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Measurement of Microwave Signal Frequency by a Pair of Spin-Torque Microwave Diodes

Petro Yu. Artemchuk[1,2], Jieyi Zhang[3], Oleksandr V. Prokopenko[1*], Elena N. Bankowski[4], Thomas J. Meitzler[4*]
Ilya N. Krivorotov[3], Jordan A. Katine[5], Vasyl S. Tyberkevych[2], and Andrei N. Slavin[2**]
[1]Faculty of Radio Physics, Electronics and Computer Systems,
Taras Shevchenko National University of Kyiv, Kyiv 01601, Ukraine
[2]Department of Physics, Oakland University, Rochester, MI 48309, USA
[3]Department of Physics and Astronomy, University of California, Irvine, CA 92697, USA
[4] U.S. Army Combat Capabilities Development Command, Ground Vehicle Systems Center, Warren, MI 48397, USA
[5]HGST Research Center, San Jose, CA 95135, USA
[*]*Senior Member, IEEE*
[**]*Fellow, IEEE*

A single resonance-type spin-torque microwave diode (STMD) can be used as a quadratic detector to determine the frequency f of an external microwave signal when the power P_{rf} of this signal is known. However, unless the signal's frequency f exactly coincides with the detector's resonance frequency f_{res}, there exists a finite frequency determination error Δf. Here we show theoretically and experimentally that, if a *pair* of independent STMDs with *different* resonance frequencies connected in parallel is used for the signal frequency determination, the knowledge of the signal power is not necessary, and the frequency determination error can be substantially reduced to e.g. $\Delta f \approx 30$ MHz at the frequency of $f \approx 5.0$ GHz.

***Index Terms*—spin torque, microwave devices, magnetic sensors, high-frequency applications, microwave magnetics.**

I. Introduction

THE operation of a spin-torque microwave diode (STMD) [1] employing a magnetic tunnel junction (MTJ) is based on three related phenomena: the spin-transfer torque (STT) [2], [3] effect, the spin-torque diode effect [1], [4] and the tunneling magnetoresistance (TMR) effect [5]–[8].

In an STMD, when a magnetization dynamics is excited in a free magnetic layer (FL) of an MTJ structure by an external microwave signal both the structure electrical resistance $R(t)$ (due to the TMR [5]–[8] effect) and current through the structure $I(t)$ will acquire microwave components resulting in the appearance of a rectified dc voltage on the magnetic structure, $U_{\mathrm{dc}} = \langle I(t)R(t)\rangle$, where $\langle \ldots \rangle$ denotes averaging over the period of oscillations of input microwave current. This effect called the spin-torque diode effect [1], [4] can be used for demodulation of microwave signals [9] and for the development of ultra-sensitive STMDs [10]–[15] with resonance volt-watt sensitivity which may exceed that of a semiconductor Schottky diode.

In typical experiments [1], [4], [13], [14], [16] STMD operates in the resonance dynamical regime, where the STT excites a small-angle magnetization precession about the equilibrium direction of magnetization in the FL of an MTJ (description of other possible non-resonance operation regime of an STMD not considered in this work can be found in [11], [12], [15], [17], [18]).

In this resonance regime an STMD operates as a frequency-selective, quadratic microwave detector with a resonance signal frequency f that is close to the ferromagnetic resonance (FMR) frequency f_{res} of the FL and the absolute value of its rectified output dc voltage U_{dc} (neglecting the phase relations between the input microwave signal and magnetization oscillations in the FL) is given by [1], [10], [18], [19]:

$$U_{\mathrm{dc}} = \varepsilon_{\mathrm{res}} P_{\mathrm{rf}} \frac{\Gamma^2}{\Gamma^2 + (f - f_{\mathrm{res}})^2} \,. \quad (1)$$

Here P_{rf} is the input microwave power, f_{res} and Γ are the FMR frequency and FMR linewidth, respectively, and $\varepsilon_{\mathrm{res}}$ is the resonance volt-watt sensitivity of an STMD defined as $U_{\mathrm{dc}}/P_{\mathrm{rf}}$ at $f = f_{\mathrm{res}}$.

Typically, $\varepsilon_{\mathrm{res}}$, f_{res} and Γ can be measured experimentally or calculated theoretically for a particular detector prior to the measurement of the input microwave signal frequency f. Then, by measuring U_{dc} for a known input microwave power P_{rf}, one can determine the frequency f of the input microwave signal from Eq. (1). Obviously, if the input microwave power P_{rf} is not known, the described method of microwave signal frequency determination is not applicable. Also, the Eq. (1) implies that the FMR curve is a symmetrical Lorentzian curve, so, unless the signal frequency f coincides precisely with the STMD resonance frequency f_{res}, one would not be able to determine the signal frequency unambiguously without knowing whether $f \leq f_{\mathrm{res}}$ or $f \geq f_{\mathrm{res}}$.

Manuscript received November 1, 2020; revised Month ?, 2020. P.Yu. Artemchuk and J. Zhang contributed equally to this work. Correspondence and requests for materials should be addressed to Oleksandr V. Prokopenko (e-mail: Oleksandr.Prokopenko@gmail.com).

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There are plenty of methods of frequency measurement that do not involve spintronic technology based on STMDs. Some of these methods are based on the application of traditional high-Q passive microwave resonators [20], [21]. The main drawback of such methods for use in micro- and nano-scale systems is the fact that the dimension(s) of the used resonator, comparable to the wavelength of the measured microwave signal, are usually much bigger than the dimensions of the systems where the measurement is made. Another option is to use *active* measurement devices based on the mixing of an input microwave signal with one or several reference microwave signals generated inside the measurement device [21], [22]. This technique can be implemented in micro- and nano-scale electronic devices (for instance, by using a current-driven spintronic nano-oscillator [23]), but such an approach requires a set of highly-stable frequency-locked reference signal generators, or a single highly-stable and tunable source of a reference signal.

In this Letter we demonstrate that the frequency detector could remain passive, unbiased (no dc current applied) and nano-sized, and, at the same time, can provide unambiguous and rather accurate frequency determination results, if, instead of a single STMD, we use a pair of STMDs with different resonance frequencies. The proposed method of frequency detection with a pair of passive STMDs implies the determination of the microwave signal frequency by comparing the measured output dc voltages induced in a pair of different STMDs by an input microwave signal and, as we demonstrate below, this method provides a substantial reduction of the frequency determination error in comparison to the case of a measurement using a single STMD.

II. Theory

The proposed frequency detector, based on a pair of STMDs, comprises two uncoupled STMDs spaced by a distance that is substantially smaller than the signal wavelength. The resonance frequencies of these STMDs are different, but sufficiently close to each other, so that the STMDs have almost identical microwave impedances, which allows one to assume that the powers $P_{\mathrm{rf},1}$ and $P_{\mathrm{rf},2}$ of the external microwave signal acting on the first and the second STMD are, practically, the same: $P_{\mathrm{rf},1} = P_{\mathrm{rf},2} = P_{\mathrm{rf}}$. We consider the simplest case, when both STMDs have symmetric Lorentzian-shaped FMR curves. Then, the output dc voltages of the both STMDs, $U_{\mathrm{dc},1}$ and $U_{\mathrm{dc},2}$, can be described by Eq. (1), where we assume that the STMDs have different resonance volt-watt sensitivities $\varepsilon_{\mathrm{res}} = \varepsilon_{\mathrm{res},i}$, different resonance frequencies $f_{\mathrm{res}} = f_{\mathrm{res},i}$, and different FMR linewidths $\Gamma = \Gamma_i$ (here $i = 1$ corresponds to the first STMD and $i = 2$ to the second one).

Considering both STMDs as independent devices, one can write for each of the two STMDs equations in the form of Eq. (1), and, using the assumption $P_{\mathrm{rf},1} = P_{\mathrm{rf},2} = P_{\mathrm{rf}}$, can find the following expression for the frequency f of the input microwave signal:

$$f = \frac{\kappa f_{\mathrm{res},1} - f_{\mathrm{res},2} + \sqrt{(\kappa - 1)\left(\Gamma_2^2 - \kappa\Gamma_1^2\right) + \kappa\Delta f_{\mathrm{res}}^2}}{\kappa - 1}. \tag{2}$$

Here, we assumed that $f_{\mathrm{res},2} > f_{\mathrm{res},1}$, and introduced a dimensionless variable $\kappa = (U_{\mathrm{dc},1}/U_{\mathrm{dc},2})(\varepsilon_{\mathrm{res},2}/\varepsilon_{\mathrm{res},1})(\Gamma_2/\Gamma_1)^2$, which can be easily calculated for a particular set of diodes. We also used the anzatz $\Delta f_{\mathrm{res}} = f_{\mathrm{res},2} - f_{\mathrm{res},1} > 0$.

The above presented solution (2) is unique in the frequency range $f_{\mathrm{res},1} \le f \le f_{\mathrm{res},2}$, and can be used for the determination of an unknown frequency f of the input microwave signal from the measured voltages $U_{\mathrm{dc},1}$ and $U_{\mathrm{dc},2}$ of STMDs with known parameters $\varepsilon_{\mathrm{res},1}$, $\varepsilon_{\mathrm{res},2}$, $f_{\mathrm{res},1}$, $f_{\mathrm{res},2}$, Γ_1, Γ_2.

This solution is valid in the case $\kappa \ne 1$, i.e. when we have diodes with distinctly different parameters. This means, that the proposed method of the external frequency determination is more effective in the case of STMDs having different FMR linewidths and different resonance volt-watt sensitivities (when $\kappa \gg 1$ or $\kappa \ll 1$), but similar resonance frequencies. It is also necessary that the dc voltages $U_{\mathrm{dc},i}(f)$ obtained by both detectors substantially exceeds the noise level. Otherwise, the solution (2) becomes almost equivalent to the solution of Eq. (1) for a single STMD.

If one considers the diodes parameters $\varepsilon_{\mathrm{res},1}$, $\varepsilon_{\mathrm{res},2}$, $f_{\mathrm{res},1}$, $f_{\mathrm{res},2}$, Γ_1, Γ_2 as frequency-independent quantities (at least in the frequency range $f_{\mathrm{res},1} \le f \le f_{\mathrm{res},2}$), the expression for the error Δf in frequency determination can be estimated from Eq. (2) as:

$$\begin{aligned} \Delta f &= \sqrt{\left(\frac{\partial f}{\partial U_{\mathrm{dc},1}}\right)^2 \Delta U_{\mathrm{dc},1}^2 + \left(\frac{\partial f}{\partial U_{\mathrm{dc},2}}\right)^2 \Delta U_{\mathrm{dc},2}^2} \\ &= \frac{\kappa}{2(\kappa-1)^2}\frac{|Q|}{S}\sqrt{\left(\frac{\Delta U_{\mathrm{dc},1}}{U_{\mathrm{dc},1}}\right)^2 + \left(\frac{\Delta U_{\mathrm{dc},2}}{U_{\mathrm{dc},2}}\right)^2}. \end{aligned} \tag{3}$$

Here $Q = (\kappa - 1)(\Gamma_1^2 - \Gamma_2^2) + \Delta f_{\mathrm{res}}[2S - (1+\kappa)\Delta f_{\mathrm{res}}]$, $S = \sqrt{\kappa(\Gamma_1^2 + \Gamma_2^2 + \Delta f_{\mathrm{res}}^2) - \kappa^2\Gamma_1^2 - \Gamma_2^2}$, $\Delta U_{\mathrm{dc},1}$ and $\Delta U_{\mathrm{dc},2}$ are the noise voltages – the total intrinsic fluctuations of the output dc voltages $U_{\mathrm{dc},1}$ and $U_{\mathrm{dc},2}$, respectively.

For a typical case of passive STMDs operating in the presence of thermal noise the voltage fluctuations $\Delta U_{\mathrm{dc},1}$ and $\Delta U_{\mathrm{dc},2}$ can be calculated from Eq. (3) in Ref. [24] (see also [18] for details).

III. Experiment

In our experiment, a microwave current $I(t)$ from an external generator was applied to an MTJ-based STMD via a bias-tee and a microwave probe. The frequency dependence of the STMD output dc voltage was measured by sweeping the microwave signal frequency f at the constant bias magnetic field applied along in-plane hard axis of the FL. To improve the signal-to-noise ratio, a lock-in detection technique was used.

A pair of uncoupled MTJ-based diodes was used as a detector array for precise determination of a frequency of an external signal [25]. In order to separately control the resonance frequencies of the two diodes, it was possible to apply different external fields, $B_{\mathrm{dc},1}$ and $B_{\mathrm{dc},2}$ to the first and the second diode, respectively. A detailed description of the experimental technique used in our measurements can be found in [25], [26].

The MTJs in STMDs used in our experiment had elliptical shapes, and both their FL and PL were in-plane magnetized (see STMDs dimensions and bias dc

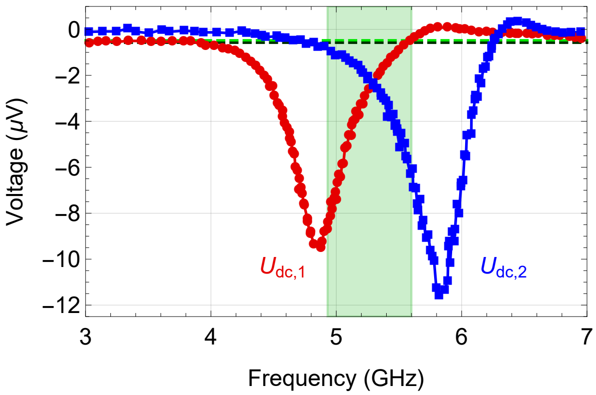

Fig. 1. Output dc voltages $U_{\mathrm{dc},1,2}$ of the two MTJ-based diodes as a function of the signal frequency f. The light green rectangle marks the frequency range from 4.93 GHz to 5.60 GHz in which the frequency determination has been investigated. The green and dark green dashed lines mark the level of 5% of the maximum magnitude of $U_{\mathrm{dc},1,2}$, respectively.

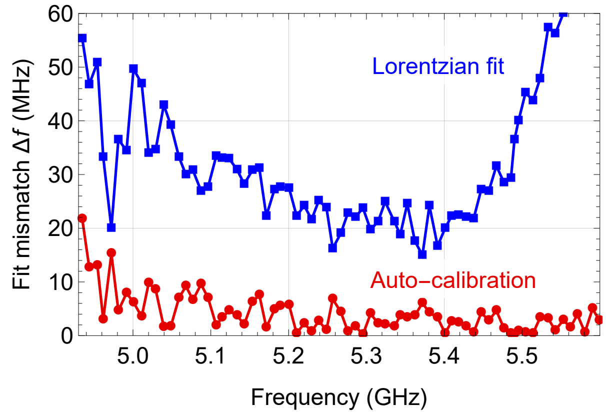

Fig. 2. Frequency mismatch Δf between the determined and actual signal frequencies on the investigated frequency range from 4.93 GHz to 5.60 GHz: blue squares - frequency determination error calculated from (3) using standard Lorentzian fit; red dots - fitting mismatch (Eq.6) of the auto-calibration protocol applied to the output dc voltages $U_{\mathrm{dc},1,2}$.

magnetic field values in Table I in the Supplementary). The STMD stack structure had the following composition: Substrate/SAF/MgO/FL/Cap (SAF: synthetic antiferromagnetic layer). The compositions of SAF and FL are PtMn(15)/$Co_{70}Fe_{30}$(2.5)/Ru(0.85)/$Co_{40}Fe_{40}B_{20}$(2.4), and $Co_{60}Fe_{20}B_{20}$(1.6 – 3.0), respectively (thicknesses are given in nanometers).

Three STMD pairs having different FL thicknesses $l = 3.0$ nm, $l = 2.3$ nm, and $l = 1.6$ nm have been fabricated. The pair of MTJs having the FL thickness $l = 1.6$ nm has demonstrated the best performance: its diodes have the highest sensitivity among the three (see Table II in the Supplementary) and their output dc voltage frequency dependencies have little deviations from the Lorentz-peak form (see Fig. 1.

The first diode in the pair which results we present here has cross-section 110 nm × 50 nm and resonance frequency $f_{\mathrm{res},1} = 4.83$ GHz and the second one has cross-section 85 nm × 50 nm with $f_{\mathrm{res},2} = 5.85$ GHz. The values of the bias dc magnetic field for the curves on the Fig. 1 are $B_{\mathrm{dc},1} = -82.7$ mT and $B_{\mathrm{dc},2} = 97.2$ mT. To show the possibility of determination of the frequency of input microwave signal we investigated the frequency range having minimum frequency $f_{\mathrm{min}} = 4.93$ GHz, maximum frequency $f_{\mathrm{max}} = 5.60$ GHz, and the width $f_{\mathrm{max}} - f_{\mathrm{min}} = 670$ MHz.

As one can see from Fig. 2, the frequency determination error Δf calculated using the Lorentzian fit technique has the value from 15 to 60 MHz in the most of the considered frequency range. Although these values are several times smaller than the frequency determination error (of the order of the FMR linewidth Γ) obtained in the case when a frequency detector based on a single STMD was used, it still might appear too large for many important practical applications. Our analysis shows that the main part of this error comes from a rather unrealistic assumption that the resonance curves of both STMDs have an ideally symmetric Lorentzian shape.

This means, that a more realistic theoretical model, that takes into account the real asymmetric shape of the STMD resonance curves is needed for the accurate determination of the external signal frequency. We, also, would like to note, that analytic accounting for the asymmetric lineshape of the STMD resonance curves $U_{\mathrm{dc}}(f)$ will require modification of Eq. (1), which, in turn, will substantially increase the number of fitting parameters, and might make the derivation of the analytical solution for the signal frequency like (2) practically impossible. Thus, we used a different and more practical method of taking into account the real asymmetric shapes of the STMD resonance curves.

IV. Auto-Calibration Protocol for an STMD pair

To make the process of the signal frequency determination less dependent on the quality and shape of the STMD FMR curves, a new auto-calibration protocol for the STMD pairs has been developed.

The developed protocol automatically compensates for the non-Lorentzian distortions of the STMD sensitivity curves $\varepsilon_{\mathrm{res}}(f)$, and can be applied to any set of the MTJ-based diodes, provided the STMD output dc voltage that has a resonant frequency dependence in the form of peak having a single maximum. Also, both the calibration, and the frequency determination procedures can be performed automatically, and do not require any additional analysis.

The calibration protocol for a pair of STMDs uses the realistic experimental frequency dependences of the output dc voltages $U_{\mathrm{dc},1}(f)$, $U_{\mathrm{dc},2}(f)$, and consists of the following steps:

1) Determination of the peak frequency $f_{\mathrm{p},i}$ and the peak (maximum) voltage $U_{\mathrm{p},i}$ for each STMD ($i = \{1, 2\}$), and calculation of the normalized voltages ν_i to avoid the influence of different resonance sensitivities $\varepsilon_{\mathrm{res},i}$ of the diodes on the frequency determination result:

$$\nu_i = \frac{U_{\mathrm{dc},i}}{U_{\mathrm{p},i}} \,. \tag{4}$$

2) Automatic selection of the calibration frequency range $(f_{\mathrm{min}}, f_{\mathrm{max}})$. This range is the frequency interval between the two peak frequencies $f_{\mathrm{p},i}$ where the output dc voltage magnitude for *each* MTJ-based diode is higher

than 5% of the maximum magnitude (this 5% cutoff level was chosen arbitrary, and is a subject to optimization). The 5% cutoff level was introduced to ensure a sufficiently large signal level from each MTJ inside the calibration range. This is needed to reduce the influence of thermal noise on the frequency determination result.

3) For each frequency inside the calibration range, one should calculate a dimensionless quantity $\eta(f)$, which we defined as the ‘detection signal’:

$$\eta(f) = \frac{\nu_2(f) - \nu_1(f)}{\nu_2(f) + \nu_1(f)} \,. \tag{5}$$

The detection signal $\eta(f)$ is more convenient than the direct voltage ratio ν_1/ν_2, because its values are bounded by -1 and $+1$, and, also, it can be easily generalized to the case of an array of multiple (more then 2) STMDs. Inside the calibration frequency range the detection signal $\eta(f)$ is a monotonic function of frequency f, which allows one to introduce the inverse function $f(\eta)$, which defines the signal frequency as a function of the detection signal η.

4) Fit the experimentally found dependence $f(\eta)$ with a polynomial function $f_{\text{fit}}(\eta)$.

To determine the unknown frequency of an input signal, one has to perform all the above presented steps, and find the unknown frequency f from the fitting curve $f_{\text{fit}}(\eta)$ using detection signal η. All these steps are straightforward, and do not require any complicated calculations.

It is clear, that the accuracy of frequency determination will be limited by the accuracy of fitting $f_{\text{fit}}(\eta)$, which we call the intrinsic error of the calibration procedure. The fitting mismatch can be found as:

$$\Delta f = |f - f_{\text{fit}}(\eta)| \,. \tag{6}$$

To investigate the fitting efficiency one can, also, use statistical parameters, such as average quadratic deviation over all of the experimental data in the calibration range. The stability of the auto-calibration approach can be estimated calculating the dispersion for the fitting mismatch. This can provide the minimum and maximum values of the frequency determination error, so this instability can be explicitly considered while using the calibration method for different frequencies in calibration range.

The results obtained using the simple Lorentzian analytical model and the auto-calibration protocol are compared in Fig. 2. One can see that, apart from a few points at the start of the calibration frequency range, the frequency mismatch produced by the use of the auto-calibration protocol (see red filled circles in Fig. 2) is uniformly below 10 MHz with the average value $\langle\Delta f\rangle = 4.0$ MHz, which is at least one order of magnitude smaller, than the required accuracy of the frequency determination. For comparison, the frequency mismatch corresponding to the standard Lorentzian fit procedure (see Eq. (2)) is also shown in Fig. 2 (see blue squares in Fig. 2). In this case the mismatch is significantly larger in the whole frequency range with average value $\langle\Delta f\rangle = 33.5$ MHz. Thus, the developed auto-calibration protocol decreases the intrinsic error of the frequency determination by about one order of magnitude. Since the technique proposed operates with normalized voltages, it may also improve the detector sensitivity to relatively low input power signals. However, all the received signals should be substantially above the thermal noise floor.

TABLE I
STATISTICAL CHARACTERISTICS OF THE FREQUENCY DETERMINATION USING THE AUTO-CALIBRATION PROTOCOL.

Signal frequency f, GHz	Mean detected frequency $\langle f_{\text{fit}}\rangle$, GHz	Systematic deviation Δf_{syst}, MHz	Random deviation Δf_{rand}, MHz	Total frequency error Δf_{tot}, MHz
5.000	4.990	9.6	27.9	29.5
5.300	5.328	28.3	18.8	34.0
5.600	5.647	47.1	37.6	60.3

To investigate the stability of the auto-calibration protocol, the statistical properties of 50 frequency determination trials have been analyzed. From the obtained data the mean detected frequency $\langle f_{\text{fit}}\rangle$ was calculated. To compare it with the real frequency f of the analyzed microwave signal we calculated the systematic frequency deviation Δf_{syst}, $\Delta f_{\text{syst}} = |f - \langle f_{\text{fit}}\rangle|$. The random deviation Δf_{rand} was defined as the standard deviation of the measured frequency from $\langle f_{\text{fit}}\rangle$. Finally, the total frequency determination error was calculated as:

$$\Delta f_{\text{tot}} = \sqrt{\Delta f_{\text{syst}}^2 + \Delta f_{\text{rand}}^2}. \tag{7}$$

The statistical properties of the auto-calibration protocol for the signal frequency determination are presented in the Table I.

From the Table I one can see, that the total frequency determination error Δf_{tot} is about 30 MHz for the input signal frequencies situated within the operational frequency range, and increases by about a factor of 2 for the frequency $f = 5.6$ GHz at the edge of the operational range. This result practically demonstrates that the detector based on a pair of uncoupled STMDs, and utilizing the developed auto-calibration protocol provides the sufficient accuracy of the frequency determination within its whole operational range.

At the same time, one may notice from the Table I a significant contribution of the systematic error Δf_{syst} to the total frequency determination error Δf_{tot}. The main cause of this systematic error might be the temperature fluctuations, which lead to the fluctuations of the STMD FMR frequency and other characteristics of the STMDs [18], [24], [27]. For example, it was shown in [27], that such fluctuations can be reduced by using standard thermal stabilization schemes. We believe, that thermal stabilization will lead to an increase in the accuracy of the frequency determination by about a factor of 2 (i.e. the frequency determination error can be reduced to $\langle\Delta f_{\text{tot}}\rangle \approx 20$ MHz). Also, experiments show that to ensure good resolution the maximum frequency difference between the adjacent STMDs should be around 2-3 FMR linewidths.

V. CONCLUSION

In conclusion, a method of the accurate determination of the microwave signal frequency using a pair of uncoupled

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resonance-type STMDs, having different resonance frequencies, and, preferably, different linewidths and sensitivities, has been proposed. The method is applicable to the signals of an unknown microwave power, and provides the frequency determination error of $\sim$ 30 MHz, which is substantially smaller than a typical STMD FMR linewidth. Also, in the case when a developed auto-calibration protocol is used, both the calibration and the frequency determination procedures can be performed automatically, and do not require any additional analysis. The developed auto-calibration protocol eliminates errors related to the non-Lorentzian distortions and asymmetry of the STMD FMR lineshape and can be applied to array of STMDs having resonance curves of any shape with a single maximum. It does not require data accumulation and can be used to monitor the microwave signal frequency in real time.

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