_d$.

Figure 4 shows influence of the product of the amplifier parameters $F$ and $G$ on the phase noise spectrum of the spin-wave delay-line oscillator. It is seen that the $FG$ determined the thermal noise floor in the operating frequency range of the amplifier. The increase of the thermal noise floor leads to an increase in the phase noise spectra close to the carrier. Therefore, the lowest phase noise occurs for minimum possible value of the $FG$ at the threshold of microwave signal generation.

Figure 5 shows the phase noise at 10 kHz offset as a function of $\tau_d$ for ideal case of lossless delay line. The calculation is based on the equation (1). The product $FG$ assumed to be constant for all values of $\tau_d$. It is evident theoretically that an unlimited increase in $\tau_d$ allows to decrease the phase noise level down to very small values.

The equation (1) does not take into account losses which take place in passive components of the ring. For our calculations we took into account losses inserted only by the spin-wave delay line. Insertion losses of other passive components are usually relatively small. They can be neglected. Insertion loss of the spin-wave delay line is defined as $\exp(-\omega_r\tau_d)$, where $\omega_r=2\pi|\gamma|\Delta H$, $\Delta H$ is a ferromagnetic resonance linewidth, $|\gamma|$ is a module of gyromagnetic ratio. Increasing the spin-wave propagation path with increasing a distance between excitation and reception antennas one can increase delay time $\tau_d$. At the same time it will also result in an increase in the spin-wave loss. In turn, it will require to increase the amplifier gain $G$. Finally, it will lead to an increase in the phase noise. Thus, we come to the following contradiction. From one hand, an increase in $\tau_d$ leads to the phase
noise reduction as $1/t_d$. From other hand, an increase in $t_d$ causes an increase of the amplifier gain which is proportional to $\exp(\omega_r t_d)$.

We have studied behaviour of the phase noise of the spin-wave delay-line oscillator taking into account both processes described above. Figure 6 shows the phase noise at 10 kHz offset as a function of $t_d$. The curves are plotted for different values of $\Delta H$. It is seen that for any nonzero value $\Delta H$ the phase noise reduces first, then in rises. Therefore, for each particular value of $\Delta H$ the optimum value of $t_d$ exists. This value provides minimum phase noise. For example, a microwave oscillator based on the spin-wave delay line made with an yttrium iron garnet (YIG) film having a thickness of 13 µm and $\Delta H=0.5$ Oe is possible to demonstrate minimum phase noise of $-110$ dBc/Hz at 10 kHz offset for $t_d=0.23$ µs.

The optimum delay time $t_{d,\text{opt}}$ for some value $\Delta H$ can be determined from the transcendental equation

$$\frac{\omega_r \exp(\omega_r t_{d,\text{opt}})}{(t_{d,\text{opt}})^3} = \frac{2 \exp(\omega_r t_{d,\text{opt}})}{(t_{d,\text{opt}})^3} - \frac{2M}{(t_{d,\text{opt}})^3} = 0,$$

where $M$ is a total loss caused by excitation and reception of spin waves and attenuation of microwave signal in passive components. Figure 7 shows the optimum delay time as a function of $\Delta H$ (solid line). The dotted line on the graph shows the minimum possible value of phase noise at 10 kHz offset as a function of $\Delta H$. It is seen that the losses in the active ring oscillator determined mainly by spin-wave damping in the delay line increases the minimum possible value of the phase noise $L_{\text{min}}$. Thus, the phase noise reduction is possible with the use of high-quality YIG films with extremely small value of $\Delta H$. It is evident that an unlimited increase in $t_d$ is theoretically unlimited decrease in the level of phase noise.

\begin{figure}[h]
\centering
\includegraphics[width=0.45\textwidth]{fig6.png}
\caption{Phase noise at 10 kHz offset as a function of $t_d$ for different values of $\Delta H$.}
\end{figure}

\begin{figure}[h]
\centering
\includegraphics[width=0.45\textwidth]{fig7.png}
\caption{The optimum value of $t_d$ (solid line) and the corresponding value of the phase noise (dashed line) as a function of $\Delta H$.}
\end{figure}

3. Conclusions

We analyzed in this work phase noise characteristics of spin-wave delay-line oscillators. The investigation shows that the phase noise is a function of both delay time and damping of spin waves which demonstrate minimum for particular parameters of the oscillator structure. Extremely small value of damping parameter of ferrite materials is necessary to fabricate the low-noise tunable microwave generators.
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