Non-linear frequency and amplitude modulation of a nano-contact spin torque oscillator

P. K. Muduli, Ye. Pogoryelov, and S. Bonetti
Materials Physics, Royal Institute of Technology, Electrum 229, 164 40 Kista, Sweden

G. Consolo
Department of Physics, University of Ferrara, 44100 Ferrara, Italy

Fred Mancoff
Everspin Technologies, Inc., 1300 N. Alma School Road, Chandler, 85224, Arizona, USA

Johan Åkerman
Materials Physics, Royal Institute of Technology, Electrum 229, 164 40 Kista, Sweden and
Physics Department, University of Gothenburg, 41296 Gothenburg, Sweden
(Dated: May 12, 2010)

We study the current controlled modulation of a nano-contact spin torque oscillator. Three principally different cases of frequency non-linearity ($d^2f/dI_{dc}^2$ being zero, positive, and negative) are investigated. Standard non-linear frequency modulation theory is able to accurately describe the frequency shifts during modulation. However, the power of the modulated sidebands only agrees with calculations based on a recent theory of combined non-linear frequency and amplitude modulation.

PACS numbers: 85.70.Kh, 85.75.-d, 84.30.Ng, 72.25.Ba

Spin-torque oscillators (STO) offer a combination of attractive properties such as ultra wide band frequency operation, extremely small footprint (without any need for large inductors), and easy integration using well-established magnetoresistive random access memory processes. The basic principle of a spin-torque oscillator based on the transfer of angular momentum from a spin-polarized current to the local magnetization. The effect usually occurs in a nanoscale device where a large current density ($\sim 10^8$ A/cm$^2$) can drive the precession of the free layer magnetization at GHz frequencies, thus acting as a nanoscale oscillator. Effective modulation of the microwave signal generated from STOs is required for communication applications. However, both the STO frequency and amplitude are typically non-linear functions of the drive current. This non-linearity is related to a change in the precession angle with the increase in the current magnitude. Experiments have shown other sources of non-linearities such as temperature and dynamic-mode hopping. The wide range of possible sources of non-linear behavior is likely to render the frequency modulation of STOs highly non-trivial.

Despite the rapidly growing literature on the many different aspects of STOs, experimental studies of frequency modulation are still limited to a single work by Pufall et al. They observed both unequal sideband amplitudes and a shift of the carrier frequency with modulation amplitude, which they ascribed to non-linear frequency modulation (NFM). While linear frequency-modulation (LFM) theory assumes that the instantaneous frequency of the modulated signal is linearly proportional to the modulating signal, NFM theory takes into account the non-linear change in the intrinsic operating frequency during modulation. Pufall et al. calculated the observed sideband amplitudes using NFM theory and found a rather large (about 50%) discrepancy between their calculated and experimentally observed sidebands, which they argued might be due to amplitude modulation or other non-linear properties of the STO.

In this work we study the frequency and amplitude modulation of a nano-contact STO for various amounts of frequency non-linearity. The frequency non-linearity is described by the second derivative of the frequency, $f$, with respect to the dc bias current, $I_{dc}$, $d^2f/dI_{dc}^2$. Three different cases of frequency non-linearity ($d^2f/dI_{dc}^2$ being zero, positive, and negative) are investigated. As expected from NFM theory, the carrier and its associated sidebands exhibit a change in frequency under modulation, which can be directly calculated from the experimentally determined non-linear properties of the frequency of the free-running STO. However, the power of the modulated sidebands is only poorly reproduced using NFM theory and we show that it is essential to consider amplitude modulation in order to reach any quantitative agreement. Using a recently proposed theory of combined nonlinear frequency and amplitude modulation (NFAM) we are able to show remarkable agreement between our experimental data and calculations, which involve no adjustable parameters. Despite the complex phenomena involved in the STO non-linearities, we show that modulation of these devices is highly predictable.

The nano-contact metallic-based STOs studied in this work have been described in detail in Ref. Using e-beam lithography, a circular Al nano-contact with nominal diameter of 130 nm is fabricated through a SiO$_2$ insulating layer, onto a $8 \times 26 \mu$m$^2$
compare three principally different cases of frequency non-
three different operating points (28, 31, and 38 mA) used to
applied at 70°.

FIG. 1: Current dependence of the free running STO: (a) fre-
power, both measured in a magnetic field of $H = 10$ kOe,
applied at 70° to the film plane. Dotted lines indicate the
different operating points (28, 31, and 38 mA) used to
compare three principally different cases of frequency non-
linearity, corresponding to $d^2f/dI_{dc}^2$ being zero, positive, and
negative, respectively. Inset in (b) shows the measured S-
parameter, $S_{11}$ at the STO.

pseudo-spin-valve mesa with the following layer struc-
ture: Si/SiO$_2$/Cu(25 nm)/Co$_8$Fe$_{19}$(20 nm)/Cu(6
nm)/Ni$_{80}$Fe$_{20}$(4.5 nm)/Cu(3 nm)/Pd(2 nm). While all
data presented here has been taken on a single device,
similar behavior has been observed in several other de-
vices of the same size.

The low frequency (100 MHz) modulating current is
jected from an RF source to the STO via a circu-
lator. The dc bias current is fed to the device by a
precision current source (Keithley 6221) through a dc-
40 GHz bias tee connected in parallel with the transmis-
sion line. The signal is then amplified using a broadband
16-40 GHz, +22 dB microwave amplifier, and finally de-
tected by a spectrum analyzer with an upper frequency
limit of 46 GHz (Rohde & Schwarz FSU46). The actual
RF current at the STO is calculated by taking into ac-
count losses and reflections due to impedance mismatch
in the transmission line. Losses in our transmission line
and circulator are characterized by injecting an input sig-
nal with the microwave source and measuring the output
with the spectrum analyzer. The reflection at the STO
is measured with a vector network analyzer and is shown in
the inset of Fig. (b). The scattering matrix element
$S_{11}$ shown in the figure is proportional to the amount of
reflection at the STO, which is as high as 70 – 80 % over
the entire measured frequency range, 0.01-26 GHz. All
other components in the transmission line, which have
nominal 50 Ω impedance, give a relative negligible con-
tribution to the total amount of reflected signal. The
signal detected at the spectrum analyzer is finally cor-
rected for the standing waves in the transmission line.
All data shown in this work have been corrected in order
to compensate for all these effects.

The measurements are performed in a magnetic field
of 10 kOe applied at an angle of 70° to the film plane to
ensure that (i) the STO operates around its maximum
output power, and (ii) only the so-called propagating
modes are excited. This mode has a higher frequency
than the ferromagnetic resonance mode and shows a blue-
shift with bias current as confirmed in Fig. (a). Fig-
ure 4 also shows that both the operating frequency and
the integrated output power (which is proportional to
the actual precession amplitude of the STO) Fig. (b)]
are strongly non-linear functions of the dc bias current.
This behavior is likely related to the excitation of closely
spaced discrete dynamic modes as the bias current is in-
creased[12-13].

To test different non-linear modulation theories, we
have chosen to focus on three principally different non-
linear situations described by three different values of
$d^2f/dI_{dc}^2$: zero, positive, and negative, correspon-
ding to a drive current of 28, 31, and 38 mA, respectively. These
three operating points are shown as dotted lines in Fig. (b). The
non-linearity can be more clearly seen in Fig. (b) which shows the frequency and integrated power of the
free-running STO around these dc bias current values in
a range equal to the maximum modulation current. The
shape of frequency vs current at 28 mA is almost lin-
ear while it is convex for 31 mA and concave for 38 mA.
The amplitude sensitivity is also clearly different at these
current values, as seen from the corresponding plots of
integrated power in Figs. (d)-(f). Around these oper-
ating points we modulate the STO using a 100 MHz RF
signal swept from 0 to 3 mA. The corresponding spectra
are shown in Fig. (b) as a function of the modulating cur-
rent amplitude. In all three cases, the number of side-
bands increases with increasing modulation amplitude.
In the case of a linear frequency dependence (28 mA,
$d^2f/dI_{dc}^2 = 0$) the carrier and sideband frequencies are
different models describing the importance of both the frequency and amplitude modulation is also taking place. Modulation provides a strong experimental evidence that the shift only depends on the magnitude of $f/dI$. It is noteworthy that this of the maximum sideband power is also shifted up/down for the upper/lower sidebands. It is strongly affected by the sign and the value of $f/dI$. When $dc > 0$ (31 mA), and $dc < 0$ (38 mA). The position of the maximum sideband power is also shifted up/down for the upper/lower sideband. It is noteworthy that this shift only depends on the magnitude of $f/dI$, and does not change sign when $f/dI$ goes from positive to negative. Even for the linear case (28 mA, $f/dI = 0$), the power of the two sidebands are unequal. The upper sideband has higher power than the lower sideband, as expected from the positive slope of amplitude versus bias current in Fig. 2(d). This case of linear frequency modulation provides a strong experimental evidence that amplitude modulation is also taking place.

In order to interpret the observed behavior and estimate the importance of both the frequency and amplitude non-linearities, we consider three qualitatively different models describing (i) LFM, (ii) NFM, and (iii) NFAM. The latter model is adapted from and specifically takes into account non-linearities in both output frequency and amplitude as a function of the input bias current.

Since LFM and NFM models have already been described in Refs.15,16, we focus on the details of the NFAM model used in our analysis. The instantaneous frequency is assumed to depend nonlinearly on the modulating signal:

$$f_i(t) = k_0 + k_1 m(t) + k_2 m(t)^2 + k_3 m(t)^3 + \ldots, \quad (1)$$

where, $m(t)$, is the modulating signal and the coefficients $k_i$ represent the $i$-th order frequency sensitivity coefficients. Similarly, the output amplitude, $A_c$ is given by

$$A_c(t) = \lambda_0 + \lambda_1 m(t) + \lambda_2 m(t)^2 + \lambda_3 m(t)^3 + \ldots, \quad (2)$$

where $\lambda_i$ is $i$th order amplitude sensitivity coefficient. The coefficients $k_i$ and $\lambda_i$ are given by the non-linear current dependence of $f$ and $A$ of the free running STO. We use sine wave modulation, $m(t) = I_m \sin(2\pi f_m t)$, where $I_m$ is the amplitude and $f_m$ is the frequency of modulating signal. The resulting NFAM spectrum becomes\(^\text{16}\)

$$S(f) = \frac{1}{4} \sum_{h=0}^{3} \gamma_h \sum_{n,m,p,q=-\infty}^{\infty} J_n(\beta_1) J_m(\beta_2) J_p(\beta_3) J_q(\beta_4) \left[ \delta(f - f_i^c - (n + 2m + 3p + 4q + h)f_m) + \delta(f - f_i^c - (n + 2m + 3p + 4q - h)f_m) + \delta(f + f_i^c - (n + 2m + 3p + 4q + h)f_m) + \delta(f + f_i^c - (n + 2m + 3p + 4q - h)f_m) \right]$$

where $\beta_1 = k_1 I_m/f_m + 3k_3 I_m^3/4f_m$, $\beta_2 = k_2 I_m^2/4f_m + k_4 I_m^4/4f_m$, $\beta_3 = k_3 I_m^3/12f_m$, and $\beta_4 = k_4 I_m^4/32f_m$ are frequency modulation indices of different order. $\gamma_0 = \lambda_0 + \lambda_2 I_m^2/2$, $\gamma_1 = \lambda_1 I_m + 3\lambda_3 I_m^3/4$, $\gamma_2 = \lambda_4 I_m^2/2$, and $\gamma_3 = 3\lambda_4 I_m^4/2$ are amplitude modulation parameters. In
the above we assumed that the frequency in Eq. (1) is non-linear up to fourth order and the amplitude in Eq. (2) is non-linear up to third order, which is found sufficient to describe the experimental data. The frequency spectrum $S(f)$ consists of a shifted carrier frequency

$$f_c^I = k_0 + k_2 I_m^2 + 3k_4 I_m^4/8 + \ldots$$  \hspace{1cm} (4)

and an infinite number of sidebands symmetrically located at $f_c^I \pm l f_m$, where $l = n + 2m + 3p + 4q \pm h$ is a positive integer identifying the sideband order. The NFAM carrier shift is identical to that obtained from an NFM model since effects due to amplitude modulation do not enter in Eq. (3). This shift can be readily calculated by means of the polynomial fitting procedure shown in Fig. 2. The comparison with the experimentally obtained values reveals a good agreement, as shown in Fig. 3. The sideband power, on the other hand, is strongly affected by the amplitude modulation, through the coefficients $\gamma_i$, and can be used to compare the NFM and NFAM models. In a 6 mA interval around each operating point, we expand the frequency dependence into a fourth-order Taylor series, and the amplitude dependence into a third-order Taylor series as shown in Fig. 2. The coefficients along with their standard errors are summarized in Table I. Using these coefficients we calculate the sideband power expected from NFM and NFAM, respectively (second and third column in Fig. 2) and also compare with LFM theory (first column in Fig. 2).

| Current (mA) | $k_0$ (GHz) | $k_1$ (MHz/mA) | $k_2$ (MHz/mA^2) | $k_3$ (MHz/mA^3) | $\lambda_0$ (pW^{1/2}/mA) | $\lambda_1$ (pW^{1/2}/mA) | $\lambda_2$ (pW^{1/2}/mA^2) | $\lambda_3$ (pW^{1/2}/mA^3) |
|-------------|-------------|----------------|------------------|------------------|-------------------------|-------------------------|-------------------------|-------------------------|
| 28          | 20.185      | 117 ± 1        | 1 ± 1            | 2 ± 0.2          | 8 ± 1                   | 10.4 ± 0.5              | 0.9 ± 0.07               | -0.2 ± 0.02             | -0.03 ± 0.01            |
| 31          | 20.545      | 147 ± 1        | 20 ± 1           | 0.8 ± 0.1        | -1 ± 0.1                | 10.9 ± 0.6              | -0.5 ± 0.07              | -0.15 ± 0.02            | 0.02 ± 0.01             |
| 38          | 21.779      | 115 ± 1        | -22.5 ± 0.6      | -3.3 ± 0.1       | 1.6 ± 0.1               | 10.8 ± 1                | 1.3 ± 0.07               | -0.1 ± 0.02             | -0.12 ± 0.01            |

The results of the two sidebands decreases by about 36% compared to NFM theory. We emphasize that none of the presented calculations involve any free parameters and are completely determined by the experimentally measured nonlinear current dependences of the free-running STO. The agreement with NFAM was also found to be valid for a range of lower modulation frequencies (down to 40 MHz) over the entire range of dc bias currents. Thus our results show that, as long as both non-linearities are accounted for, the proposed scheme of combined modulation is able to accurately predict the resulting sideband powers and frequency shifts over a wide range of varying operating conditions. Consequently, the STO behaves as an ordinary RF oscillator and should lend itself to communication applications.

In conclusion, we have carried out a detailed modulation study on a nano-contact STO. In particular, we have studied the impact of different levels of frequency non-linearity. In the non-linear cases, both carrier and sidebands frequencies are shifted as a function of the modulation current. Both frequency and amplitude non-linearities produce a significant asymmetry in the power of the upper and lower sidebands. We find that a combined non-linear frequency and amplitude modulation model can accurately describe all our experimental data without any adjustable parameters. The modulation of an STO is therefore predictable and independent of the complex mechanism behind the non-linearity. The results are significant for the continued development of communication and signal processing applications of spin torque oscillators.

Support from the Swedish Foundation for Strategic Research (SSF), the Swedish Research Council (VR), the Göran Gustafsson Foundation and the Knut and Alice Wallenberg Foundation are gratefully acknowledged. Johan Akerman is a Royal Swedish Academy of Sciences Research Fellow supported by a grant from the Knut and Alice Wallenberg Foundation. Giancarlo Consolo gratefully thanks support from CNISM through “Progetto Innesco”. We thank Randy K. Dumas for critical reading of the manuscript.
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