High-data-transfer-rate read heads composed of spin-torque oscillators

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Abstract. The signal-to-noise ratios (SNRs) of the high-data-transfer-rate read heads beyond 3 Gbits/s composed of spin-torque oscillators (STOs) are calculated under the thermal magnetization fluctuations by using the recent nonlinear theories. The STO head senses the media field as a modulation in the oscillation frequency, enabling high signal transfer rates beyond the limit of ferromagnetic relaxation. The output (digital) signal is obtained by FM (frequency modulation) detection, which is commonly used in communication technologies. As the problem of rapid phase diffusion in STOs caused by the thermal fluctuations is overcome by employing a delay detection method, the sufficiently large SNRs are obtained even in nonlinear STOs less than 30 x 30 nm² in size.

1. Introduction

The areal density of commercial hard disk drives is expected to reach 2 Tbit/in² around 2015 [1] and the signal-to-noise ratio (SNR) of the magnetoresistive (MR) reader faces the challenge from the thermal magnetic noise [2]. The noise originates from the magnetization fluctuations in the thermal equilibrium and generally exists in the passive MR devices. Here, we consider an application of active devices, that is, spin-torque oscillators (STOs) to read heads [3][4], and calculate the SNRs of the output signals by using the recent nonlinear theories of STOs [5][6]. The STO heads are compatible with the high data-transfer rate beyond 3 Gbps (Gbits per second), which are important in large-scale magnetic storage. In conventional read heads, the magnetization vector \( \mathbf{M} \) in the free layer changes directions, responding to the media fields \( \pm h_s \) applied perpendicular to the bias field \( H_{\text{bias}} \), as shown in figure 1 (a). The rate of the change is, however, limited by the energy relaxation rate, i.e., the linewidth of ferromagnetic resonance \( \Gamma_G = \alpha \gamma (4\pi M)/2 \leq 1 \text{ ns}^{-1} \), where \( \alpha \sim 0.01 \) and \( \gamma = 17.6 \times 10^6 \text{ rad/s} \) are the Gilbert damping parameter and the gyromagnetic ratio, respectively, and \( 4\pi M = 4\pi |\mathbf{M}| \leq 10^4 \text{ emu/cm}^3 \). It is, therefore, difficult for the conventional read heads to comply with the high-speed signal processing far beyond 1 Gbps. On the contrary, the precession frequency of the magnetization in STO is expected to change promptly irrespective of the relaxation rate in response to \( \pm h_s \) applied along \( H_{\text{bias}} \), as shown in figure 1 (b), followed by a small change of the precession angle \( \theta \). The prompt frequency changes are also predicted by micromagnetic simulations [7]. An FM (frequency modulation) signal from the STO head is schematically shown in figure 2, in which the small change in amplitude caused by that of the angle \( \theta \) is suppressed by a power limiter (PWL in figure 3). \( T \) is the 1 bit period (1 time slot) and \( 1/T \) is the data-transfer rate. The FM signal is converted to a train of...

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voltage pulses (a digital signal) by FM detection commonly used in communication technologies. It is, however, noted that frequency (phase) stability of STOs is very poor compared with that of conventional electronic oscillators. Although the thermal magnetization fluctuations in STOs are much different from those in the passive MR devices [5], the fluctuation cause rapid phase diffusion (phase noise) in the STO signal. The phase correlation time, i.e., the characteristic time of phase stability is less than 0.1 µs at room temperature for most devices, making the synchronous detection of the signal difficult. A delay detection method is instead employed for the FM detection, in which phase correlation only in the 1 bit period $T < 1$ ns is important as explained in the next section. The SNRs of the output (digital) signals are calculated for 3, 6 and 9 Gbps heads of various sizes under the thermal magnetization fluctuations. The sufficiently large SNRs are obtained even in nonlinear STOs less than $30 \times 30 \text{nm}^2$ in size, showing that the STO read heads beyond 3 Gbps are promising. Electrical noises such as Johnson and shot noises are also considered, which cause phase fluctuations in the FM signal depending on the amplitude (power) of the signal.

**Figure 1.** (a) Magnetization vector $\mathbf{M}$ in the free layer changes directions, responding to the media field $\pm h_s$ applied perpendicular to the bias field $\mathbf{H}_{\text{bias}}$. (b) Precession frequency of $\mathbf{M}$ in STO changes in response to $\pm h_s$ applied along $\mathbf{H}_{\text{bias}}$. The frequency changes are $\pm \delta \omega$.

**Figure 2.** FM signal from the STO head in the media field $\pm h_s$. $T$ is the 1 bit period and $1/T$ is the data-transfer rate.

### 2. Delay Detection of FM Signals from STO and SNRs of Output Signals

A typical circuit for delay detection is shown in figure 3. Signal $s_0(t)$ from STO is divided into signals $s(t)$ and $s(t - T)$ of equal amplitude, the latter of which is delayed 1 bit period $T$. Amplitude (power) fluctuations in $s_0(t)$ are suppressed by a power limiter (PWL) placed before the divider. The output voltage $v(t)$ is obtained by multiplying $s(t)$ and $s(t - T)$ and passing through a low-pass filter (LPF). $s(t)$ and $s(t - T)$ are expressed, respectively, as

\begin{align}
    s(t) &= A \cos \omega_0 t + \varphi(t), \\
    s(t - T) &= A \cos \omega_0 (t - T) + \varphi(t - T),
\end{align}

where $\omega_0$ is the STO frequency in the absence of the media field. Setting the cutoff frequency of LPF appropriately, the output voltage $v(t)$ is given by

\begin{equation}
    v(t) = C s(t) \cdot s(t - T) \big|_{\text{LPF}} = C(A^2/2) \cos(\omega_0 T + \varphi(t) - \varphi(t - T))
\end{equation}

where the proportionality constant $C$ of the dimension (voltage)$^3$ is made unity for simplicity. Under the quadrature condition of $\omega_0 T = 2n\pi - \pi/2$ ($n$: integer), equation (3) reduces to

\begin{equation}
    v(t) = (A^2/2) \sin(\varphi(t) - \varphi(t - T)).
\end{equation}
The oscillation frequency shifts $+\delta \omega (-\delta \omega)$ in the media field $+h_s (-h_s)$ and the phase $\varphi (t)$ increases (decreases) linearly with time, i.e., $d\varphi = \pm \delta \omega \, dt$. For example, the phases $\varphi (t)$ and $\varphi (t-T)$ and the phase difference $\varphi (t) - \varphi (t-T)$ vary as curves (a), (b) and (c), respectively, in figure 4, where bit boundaries are at $t = mT$ ($m$: integer). Phase diffusion caused by the thermal magnetization fluctuations is neglected for the moment. In the MSK (minimum shift keying) method, which is widely used in FM communications, the condition of fluctuations is neglected for the moment. In the MSK method, which is $\pm \pi/2$ at bit boundaries. Detecting $v (t)$ at the boundaries, the output voltages of $\pm A/2$ are obtained corresponding to the media fields $\pm h_s$, respectively, in the preceding bit. Considering STO composed of a free layer of in-plane magnetization with $H_{bias}$ applied in the plane, the oscillation frequency $f_0 = \omega_0/2\pi$, the frequency shift $\delta f = \delta \omega/2\pi$, the in-plane field $H = H_{bias} + H_k$ and the media field $h_{s}$, which satisfy both the quadrature and the MSK conditions are summarized in table 1 in the cases of $1/T = 3$ ns $^{-1}$ (3 Gbps), 6 ns $^{-1}$ and 9 ns $^{-1}$, where $H_k$ is the in-plane anisotropy field in the free layer. $H$ and $h_s$ are calculated from $\omega_0$ and $\delta \omega$, respectively, by using the Kittel equation $\omega_0 = \gamma (4\pi MH)^{1/2}$ and the differential $\delta \omega = h_s (\gamma/2) (4\pi MH)^{1/2}$ with a practical value of $4\pi M = 10^4$ emu/cm$^3$ ($M = 796$ emu/cm$^3$).

![Figure 3](image-url)  
**Figure 3.** Typical circuit for delay detection. Signal $s_0(t)$ from STO is divided into signals $s(t)$ and $s(t-T)$ of equal amplitude, the latter of which is delayed 1 bit period $T$. Power (amplitude) fluctuations in $s_0(t)$ are suppressed by a power limiter (PWL) placed before the divider.

![Figure 4](image-url)  
**Figure 4.** Curves (a), (b) and (c) show the time-dependence of $\varphi (t)$, $\varphi (t-T)$ and $\varphi (t) - \varphi (t-T)$, respectively.

**Table 1.** The oscillation frequency $f_0$, the frequency shift $\delta f$, the in-plane field $H = H_{bias} + H_k$ and the media field $h_s$, which satisfy both the quadrature $2\pi f_0 T = 2\pi \varphi - \pi/2$ and the MSK $2\pi \delta f T = \pi/2$ conditions in the cases of $1/T = 3$ ns $^{-1}$ (3 Gbps), 6 ns $^{-1}$, and 9 ns $^{-1}$.

| $1/T$ (ns$^{-1}$) | $n$ | $f_0$ (GHz) | $\delta f$ (GHz) | $H$ (Oe) | $h_s$ (Oe) |
|------------------|-----|-------------|-----------------|--------|-----------|
| 3                | 2   | 5.25        | 0.75            | 352    | 100       |
| 3                | 3   | 8.25        | 0.75            | 868    | 158       |
| 3                | 4   | 11.25       | 0.75            | 1614   | 215       |
| 6                | 1   | 4.5         | 1.5             | 258    | 172       |
| 6                | 2   | 10.5        | 1.5             | 1406   | 402       |
| 9                | 1   | 6.75        | 2.25            | 581    | 387       |

Taking into account the phase diffusion $\varphi_D (t)$ caused by thermal magnetization fluctuations, equations (1) and (2) are replaced by equations (5) and (6), respectively.

$$s(t) = A \cos [\omega_0 t + \varphi (t) + \varphi_D (t)]$$  \hspace{1cm} (5)
$$s(t-T) = A \cos [\omega_0 (t-T) + \varphi (t-T) + \varphi_D (t-T)]$$  \hspace{1cm} (6)
\( \varphi (t) \) is a phase in the absence of the thermal fluctuations and \( \omega_0 \) is a peak frequency in the power spectrum in the absence of the media fields \( \pm h_s \). Assuming \( d\varphi_D (t)/dt \ll \omega_0 \), the output voltage \( v(t) \) is given by equation (7) corresponding to equation (3). 

\[
v(t) = s(t) \cdot s(t - T) \bigg|_{PF} = (A^2 / 2) \cos[\omega_0 T + \varphi(t) - \varphi(t - T) + \varphi_D (t) - \varphi_D (t - T)]
\] (7) 

Under both the quadrature and the MSK conditions mentioned above, the output voltage at the bit boundary \( t = t_m = mT \) is 

\[
v = v(t_m) = \pm (A^2 / 2) \cos[\varphi_D (t_m) - \varphi_D (t_m - T)].
\] (8) 

The ensemble average of the output voltage \(<v>\) is expressed as 

\[
<v> = \pm (A^2 / 2) <\cos[\varphi_D (t_m) - \varphi_D (t_m - T)].
\] (9) 

According to the recent theories [5], the ensemble average \( K(\tau) = <\cos[\varphi_D (t) - \varphi_D (t - \tau)]> \) in nonlinear STOs sufficiently above the threshold is given by 

\[
K(\tau) = <\cos[\varphi_D (t) - \varphi_D (t - T)]> = \exp[-\Delta \varphi_D^2 (\tau)/2],
\] (10) 

where the phase variance \( \Delta \varphi_D^2 (\tau) \) is 

\[
\Delta \varphi_D^2 (\tau) = <\varphi_D^2 (\tau) > - <\varphi_D (\tau)>^2 = \Delta \omega_0 [(1 + \nu^2)\tau - \nu^2 (1 - e^{-2\Gamma_p \nu})/(2\Gamma_p)].
\] (11) 

\( \nu \) and \( \Gamma_p \) are the nonlinear frequency shift coefficient and the effective damping rate, respectively. \( \Delta \omega_0 \) is the full linewidth of the corresponding linear STO (\( \nu = 0 \)) [4] given by 

\[
\Delta \omega_0 = \frac{2H + 4\pi M \gamma a k_B T}{2H} \frac{1}{p} \cong \frac{4\pi M \gamma a k_B T}{2H} \frac{1}{p},
\] (12) 

where \( p \leq 1 \) is the normalized power of oscillation. \( k_B T \) and \( V \) are the thermal energy and the volume of the free layer, respectively. Defining the noise voltage \( v_n \) and the SNR by equations (13) and (14), respectively, 

\[
v_n = \sqrt(<v^2> - <v>^2)
\] (13) 

\[
\text{SNR} = <v>/v_n\]
(14) 

the SNR of the output signal is given by 

\[
\text{SNR} = \sqrt{2} \exp[-\Delta \varphi_D^2 (T)/2]/\sqrt{1 + \exp[-2\Delta \varphi_D^2 (T)] - 2 \exp[-\Delta \varphi_D^2 (T)]}.
\] (15) 

Considering the free layer of the size \( L \times L \ \text{nm}^2 \) and the thickness \( d \ \text{nm} \ (V = L \times L \times d \ \text{nm}^3) \), dependence on \( L \) of the SNR is calculated [4]. The results are shown (in decibels) in figure 5 in the case of \( 1/T = 3 \ \text{ns}^{-1} \) (3 Gbps). Solid and dashed curves in the figure are under the fields of \( H = 352 \ \text{Oe} \) and 868 Oe (see table 1), respectively, where \( M = 796 \ \text{emu/cm}^3 \ (4\pi M = 10^4 \ \text{emu/cm}^3) \), \( \Gamma_p = 0.15 \ \text{ns}^{-1} \) [8], \( \alpha = 0.01 \), \( d = 3 \ \text{nm} \), \( T = 300 \ \text{K} \) and \( p = 0.5 \). The nonlinear coefficient \( \nu \) is varied as 1, 3, and 5, and
the top and the bottom solid/dashed curves correspond to \( \nu = 1 \) and \( \nu = 5 \), respectively. Figure 6 shows similar results in the cases of 6 Gbps (solid curves) and 9 Gbps (dashed curves) under the fields of 258 Oe and 581 Oe, respectively, where the same values are used for \( M, \Gamma_p, \alpha, d, T \) and \( p \) as those in figure 5. The top and the bottom solid/dashed curves correspond to \( \nu = 1 \) and \( \nu = 5 \), respectively. Figures 5 and 6 show that the SNRs larger than 30 dB are attainable even for \( L \leq 30 \) nm by reducing \( \nu \) and/or increasing \( H \) appropriately.

![Figure 5. Dependece of SNR in decibels on \( L \) in the case of 3 Gbps.](image1)

![Figure 6. Dependece of SNR in decibels on \( L \) in the cases of 6 Gbps (solid curves) and 9 Gbps (dashed curves).](image2)

The decrease of the SNR by electrical noises such as Johnson and shot noises is calculated by adding the electrical noise \( n(t) = n_c(t)\cos \omega_0 t + n_s(t)\sin \omega_0 t \) to \( s_0(t) \) [4]. In the case of the total electrical noise of 100 pW, the output power of STO larger than 10 nW is sufficient to avoid the further degradation of the SNRs by the electrical noises.

3. Summary

Application of active devices, i. e., STOs to high-signal-transfer-rate read heads beyond 3 Gbps is considered and the SNRs under the thermal magnetization fluctuations are calculated by using the recent nonlinear theories. The STO head senses the media field as a modulation of the oscillation frequency, enabling the high signal transfer rates beyond the limit of ferromagnetic relaxation. The problem of rapid phase diffusion caused by the thermal fluctuations is overcome by employing a delay detection method, which is commonly used in communication technologies, and the sufficiently large SNRs are obtained in STOs less than 30 x 30 nm\(^2\) in size.

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