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Circuit Level Model of Phase-Locked Spin Torque Oscillators

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1. Introduction

Spin Torque Oscillator (STO) is a new device which has great potential as a microwave source in various wireless devices. STOs have many advantages in the aspects of integration, tuning range and energy efficiency. However, practical use of STOs is being limited by small output power and wide linewidth. Various researches to overcome these limitations are in progress in two directions. One is to use Magnetic Tunnel Junction (MTJ) devices which have large resistance. The other approach is to exploit mutual phase-clocking of STOs to increase the output power. In this paper, we propose a circuit-level model of two coupled STOs which can replicate phase-locking behavior of two STO devices under proper operating conditions. Our model was verified by comparing simulation results through Hspice simulation with measurement data.

2. Interaction Model of Two STOs

Phase-Locking of Two STOs

When an external RF source is applied to an auto-oscillator and the frequency of the external signal and generation frequency of auto-oscillator are close enough, the generation frequency of the oscillator follows the frequency of the external signal. The auto-oscillator eventually generates output signal that has the same frequency with the external signal. If two oscillators are connected electrically, output of one oscillator plays a role as an external coupling signal to the other oscillator and vice versa. Consequently, under specific conditions, two oscillators operate like a single oscillator having the same generation frequency and phase.

This mutual phase-locking has been also observed in STOs. In a double-point-nano-contact structure, synchronization is arisen through two important physical mechanisms. The one is interaction through the common magneto-dipolar field generated by the precession of magnetization, and the other is interaction through the propagating spin waves which are generated at each contact and propagate towards the other contact [1]. If the strength of coupling which is induced by these two mechanisms is sufficiently large, output signals at two contacts are phase -locked.

Analytic Model of Two STOs to interact

An analytic model of single STO has been proposed by the authors for circuit level simulation [2]. Our previous model accurately replicates three characteristics of single STO which are generation frequency, linewidth, and mean power, when there is no coupling between STOs. Based on our previous work, we propose a new analytic model of STOs which can replicate phase-locking behavior due to interactions between two STOs.

In connected STOs with nano-contact sturucture, interaction exists between two STOs. So generation frequency of the one contact ω_g is represented as the sum of free-running generation frequency $\omega_{g(single)}$ without coupling and a term representing interaction as is shown in equation (1)[1].

$$\omega_{g,1} = \omega_{g,1(single)} + \alpha * \tilde{\Omega}_{1,2} \sin(\tilde{\varphi}_2 - \tilde{\varphi}_1 + \tilde{\beta}_{1,2}) \quad (1.a)$$
$$\omega_{g,2} = \omega_{g,2(single)} + \alpha * \tilde{\Omega}_{2,1} \sin(\tilde{\varphi}_1 - \tilde{\varphi}_2 + \tilde{\beta}_{2,1}) \quad (1.b)$$

Here, the interaction term is composed of coupling frequency $\tilde{\Omega}$ and coupling phase $\tilde{\beta}$. In our model, magneto-dipolar coupling is ignored because effect of spin waves is much more dominant than magneto-dipolar coupling [1],[3]. A fitting parameter, α, is introduced in our model to reduce slight difference between the original equation and measurement data.

Now, if each generation frequency is close enough, i.e., the frequency difference between two STOs is smaller than phase-locking bandwidth, two STOs are phase-locked and so they have exactly same frequency ω_{locked} as is shown in equation (2).

$$\omega_{locked} = \bar{\omega} - \sqrt{\Delta^2 - \delta^2} \tan(\beta - \arctan\nu) \quad (2)$$
$$\text{where } \bar{\omega} = \frac{\omega_{g,1} + \omega_{g,2}}{2}$$

In the phase-locking region, average output power becomes twice of sum of each STO's output power, and also, generation linewidth is reduced by 10~30% [4].

Modeling in Verilog-A

The behavior of two STOs interacting each other is modeled in Verilog-A which is a hardware-description language for mixed-mode circuit design. At first, three characteristics of each STO is described based on our previous model [2]. Then, locking condition is examined to determine phase-locking. Also, random frequency fluctuation is added to generation frequency to model linewidth. Finally, the sinusoidal output is generated as a voltage signal to satisfy three characteristics. Outline of our model is shown in Table 1.

3. Circuit-Level Simulation

In order to verify our model, a current mirror circuit connected with our interaction model of two STOs is simulated using Hspice (Fig.1). We observed the output voltage by changing dc bias current into two STOs with fixed external magnetic field.

Fig. 2 shows the simulation results compared with measurement data. The external magnetic field is fixed at 8.52kOe while dc bias current increases from 30mA to 55mA. Each generation frequency shows blue shift and becomes closer with each other. At about 47mA, two frequencies are combined into single frequency and that means two STOs are perfectly phase-locked. Our simulation results show good agreement with experimental data [4].

Fig.3(a) and Fig.3(b) shows frequency spectrum when dc current is 38mA and 53mA, respectively. Two different peaks are observed clearly before locking, whereas large single peak is dominant when phase-locked. Inset of Fig.3.b is output signal in time domain and it shows stable oscillation.

Fig. 4 shows simulation results of how frequency, power, and linewidth of two connected STOs change with respect to dc current. Two STO are synchronized at dc current = 54mA. In phase-locking regime, output power increase about twice of sum of each power, and linewidth decrease significantly. Our simulation results show good agreement with measurement data [5] in overall shape, even though results of mean power and linewidth are slightly different from experiment at some points.

4. Conclusions

In this paper, physics-based circuit level model of two connected STO is proposed. Especially, interaction between two STOs due to spin wave mechanism has been included in our model such that phase-locking of STOs can be accurately represented. Our model has been verified though Hspice simulation on a current mirror circuit connected with our interaction model of two STOs. Simulation results show good agreement with experimental data.

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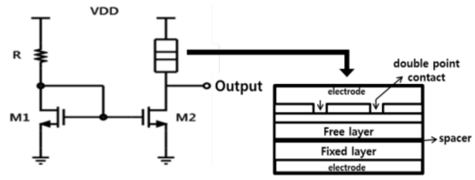

Fig.1. Current-Mirror Circuit with Interaction Model of Two STOs

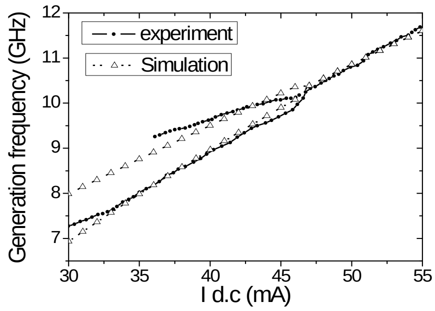

Fig.2. Generation Frequency vs. DC Bias Current

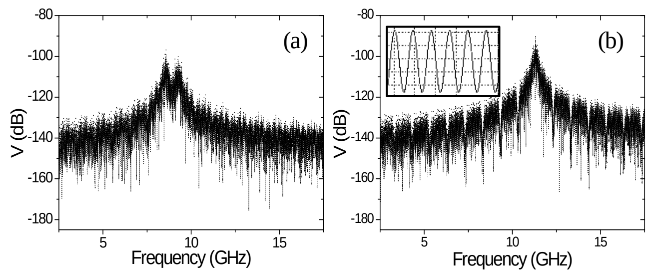

Fig.3. Output spectrum in Frequency Domain
(a) DC current = 38mA and (b) DC current = 53mA

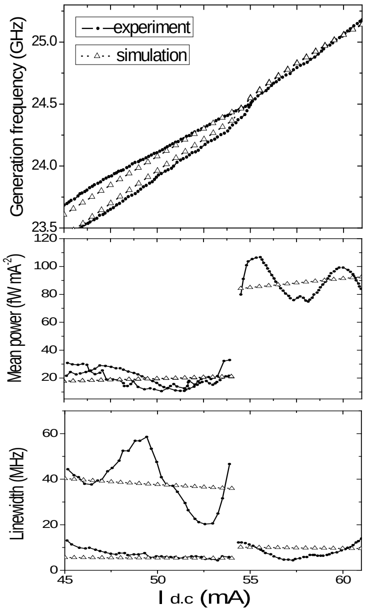

Fig.4. Comparison of Simulation with Experiment as a Function of DC Current (a) Frequency (b) Mean Power and (c) Linewidth, with Fixed External Magnetic Field (10kOe, 66deg.)

```
Module PHASE_LOCKING_STO (top, bottom);
    // definition of device parameter & variable
    // definition of functions (frequency, linewdith, power of single STO)
        analog begin
        // calculation of internal parameter
        // calculation of three characteristics considered interaction
        if (frequency_d > bandwidth) begin    //before phase-locked
            f1 = w_g1_coupling;
            ......
            time_signal1 = ......
            time_signal2 = ......
            V(top,bottom) <+ (dc_resistance*(Itb1+Itb2))+time_signal1+time_signal2;
            end
        else  begin                             //after phase-locked
            f1 = w_g_locked;
            f2 = w_g_locked;
            ......
            time_signal = sqrt(abs(power1))*cos(2*`pi*(f1+fluctuation)*$abstime);
            V(top,bottom) <+ dc_resistance*(Itb1+Itb2) + time_signal;
            end
endmodule
```

Table1. Verilog-A Model