# Frequency control of spin torque oscillation in magnetic metamaterials for microwave generator

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**Abstract**

The combination of magnetic metamaterials and spintronics devices has been theoretically investigated. The magnetic metamaterials consisting of magnetic nano-dots realize a microwave generator, in which the oscillation frequency can be controlled by an external applied field and the magnetic interaction among dots, using spin torque oscillation (STO). The oscillation frequency is calculated by an analytic equation of a forced oscillation, that is transformed from the Landau-Lifshitz-Gilbert (LLG) equation. As a result, it is shown that the reduction of the effective Gilbert damping and the increase of oscillation frequency can be achieved independently in the microwave generator with STO.

## 1. Introduction

A great achievement of metamaterials has been a control of the permeability and permittivity for electromagnetic waves [1]. Now the concept of the metamaterials interacts with another research field, for example, spintronics. One of such interactions results in the magnetic metamaterials, which enable us to control the Gilbert damping in the magnetic resonance state [2, 4, 3]. The magnetic metamaterials are expected to bring about novel spintronics devices.

Recently, the spin torque oscillation (STO) [5] in spintronics devices is of great interest in terms of an on-chip microwave generator for microwave assisted magnetic recording [6]. For the microwave generator using the STO, there are two important criteria. The first one is the operation frequency; a high frequency is preferred for high-speed writing. Second, a smaller effective Gilbert damping is indispensable for a high output power and for a energy saving.

Previously, we investigated the analytic solution of the Landau-Lifshitz-Gilbert (LLG) equation in magnetic metamaterials consisting of magnetic nano-dots [2]. The LLG equation was transformed into a forced oscillation equation in ferromagnetic resonance (FMR). The solution indicated a way of controlling the effective Gilbert damping using magnetic dipole fields among nano-dots in magnetic metamaterials. Under the STO, the effective Gilbert damping is known to be a linear function of the injected spin current [7]. We derived also this relation from the transformed oscillation equation of the LLG equation [4]. In this contribution, we discuss the STO frequency and the effective Gilbert damping in a magnetic metamaterial having a magnetic nano-dots array.

## 2. Oscillation equation

We suppose that a magnetic metamaterial for microwave generators is composed of the array of magnetic nano-dots as illustrated in Fig. 1(a). Each nano-dot consists of the magnetic tunnel junction (MTJ) or the

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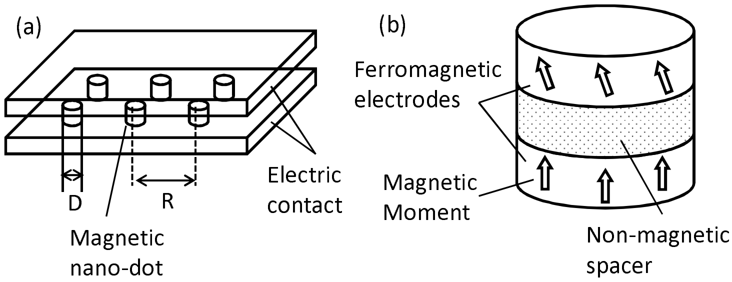


Fig. 1: The schematic drawing of (a) a microwave generator composed of the array of magnetic nano-dots, and (b) the layered structure of a single dot.

current perpendicular to plane giant magneto-resistive (CPP-GMR) element. A single nano-dot includes two ferromagnetic electrodes, which are separated by a non-magnetic spacer either in MTJ or CPP-GMR as shown in Fig. 1(b). In the MTJ, the spacer is an insulator. In the CPP-GMR, a spacer is a conductor. Arrows represent the direction of spins; spins in each electrode are influenced by the perpendicular magnetic anisotropy. The electric resistance of each dot depends on the angle between spins in the upper and lower electrodes. In a state of microwave oscillation, the spin in upper electrode shows the gyro magnetic precession. All dots having the diameter $D$ and the spacing $R$ are adjacent to the electric contact film. $D$ and $R$ should be limited in the several tens of nanometer.

Based on the model described in Fig. 1, the magnetic state in the microwave generator is discussed in an analytic formula. The magnetic precession is described using the LLG equation. The transformed oscillation equation from the LLG equation is expressed as

$$A\frac{d^2m}{dt^2} + B\frac{dm}{dt} + Cm = f\cos\omega t, \tag{1}$$

$$A = 1 + \alpha^2, \tag{2}$$

$$B = 2\alpha\gamma\left(H + C_{zz}\mu_s\right)\mu_s S - \beta(\theta)\tilde{I}_s\left(2-\alpha^2\right)Ss$$
$$-\gamma\mu_s\left[C_{xy} + \alpha C_{xx} - \frac{(H+\mu_s C_{zz})\mu_s C_{xy}}{\gamma H}\right], \tag{3}$$

$$C = \gamma^2\left(H + C_{zz}\mu_s\right)^2 + \alpha\gamma H\beta(\theta)\tilde{I}_s S^2 s - \gamma^2\mu_s\left[HC_{yy} + \alpha HC_{xy} + (H + C_{zz}\mu_s)C_{xx}\right], \tag{4}$$

where $S$ and $s$ respectively stand for the spin element in the ferromagnetic electrode and injected spin element. Both $S$ and $s$ are regarded as the Heisenberg spin and are projection in the perpendicular direction in Fig. 1. A variable $m$ represents the amplitude of the magnetic precession for the spin $S$. $\omega$ is an angular velocity. $\mu_s$ is a magnetic moment of the spin. The $H$, $\gamma$, and $\alpha$ stand for the applied magnetic field, the gyro magnetic ratio, and the intrinsic Gilbert damping factor, respectively. $\tilde{I}_s$ represents the injected spin current into the ferromagnetic electrode, and $\beta(\theta)$ shows the angle dependent efficiency of the spin transfer torque between $S$ and $s$. The coefficients $C_{\lambda\nu}(\lambda,\nu = x,y,z)$ are the structure parameters to define the magnetic dipole field expressed in Ref. [2].

## 3. Results and discussion

The effective Gilbert damping and the oscillation frequency are respectively given by $B/2\sqrt{C}$ and $\sqrt{C}$ in Eq.(1), when $\alpha \ll 1$. In the case of a harmonic oscillation for the isolated dots, a frequency is simply given by $\gamma H$. Namely, $C/\gamma^2H^2$ corresponds to the change in a frequency. If $\alpha \ll \gamma H$, the shift of the frequency due to the second term in the right hand side of Eq.(4) approximately becomes zero. Therefore, the frequency of a microwave generator is only dependent on the magnetic dipole interaction. In other words, the arbitrary spin current can be injected without a change in the oscillation frequency.

A simple expression by Kittel defines the natural frequency as $\omega = \gamma(H - 4\pi N_d M_s)$, where $M_s$ is a saturation magnetization. In this equation, the term of $4\pi N_d M_s$ denotes the demagnetizing field regarding as the magnetic shape anisotropy, that is determined by the magnetic dipole interaction. The effect of the magnetic shape anisotropy appears in $C_{zz}\mu_s$.

The additional factors $C_{xx}$, $C_{yy}$ and $C_{xy}$ are strongly related to the oscillating spins in the magnetic precession. The dynamical motion of the magnetic moments increases the magnetic resonance field through the magnetic dipole interaction in the FMR [3]. These results indicate that the frequency is shifted owing to the dynamical effect of spins in the magnetic resonance of STO.

From Eq.(3), the effective Gilbert damping ($\alpha_{\rm eff} = B/2\sqrt{C}$) is given by the linear function of the spin current $\tilde{I}_s$. The increase of $\tilde{I}_s$ leads to decrease of $\alpha_{\rm eff}$. The continuous oscillation is realized when $\alpha_{\rm eff}$ reaches at zero. In this sense, $\alpha_{\rm eff}$ at $\tilde{I}_s = 0$ is important because a small spin current is required to achieve the energy saving of devices. As shown in Eq.(3), the change of structure parameters of $C_{xx}$, $C_{yy}$ and $C_{xy}$ possibly reduces $\alpha_{\rm eff}$ at $\tilde{I}_s = 0$. The structure parameters can be controlled by the alignment of magnetic dots.

## 4. Conclusion

The combination of the magnetic metamaterial and the spintronics devices enable us to realize a novel microwave generator using the STO. The oscillation frequency is controlled by the alignment of the magnetic nano-dots consisting of MTJ or CPP-GMR because the magnetic dipole interaction among dots changes the ferromagnetic resonance state. On the other hand, the effective Gilbert damping is decreased by the STO. As a result, the reduction of the effective Gilbert damping and the increase of oscillation frequency can be achieved independently in the microwave generator with STO.

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