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Delayed Antiferromagnetic Spin Hall Oscillator as Random THz Signal Source

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Antiferromagnetic spin Hall oscillator with delay under action of DC signal is studied numerically. The delay in oscillator can be attributed to internal inertia of the antiferromagnetic lattice, or could be introduced artificially by electrical means. We have shown that as result of this delay system output becomes random. Such behavior arises from nonlinearity of the system, and somewhat resembles Ikeda equation dynamics. We have also calculated Poincare section of the system, to further confirm stochastic nature of the system output. Results show that phase trajectories of the system are scattered all over the phase plane, as simulation time increases. Also we have calculated Fourier transform of the output signal. Obtained spectrum also shows system output random nature. Obtained results are important for further development of antiferromagnetic terahertz-frequency spintronic oscillators and their applications as random signal sources. Such high frequency random signal sources can revolutionize cryptography and probabilistic computing.

Keywords: Antiferromagnet, Oscillator, Randomness.

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1. INTRODUCTION

Multilayered magnetic structures are the cornerstones of modern spintronics [1]. Spin Hall and spin-torque nano-oscillators based on different multilayer structures are well known sources of high frequency AC signal [2-7]. Typical configuration for such systems is bilayer (magnetic/heavy metal) nanostructures, fabricated via nanodeposition [4-5]. Heavy metal plays crucial role in such bilayer systems, due to strong spin-orbit coupling essential for device operation, via direct and inverse Spin Hall effect.

However, such systems, utilizing ferromagnets have a principle operation frequency limitation of ~ 50 GHz. This limitation can be lifted when moving to antiferromagnets (AFMs) possessing a very strong internal magnetic field of the exchange origin have characteristic working frequencies of several hundreds of GHz and even several THz [8-11]. AFM materials and AFM Spin Hall oscillators (SHO) open up a possibility of creation of THz frequency DC current controlled nanoscaled devices for modern spintronics applications.

Such AFM systems, however, have been not thoroughly studied at the moment. A lot of features of such devices are yet to be investigated, both theoretically and experimentally. In our previous work we studied mutual and external synchronization of such AFM SHOs [12-14] and stochastic generation regime of such oscillator [15]. Stochastic regime of such system opens up one of the most interesting and promising application for AFM SHO. THz frequency random generator will revolutionize probabilistic computing and cryptography, if implemented. Thus detailed analysis of such regime in AFM SHO is very important task.

In this paper we will numerically investigate the dynamics of AFM SHO taking into account possible delay in the system, due to AFM lattice inertia or introduced artificially by electrical means. Such a delay, despite being picoseconds long can drastically change AFM SHOs dynamics, that we will show in this paper.

2. THEORETICAL MODEL

To describe the magnetic dynamics of AFM oscillator under the action of external signal we can use the following equation derived from the so-called sigma-model [9, 16]:

$$\frac{1}{\omega_{ex}}\ddot{\varphi}+\alpha\dot{\varphi}+\frac{\omega_e}{2}\sin 2\varphi-\tau=0\ , \qquad (1)$$

where φ is the Neel vector angle in an AFM, ω_{ex} is the AFM exchange frequency, α is the Gilbert damping constant, $\omega_e=\gamma H_e$, γ is the modulus of the gyromagnetic ratio, and H_e is the easy plane anisotropy field. We consider a normalized electric current (in angular frequency units), which determines the oscillator behavior as DC component τ. In previous works we have considered also AC component added to the current, to investigate various synchronization regimes [13,14], however in current work we will limit ourselves to only DC component of the current, for simplicity. Without AC current system works as simple generator, when DC current exceeds threshold value $\tau_{th}=\omega_e/2$ [9] Neel vactor of the AFM starts rotating with constant velocity. This rotation by means of inverse Spin Hall effect can be converted back into THz frequency current.

Equation (1) describes dynamic of the Neel vector that rotates in the easy plane of the AFM. This is simplified equation that can be obtained from the full Landau-Lifshitz system of equations for two sublattices magnetization vectors. However, taking into account inertia of AFM system equation (1) can be modified in the following way:

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$$\frac{1}{\omega_{ex}}\ddot{\varphi}(t)+\alpha\dot{\varphi}(t)+\frac{\omega_e}{2}\sin 2\varphi(t-\tilde{t})-\tau=0\,, \qquad (2)$$

where $\tilde{t}$ – is some delay, due to magnetic lattice inertia, that influences the system dynamics. Detailed calculation of this delay values lies beyond the scope of the current work, thus we will use theoretical estimate for this delay to be around tens of picoseconds. Moreover, such delay can be introduced to the system not only in natural but by artificial way, recalling the exact structure of the AFM oscillator [9].

3. RESULTS AND DISCUSSION

For our modeling we will use the following oscillator parameters: $\alpha=0.01$, $H_{ex}=9\cdot10^6\,\text{Oe}$, $H_e=625\,\text{Oe}$, while and AC signal amplitude τ will be varied. Lattice delay will be $\tilde{t}=10$ ps.

First we will consider the case of underexcited AFM oscillator, when AC current amplitude is smaller then threshold [9]: $\tau<\omega_e/2$. In this case there is no oscillations in the system for the equation (1), except some rapid transient process occurring while nonzero initial conditions relax to zero solution: $\varphi=\dot{\varphi}=0$. However, introducing some delay in the system and moving to equation (2) for same underexcited AFM oscillator with nonzero delay we obtain stochastic output signal, as it is shown on Fig.1. As we can see, introducing even small delay of 10 ps to the system drastically alters the AFM SHO dynamics. Now output signal randomly fluctuates around 0 value. Typical time scales between this random fluctuations is picoseconds, thus we have THz frequency random signal source in this case.

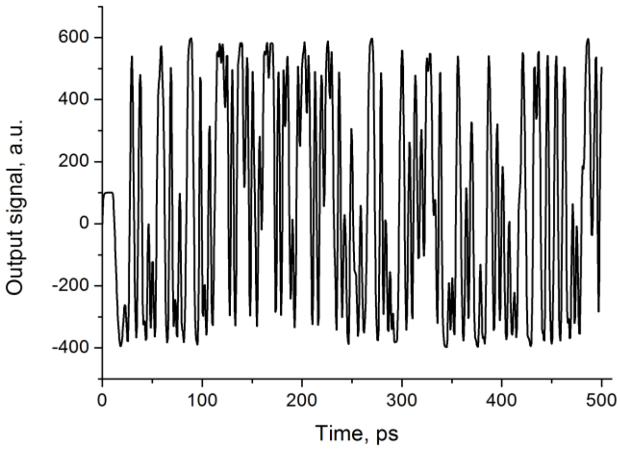

Fig. 1 – Time dependence of the AFM oscillator output signal. DC current $\tau/\omega_e=0.1$, delay $\tilde{t}=10$ ps

Fig. 2 shows output signal time dependence for the same delay, but for excited AFM SHO case, when $\tau>\omega_e/2$, namely $\tau=0.55\omega_e$. Once again we are observing stochastic behavior of the system with random output, however now mean value of the signal is larger then 0, that too be expected for excited AFM SHO. Without delay in this case we will get normal AFM SHO generation regime with generating frequency close to $2\tau/\alpha$ as it was shown before [9, 13].

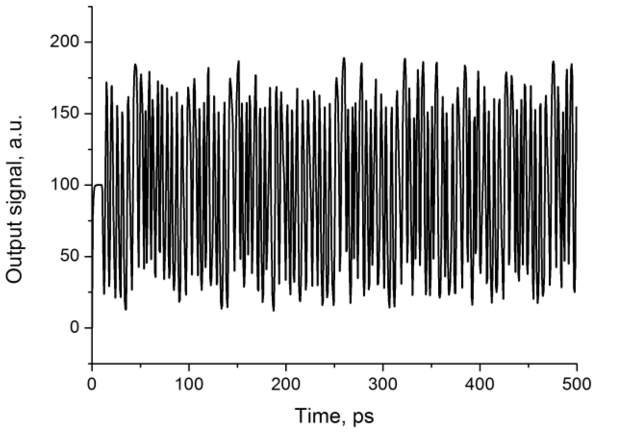

Fig. 2 – Time dependence of the AFM oscillator output signal. DC current $\tau/\omega_e=0.55$, delay $\tilde{t}=10$ ps

It should be noted, that in our previous work [15] we have also investigate stochastic regime of AFM SHO. However in that case, stochastic regime was achieved by applying additional AC current to the system, leading to stochastic behavior for some values of AC current amplitude and frequency. In the case of delayed equation (2) such signal is not needed. On the other hand controlling external AC signal parameters

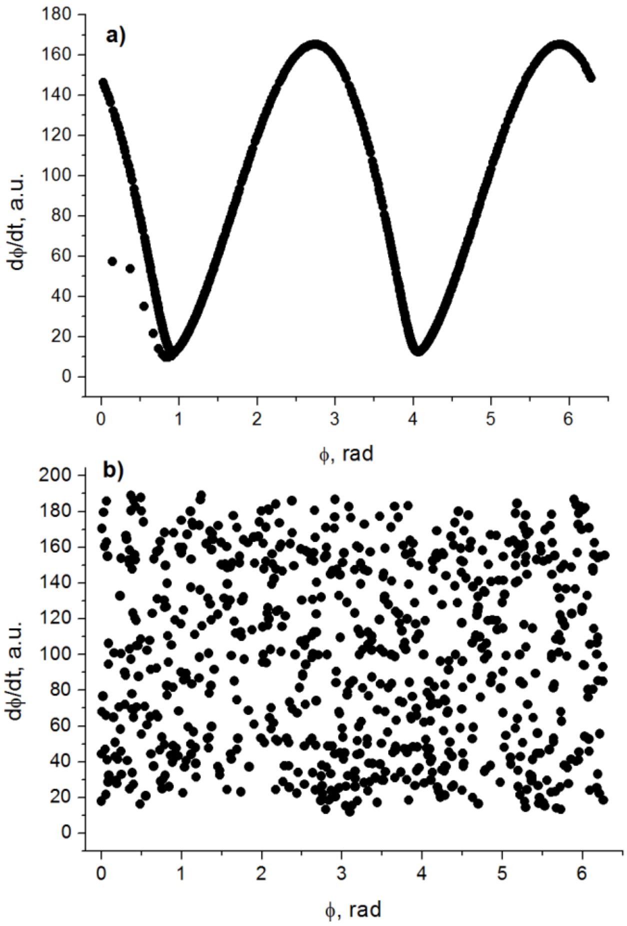

Fig. 3 – Poincare section of AFM SHO without delay a) and with $\tilde{t}=10$ ps delay b). DC current $\tau/\omega_e=0.55$

To further confirm stochastic nature of the system dynamics we have calculated the Poincare section [17] of the system. This is a well known method of dynamical systems analyses, that allows to visually investigate how phase trajectories of the system behaves in time To do that, we have stored values of the system phase coordinates $(\varphi, \dot{\varphi})$ during the evaluation for discrete values of time, proportional to generation frequency $\omega_{gen} = 2\tau / \alpha$. In other words we have stored system states with ω_{gen} period. Such approach is similar to analyses of so-called Duffing equation [17].

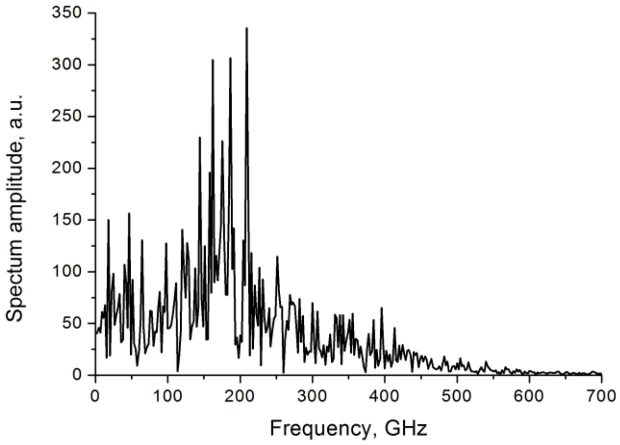

Fig. 4 – Fourier spectrum of the AFM SHO signal output. DC current $\tau / \omega_e = 0.55$, delay $\tilde{t} = 10$ ps

Results of Poincare section caclulation are shown on Fig. 3. for no delay and 10ps delay cases. As we can see, comparing to no delay case, Poincare section of the system for delayed equation is much more complex and indicates random nature of the system dynamics. For no delay case deterministic nature of the system dynamics manifests in limited number of points and as time goes new phase trajectories perfectly match previous ones, overlapping them. Thus we see some determined curve on Fig. 3 (a). Some outlier points correspond to initial states of system dynamics, when generation regime is only established. In contrast on Fig. 3 (b) there is no established phase trajectory of the system, thus Poincare map in this case consists of number of points, not resembling any structure. Moreover, the larger simulation time we will choose, more and more points there will be on the map. Given infinite time, entire $(\varphi, \dot{\varphi})$ plane will be covered with points. This indicates random nature of the system.

Finally, Fig. 4 shows Fourier spectrum of the AFM SHO output from Fig. 2. Again we can see complicated spectrum of the system, indicating noise-like output of the AFM SHO when delay introduced. There are some prominent frequency peaks in the spectrum, however overall system dynamics is not periodic.

All this analyses clearly indicates that introduced delay in equation (2) drastically alters dynamics of AFM SHO. Output of the system becomes clearly random, however exact investigation of this output features and noise statistics lies beyond the scope of current work. It should be also noted, that delayed equations are well known for it's complicated dynamics and possibility of stochastic solutions [18]. Thus introduction of the delay in equation (2) is one of the ways to transform AFM SHO into THz frequency random generator.

4. CONCLUSIONS

In this work we have investigated delayed AFM SHO and has shown that such a system can be considered as THz frequency random signal source. Mentioned delay in the system can be introduced both as natural effect, due to AFM lattice inertia, and artificial effect, as delay line attached to the system. As a result of delay introduction to the system AFM SHO output becomes random, consisting of picoseconds period random spikes with varying amplitude. Poincare section and Fourier spectrum of the system both confirm stochastic nature of the output signal. Obtained results are important for THz spintronics and probabilistic computing utilizing novel magnetic systems.

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Антиферомагнітний спін-Холл осцилятор з затримкою як джерело випадкового ТГц сигналу

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Чисельними методами досліджено антиферомагнітний спіновий осцилятор Холла із запізненням під дією постійного струму. Затримку осцилятора можна пояснити внутрішньою інерцією антиферомагнітної решітки або ввести штучно електричними засобами. Ми показали, що в результаті цієї затримки вихідний сигнал системи стає випадковим. Така поведінка є результатом нелінійності системи та дещо нагадує динаміку рівняння Ікеди. Ми також обрахували перервз Пуанкаре системи, щоб додатково підтвердити стохастичний характер динаміки системи. Результати показують, що фазові траєкторії системи розбігаються по всій фазовій площині зі збільшенням часу моделювання. Також нами було розраховано Фур'є спектр вихідного сигналу. Отриманий спектр також демонструє випадкову природу вихідного сигналу системи. Отримані результати важливі для подальшого розвитку антиферомагнітних спінтронних генераторів терагерцової частоти та їх застосування як джерел випадкових сигналів. Такі високочастотні джерела випадкового сигналу можуть революціонізувати криптографію та ймовірнісні обчислення.

Ключові слова: Антиферомагнетик, Осцилятор, Випадковість.