Comprehensive and Macrospin-Based Magnetic Tunnel Junction Spin Torque Oscillator Model – Part II: Verilog-A Model Implementation

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Abstract—The rapid development of the magnetic tunnel junction (MTJ) spin torque oscillator (STO) technology demands an analytical model to enable building MTJ STO-based circuits and systems so as to evaluate and utilize MTJ STOs in various applications. In Part I of this paper, an analytical model based on the macrospin approximation, has been introduced and verified by comparing it with the measurements of three different MTJ STOs. In Part II, the full Verilog-A implementation of the proposed model is presented. To achieve a reliable model, an approach to reproduce the phase noise generated by the MTJ STO has been proposed and successfully employed. The implemented model yields a time domain signal, which retains the characteristics of operating frequency, linewidth, oscillation amplitude and DC operating point, with respect to the magnetic field and applied DC current. The Verilog-A implementation is verified against the analytical model, providing equivalent device characteristics for the full range of biasing conditions. Furthermore, a system that includes an MTJ STO and CMOS RF circuits is simulated to validate the proposed model for system- and circuit-level designs. The simulation results demonstrate that the proposed model opens the possibility to explore STO technology in a wide range of applications.

Index Terms—spin torque oscillator, magnetic tunnel junction, macrospin, analytical model.

I. INTRODUCTION

S PINTRONICS is an emerging technology, utilizing both fundamental electronic charge and spin [1]. Spin is the intrinsic angular momentum of the electron. The spin-transfer-torque magnetoresistive random access memory (STT-MRAM), which is based on spintronic effects, has revolutionized the magnetic storage industry [2]–[4].

In the past few years, extensive research on modeling this device has been carried out [5]–[7]. The developed models of STT-MRAM enable estimation of the performance of STT-MRAMs together with its CMOS circuits, further accelerating the development of STT-MRAM technology.

Meanwhile, the spin torque oscillator (STO) [8], which is another interesting spintronics-based device, has recently received a rapidly increased attention. The STO provides a widely tunable voltage oscillation at microwave frequencies, greatly extending the possible application range of spintronics. Possible applications of STOs include frequency detection [9], [10], magnetic field sensing [9], [11], microwave sources [9], [12], [13] and microwave communications [14], [15]. Particularly, the magnetic tunnel junction (MTJ) STO, which provides comparatively large output power, show great potential to be used in different applications. This motivates the focus of this work on the MTJ STO. However, unlike for the case of STT-MRAM, very little progress has been achieved in modeling the STOs for circuit- and system-level design, impeding the development of STO-based applications. The only existing MTJ STO models [16], [17] are limited by several factors. For instance, they offer a limited applicable range, inaccurate DC operating point, and utilize expressions that are not fully validated by experiments or theory. A new analytical MTJ STO model, which can overcome these issues, has been proposed in Part I [18]. To further allow being used by a circuit simulator, such as Cadence Spectre-RF, which can analyze the analog and RF performances of STO-based circuits and systems, the analytical MTJ STO model should be implemented in a hardware description language. Verilog-A is a hardware description language, which uses mathematical expressions to model the behaviors of arbitrary types of devices and components, while allowing device-, circuit- and system-level design and analyses. Therefore, Verilog-A is suitable and will be used for modeling MTJ STOs. In the existing MTJ STO models [16], [17], however, the information of full Verilog-A implementation is absent. In the STO Verilog-A model [19], which has been proposed by the same research group as [10], [17] and has not been validated by MTJ STOs, it is not possible to change the bias magnetic field in the Verilog-A model since the calculation of the effective magnetic field is not included. Instead, the
An accurate Verilog-A model of oscillators should memorize its phase along the simulation time. However, a solution to keep the phase information between adjacent simulation time steps has not been found. In one common Verilog-A phase noise generation method \[\text{[22]},\] the step-specific perturbed frequency \[f_{\text{VCO}} + \Delta f_{\text{VCO}}\] is integrated all the way from \(t = 0\) up to \(t\), resulting in a discontinuous phase jump whenever \(\Delta f_{\text{VCO}}\) is updated. The method used in the existing Verilog-A STO model \[\text{[19]}\] instead implements a phase noise \(\varphi_{\text{STO}}(t)\) that is discontinuously updated every couple of nanoseconds. In both methods, the comparatively large and discontinuous phase changes result in significant signal discontinuities for sinusoidal signals. This type of discontinuity is not a characteristic of MTJ STOs and, moreover, may cause convergence issues during simulations.

The solution for achieving an accurate and reliable MTJ STO model is to instead implement a \(\varphi(t)\), which bears a continuous, linear phase change in between the fixed points of randomized phase fluctuation. The flow chart of the divergence-free implementation of \(\varphi(t)\) is illustrated in Fig. 1. The first step is to create a vector \(\Delta f[^\prime]\), which gives the random frequency fluctuation as a function of the linewidth (assumed that the frequency noise is white, i.e. \(\text{white frequency noise}\).
that the linewidth has a Lorentzian lineshape), changing every $\Delta t$. $\Delta t$ is the virtual time step, which reflects how often the frequency fluctuation happens and can be defined by the user. Moreover, the user-set $\Delta t$ is necessary in order to implement the Verilog-A model, because the circuit simulator provides an adaptive time step determined by the local truncation error (LTE) \cite{23} so that the real simulation time step cannot be fully controlled by the user nor the programmer. Hence, the real simulation time step cannot be used to update the frequency fluctuations. To obtain the correct linewidth, the dataset of $\Delta f[\cdot]$ follows a normal distribution with a mean of 0 and a standard deviation of $\sqrt{\frac{\Delta \omega}{\Delta t}}$, resulting in a phase variance that is growing linearly with time in a rate consistent with the specific level of white frequency noise for the specific linewidth $2\Delta \omega$ \cite{21}. The virtual time step $\Delta t$ is related to the upper cut-off frequency for white noise in the frequency noise spectrum, and should be set to a value smaller than one order of magnitude lower than the inverse cut-off frequency in order to produce white frequency noise all the way up to the cut-off. For cut-off frequencies of 100 MHz or 1 GHz, this means that the virtual time step $\Delta t$ should be set to lower than 1 ns or 100 ps respectively. Failing to set a short enough $\Delta t$ will result in a too narrow white band in the frequency noise spectrum, resulting in a decreased spectral linewidth. In this work, $\Delta t = 100$ ps is employed. The length of $\Delta f[\cdot]$ is the ratio between the simulation time $t_{\text{sim}}$ and the virtual time step $\Delta t$.

The second step in implementing $\varphi(t)$ is to create another vector $\Sigma \Delta \varphi[\cdot]$, which is used to store the phase deviation accumulated from the reference time ($t=0$) to each virtual time step. The relationship between $\Delta f[\cdot]$ and $\Sigma \Delta \varphi[\cdot]$ is illustrated in Fig. 2. In the first period between $t=0$ and the first virtual time step ($t=1$), $\Sigma \Delta \varphi[j] = 0$ is 0. During the period between $t=j$ and $t=j+1$ ($j>0$), the total accumulated phase deviation caused by the frequency fluctuation(s) in the past period(s) (from $\Delta f[0]$ to $\Delta f[j-1]$) is stored in $\Sigma \Delta \varphi[j]$ . A large $\Delta f[j]$ leads to a large phase deviation that will be fully presented at the next time step ($t=j+1$). The first two steps in implementing $\varphi(t)$ are necessarily conducted in the initial step event, so that the two vectors are generated only once during the simulation.

The third step, as shown in Fig. 1, is to generate the required $\varphi(t)$. $\varphi(t)$ at an arbitrary time, can be expressed as the sum of the accumulated phase deviation $\Sigma \Delta \varphi[k]$ up to the last virtual time step, and the phase deviation produced from the last virtual time step to the absolute time. The parameter $k$ is employed to count the past number of virtual time steps, and it is updated every $\Delta t$ by using the timer function in Verilog-A. It should be noted that the initial value of $k$ is set to -1 since the timer function is called at the beginning of each time period. The absolute time is fetched by calling the $\$\text{absftime}$ function. The relationship between $\varphi(t)$, $\Delta f[k]$ and $\Sigma \Delta \varphi[k]$ is presented in Fig. 2. Specifically, the slope of $\varphi(t)$ is the instantaneous frequency deviation $\Delta f[k]$, so that the phase deviation generated from the last virtual time step to the absolute time is $((\$\text{absftime} - k \cdot \Delta t) \cdot \Delta f[k])$. By summing $\Sigma \Delta \varphi[k]$ and $((\$\text{absftime} - k \cdot \Delta t) \cdot \Delta f[k])$, the required $\varphi(t)$ is realized.

The proposed phase noise generation approach successfully overcomes the phase discontinuity issue identified in the existing Verilog-A models for oscillators \cite{19}, \cite{22}. However, the proposed noise generation approach makes the proposed MTJ STO model less suitable for simulations which involve momentary variations in the operating conditions, such as the modulation of current or field. Nevertheless, at the early stage of evaluating STOs in various applications and designing STO-based building blocks towards applications, these simulations involving momentary variations in the operating conditions are not yet critical.

### III. Simulation Results

Transient simulations of the aforementioned analytical model implemented in Verilog-A, are carried out using the
1.5 mA, while sweeping $\phi$ simulation using the parameters from [25] and are performed. The time domain signals of the transient using the parameters from different MTJ STOs [25]-[27] the frequency fluctuation of the MTJ STO, transient sim-

Martin Center, 1.5 mA is used (I = 1.5 mA) as an example. As it can also be seen in Fig. 3, the phase noise at large in-plane external field angles degrades significantly, which is in accord with the theoretical linewidth in Fig. 4(a) of [18]. In such cases, where the phase noise is considerable, the simulation does not suffer from any signal discontinuity or convergence issues, thanks to the proposed method used to generate the phase noise. Additionally, noticed from Fig. 3, the DC voltage across the MTJ STO increases as a function of $\phi_{\text{ext}}$, which is in agreement with Eq. (5) in [18].

To quantify the characteristics of the MTJ STO Verilog-A model as a function of $\phi_{\text{ext}}$, the time domain signals obtained from the transient simulations ($1 \mu s$) are converted (in Cadence) to the frequency domain using FFT so as to obtain power spectral densities (PSDs) of the signals, which are depicted in Fig. 4(a). To perform the FFT, a Hamming window of the full waveform length 1 $\mu s$ (16384 samples) is employed. This results in a resolution bandwidth of $(1 \mu s)^{-1} = 1$ MHz.

Fig. 4(a) shows the PSDs, which contain the information of the operating frequency and linewidth of the MTJ STO’s signals as a function of $\phi_{\text{ext}}$. As $\phi_{\text{ext}}$ is increased, the operating frequency initially decreases, reaches a minimum

Figure 3: Transient simulation results of the proposed MTJ STO model as a function of $\phi_{\text{ext}}$ (I$_{\text{DC}}$ = 1.5 mA)

Figure 4: PSDs of the time domain signals as a function of (a) $\phi_{\text{ext}}$ (I$_{\text{DC}}$ = 1.5 mA); (b) I$_{\text{DC}}$ ($\phi_{\text{ext}} = 45^\circ$)
and thereafter increases, agreeing with the measured data given in Fig. 2(a) of [18]. For different $\phi_{\text{ext}}$, the operating frequency and linewidth of the proposed MTJ STO model implemented in Verilog-A are in accordance with the one obtained from the theoretical analysis, as given in Fig. 2(a) and Fig. 4(a) of [18]. Particularly, as it can be noticed from Fig. 4(a), the linewidth at $\phi_{\text{ext}} = 55^\circ$, is much narrower than that at $\phi_{\text{ext}} = 40^\circ$, indicating less random frequency fluctuations and confirming the estimation based on Fig. 3. Moreover, as it can be observed from Fig. 4(a), the signal with comparatively large output power can be found between 40$^\circ$ and 55$^\circ$, which is also in agreement with the analytical and measured results in Fig. 3(a) of [18].

The dependence of $I_{\text{DC}}$ on the characteristics of the MTJ STO is also examined by performing transient simulations of the proposed Verilog-A model with different $I_{\text{DC}}$. The PSDs of the transient simulation results as a function of $I_{\text{DC}}$ at $\phi_{\text{ext}} = 45^\circ$ is depicted in Fig. 4(b). The rise in $I_{\text{DC}}$ causes a decline in the operating frequency and an increase in the output power, which matches the theoretical results and experiments.

Effort has been made in this work to achieve the compact MTJ STO model and improve the simulation speed. Therefore, the time required for transient simulations of the proposed model is of interest. To benchmark the simulation speed, a 1 $\mu$s simulation with a maximum time step of 5 ps is performed. By averaging the runtime of 10 simulations containing approximately 470900 transient steps, a simulation takes only 52.6 s. The simulations are performed on a server with 2x AMD Opteron 6172, and occupy one core. Regarding the micromagnetics-based model, which is most efficiently simulated on graphic processing units (GPUs) or supercomputer clusters, the typical runtime is roughly 24 hours for a similar device. Compared with the micromagnetics-based model discussed in Part I [18], the proposed model offers rapid simulations with a similar degree of accuracy.

**B. Hybrid simulation of the MTJ STO model with CMOS circuits**

Hybrid simulation of the MTJ STO model with CMOS circuits is of great importance since it provides validation of the proposed model at system- and circuit-level throughout its range of operation. Furthermore, it can fully cross-verify the model and the designed CMOS circuits. To perform the hybrid simulation, a system including the proposed MTJ STO model as well as CMOS circuits is considered. In this system, the MTJ STO model employs the parameters from [20] since this MTJ STO has a resistance close to 50 $\Omega$, which eases analyses. Firstly, proper biasing circuits for driving the MTJ STO are investigated and analyzed. For instance, the current mirror, which has been employed in [16], [17] to provide the current biasing for the MTJ STO, is simulated with the proposed MTJ STO model and examined. The simulation results, however, suggest that using the current mirror to bias the MTJ STO is not suitable. The reason is that the resistance (biasing voltage) of the MTJ STO changes when $\phi_{\text{ext}}$ is varied, as illustrated in Fig. 3. Therefore, different resistances at different $\phi_{\text{ext}}$ make it impossible for the current mirror to accurately copy the current from a current source to the MTJ STO under all circumstances. Thereafter, a traditional RC bias-T, as shown in Fig. 5, is simulated with the proposed MTJ STO model. According to the simulation results, this RC bias-T can more successfully be utilized by MTJ STOs since the performance of the bias-T is not influenced by the variable resistance (biasing voltage) of MTJ STO. Consequently, the RC bias-T is used in this work to build the system. The selection of the biasing circuits for the MTJ STO demonstrates that the proposed MTJ STO model is very useful for the device and circuit community to identify the suitable circuit topologies and to design dedicated circuits for MTJ STOs, owing to the complete implementation of the proposed model in Verilog-A.

To complete a system, which provides low-noise amplification to MTJ STO signals and can be used in either applications or measurements, a wideband Balun-low noise amplifier (LNA) [22] is employed. An output buffer and an AC coupling capacitor are added to present a system (Fig. 5) that is able to drive 50 $\Omega$ load. The buffered wideband Balun-LNA is fully-ESD protected, and it is implemented in CMOS 65 nm process with a 1.2 V power supply.

Before performing the transient simulation of the system, the unloaded MTJ STO is simulated at $I_{\text{DC}} = 3$ mA and $\phi_{\text{ext}} = 40^\circ$, where a comparatively high voltage generated by the MTJ STO can be obtained. This voltage will be used as the reference voltage to compare with the voltage signals obtained from the MTJ STO together with the Balun-LNA. The transient simulation of the system is then conducted at the same biasing condition. The obtained time domain signals, including the voltage generated by the unloaded MTJ STO, the voltage that can be delivered from the MTJ STO to the Balun-LNA, and the amplified voltage at the differential output of the Balun-LNA, are plotted in Fig. 6. The output signals of the MTJ STO before and after being connected by the Balun-LNA show that the DC voltage is sustained due to employed bias-T, and the DC resistance ($R_{\text{DC}}$) is close to 50 $\Omega$. In addition, approximately 2/3 of the AC
The evaluated hybrid simulation demonstrates that the performance of an MTJ STO-based system can be easily, reliably and accurately predicted by the circuit simulator using the proposed MTJ STO Verilog-A model.

IV. Conclusion
The analytical model of the MTJ STO proposed in Part I of this paper has been fully implemented in Verilog-A, enabling its direct use in STO-based systems. During the implementation, an approach to replicate the phase noise, hence the generated signal of the MTJ STOs, has been developed. This approach makes a reliable MTJ STO model possible, and allows different performance analyses so as to extensively explore possible applications. The simulation results of the stand-alone MTJ STO model and the MTJ STO-based system show that the implemented model gives identical characteristics as those obtained from the proposed analytical model. Additionally, the results demonstrate that the proposed MTJ STO model is useful for estimating as well as improving overall performance of the MTJ STO-based circuits and systems. Consequently, the proposed MTJ STO has the potential to accelerate the development of MTJ STO technology towards its future applications.

References
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