Synchronization of an array of point contact spin transfer torque driven nano-oscillators

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Using macromagnetic simulation, we present the nonlinear magnetization dynamics of an array of spin transfer torque(STT) driven nano oscillators(STNO). We consider a linear array of magnetically isolated nano contacts connected in parallel to each other and with a common bias current source. We have defined the model and circuit implementation. Further, we have deduced the form of the associated coupling term which arises due to parallel connection by employing an equivalent electrical circuit. By tuning the external bias current we have demonstrated the synchronization dynamics of an array of two parallel STNOs by numerically integrating the underlying Landau-Lifshitz-Gilbert-Slonczewski (LLGS) equation.

Although spin transfer nano-oscillator is a possible nano-device to replace the currently available class of microwave generators which are using LC tanks, the weak output power (typically below 1 nW) issue needs to be solved to achieve compatibility with the existing communication devices. To enhance the output power, the most investigated route is to synchronize/phase-lock an array of STNOs[4]. Various ways of achieving synchronization among STNOs have been reported[2]. These include synchronization due to a common microwave current, due to a common microwave field[7] and in an array of serially coupled STNOs[6, 3].

In this paper, we have investigated the other possible electrical connections among the STNOs. Apart from serial connection as pointed out in ref.[3], STNOs can be coupled through a parallel electrical connection. In order to study the magnetization dynamics of the STNOs connected in parallel, we have designed a schematic structure of arrangement for the STNOs in a typical trilayer nano film system. We have deduced the coupling term which arises due to parallel connection using an equivalent electrical circuit. By tuning the common external bias current source we have shown the possibility of synchronization dynamics in an array of two parallel STNOs.

Next, we consider a GMR trilayer structure which consists of a common ferromagnetic fixed layer, non-ferromagnetic conducting spacer and three free layers forming an array of three parallel STNOs. A schematic representation of the device considered is shown in Fig.1. The macrospin magnetization dynamics of the i^{th} free layer is described by the LLGS equation[1, 2] for the normalized

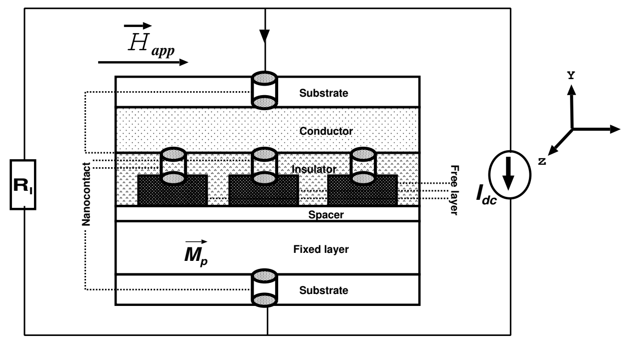

Figure 1: Schematic representation of an array of three STNOs connected in parallel to each other.

unit magnetization vector $\vec{m}_i = m_i^x\hat{i}+m_i^y\hat{j}+m_i^z\hat{k}$, $|\vec{m}_i|^2 = 1$. It reads

$$\frac{d\vec{m}_i}{dt} = -\gamma\vec{m}_i \times \vec{H}_i^{eff} + \alpha\vec{m}_i \times \frac{d\vec{m}_i}{dt} - \gamma\beta_i(t)\vec{m}_i \times (\vec{m}_i \times \hat{M}_p), i = 1, 2, ...N. \quad (1)$$

The free layer is a permalloy thin film of dimension $100\ nm \times 200\ nm \times 5\ nm$ extended along the $x - y$ plane. $\hat{m}_p$ is the normalized magnetization of the fixed layer pinned along the x-axis. The effective field for the i^{th} STNO is given by

$$\vec{H}_i^{eff} = \vec{H}_{app} + \kappa_i m_i^x\hat{i} - 4\pi m_0 m_i^z\hat{k}, \quad (2)$$

which comprises of a common applied external magnetic field

$$\vec{H}_{app} = (h_{dc} + h_{ac}\cos\omega t)(\sin\vartheta\cos\varphi, \sin\vartheta\sin\varphi, \cos\vartheta), \quad (3)$$

a uniaxial anisotropy of strength κ_i along the easy axis (x-axis) and the demagnetization field due to the shape of the free layer which is assumed to be a thin film along the easy plane. We choose all the parameters involved in Eq. (1) as $\alpha = 0.01$ and the gyromagnetic ratio as $\gamma = 0.01767$ Oe^{-1} ns^{-1}. The difference arises in the density of the spin current($\beta_i(t)$) which is given by

$$\beta_i(t) = \hbar\eta J_i(t)/2m_0Ve, \quad (4)$$

where $\eta = 0.35$ is the spin polarization ratio, $J_i(t)$ is the current flowing through i^{th} STNO defined below in Eq. (6), m_0 is the saturation magnetization taken as $4\pi m_0 = 8.4$

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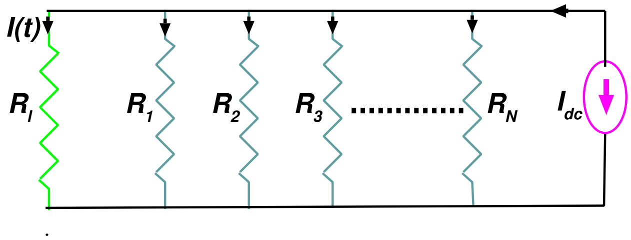

Figure 2: Equivalent electrical circuit for a parallel array of N STNOs biased by a dc source I_{dc} and $I(t)$ is the output current flowing across the load resistance R_l.

kOe for a typical bulk permalloy thin film and V is the volume of the free layer.

The equivalent electrical circuit of Fig.1 is given in Fig. 2. Note here that each STNO is denoted as a time dependent resistor($R_i(t)$) whose resistance can vary between anti-parallel magneto-resistance (R^{ap}) and parallel magneto-resistance (R^p) and it depends on the angle between the magnetization of fixed and free layers($\theta(t)$). In this manner, the relative direction of magnetization changes between that of the two magnetic layers and hence the magneto-resistance value of STNO varies around a dc value, which can be denoted as R_i^0 . The time-variant part of the resistance value of the i^{th} STNO, which is caused by the relative orientation of magnetization changes, is represented as $\Delta R_i \cos[\theta_i(t)]$. Hence the electrical resistance of the i^{th} STNO can be written as

$$R_i(t) = R_i^0 + \Delta R_i \cos[\theta_i(t)], \tag{5}$$

where $R_i^0 = (R_i^p + R_i^{ap})/2$, $\Delta R_i = (R_i^{ap} - R_i^p)/2$. The microwave current($J_i(t)$) flowing through each of the coupled STNOs connected in parallel is given by

$$J_i(t) = \frac{I_{dc} R_l}{(\sum_i R_i^0 + \Delta R_i \cos[\theta_i(t)])(1 + R_l \mathcal{R})}, \tag{6}$$

where $R_i^p, R_i^{ap}, \theta_i(t)$ are the resistance, magnetoresistance and the instantaneous angle between free and fixed layers of the i^{th} STNO, respectively and $\mathcal{R} == \sum_i \frac{1}{R_i}$.

To begin with, we consider the typical nonlinear behaviour of a single decoupled STNO in the absence of any external microwave source. Further, in the absence of external microwave field $h_{ac} = 0$, we choose (ϑ,φ)=($\pi/2$,0) so that a static field of strength h_{dc} is applied along the x-direction. The inevitable errors in nanolithography process leads to the difference in the shape of the STNOs from sample to sample, which is taken into account by considering the device variability [6]. The device variability among the STNOs is considered in terms of uniaxial anisotropy ($\vec{H}_k = \kappa_i m_i^x \hat{i}$) by choosing the values of κ_i as 45 and 46 Oe for the case of two STNOs. We also assume the resistance(R_i^p) and the magnetoresistance(R_i^{ap}) of all the oscillators to be 10Ω and 11Ω, respectively, see Eq. (5). For the above choice of parameters, a single uncoupled STNO exhibits limit cycle oscillations in the microwave range. The corresponding

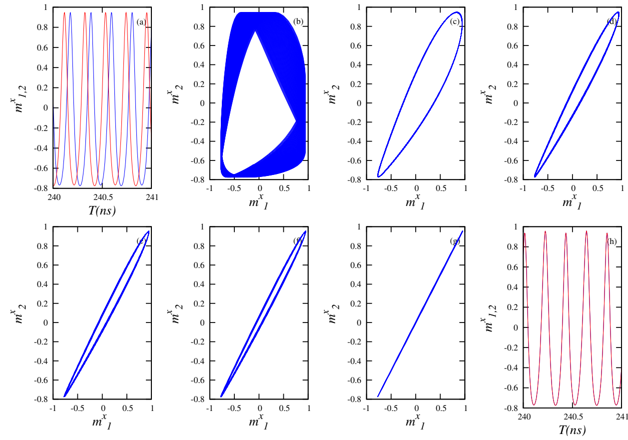

Figure 3: Magnetization dynamics of two STNOs connected in parallel with each other. (a)Time series plot of m_1^x and m_2^x in the absence of external microwave magnetic field($h_{ac} = 0$) and (b) their corresponding phase portrait. With the application of microwave magnetic field the magnetization dynamics is illustrated as phase portraits in (c),(d),(e) and (f) for increasing values of $h_{ac} = 10, 20, 30, 40$ and 50 Oe, repectively. (g) Time series plot of m_1^x and m_2^x in the presence of external microwave magnetic field($h_{ac} = 50$ Oe). (h) Further confirmation of complete synchronization.

frequency of the single STNO can be tuned by varying the input direct current(I_{dc}) and/or the static magnetic field strength(h_{dc}). The macromagnetic simulation of the considered device consisting of $N = 2$ STNOs connected in parallel has been carried out by directly integrating Eq. (1) using the variable step-size Runge-Kutta method. We have carried out the simulation with accuracy upto six digits in the normalization of the magnetization vector ($|\vec{m}_i|^2 = 1$). Our task is to find the synchronization between two STNOs represented in Eq. (1) by varying the external dc current I_{dc} with the application of an external ac magnetic field. The microwave magnetic field with frequency $\omega = 15$ GHz (which is chosen as almost twice the free-running frequency of the single STNO such that it will not affect the measurement of output signal[7]) is applied along the x-direction. For increasing values of the strength of the ac magnetic field h_{ac}, the desynchronization(Fig.3(a) and (b)) and synchronization dynamics of two parallelly connected STNOs are presented in Fig.3. It is interesting to note that with the application of microwave magnetic field of sufficient strength(say 10 Oe), see Fig.3(c), the two STNOs tend to synchronize. On increasing the strength of the magnetic field the onset of synchronization gets stronger which is evident in Figs.3(d),(e) and (f). On further increasing h_{ac} the system reaches the complete synchronization state for the value of $h_{ac} = 50$ Oe which is clearly elucidated by a diagonal line in the phase portrait, Figs.3(g). This is further confirmed in Fig.3(h) showing complete synchronization. The output microwave current($I(t)$) measure across the

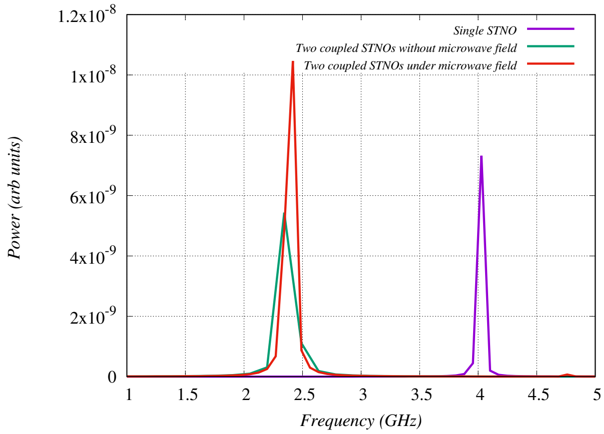

Figure 4: Microwave power outputs measured across the active load resistor (R_l) are plotted for single STNO with $\kappa = 45$ Oe and for two parallel coupled STNOs of anisotropy $\kappa = 45, 46$ Oe with and without external microwave magnetic field.

load resistor (R_l) is calculated using $I(t) = \frac{I_{dc}}{1+R_l\mathcal{R}}$. The power output has been calculated by taking a Fourier power transformation of the output current. For comparison, we have plotted the power output for a single STNO (where $\mathcal{R} = \frac{1}{R(t)}$) and that for the case of two parallel coupled STNOs without/with external microwave field. Under the action of the external microwave field the parallel connected STNOs get synchronized and hence the power has been increased 1.4 times that of the single oscillator. One can also observe that the power of the two coupled STNOs increased two fold under the action of external alternating magnetic field. Extending the above analysis to more number of oscillators with randomly distributed anisotropy parameter is currently under study.

To conclude, we have studied the synchronization dynamics of STNOs connected in parallel array for the parameters of a typical nano-contact. Using the current divider relation, the microwave current through each STNO and also the output microwave current measure across the active load resistor have been derived. By employing a macrospin simulation of the LLGS equation, we have obtained the synchronization of the two coupled STNOs by applying an external microwave magnetic field. We have also carried out a similar study on more number of oscillators exhibiting synchronization dynamics at various strengths of external current and field. The full details will be reported elsewhere.

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