Observation of spin-motive force in ferrimagnetic GdFeCo alloy films

Shun Fukuda¹, Hiroyuki Awano¹ and Kenji Tanabe¹*
¹Toyota Technological Institute, Nagoya, 468-8511, Japan
*electronic mail: tanabe@toyota-ti.ac.jp

Abstract

We investigated the spin-motive force (SMF) in ferrimagnetic GdFeCo alloy films using the spin-torque-induced ferromagnetic resonance method. The amplitude of the SMF is enhanced by the Gd doping near a Gd composition of the boundary between in-plane and perpendicularly magnetized films, which is roughly consistent with the analysis based on the SMF theory. Moreover, we find that the sign of the SMF is independent of the spin polarization and that the s-f coupling at Gd atoms does not play as a gauge field for a conduction electron unlike the s-d exchange coupling at transition metals such as Fe and Co.
Introduction

Recently, non-uniform magnetic structures such as magnetic domain wall\(^1\)-\(^2\), magnetic vortex\(^3\)-\(^5\), anti-vortex\(^6\)-\(^8\), and skyrmion\(^9\)-\(^13\) have attracted much attention in both fundamental and applied physics. The magnetic domain wall and skyrmion, which can be controlled by a current, have been studied toward practical application for future memory devices\(^1,2,11\). Moreover, the non-uniform magnetic structure induces effective electric and magnetic fields for conduction electrons. The effective magnetic field induced by the skyrmions has been detected as a Hall effect, which is termed the topological Hall effect\(^12\)-\(^16\). The effective electric field induced by their dynamics is termed the spin-motive force (SMF)\(^17\)-\(^29\). These phenomena are of great interest as the emergent electromagnetism in fundamental physics.

The first observation of the SMF had been reported by Yang and Beach et al. in 2009\(^21\). They accurately controlled magnetic-field-driven domain wall motion in NiFe alloy wires and detected the SMF induced by the motion using the unique lock-in method. After that, several studies on the SMF were also reported by other groups\(^22\)-\(^24,28,29\). In all the studies, however, transition metal alloys such as NiFe alloy\(^22\)-\(^24,29\) and related oxides such as the magnetite Fe\(_3\)O\(_4\)\(^28\) were used and the relationship between material parameters and the SMF is still unclear. Furthermore, the detected voltages are almost 0.1 - 1 \(\mu\)V and we have no guidelines for the material development owing to the enhancement of the SMF.

Here, we investigate the SMF in GdFeCo alloy films and report the influence of Gd on the SMF. The GdFeCo alloy\(^30\)-\(^36\) is a ferrimagnetic material, where magnetic moment of FeCo is antiparallel to that of Gd. We can fabricate RE-rich films, where net magnetization is parallel to the moment of the rare-earth metal (Gd), and TM-rich films, where the transition metal (FeCo) mainly contributes net magnetization, by controlling the composition of the alloy. The boundary composition between the RE-rich and the TM-rich alloys is termed the magnetization compensation point (MCP, \(x = x_c\)). The GdFeCo alloy has perpendicular magnetic anisotropy near the MCP. Moreover, Gd is one of the ferromagnetic materials at room temperature and has the s-f exchange coupling unlike the s-d exchange coupling in the transition metals. Therefore, GdFeCo is one of the suitable materials in studies on the relationship between the SMF and some material parameters such as the saturation magnetization, the diamagnetic field, the spin polarization, the magnetic anisotropy, and the s-f exchange coupling.

Experiment

The Si\(_3\)N\(_4\) (10 nm)/Gd\(_x\)(Fe\(_{82}\)Co\(_{28}\))\(_{1-x}\) (16 nm)/Pt (10 nm) strips were fabricated by a magnetron sputtering, electron-beam lithography, and a lift-off process. Since the Gd metal is easily oxidized, a base pressure in the chamber of the sputtering has been kept low enough and typically lower than 2.0 \(\times\) \(10^{-6}\) Pa. The GdFeCo alloy layer was deposited by a co-sputtering method from Gd and FeCo
targets and the composition of the alloy can be changed by optimization of the cathode power. The composition of all the samples was checked by an energy dispersive X-ray spectrometry. The Pt layer under the GdFeCo layer is used as an electrode for rf currents that induces spin torques and/or rf Ampère magnetic fields, which is quite similar to an experimental method of the spin-torque ferromagnetic resonance (ST-FMR). The SiN layer on the GdFeCo layer is a capping layer to prevent the oxidation of the GdFeCo layer. The widths of the strips are changed along a longitudinal direction of the strips and the structures are not rectangular, but trapezoidal.

We measured the SMF by using the unique ST-FMR method proposed by Nagata et al.\textsuperscript{28} in Fig. 1(a). When an rf-current is injected into a bilayer of Pt/GdFeCo, a magnetic resonance is excited by the rf spin current and the Ampère field induced by the rf current in the Pt layer\textsuperscript{37}. Since the rf current density \( j_e \) is inversely proportional to the shrinking width of the strip \( w \), the cone angle of the magnetization precession is changed along the longitudinal direction of the strips. Thus, the excited magnetic resonance becomes non-uniform dynamics and is expected to induce the SMF voltage along the longitudinal direction. The SMF voltage was measured by using a lock-in and an amplitude modulation methods. The measured dc voltage involves the SMF and the other contribution that originates from the rectification effect of the anisotropic magnetoresistance and the rf current. Although the rectification effect vanishes when the external magnetic field is parallel to the longitudinal direction of the strips, it appears even if the field slightly differs from the longitudinal direction of the strips. The SMF is detected as a symmetrical component centered at zero magnetic field. On the other hand, whereas the rectification voltage involves both symmetric and anti-symmetric components centered at the resonant magnetic field, both of the contributions are anti-symmetric at zero magnetic fields\textsuperscript{37}. Therefore, we extracted the SMF from the measured dc voltage using the symmetry for the magnetic field.

**Results**

Figure 1(b) shows the measured typical dc voltage, whose shape is similar to the Lorentz function. We extract the SMF by using a fitting function of

\[ V = V_0 + V_1 \left[ S_H(H_0) + S_H(-H_0) \right] + V_2 \left[ S_H(H_0) - S_H(-H_0) \right] + V_3 \left[ A_H(H_0) + A_H(-H_0) \right], \]

where \( S_H(H_0) = \Delta H^2 / (H_0 - H_R)^2 + \Delta H^2 \) and \( A_H(H_0) = (H_0 - H_R) \Delta H / ((H_0 - H_R)^2 + \Delta H^2) \). \( H_0 \) is the external magnetic field, \( H_R \) is the resonant magnetic field and \( \Delta H \) is the full width at half maximum (FWHM). The second term has the same symmetry as the SMF and the third and fourth terms attribute to the symmetric and the anti-symmetric components centered at the resonant magnetic field, respectively. The fitting provides information on the resonant frequency, the FWHM, the signal amplitude of the SMF, and the rectification effect.
Figures 2(a-b) show the signal amplitude $V_1$ as a function of the right and left width of the strip. Although the signal of almost 100 nV is detected in the trapezoidal strips, the signal disappears in the rectangular strip, $w_r = w_l = 100 \ \mu$m. The sign of the detected signal depends on the shrinking sides of the strip. Since the amplitude of the SMF, which is induced by the non-uniform magnetic dynamics, should increase with increasing difference between the widths at the sides of the strip, the dependency of the experimental results is consistent with the SMF theory. Moreover, the SMF is represented as

$$V_1 \propto \frac{1}{w_l^2} - \frac{1}{w_r^2}$$

from the calculation (as shown below). The solid curves in Figs. 2(a-b) indicate the fitting curves of the Eq. (2), which is roughly consistent with the experimental results. Hence, these results reveal that $V_1$ is the SMF.

Figure 2(c) shows the Gd-composition dependence of the SMF voltage $V_1$. The deposited GdFeCo film has the MCP at about $x_c = 0.23$ (as shown below). Hence, it is TM-rich when $x < 0.23$ and RE-rich when $x > 0.23$. The GdFeCo film is in-plane from $x = 0.0$ to $x = 0.17$ and in $x > 0.27$ owing to the large diamagnetic fields, which is proportional to the saturation magnetization. The alloy films at $x = 0.18, 0.27$, which were perpendicularly magnetized, were measured by controlling the magnetization direction via the large in-plane magnetic field. Except for $x = 0.12$, the detected voltage surprisingly increases with increasing Gd composition as $x < 0.17$, which indicates that the SMF can become larger than that in alloys that consist of only transition metals such as the FeCo alloy and the permalloy via the Gd doping. Moreover, we notice that the sign of the SMF is not changed at the MCP ($x = x_c$), which means that the sign is independent of the spin polarization. Although the no change is contradictory to the SMF theory\textsuperscript{20}, it is consistent with the previous result\textsuperscript{28} reported by Nagata et al. The voltage detected in the RE-rich films is smaller than that in the TM-rich films, which suggests that the s-f coupling at Gd atoms does not play as a gauge field for a conduction electron, unlike the s-d exchange coupling\textsuperscript{20}.

**Discussion**

To understand the enhancement of the SMF via the Gd doping as $x < 0.17$, we model the motion of the magnetic moment in GdFeCo by assuming that net magnetic moment that consists of Gd and FeCo is a single magnetic moment and derive its equation by utilizing the Landau–Lifshitz–Gilbert (LLG) equation with the spin torque term, the magnetic anisotropy and the diamagnetic field:

$$\frac{dn}{dt} = -\gamma n \times H_{\text{eff}} + \alpha n \times \frac{dn}{dt} + \frac{\hbar}{2\epsilon\mu_0 M_s t} \int (n \times s) \times n. \quad (3)$$

Here, $n$ is a normalized magnetization vector, $\gamma$ is the gyromagnetic ratio, $\alpha$ is the Gilbert damping constant, $\mu_0$ is the permeability, $M_s$ is the saturation magnetization of GdFeCo and $t$ is
the thickness of the GdFeCo layer. The xyz-coordinate direction is defined as the xyz arrows in Fig. 1. \( \mathbf{H}^{\text{eff}} = (h_x - (4\pi M_s N_y + A_y) n_y, H_0)^T \), where \( h_x \) is the Ampère field induced by the rf current, \( N_y \) is the diamagnetic coefficient, \( A_y \) is the anisotropic coefficient, and \( H_0 \) is the external magnetic field. Since the GdFeCo film is perpendicularly magnetized near the MCP \((x = x_c)\), we add only the perpendicular magnetic anisotropy to the LLG equation. When \( \alpha \ll 1 \), \( |n_x|, |n_y| \ll 1 \), and \( |h_x| \ll |H_0| \),

\[
\begin{align*}
n_x &= \frac{[A_H \omega (y h_x) + S_H \omega R (\beta l_y)] + i[-S_H \omega (y h_x) + A_H \omega R (\beta l_y)]}{\alpha \omega R (2H_R + k)} \\
n_y &= \frac{[-S_H \omega (y h_x) + A_H \omega R (\beta l_y)] + i[-A_H \omega (y h_x) - S_H \omega R (\beta l_y)]}{\alpha \omega R (2H_R + k)}
\end{align*}
\]

where \( k = 4\pi M_s N_y + A_y \), \( \omega = \gamma \sqrt{H_R (H_R + k)} \) is an angular frequency of the rf current, \( H_R \) is a resonant field, and \( \omega_R = \gamma H_R \). By substituting \( N_y = 1 \) and \( A_y = -H_y^{\text{ani}} \), we can obtain the relationship between the resonant field and the frequency \( f \),

\[
f = \frac{\gamma}{2\pi} \sqrt{H_R (H_R + 4\pi M_s - H_y^{\text{ani}})}.
\]

\( S_H \) and \( A_H \) are the Lorentz and the anti-Lorentz functions in the Eq. (1), respectively. These FWHMs \( \Delta H \) are proportional to the frequency,

\[
\Delta H = \frac{2\pi \alpha}{\gamma} f.
\]

Assuming \( h_x = h e^{i\omega t} \) and \( j_s = j e^{i\omega t} \), we can obtain

\[
\begin{align*}
n_x &= \frac{\sqrt{S_H \omega R (\beta l_y)^2 + (\omega R \beta)^2}}{\omega R (\omega y H_R + k)} \frac{1}{\omega} \cos(\omega t + \delta) \\
n_y &= \frac{\sqrt{S_H \omega R (\beta l_y)^2 + (\omega R \beta)^2}}{\alpha \omega R (\omega y H_R + k)} \frac{1}{\omega} \sin(\omega t + \delta)
\end{align*}
\]

\[
\tan \delta = \frac{A_H \omega R \beta j - S_H \omega y h}{S_H \omega R \beta j + A_H \omega y h}
\]

which reveal that the magnetization trajectory is not a circular orbit, but an elliptical orbit when \( 4\pi M_s - H_y^{\text{ani}} \neq 0 \). In particular, the eccentricity mainly depends on the magnetic anisotropy and the diamagnetic field and is independent of the ratio of the rf spin current to the rf Ampère field. On the other hand, the phase of the trajectory is strongly influenced by the ratio of the rf spin current to the rf Ampère field.

Figures 3(a-c) show the resonant field \( H_r \) and the FWHM \( \Delta H \), and the SMF voltage \( V_1 \) as a function of the frequency of the rf current. \( 4\pi M_s - H_y^{\text{ani}} \) is estimated by using the fitting function of the Eq. (5). Since the anisotropic field is parallel to the diamagnetic field, \( 4\pi M_s - H_y^{\text{ani}} \) is regarded as a single parameter. The saturation magnetization \( 4\pi M_s \) is estimated from the M-H curve.
The SMF voltage should be the product of the Gilbert damping constant, which corresponds to the direction of the magnetization. The SMF voltage is calculated by \( V_{SMF} = \frac{1}{2} E_x dz \). By substituting the Eq. (7) into the Eq. (8),

\[
V_{SMF} = S_H \frac{\hbar l^2}{4\alpha^2 \gamma e t^2} \left( \frac{1}{w_r^2} - \frac{1}{w_r^2} \right) \frac{(H_R + k)(y\tilde{h})^2 + H_R(\beta j)^2}{(2H_R + k)^2},
\]

where, \( l \) is the amplitude of the rf current, \( \tilde{h} = h/j_e \), and \( j = j/j_e \) because both \( h \) and \( j \) are proportional to the current density, \( j_e \). The equation reveals that the SMF voltage should be the Lorentz function and be proportional to \( w_r^{-2} - w_r^{-2} \). Since the SMF voltage is inversely proportional to the square of the Gilbert damping constant, we evaluate the SMF as the product of the SMF voltage and the square of the damping constant, \( \alpha^2 V_{SMF} \). Besides, the SMF depends on two unknown parameters, which indicates the contributions of the rf Ampère field \( \gamma \tilde{h} \) and the rf spin current \( \beta j \), and we cannot analyze the experimental data using the equation. Hence, we roughly assume \( \gamma \tilde{h} \approx \beta j \) from the obtained fitting parameters of \( V_2 \) and \( V_3 \) in the Eq. (1). Then, \( \alpha^2 V_{SMF} \) is represented by

\[
\alpha^2 V_{SMF} \propto \left\{ \gamma^2 (4\pi M_s - H_{x}^{ani})^2 + 4\omega^2 \right\}^{\frac{1}{2}},
\]

which means that the SMF voltage decreases with increasing the frequency of the rf current. The equation is applied to the SMF-voltage dependence of the frequency in Fig. 3(c). When we fit the dependency by using the fitting function of \( V_1 = a_0 + a_1 \left( \gamma^2 k^2 + 4\omega^2 \right)^{\frac{1}{2}} \), the fitting curve is good agreement with the decreasing tendency in Fig. 3c, which suggests the validity of the approximation.

Figures 4(a-c) show the Gd-composition dependences of the Gilbert damping constant \( \alpha \), the saturation magnetization \( 4\pi M_s \), \( 4\pi M_s - H_{y}^{ani} \), and \( \alpha^2 V_1 \). The damping constant of about 0.001 is quite small at \( x = 0 \), which is roughly consistent with the previous studies. The damping constant trends to increase with increasing Gd composition \( x \), which is also consistent with the previous experimental report. The theoretical suggestion indicates that the damping constant diversifies to infinity at an angular momentum compensation point, which is the composition that the angular momentum of FeCo and Gd cancel out. The dependence of \( 4\pi M_s \), which is obtained from the M-H curve, shows that the MCP is near \( x = 0.23 \) and the dependence of \( 4\pi M_s - H_{y}^{ani} \) shows that the boundary composition between the in-plane and perpendicularly magnetized films is near \( x = 0.17, 0.28 \). According to the Eq. (9), since the height \( V_1 \) in the Lorentz distribution strongly depends on the damping constant, the SMF is evaluated as the product of \( V_1 \) and \( \alpha^2 \) as shown in Fig. 4(c).
As a result, $\alpha^2 V_1$ increases with increasing Gd composition up to $x = 0.16$, which is close to the boundary composition, and decreases with increasing Gd composition after that. The curve in Fig. 4(c), which is a guide by eye, is approximately drawn by using the Eq. (10). Since the curve overlaps with the experimental data, the enhancement via the Gd doping can be roughly expressed by the competition between the diamagnetic field and the magnetic anisotropic field. In other words, when the trajectory of the magnetization precession becomes circular, the output of the SMF is maximized.

We now briefly comment on the guideline of the material development due to the enhancement of the SMF voltage, which is discovered from our study. Firstly, what is most important is that the trajectory of the magnetization precession is circular. The SMF increases with decreasing eccentricity of the trajectory. Secondly, the SMF voltage is inversely proportional to the square of the Gilbert damping constant. Hence, ultralow damping materials are desired. Finally, the s-f exchange coupling is unsuitable for a gauge field\textsuperscript{18-20} to induce the SMF.

**Conclusion**

We have investigated the SMF induced in the ferrimagnetic GdFeCo alloy films by using the unique spin-torque ferromagnetic resonance method. The amplitude of the SMF, which strongly depends on the Gd composition, is maximized at the boundary composition between the in-plane and the perpendicularly magnetized films, which shows that the trajectory of the magnetization precession is crucial in order to enhance the SMF. Since the SMF voltage is inversely proportional to the square of the damping constant, ferromagnetic materials with ultralow damping constants are desired to enhance the SMF voltage. Moreover, we find that the sign of the SMF is not changed with the spin polarization. The no change, which is contradictory to the SMF theory, is consistent with the previous experimental results. The SMF voltages in the RE-rich alloys are smaller than those in the TM-rich alloys, which suggests that the s-f exchange coupling at the Gd atoms is unsuitable for a gauge field to induce the SMF.
Acknowledgments

We would like to thank Mr. A. Takahashi and Dr. S. Sumi for collaboration at an early stage of this work. This work was partly supported by a Grant-in-Aid for Young Scientists (B) (No. 18K14123) from JSPS and a Toyota Riken scholar from the Toyota Physical and Chemical Research Institute.

References

1) A. Yamaguchi, T. Ono, S. Nasu, K. Miyake, K. Mibu, and T. Shinjo, Phys. Rev. Lett. 92, 077205 (2004).
2) S. S. P. Parkin, M. Hayashi, and L. Thomas, Science 320, 190 (2008).
3) K. Yamada, S. Kasai, Y. Nakatani, K. Kobayashi, H. Kohno, A. Thiaville, and T. Ono, Nat. Mater. 6, 270 (2007).
4) K. Nakano, K. Tanabe, R. Hiramatsu, D. Chiba, N. Ohshima, S. Kasai, T. Sato, Y. Nakatani, K. Sekiguchi, K. Kobayashi, and T. Ono, Appl. Phys. Lett. 102, 072405 (2013).
5) K. Tanabe, D. Chiba, and T. Ono, Jpn. J. Appl. Phys., Part 1 49, 078001 (2010).
6) K. Shigeto, T. Okuno, K. Mibu, T. Shinjo, and T. Ono, Appl. Phys. Lett. 80, 4190 (2002).
7) K. Tanabe and K. Yamada, Appl. Phys. Lett. 110, 132405 (2017).
8) K. Tanabe and K. Yamada, Appl. Phys. Exp. 11, 113003 (2018).
9) U. K. Rössler, A. N. Bogdanov, and C. Pfleiderer, Nature 442, 797 (2006).
10) S. Mühlbauer, B. Binz, F. Jonietz, C. Pfleiderer, A. Rosch, A. Neubauer, R. Georgii, and P. Böni, Science 323, 915 (2009).
11) A. Fert, V. Cros, and J. Sampaio, Nat. Nanotechnol. 8, 152 (2013).
12) M. Lee, W. Kang, Y. Onose, Y. Tokura, and N. P. Ong, Phys. Rev. Lett. 102, 186601 (2009).
13) A. Neubauer, C. Pfleiderer, B. Binz, A. Rosch, R. Ritz, P. G. Niklowitz, and P. Böni, Phys. Rev. Lett. 102, 186602 (2009).
14) J. Ye, Y. B. Kim, A. J. Millis, B. I. Shraiman, P. Majumdar, and Z. Tešanović, Phys. Rev. Lett. 83, 3737 (1999).
15) Y. Taguchi, Y. Oohara, H. Yoshizawa, N. Nagaosa, and Y. Tokura, Science 291, 2573 (2001).
16) Y. Machida, S. Nakatsuji, S. Onoda, T. Tayama, and T. Sakakibara, Nature 463, 210 (2010).
17) L. Berger, Phys. Rev. B 33, 1572 (1986).
18) G. E. Volovik, J. Phys. C 20 L83 (1987).
19) A. Stern, Phys. Rev. Lett. 68, 1022 (1992).
20) S. E. Barnes and S. Maekawa, Phys. Rev. Lett. 98, 246601 (2007).
21) S. A. Yang, G. S. D. Beach, C. Knutson, D. Xiao, Q. Niu, M. Tsoi, and J. L. Erskine, Phys. Rev. Lett. 102, 067201 (2009).
22) Y. Yamane, K. Sasage, T. An, K. Harii, J. Ohe, J. Ieda, S. E. Barnes, E. Saitoh, and S.
Maekawa, Phys. Rev. Lett. 107, 236602 (2011).
23) K. Tanabe, D. Chiba, J. Ohe, S. Kasai, H. Kohno, S. E. Barnes, S. Maekawa, K. Kobayashi, and T. Ono, Nat. Commun. 3, 845 (2012).
24) M. Hayashi, J. Ieda, Y. Yamane, J. Ohe, Y. K. Takahashi, S. Mitani, and S. Maekawa, Phys. Rev. Lett. 108, 147202 (2012).
25) K.-W. Kim, J.-H. Moon, K.-J. Lee, and H.-W. Lee, Phys. Rev. Lett. 108, 217202 (2012).
26) J.-i. Ohe, and Y. Shimada, Appl. Phys. Lett. 103, 242403 (2013).
27) Y. Yamane, S. Hemmatiyan, J. Ieda, S. Maekawa and J. Sinova, Sci. Rep. 4, 6901 (2014).
28) M. Nagata, T. Moriyama, K. Tanabe, K. Tanaka, D. Chiba, J. Ohe, Y. Hisamatsu, T. Niizeki, H. Yanagihara, and E. Kita, Appl. Phys. Express 8, 123001 (2015).
29) W. Zhou, T. Seki, H. Imamura, J. Ieda, and K. Takanashi, Phys. Rev. B 100, 094424 (2019).
30) P. Hansen, C. Clausen, G. Much, M. Rosenkranz, and K. Witter, J. Appl. Phys. 66, 756 (1989).
31) C. D. Stanciu, A. V. Kimel, F. Hansteen, A. Tsukamoto, A. Itoh, A. Kirilyuk, and T. Rasing, Phys. Rev. B 73, 220402(R) (2006).
32) M. Binder, A. Weber, O. Moseendz, G. Woltersdorf, M. Izquierdo, I. Neudecker, J. R. Dahn, T. D. Hatchard, J. U. Thiele, C. H. Back, and M. R. Scheinfein, Phys. Rev. B 74, 134404 (2006).
33) X. Jiang, L. Gao, J. Z. Sun, and S. S. P. Parkin, Phys. Rev. Lett. 97, 217202 (2006).
34) K. J. Kim, S. K. Kim, Y. Hirata, S. H. Oh, T. Tono, D. H. Kim, T. Okuno, W. S. Ham, S. Kim, G. Go, Y. Tserkovnyak, A. Tsukamoto, T. Moriyama, K. J. Lee, and T. Ono, Nat. Mater. 16, 1187 (2017).
35) D.-H. Kim, T. Okuno, S. K. Kim, S.-H. Oh, T. Nishimura, Y. Hirata, Y. Futakawa, H. Yoshikawa, A. Tsukamoto, Y. Tserkovnyak, Y. Shiota, T. Moriyama, K.-J. Kim, K.-J. Lee, and T. Ono, Phys. Rev. Lett. 122, 127203 (2019).
36) T. Seki, A. Miura, K. Uchida, T. Kubota, and K. Takanashi, Appl. Phys. Express 12, 023006 (2019).
37) L. Liu, T. Moriyama, D. C. Ralph, and R. A. Buhrman, Phys. Rev. Lett. 106, 036601 (2011).
38) M. A. W. Schoen, D. Thonig, M. L. Schneider, T. J. Silva, H. T. Nembach, O. Eriksson, O. Karis and J. M. Shaw, Nature Physics 12, 839 (2016).
Fig. 1. (a) Schematic illustration of the measurement setup. (b) The detected typical dc voltage as a function of the external magnetic field. The blue curve represents the fitted data. The power of the rf current is 10 dBm. The Fe$_{82}$Co$_{18}$ alloy is used. (c) Each component of the fitting function. The data in the upper figure has the same symmetry as the SMF. On the other hand, the data in the lower figure has the same symmetry as the signals of the rectification effect.
Fig. 2. (a-b) The detected voltages, $V_1$, as a function of the widths of the left and the right edges of the ferromagnetic strips. The frequency and the power of the rf current are 6 GHz and 10 dBm, respectively. $w_r$ and $w_l$ are defined in the insets. (c) The Gd composition dependence of the detected voltages, $V_1$. The frequency and the power of the rf current are 6 GHz and 10 dBm, respectively. The width of the left edge is 100 $\mu$m and the width of the right edge is 20 $\mu$m.
Fig. 3. (a-c) The resonant field, the FWHM, and the SMF voltage as a function of the frequency of the rf current. The power of the rf current is 10 dBm. The width of the left edge is 100 μm and the width of the right edge is 20 μm. (d) The magnetization-field curve. The composition of the used alloy is $x = 0.16$. 
Fig. 4. (a) The Gilbert damping constant as a function of the Gd composition. (b) The saturation magnetization and $4\pi M_s - H_y$ as a function of the Gd composition. (c) $\alpha^2 V_1$ as a function of the Gd composition. The frequency and the power of the rf current are 6 GHz and 10 dBm, respectively. The blue curve is a guide for the eye, which is written by using the Eq. (10).