Journal of Physics: Conference Series

PAPER • **OPEN ACCESS**

Transformation of modulated signals in the spin-torque nanooscillator

To cite this article: A R Safin and A S Tatarenko 2019 *J. Phys.: Conf. Ser.* **1352** 012043

IOP Conf. Series: Journal of Physics: Conf. Series **1352** (2019) 012043 doi:10.1088/1742-6596/1352/1/012043

Transformation of modulated signals in the spin-torque nanooscillator

A R Safin[1] and A S Tatarenko[2]

[1] National Research University "MPEI", Krasnokazarmennaya str.14
111250, Moscow, Russia
[2] Yaroslav-the-Wise Novgorod State University, ul. B. St. Petersburgskaya, 41
173003 Veliky Novgorod, Russia

E-mail: Alexandr.Tatarenko@novsu.ru

Abstract. Transformation of modulated by amplitude and phase signals in the spin-torque nanooscillator is investigated. Frequency dependences of transmission ratios of amplitudes and oscillation phases at the modulating current are received. Existence of detuning of a locking frequency of rather natural frequency of the spin transfer nano-oscillator and frequency dependence of a threshold parameter near the natural frequency leads to emergence of cross transmission ratios of variations of amplitude in a variation of a phase and variations of a phase in amplitude variation Thus, we showed, that the network of the mutually coupled oscillators can be used as the modulator/demodulator of a phase and frequency at strong nonisochronous.

1. Introduction

The perspective direction of the spintronics is the generation of millimeter and sub-millimeter waves in magnetic multilayer nanostructures caused by effect of a spin transfer torque [1, 2]. A great attention has attracted by studies of the phase locking in the arrays of spin transfer nano-oscillators, which benefit from the spin-transfer torque phenomenon.

There are several studies of spin transfer nano-oscillators phase locking achieved by various physical mechanisms: through electrical connection in series of oscillators, by spin-wave propagation, by antivortices, and by dipolar coupling. Nevertheless, the theoretical description of the synchronization dynamics of spin-torque nanooscillator is more complicated than traditional limit-cycles oscillators (van der Pole oscillators, Josephson junctions, rotating pendula) which have constant orbit radius, and can be described in single oscillator case by the Adler equation.

In real networks there are as many frequencies (we will call them "modes") as the number of oscillators. When more than two oscillators are mutually coupled the finding of each mode structure and determination of their stability (or stability of group of them) becomes the main problem that has to be clarified. When the dissipation parameter is small enough, one can use the linear normal mode formalism for analyzing of the dynamics of the network of oscillators. If this condition is not satisfied, one can use the nonlinear normal mode formalism, which is much harder than the linear one. In general, the majority of these networks has the small dissipation parameter, and therefore it is possible to use the linear normal mode formalism for these systems.

The main shortcomings [3] of the spintronic-based oscillators (Spin-Torque Nanooscillator – STNO) are low output power (tens of nanowatts) and high values of a spectrum linewidth (hundreds MHz). Therefore different ways of power increasing and reduction of linewidth were developed. For example, mutual synchronization of several STNOs [3, 4], injection locking of the single oscillator [3] and synchronization by the phase-locked loop scheme [5]. Neuromorphic and CMOS applications of STNOs were discussed in [6, 7].

In this work using the spin-wave approach [3], we construct the theory of transformation of the modulated oscillations in the STNO. Both an external source and another oscillator as a part of the network can cause the weak modulating influence.

2. Transformation of the modulated signals in the STNO

Let the STNO is affected by the modulated signals – low-frequency current $I(t)$ and a phase $\Psi(t)$ such that

$$I(t) = I_0 + v(t),$$

$$\Psi(t) = \Psi_c(t) + \psi(t) \tag{1}$$

where $v(t)$, $\psi(t)$ - are the small modulation components of current and phase of the synchronizing signal, respectively; I_0, $\Psi_c(t)$ – are the values of I and Ψ for unmodulated synchronizing signals $|v| << I_0, |\psi| << \pi$.

Mathematical model of the STNO under external influence is the equation for the complex amplitude of the spin wave $\dot{c}(t)$ a free layer (see in more detail [3]) in the following form:

$$\frac{d\dot{c}}{dt} + j\left(\omega_0 + N|\dot{c}|^2\right)\dot{c} + \Gamma_G\left(1 + Q|\dot{c}|^2\right)\dot{c} - \sigma I(t)\left(1 - |\dot{c}|^2\right)\dot{c} = \Lambda \cdot e^{j\Psi(t)} \tag{2}$$

where ω_0 is the frequency of ferromagnetic resonance, N is the nonisochronous parameter, Γ_G is the coefficient of linear positive damping, Q is the constant of nonlinear damping, Λ - amplitude of high-frequency signal and $j = \sqrt{-1}$ is the imaginary unit.

Small modulation components of a locking signal will cause a response of the STNO in the form of small variations of amplitude $u(t)$ and a phase $\varphi(t)$ of synchronized signal, i.e. for the

$$\dot{c} = Ue^{j\Phi},$$

$$U = U_0 + u(t),$$

$$\Phi = \Phi_0 + \varphi(t) \tag{3}$$

where U_0, Φ_0 are the amplitude and phase of the oscillator at its synchronization by a nonmodulated signal.

Let's find the matrix $\hat{\boldsymbol{K}}$, which is

$$\begin{pmatrix} \boldsymbol{u} \\ \boldsymbol{\varphi} \end{pmatrix} = \hat{\boldsymbol{K}} \cdot \begin{pmatrix} \boldsymbol{v} \\ \boldsymbol{\psi} \end{pmatrix} = \begin{pmatrix} \boldsymbol{K}_{uv} & \boldsymbol{K}_{u\psi} \\ \boldsymbol{K}_{\varphi v} & \boldsymbol{K}_{\varphi\psi} \end{pmatrix} \cdot \begin{pmatrix} \boldsymbol{v} \\ \boldsymbol{\psi} \end{pmatrix} \tag{4}$$

where $\boldsymbol{K}_{\alpha\beta}$ – are the operational coefficients of transformation, which depend on the differential operator $\boldsymbol{p} \equiv \boldsymbol{d} / \boldsymbol{dt}$.

Using linear approximation of the equation (2) and if $\boldsymbol{\Psi}_c(\boldsymbol{t}) \approx \boldsymbol{\Phi}_0$ (in the center of the phase-locking band), we can find the linear expressions for $\boldsymbol{K}_{\alpha\beta}$

$$\boldsymbol{K}_{uv}(\boldsymbol{p}) = \frac{\boldsymbol{\sigma}(\boldsymbol{Q}+1)}{(\varsigma+\boldsymbol{Q})} \cdot \frac{\boldsymbol{U}_0\boldsymbol{p}+\boldsymbol{\Lambda}}{\boldsymbol{p}\left(\boldsymbol{p}+2\Gamma_G(\varsigma+\boldsymbol{Q})\boldsymbol{U}_0^2\right)} \tag{5}$$

$$\boldsymbol{K}_{u\psi}(\boldsymbol{p}) = 0 \tag{6}$$

$$\boldsymbol{K}_{\varphi v}(\boldsymbol{p}) = -\frac{\left(\omega_0 + 3\boldsymbol{N}\boldsymbol{U}_0^2\right)}{(\varsigma+\boldsymbol{Q})} \cdot \frac{\varsigma(\boldsymbol{Q}+1)}{\boldsymbol{p}\left(\boldsymbol{p}+2\Gamma_G(\varsigma+\boldsymbol{Q})\boldsymbol{U}_0^2\right)} \tag{7}$$

$$\boldsymbol{K}_{\varphi\psi}(\boldsymbol{p}) = \frac{\boldsymbol{\Lambda}}{\boldsymbol{U}_0\boldsymbol{p}} \tag{8}$$

Here $\varsigma = \boldsymbol{I}_0\boldsymbol{\sigma} / \Gamma_G$ – is the threshold parameter. The corresponding dependence of transmission operator (5) on frequency f for the various ς is presented in figure 1.

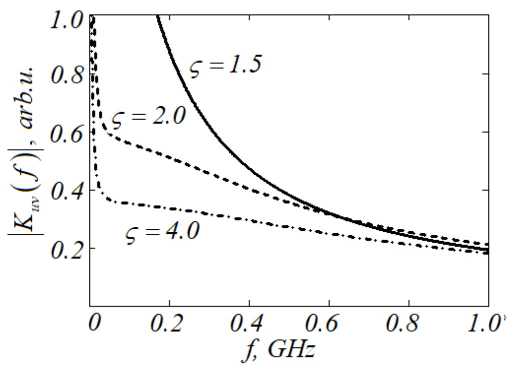

Figure 1. The dependence of transmission operator $\left|\boldsymbol{K}_{uv}(\boldsymbol{f})\right|$ on frequency $\boldsymbol{f}$ for the various threshold parameters ς .

Dependences $\left|K_{\varphi v}\left(f\right)\right|,\left|K_{\varphi\psi}\left(f\right)\right|$ behave similarly as $\left|K_{uv}\left(f\right)\right|$ here are not presented. With growth of ς, filter threshold frequency decreases.

3. Summary

In relation to amplitude and phase variations of a locking signal the STNO behaves as a low-pass filter. Parameters of this filter are strongly influenced by parameters of an input signal, detuning and the nonisochronous parameter. Existence of detuning of a locking frequency of rather natural frequency of the STNO and frequency dependence of a threshold parameter ς near the natural frequency leads to emergence of cross transmission ratios of variations of amplitude in a variation of a phase and variations of a phase in amplitude variation (expressions (5)–(8)). The last allows using locked STNO as transformers of amplitude shift keying in phase and vice versa. At a deviation from the center of a phase locking state the transformation operators become much more difficult.

Acknowledgments

This work was supported by the Russian Science Foundation, project no.18-07-00485.

References

[1] Slonczewski J C 1996 Current-driven excitations of magnetic multilayers *J. Magn. Magn. Mater.* **159** 1–7
[2] Berger L 1996 Emission of spin waves by a magnetic multilayer traversed by a current *Phys. Rev. B* **54** 9353–9358
[3] Slavin A N and Tiberkevich V S 2009 Nonlinear auto-oscillator theory of microwave generation by spin-polarized current *IEEE Trans. Magn.* **45 (4)** 1875–1918
[4] Safin A R, Udalov N N and Kapranov M V 2014 Mutual phase locking of very nonidentical spin torque nanooscillators via spin-wave interaction *Eur. Phys. J. Appl. Phys.* **67 2** 20601–20607
[5] Mitrofanov A A, Safin A R, Udalov N N and Kapranov M V 2017 Theory of spin torque nano-oscillator-based phase-locked loop *Journ. of Appl. Phys.* **122** 123903–123909
[6] Zahedinejad M, Mazaraati H, Fulara H, Yue J, Jiang S, Awad A A and Åkerman J 2018 CMOS compatible W/CoFeB/MgO spin Hall nano-oscillators with wide frequency tenability *Appl. Phys. Lett.* **122** 132404–132408
[7] Torrejon J et al., 2017 Neuromorphic computing with nanoscale spintronic oscillators *Nature* **547** 428–431