

Noise properties of a resonance-type spin-torque microwave detector

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We analyze performance of a resonance-type spin-torque microwave detector (STMD) in the presence of noise and reveal two distinct regimes of STMD operation. In the first (high-frequency) regime the minimum detectable microwave power $P_{\min}$ is limited by the low-frequency Johnson-Nyquist noise and the signal-to-noise ratio (SNR) of STMD is proportional to the input microwave power P_{RF} . In the second (low-frequency) regime $P_{\min}$ is limited by the magnetic noise, and the SNR is proportional to $\sqrt{P_{\text{RF}}}$. The developed formalism can be used for the optimization of the practical noise-handling parameters of a STMD.

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It has been shown in [1, 2] that a magnetic tunnel junction (MTJ) subjected to the external microwave current $I_{\text{RF}}(t) = I_{\text{RF}} \cos(2\pi ft)$ can perform as a resonance-type quadratic detector of microwave radiation generating the DC voltage U_{DC} proportional to the acting microwave power $U_{\text{DC}} = \varepsilon P_{\text{RF}}$ ($P_{\text{RF}} \sim I_{\text{RF}}^2$). The detector operation is based on the spin-torque effect [3, 4] and the detector sensitivity ε has a maximum value $\varepsilon = \varepsilon_{\text{res}}$ when the frequency of the external microwave signal is close to the eigen-frequency f_0 of the MTJ nanopillar, $f = f_0$.

The resonance sensitivity ε_{res} of the spin-torque microwave detector (STMD) was calculated in [5]:

$$\varepsilon_{\text{res}} = \frac{U_{\text{DC}}}{P_{\text{RF}}} = \left(\frac{\gamma \hbar}{4e} \right) \frac{P^3}{M_s V \Gamma} Q(\theta_0), \quad (1)$$

where $\gamma \approx 2\pi \cdot 28 \text{ GHz/T}$ is the modulus of the gyro-magnetic ratio, $\hbar$ is the reduced Planck constant, e is the modulus of the electron charge, P is the spin-polarization efficiency of the MTJ, M_s is the saturation magnetization of the free layer (FL) of MTJ, $V = \pi r^2 d$ is the volume of the FL (r is its radius and d is its thickness), Γ is the magnetization damping rate in the MTJ FL proportional to the Gilbert damping constant α , and $Q(\theta_0)$ is the geometrical factor that depends on the angle θ_0 between the directions of the equilibrium magnetization in FL and pinned layer (PL) of the MTJ. For an in-plane magnetized MTJ, $Q(\theta_0) = \sin^2 \theta_0 / (1 + P^2 \cos \theta_0)^2$.

Estimations based on Eq. (1) [5] and recent experimental results [2, 6] have demonstrated that the STMD sensitivity can exceed that of passive semiconductor Schottky-diode microwave detectors ($\varepsilon \sim 1000 \text{ V/W}$), which makes STMD very interesting for practical applications in microwave measurement technology.

The operation and the minimum detectable power of all types of microwave detectors are limited by noise

(in particular, by the low-frequency Johnson-Nyquist (JN) noise in the case of unbiased Schottky diodes [7]), and, therefore, it is important to understand the noise-handling properties of the novel STMD based on MTJ.

In this Letter we present theoretical analysis of the noise properties of a passive STMD (no DC bias current) using the STMD model developed in [5] with additional terms describing influence of thermal fluctuations. In our analysis we took into account three different sources of noise:

(a) Low-frequency Johnson-Nyquist (JN) noise voltage $U_{\text{N}}(t)$ associated with the MTJ resistance R_0 . This type of noise is additive and is independent of the magnetization dynamics.

(b) High-frequency JN noise current $I_{\text{N}}(t)$ which transforms into a non-additive low-frequency noise after mixing with the microwave oscillations caused by the input microwave signal.

(c) Magnetic noise (MN), which is caused by the thermal fluctuations of the magnetization direction in the MTJ FL. This noise, modeled by a random magnetic field $\mathbf{B}_{\text{N}}(t)$, leads to the fluctuations of the electrical resistance of the STMD and transforms to low frequencies after mixing with the driving current $I_{\text{RF}}(t)$.

The dynamics of magnetization $\mathbf{M}$ in the MTJ FL under the action of a microwave current containing both deterministic and noise components $I(t) = I_{\text{RF}}(t) + I_{\text{N}}(t)$ and noise magnetic field $\mathbf{B}_{\text{N}}(t)$ is described by the Landau-Lifshits-Gilbert-Slonczewski equation:

$$\frac{d\mathbf{M}}{dt} = \gamma[\mathbf{B}_{\text{eff}}(\mathbf{M}) \times \mathbf{M}] + \frac{\alpha}{M_s} \left[\mathbf{M} \times \frac{d\mathbf{M}}{dt} \right] + \frac{\sigma I(t)}{M_s} [\mathbf{M} \times [\mathbf{M} \times \mathbf{p}]] + \gamma[\mathbf{B}_{\text{N}}(t) \times \mathbf{M}], \quad (2)$$

where $\mathbf{B}_{\text{eff}}(\mathbf{M})$ is the effective magnetic field, which includes the external bias magnetic field $\mathbf{B}_0$ and the demagnetization field, $\mathbf{p}$ is the unit vector in the direction of the magnetization of the MTJ PL, $\sigma = (\gamma \hbar / 2e) P / [(1 + P^2 \cos \theta) M_s V]$ is the current-torque proportionality coefficient, and θ is the angle between vectors $\mathbf{M}$ and $\mathbf{p}$.

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We performed analysis for a “planar” STMD, in which both FL and PL are magnetized in-plane. In this case, the MTJ eigen-frequency is $f_0 = (\gamma/2\pi)\sqrt{B_0(B_0 + \mu_0 M_s)}$ and the damping rate has the form $\Gamma = \alpha\gamma(B_0 + \mu_0 M_s/2)$, where μ_0 is the vacuum susceptibility. We assumed that $f = f_0 \gg \Gamma/(2\pi)$. Using Eq. (2), we found the linear FL magnetization response to current $I(t)$ and field $B_N(t)$ in the frequency domain. The output STMD signal was calculated as the low-frequency part of the voltage $[R(\theta)I(t) + U_N(t)]$, where $R(\theta) = R_\perp/(1 + P^2 \cos \theta)$ is the MTJ magnetoresistance, $R_\perp = RA/(\pi r^2)$ is the MTJ resistance in the perpendicular magnetic state ($\theta = \pi/2$), and RA is the resistance-area product of the MTJ. We assumed that all three noise sources are independent Gaussian processes with uniform spectral densities $S(U_N) = S(I_N)R_0^2 = 2k_B T R_0$ and $S(B_N) = 2\alpha k_B T/(\gamma M_s V)$, where k_B is the Boltzmann constant, T is the noise temperature (assumed to be the same for all noise sources), and $R_0 = R(\theta_0)$ is the equilibrium resistance of MTJ. The detailed derivation of the noise spectrum of STMD will be presented elsewhere [8].

We found that the noise of the output voltage $U_{DC} = \varepsilon_{\text{res}} P_{\text{RF}}$ has characteristic spectral width of Γ and, for typical frequency bandwidth of measurement $\Delta f \ll \Gamma/(2\pi)$, can be considered as frequency-independent. The root mean square fluctuations ΔU_{DC} can be written in the simple form

$$\Delta U_{DC} = U_{JN} \sqrt{1 + \frac{U_{DC}}{U_{IM}} + \frac{U_{DC}}{U_{MN}}}, \quad (3)$$

where the three terms in the right-hand side part of the equation describe, respectively, the influence of the three above mentioned noise sources and

$$U_{JN} = \sqrt{4k_B T R_0 \Delta f}, \quad (4a)$$

$$U_{IM} = \frac{R_0}{4\varepsilon_{\text{res}}}, \quad U_{MN} = \frac{\gamma \hbar B_0}{2e P}. \quad (4b)$$

For typical parameters (see e.g. [5, 9]) of an MTJ nanopillar ($r = 50$ nm, $d = 1$ nm, $P = 0.7$, $\theta_0 = 45$ deg, $R_0 = 500 \Omega$ (giving $RA = 5.29 \Omega \mu\text{m}^2$), $\alpha = 0.01$, $\mu_0 M_s = 0.8$ T, $B_0 = 38$ mT (giving $f_0 = 5$ GHz)) Eq. (1) gives the resonance STMD sensitivity in the passive regime $\varepsilon_{\text{res}} \approx 700$ V/W, which is comparable to the sensitivity of Schottky diodes [9]. At room temperature $T = 300$ K and for the measurement bandwidth of $\Delta f = 1$ MHz Eqs. (4) give the following estimations for the noise-induced voltages: $U_{JN} = 2.88 \mu\text{V}$, $U_{IM} = 175.9$ mV, $U_{MN} = 3.14 \mu\text{V}$.

It is clear that the characteristic voltage U_{IM} of the non-additive high frequency JN noise is much larger than the voltages created by the low frequency JN noise U_{JN} , magnetic noise U_{MN} , and the typical DC voltage output U_{DC} of the STMD. This means that the influence of the high-frequency JN noise in Eq. (3) can be completely ignored. Note, also, that, in contrast with the other characteristic noise voltages, the voltage U_{MN} caused by the

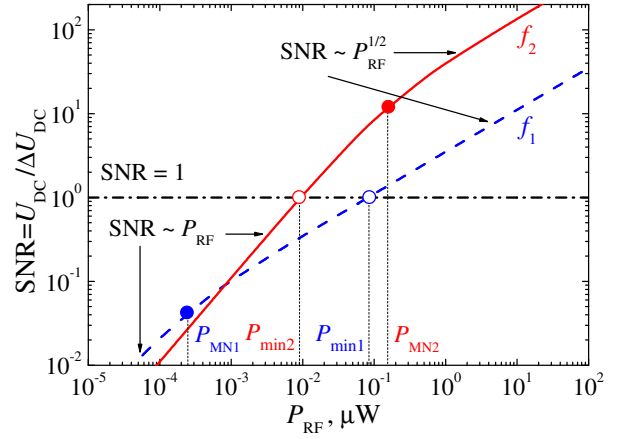


FIG. 1. Dependence of the SNR of STMD on the input microwave power P_{RF} calculated from Eq. (5) for two different frequencies of the input microwave signal: $f_1 = 1$ GHz (dashed blue line) and $f_2 = 25$ GHz (solid red line). All other parameters are the same as indicated below Eqs. (4). P_{min} is the minimum detectable power of STMD (at $\text{SNR} = 1$) and P_{MN} is the frequency-dependent characteristic power of magnetic noise.

magnetic noise is proportional to the bias magnetic field B_0 , and, therefore, increases with the increase of the frequency of the input microwave signal.

Now, introducing the microwave powers $P_{\text{RF}} = U_{DC}/\varepsilon_{\text{res}}$, $P_{\text{JN}} = U_{JN}/\varepsilon_{\text{res}}$, $P_{\text{MN}} = U_{MN}/\varepsilon_{\text{res}}$ and using Eq. (3), we can write a simple expression for the signal-to-noise ratio (SNR) of the STMD in terms of these characteristic powers:

$$\text{SNR} = \frac{U_{DC}}{\Delta U_{DC}} = \frac{P_{\text{RF}}}{P_{\text{JN}}} \sqrt{\frac{P_{\text{MN}}}{P_{\text{MN}} + P_{\text{RF}}}}. \quad (5)$$

The simple analysis of Eq. (5) demonstrates that there are two distinct regimes of operation of the resonance STMD in the presence of thermal noise. We shall classify them by the type of noise that limits the minimum detectable power of STMD P_{min} (power corresponding to $\text{SNR} = 1$).

The first regime corresponds to the case of relatively high frequencies of the input microwave signal, when $P_{\text{MN}} \gg P_{\text{RF}}$ (for $P_{\text{RF}} \sim P_{\text{min}}$). In this regime, similar to the conventional semiconductor diodes, the minimum detectable power is limited by the low-frequency JN noise, $P_{\text{min}} = P_{\text{JN}}$, and the SNR of STMD is linearly proportional to the input microwave power P_{RF} ($\text{SNR} \simeq P_{\text{RF}}/P_{\text{JN}}$).

The second regime takes place in the opposite limiting case of relatively low input frequencies, when $P_{\text{MN}} \ll P_{\text{RF}}$. In this case the SNR of STMD increases with P_{RF} much slower than in conventional diodes, and is proportional to the square root of the input microwave power: $\text{SNR} \simeq \sqrt{P_{\text{RF}}/P_{\text{min}}}$. The minimum detectable power $P_{\text{min}} = P_{\text{JN}}^2/P_{\text{MN}}$ in this regime is limited by the magnetic noise in the FL of the MTJ.

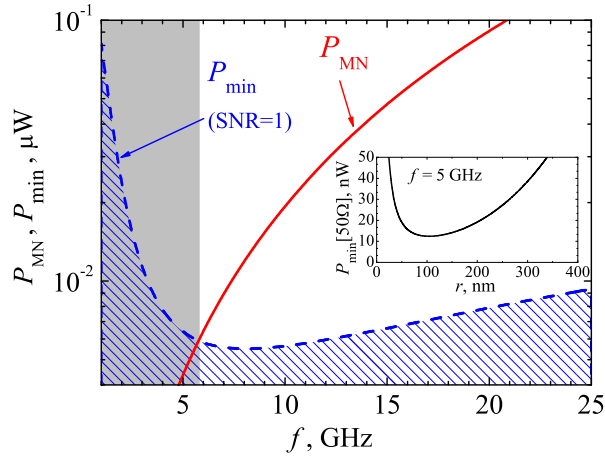


FIG. 2. Characteristic power of magnetic noise P_{MN} (solid red line) and minimum detectable power P_{min} of STMD (dashed blue line) as functions of the input microwave frequency f . The blue dashed area corresponds to undetectable signals $P_{RF} < P_{min}$ and gray shaded area shows the low-frequency STMD regime, where the magnetic noise is dominant in the whole practical region $P_{RF} > P_{min}$. Inset: minimum detectable microwave power delivered to a 50- Ω transmission line $P_{min}[50\Omega]$ for $f = 5$ GHz as a function of the radius r of the MTJ nanopillar. STMD parameters are indicated below Eqs. (4).

We note, that if at a fixed frequency of the input signal the SNR of an STMD is measured in a wide range of input powers, covering both the above described limiting cases, it is possible to find the characteristic power of the magnetic noise P_{MN} with a good accuracy, and, using expression (4b) for U_{MN} , to determine with the same accuracy the MTJ spin-polarization efficiency P .

The existence of two distinct regimes of STMD operation is illustrated in Fig. 1, where two curves calculated from Eq. (5) show the STMD SNR as functions of the input power for signal frequencies $f_1 = 1$ GHz (dashed blue line) and $f_2 = 25$ GHz (red solid curve). It can be seen, that both curves (presented in logarithmic coordinates) demonstrate the clear change of slope from 1 to 1/2 in the region, where the input power P_{RF} is close to the characteristic power of the magnetic noise P_{MN} (which increases

with the increase of the input signal frequency). The minimum detectable power P_{min} (corresponding to $SNR = 1$) in the high-frequency case is smaller than P_{MN} and lies in the region of the linear dependence of SNR on P_{RF} (solid red line in Fig. 1). The situation is opposite in the low frequency case (blue dashed curve in Fig. 1), when $P_{min} > P_{MN}$ and lies in the region, where the slope of the SNR curve is equal to 1/2.

The evolution of the characteristic powers P_{MN} and P_{min} with the increase of frequency of the input microwave signal is shown in Fig. 2. The curve $P_{MN}(f)$ separates the plane into the region, where magnetic noise is dominant (above the curve), and the region, where the STMD operation is limited by the JN noise (below the curve). It is, clear, that the smallest detectable power is achieved near the border of these two regimes.

When an STMD based on an MTJ nanopillar is used as a sensor of microwave radiation, it is typically connected to a standard transmission line with the impedance of $Z_{TL} = 50\Omega$. The minimum detectable microwave power delivered to a 50- Ω transmission line can be written as [10] $P_{min}[50\Omega] = (1/4)(R_0 + Z_{TL})^2 P_{min}/Z_{TL}R_0$. Using this expression and taking into account the size dependence of the STMD resistance ($R_0 \propto 1/r^2$), it is possible to show that $P_{min}[50\Omega]$ has a clear minimum as a function of the nanopillar radius r . For instance, the optimum value of the nanopillar radius is $r_{opt} \approx 100$ nm for the input frequency $f = 5$ GHz (see the inset in Fig. 2).

In conclusion, we have demonstrated that STMD in the presence of noise can operate in two distinct regimes, one of which is limited by magnetic noise and is different from the regime of operation of traditional semiconductor detectors. We have, also, suggested that the measurements of STMD SNR in a wide range of input powers can be used to determine the spin-polarization efficiency P of MTJ nanopillars, and have shown that the developed formalism can be used for the optimization of noise-handling parameters of a STMD.

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