Spin-torque nano-oscillator as a microwave signal source

Oleksandr Prokopenko,[1,*] Elena Bankowski,[2] Thomas Meitzler,[2] Vasil Tiberkevich,[3,†] and Andrei Slavin[3,‡]

[1] *Faculty of Radiophysics, National Taras Shevchenko University of Kyiv, Kyiv 01601 MSP, Ukraine*
[2] *U.S. Army TARDEC, Warren, MI 48397, USA*
[3] *Department of Physics, Oakland University, Rochester, MI 48309, USA*

(Dated: April 18, 2010)

We evaluate a possibility to use spin-torque nano-oscillators (STNOs) and oscillator arrays as new sources of microwave signals for telecommunication devices. The microwave signal generated by STNO can be received as oscillation of the device magnetoresistance (MR) or as direct electromagnetic emission of two effective magnetic dipoles. We calculate the dipolar microwave power emitted by STNO in free space and in several types of transmission lines and resonators. We demonstrate that, although the power of a single STNO received through the MR effect is, typically, larger than the power of direct microwave emission of effective dipoles, the latter mechanism might have an advantage for sufficiently large arrays of coupled STNOs.

PACS numbers: 85.75.-d, 07.57.Hm, 84.40.-x

Spin-transfer-torque effect in magnetic multilayers theoretically predicted in[1,2] and experimentally observed in[3–8] provides a new method of generation of microwave oscillations in nano-magnetic systems and leads to the development of novel active microwave devices – spin-torque nano-oscillators[9] (STNOs) (Fig. 1(a)). In practically all known experimental works involving STNOs[3–8] the generated microwave signal is extracted as a microwave component of the current traversing the device driven by dc bias current $I_{\rm dc}$ formed because the magnetoresistance (MR) of the device is oscillating with microwave frequency due to the fact that the magnetization of the "free" magnetic layer (FL) of STNO is precessing while the magnetization of a "pinned" magnetic layer (PL) is at rest (see Fig. 1(a)). Thus, the total resistance of the device is: $R(t) = R_{\rm dc} + R_{\rm rf}\cos(2\pi f t)$, where f is the frequency of the magnetization precession in the FL. The microwave power generated by a single STNO through the MR mechanism can be evaluated as:

$$P_{\rm MR} \approx \frac{1}{2} I_{\rm dc}^2 R_{\rm dc} \rho_{\rm MR}^2, \quad (1)$$

where $\rho_{\rm MR} = R_{\rm rf}/R_{\rm dc}$ is the magnetoresistance coefficient. In the case of a STNO based on the giant magnetoresistance (GMR)[3,5] effect this power is relatively small (around one nW), while in the case of a STNO based on the tunneling magnetoresistance (TMR)[4,7] effect it can reach 1 μW.

The magnetization precession excited by spin-polarized current in a FL of a STNO can manifest itself not only through the above discussed GMR and TMR effects. The precessing magnetization of the FL creates oscillating dipolar magnetic field that can be registered and channeled, if an appropriate transmission line is coupled to a generating STNO. The problem of the direct dipolar emission of microwave signal generated by STNO in a free space has been recently considered in[12]. It was found in[12] that the microwave signal directly emitted by STNO into a free space is substantially smaller then the signal that could be extracted from STNO through the MR effect. The situation, however, can be different if the emission is taking place in a microwave transmission line or a resonator, or/and if an array of many phase-locked (or synchronized) STNOs[6,8,10] placed in a microwave resonator is used to generate a microwave signal.

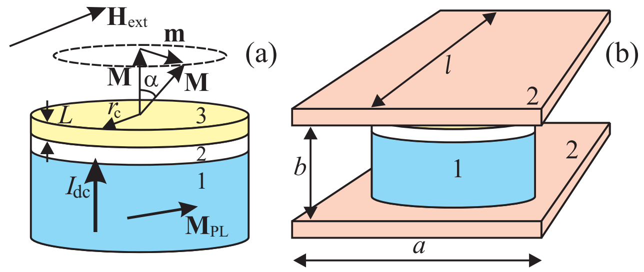

FIG. 1: (a) Model of a spin-torque nano-oscillator (STNO) consisting of three layers of the lateral radius $r_{\rm c}$: a "pinned" magnetic layer (PL) (1), a non-magnetic spacer (2), and a "free" magnetic layer (FL) (3) of the thickness L. Here $\mathbf{M}_{\rm PL}$ is the magnetization vector in the PL (1), the direction of which is defined by the external bias magnetic field $\mathbf{H}_{\rm ext}$ and the structure geometry, $\mathbf{M}$ is the magnetization vector of the FL (3), $\mathbf{m}$ is the variable microwave magnetization excited in the FL by the spin-polarized dc current $I_{\rm dc}$, and α is the angle of magnetization precession in the FL; (b) STNO (1) placed inside a half-wavelength microstrip resonator, where l of resonator length, a is the width of the microstrips (2), and b is the distance between the microstrips.

The goal of our current work was to evaluate the magnitude of the microwave power that can be extracted from an STNO through the oscillating dipolar fields when the STNO is coupled to different microwave systems, and to compare this power with the power that can be extracted through the traditional MR mechanism. Our electrodynamic calculations briefly described below demonstrate that, although for a *single* STNO the MR mechanism is much more efficient than the direct dipolar electromagnetic emission, the latter mechanism can have a significant advantage in the case of a sufficiently large array of

Report Documentation Page

Form Approved
OMB No. 0704-0188

1. REPORT DATE **18 APR 2010**	2. REPORT TYPE **N/A**	3. DATES COVERED **-**

4. TITLE AND SUBTITLE
Spin-torque nano-oscillator as a microwave signal source (PREPRINT)

5a. CONTRACT NUMBER

5b. GRANT NUMBER

5c. PROGRAM ELEMENT NUMBER

6. AUTHOR(S)
Oleksandr Prokopenko; Elena Bankowski; Thomas Meitzler; Vasil Tiberkevich; Andrei Slavin

5d. PROJECT NUMBER

5e. TASK NUMBER

5f. WORK UNIT NUMBER

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)
National Taras Shevchenko University of Kyiv, Kyiv 01601 MSP, Ukraine U.S. Army TARDEC, Warren, MI 48397, USA Department of Physics, Oakland University, Rochester, MI 48309, USA

8. PERFORMING ORGANIZATION REPORT NUMBER
20758

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)
US Army RDECOM-TARDEC 6501 E 11 Mile Rd Warren, MI 48397-5000, USA

10. SPONSOR/MONITOR'S ACRONYM(S)
TACOM/TARDEC

11. SPONSOR/MONITOR'S REPORT NUMBER(S)
20758

12. DISTRIBUTION/AVAILABILITY STATEMENT
Approved for public release, distribution unlimited

13. SUPPLEMENTARY NOTES
Submitted for publication in Applied Physics Letters, The original document contains color images.

14. ABSTRACT

15. SUBJECT TERMS

16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
a. REPORT **unclassified**	b. ABSTRACT **unclassified**	c. THIS PAGE **unclassified**	**SAR**	**3**	

Standard Form 298 (Rev. 8-98)
Prescribed by ANSI Std Z39-18

synchronized STNO placed in a microwave resonator.

In our current work we, first of all, calculated the microwave power that can be emitted by a single STNO into free space (in near- and far-field zones), and, then, calculated the power of the STNO emission into microwave transmission lines (rectangular waveguide and microstrip line) and into microwave resonators (rectangular and microstrip). In this calculations we used a simple model of direct microwave emission from a system of two effective magnetic dipoles developed in[12], the expressions for the fields of a magnetic dipole[12,13], and the standard expressions for the electromagnetic fields of fundamental modes in the considered transmission lines and resonators[13]. In our calculations we assumed that the magnetization of the FL is uniform (macrospin approximation) and that the sizes of the effective magnetic dipoles are much smaller than the wavelength λ of the microwave signal. In our model the microwave component m of the FL magnetization depends on the precession angle α as $m(\alpha) = M \sin\alpha$ (see Fig.1(a)) and the microwave power emitted from STNO is defined as $P(\alpha) = P_{\rm DIP} \sin^2 \alpha$. To evaluate the *maximum* value of emitted microwave power we assumed that the magnetization precession angle has a maximum value equal to $\alpha_{\rm max} = 90°$. In such a case the magnitude of the microwave magnetization m also has its maximum value $m_{\rm max} = M$. In our primary calculations we used the following typical parameters of STNO: saturation magnetization of the STNO FL $\mu_0 M = 800$ mT (where μ_0 is vacuum permeability), radius of the STNO $r_{\rm c} = 100$ nm, thickness of the STNO FL $L = 5$ nm, volume of the STNO FL $V = \pi r_{\rm c}^2 L$, and the frequency of the magnetization precession $f = 10$ GHz. We also assumed that the permittivity ϵ and permeability μ of the media are approximately equal to the vacuum permittivity ϵ_0 and vacuum permeability μ_0, respectively.

Using the described above model we obtained the following generalized expression for the maximum microwave power emitted by a single STNO in the considered microwave systems:

$$P_{\rm DIP}(f) = \frac{8}{3}\pi^3 P \frac{V}{V_{\rm eff}} Q, \qquad (2)$$

where $P = \mu_0 m_{\rm max}^2 V f$ is the characteristic microwave power emitted from the FL of a STNO, $V_{\rm eff}$ is the effective volume of a particular microwave system coupled to STNO and Q is the quality factor of this system. The values of the maximum microwave power emitted by a single STNO calculated for different systems are presented in Table I along with the expressions for the effective volume $V_{\rm eff}$ for these systems.

The results presented in the Table I demonstrate that, although the power emitted from an STNO into a free space is very low, the coupling of an STNO to a microwave system can substantially increase the output power. In particular, if we place an STNO in the center of a gold nano-loop of a round shape (radius $r_{\rm L} = 10$ μm, square cross-section $S_{\rm L} = 50 \times 50$ nm^2, and the the characteristic resistance $R_{\rm L} = \rho_{\rm g} 2\pi r_{\rm L}/S_{\rm L} = 503$ Ohm, where $\rho_{\rm g} = 20$ nOhm $\cdot$ m is the resistivity of gold) we can increase the emitted power by approximately 10^{10} times, because the power can be collected by the loop in a near-field zone (see Table I). A similar power enhancement can be achieved if an STNO is placed between the plates of a nano-sized square capacitor (the length and width of the capacitor plates are $a = 10$ μm and the distance between the plates is $b = 50$ nm) (see Table I). If we place an STNO in a rectangular waveguide or into a microstrip transmission line with the cross-section of $a \times b$, the electromagnetic field generated by a STNO can excite the fundamental propagating modes in these transmission lines, but, as it can be seen from Table I, this approach is less effective than the previous one. In order to increase the emitted power, a STNO can be placed in a microwave resonator with a sufficiently high Q, which allows one to increase the emitted power Q times (see Ex. (2)). However, our calculations performed for a rectangular resonator (having sizes a, b and l and a reasonably high quality factor of $Q = 10^5$) demonstrated that the power emitted in such a resonator is smaller than the power that can be collected by e.g. a nano-loop situated in the near-field zone of an STNO. The power emitted into a resonator can be increased if the effective volume $V_{\rm eff}$ of the resonator is reduced. To achieve this it is possible to place an STNO inside a parallel-plate resonator (the simplest model for a microstrip resonator) having the width a, height b and length $l = \lambda/2$ (see Fig. 1(b)). For the reasonable sizes of the microstrip resonator the emitted power of several pW can be obtained (see Table I).

The calculations using Ex. (1) and Ex. (2) have demonstrated that absolute values of microwave power emitted by a single STNO are rather small. Thus, to create a practical source of microwave signals based on STNOs it would be useful to use arrays of coupled and synchronized STNOs[6,8,10].

There are two approaches to create such an array of STNOs. The first (traditional) approach is to form an array of N oscillators connected in parallel or in series and coupled by a common bias current. In such a case, as it was shown in[11], the output power extracted through the MR mechanism from an array of N synchronized STNOs is N times larger than the power of a single STNO. The second approach is to place N STNOs (coupled through their dipolar electromagnetic fields) inside a resonator with a high Q-factor and extract the power through the above described dipolar emission mechanism. In that case, as it was shown in[14], the output power of the N-oscillator array can be N^2 times larger than the power of a single oscillator, as long the total microwave power extracted from the resonator coupled to the array remains smaller then the power caused by Gilbert damping in a single STNO in the array[15].

Using the theory developed in[11] and assuming that a synchronized array of N STNOs is placed in a microwave resonator, we can obtain the condition on the number

TABLE I: Expressions for $V_{\rm eff}$ and values for maximum microwave power emitted by a single STNO calculated using Ex. (2)

Case	Expression for $V_{\rm eff}$	Parameters	Maximum power, W
Free space	λ^3	$\lambda = 3$ cm, $Q = 1$	$3.9 \cdot 10^{-22}$
Nano-loop	$4\pi r_c^2 R_L/3\mu_0 f$	$R_L = 503$ Ohm, $Q = 1$	$6.0 \cdot 10^{-12}$
Nano-sized square capacitor	$2\pi^3\lambda^2 L^2 b/3a^2$	$a = 10$ μm, $b = 50$ nm, $Q = 1$	$1.1 \cdot 10^{-11}$
Rectangular waveguide	$16\pi a^2 b\chi/3$	$a = 23$ mm, $b = 50$ nm, $\chi = \eta/\sqrt{1-\eta^2}$, $\eta = \lambda/2a \approx 0.65$, $Q = 1$	$2.7 \cdot 10^{-17}$
Microstrip line	$64\pi ab\lambda/3$	$a = 10$ μm, $b = 50$ nm, $Q = 1$	$1.0 \cdot 10^{-14}$
Rectangular resonator	$4\pi^3\lambda^2 b(1+\chi^2)^2/3\chi$	$a = 23$ mm, $b = 50$ nm, $Q = 10^5$	$1.6 \cdot 10^{-13}$
Microstrip resonator	$16\pi^3 ab\lambda/3$	$a = 10$ μm, $b = 50$ nm, $Q = 10^3$	$4.2 \cdot 10^{-12}$

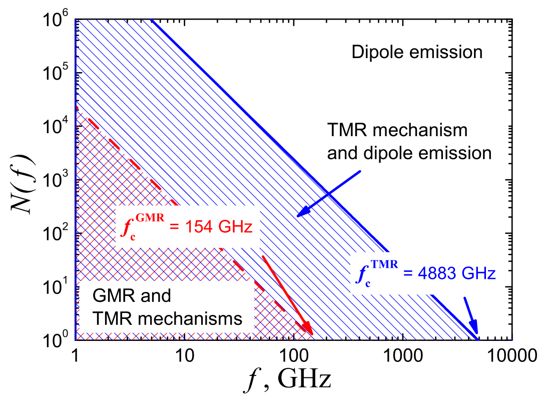

FIG. 2: Dependence of the critical number N_c (3) of STNOs in a synchronized array placed in a microstrip resonator on the generation frequency f. If $N > N_c$ the microwave power that could be extracted from the array through the dipolar emission mechanism exceed the power that could be extracted through the MR mechanism.

$N(f)$ of STNOs in the array, that guarantees that the microwave power extracted through the dipolar emission is larger than the power obtained through the MR:

$$N(f) \geq N_c = \frac{P_{\rm MR}}{P_{\rm DIP}(f)} = \frac{f_c^2}{f^2}, \qquad (3)$$

where f_c is the characteristic frequency of the system (STNO + resonator) at which $P_{\rm DIP}(f) = P_{\rm MR}$ for a single STNO. The straight lines showing the dependence of the critical number of STNOs in an array N_c (3) on the generation frequency f for STNOs using the GMR (dashed line) and TMR (solid line) effects are presented in Fig. 2. These lines were calculated for the case of STNOs coupled to a microstrip resonator (see the last line in Table I) assuming that $P_{\rm MR} = 1$ nW for the GMR STNO and $P_{\rm MR} = 1$ μW for the TMR STNO. The characteristic frequencies f_c in these two cases are $f_c^{\rm GMR} \simeq 154$ GHz and $f_c^{\rm TMR} \simeq 4.883$ THz, respectively. The regions above the GMR (dashed) and TMR (solid) lines are the regions where the direct dipolar emission from a synchronized array of STNOs provides the larger output microwave power than the corresponding (GMR or TMR) MR effects.

In conclusion, we demonstrated that, although the power of a single STNO received through the MR effect is, in most cases, larger than the power of the direct dipolar emission from the same STNO, the latter mechanism might become preferable for sufficiently large arrays of coupled and synchronized STNOs.

This work was supported in part by the by the Contract No. W56HZW-09-PL564 from the U.S. Army TARDEC, RDECOM, by the Grant No. ECCS-0653901 from the National Science Foundation of the USA, by the Oakland University Foundation, and by the Grant No. M/175-2007 from the Ministry of Education and Science of Ukraine.

* Electronic address: ovp@univ.kiev.ua
† Electronic address: tyberkev@oakland.edu
‡ Electronic address: slavin@oakland.edu
[1] J.C. Slonczewski, J. Magn. Magn. Mat. **159**, L1 (1996).
[2] L. Berger, Phys. Rev. B **54**, 9353 (1996).
[3] S.I. Kiselev *et al.*, Nature **425**, 380 (2003).
[4] K.J. Lee *et al.*, Nature Mater. **3**, 877 (2004).
[5] I.N. Krivorotov *et al.*, Science **307**, 228 (2005).
[6] F.B. Mancoff *et al.*, Nature **437**, 393 (2005).
[7] D. Houssameddine *et al.*, Nature Mater. **6**, 447 (2007).
[8] A. Ruotolo *et al.*, Nature Nanotech. **4**, 528 (2009).
[9] A. Slavin, and V. Tiberkevich, IEEE Trans. Magn. **45**, 1875 (2009).
[10] V. Tiberkevich *et al.*, Appl. Phys. Lett. **95**, 262505 (2009).
[11] B. Georges *et al.*, Appl. Phys. Lett. **92**, 232504 (2008).
[12] N. Amin, H. Xi, and M.X. Tang, IEEE Trans. on Magn. **45**, 4183 (2009).
[13] S. Ramo, J.R. Whinnery, and T. van Duzer, *Fields and Waves in Communication Electronics* (John Wiley & Sons, New York, 1984).
[14] A. Pikovsky, M. Rosenblum, and J. Kurths, *Synchronization: a universal concept in nonlinear sciences* (University Press, Cambridge, 2007).
[15] In our case this threshold is reached at $N \sim 10^4$.