Switching ferromagnetic spins by an ultrafast laser pulse: Emergence of giant optical spin-orbit torque

G. P. Zhang¹, Y. H. Bai² and Thomas F. George³

¹Department of Physics, Indiana State University - Terre Haute, IN 47809, USA
²Office of Information Technology, Indiana State University - Terre Haute, IN 47809, USA
³Office of the Chancellor and Center for Nanoscience, Departments of Chemistry & Biochemistry and Physics & Astronomy, University of Missouri-St. Louis - St. Louis, MO 63121, USA

received 5 July 2016; accepted in final form 19 September 2016
published online 7 October 2016

PACS 75.78.Jp – Ultrafast magnetization dynamics and switching
PACS 75.40.Gb – Dynamic properties (dynamic susceptibility, spin waves, spin diffusion, dynamic scaling, etc.)
PACS 78.20.Ls – Magneto-optical effects

Abstract – Faster magnetic recording technology is indispensable to massive data storage and big data sciences. All-optical spin switching offers a possible solution, but at present it is limited to a handful of expensive and complex rare-earth ferrimagnets. The spin switching in more abundant ferromagnets may significantly expand the scope of all-optical spin switching. Here by studying 40000 ferromagnetic spins, we show that it is the optical spin-orbit torque that determines the course of spin switching in both ferromagnets and ferrimagnets. Spin switching occurs only if the effective spin angular momentum of each constituent in an alloy exceeds a critical value. Because of the strong exchange coupling, the spin switches much faster in ferromagnets than weakly coupled ferrimagnets. This establishes a paradigm for all-optical spin switching. The resultant magnetic field (65 T) is so big that it will significantly reduce high current in spintronics, thus representing the beginning of photospintronics.

Copyright © EPLA, 2016

Introduction. – Magnetic switching is the single most important operation for any modern magnetic storage device, where a magnetic field is employed to switch microscopic spins from one direction to another. However, as the areal density increases, the switching speed becomes a major bottleneck for future technological advancement. A possible solution emerged when Beaurepaire et al. [1] reported that a 60 fs laser pulse reduced the spin moment of ferromagnetic nickel films within 1 ps. Their finding heralded the arrival of femtotechnology [2–4], and research efforts intensified immediately [5,6]. However, for over a decade, the focus has been on demagnetization, not magnetic switching. A major breakthrough came when Staniciu and coworkers [7] demonstrated that a single laser pulse could permanently switch the magnetic spin orientation in amorphous GdFeCo samples. This all-optical helicity-dependent spin switching (AOS) ignited the research community since it may be an alternative to the current magnetic storage technology [4]. However, most AOS samples are amorphous [8,9] and are hard to simulate without significant approximations. To this end, a unified understanding is still missing, but several promising mechanisms have been proposed, which include the inverse Faraday effect [7,10], spin-flip stimulated Raman scattering [11,12], magnetic circular dichroism [13], magnetic sublattice competition [14], pure thermal effect [15,16] and ultrafast exchange scattering [17]. Recently, Lambert et al. [18] reported AOS in an ultrathin ferromagnetic [Co(0.4 nm)/Pt(0.7 nm)]₃ multilayer. Medapalli et al. [19] demonstrated that the helicity-dependent switching in Co/Pt proceeds in two steps [20]. Such a system is much more amenable to the simulation without any major approximation, and its magnetic properties have been well known for some time [21]. It is likely that a detailed study of such a system may shed new light on AOS.

Spin reversal theory. – We employ a thin film of 101 × 101 × 4 or 40804 lattice sites in a simple cubic structure (see the top half of fig. 1) with an open boundary condition. Each site has a spin $\mathbf{S}$, which is exchange-coupled to the nearest-neighboring spins through the exchange interaction $J_{ex}$. Our Hamiltonian [22–25], which is often
The light propagates along the +z-direction with a complete model. We assume that the electron moves along the +z-axis, so that all the spatial variables are dimensionless measured in the unit of the lattice site number along each direction, so that all the spatial variables are dimensionless or in the unit of the site number. The laser spot is centered at \( x_c = 51 \) and \( y_c = 51 \) with radius \( r \) and lateral spatial profile \([10]\) \( e^{-((x-x_c)^2+(y-y_c)^2)/r^2} \) (in the xy plane). The laser electric field is described by

\[
E(r, t) = A(t) \exp \left[-\frac{(x-x_c)^2 + (y-y_c)^2}{r^2} - \frac{z}{d}\right],
\]

where \( x \) and \( y \) are the coordinates in the unit of the site number. Since in the following our spins are all initialized along the \(-z\)-axis, we choose a left-circularly polarized field \( A(t) \) which has a Gaussian shape \( A(t) = A_0 e^{-t^2/T^2} \left[ -\sin(\omega t)\hat{x} + \cos(\omega t)\hat{y}\right] \), where \( \omega \) is the laser carrier frequency, \( T \) is the laser pulse duration, \( A_0 \) is the laser field amplitude, \( t \) is time, \( \hat{x} \) and \( \hat{y} \) are unit vectors, respectively. We choose \( T = 100 \) fs. We only consider a resonant excitation where the laser photon energy \( h\omega = 1.6 \) eV matches the system energy \( h\Omega \); for an off-resonant excitation, we refer the reader to a prior study [24]. In transition metals, the penetration depth is about 14 nm, which corresponds to 30 layers, so we choose \( d = 30 \). To compute the spin evolution, we employ Heisenberg’s equation of motion, \( \hbar \dot{A} = [A, H] \), where we make the time-dependent Hartree-Fock approximation, so that all the operators are replaced by their respective expectation values, and then we solve the equation numerically. Our calculation of the spin change is similar to that of Wienholdt et al. [27] though they used a thermal field.

**Dependence of spin switching on spin angular momentum.** We choose eight initial spin momenta \( S_z(0) \) from 0.2 \( \hbar \) to 1.6 \( \hbar \) in steps of 0.2 \( \hbar \), which covers most magnetic materials. For each \( S_z(0) \), we vary the laser field amplitude \( [3,19] A_0 \) from 0.01 to 0.08 \( \text{V/Å} \) in steps of 0.002 \( \text{V/Å} \). This step is tedious but necessary, since different \( S_z(0) \) have different optimal field amplitudes for spin reversal. We fix the spin-orbit coupling at \( \lambda = 0.06 \text{eV}/\hbar^2 \), the exchange interaction \( J_{ex} \) at 1 \( \text{eV}/\hbar^2 \), and the spot radius of \( r = 100 \). The spins are initialized along the \(-z\)-axis, equivalent to applying a magnetic uniaxial anisotropy. A spin reversal is considered achieved if the z-component spin angular momentum \( S_z \) changes from a negative value to a large and positive value at the end of the dynamics. Figure 2(a) shows the normalized and system-averaged spin as a function of time for each \( S_z(0) \) at its respective optimal laser field amplitude. All the curves, except for \( S_z(0) = 0.2 \hbar \), are vertically shifted for clarity. The dotted horizontal lines denote 0 \( \hbar \). We start with \( S_z(0) = 0.2 \hbar \), and we see that the spin does not switch and only oscillates around 0 \( \hbar \) with a period determined by the product of \( \lambda \) and \( S_z(0) \) [24,28]. When we increase \( S_z(0) \) to 0.4 \( \hbar \), the oscillation is attenuated and the final spin is barely above 0 \( \hbar \). And the situation does not change much for \( S_z(0) = 0.6 \hbar \). However, when we continue to increase \( S_z(0) \) above 0.8 \( \hbar \), the spin ringing is strongly reduced, and the final spin settles down at a large positive value, an indication of spin reversal. Above 0.8 \( \hbar \), the situation gets better. For this reason, we define a critical spin angular momentum \( S_z^c = 0.8 \pm 0.2 \hbar \) for AOS.
A crease may offer an alternative to the existing models. If we in-
model but instead they simply suggest that our model
phase diagram of spin reversal ($r = 100$ and
exchange integral finally on the laser field amplitude for three values of the

To quantify AOS, we define the spin switchability as
$\eta = \frac{S_z(0)}{S_z(0)} \times 100\%$, where $S_z^f$ is the final spin angular
momentum. This definition is different from that of Va-
haplar et al. [10]. We fix $S_z(0) = 1.2\ h$, but change the
spin-orbit coupling $\lambda$. Note that our conclusions are the
same for different $S_z(0)$ as far as it is above $S_z^c$. Figure 2(b)
shows that a minimum of $\lambda = 0.04\ eV/\hbar^2$ is required to re-
verse spins. Too small a $\lambda$ only leads to a strong spin
oscillation, regardless of the laser field amplitude. This
indicates a unique role of spin-orbit coupling (SOC) in AOS.
The roles of the exchange interaction and laser field am-
plitude are shown in fig. 2(c), where we fix $S_z(0) = 1.2\ h$, $r = 100$ and $\lambda = 0.06\ eV/\AA^2$. We notice that as $A_0$
increases, $S_z$ sharply increases and reaches its maximum. If we
increase it further, $S_z$ is reduced since the spin
overshoots, and an asymmetric peak is formed. This constit-
utes our first criterion that the laser amplitude must fall
into a narrow region for AOS to occur. This is consistent with Medapalli et al.’s finding (see fig. 1(c) of their pa-
per [19]); such a helicity-dependent switching also agrees with another study by El Hadri et al. [20]. These agree-
ments do not necessarily validate all the aspects of our
model but instead they simply suggest that our model
may offer an alternative to the existing models. If we in-
crease $A_0$ further, a second peak appears since the spin re-
switching starts. These double peaks do not appear for a smaller $S_z(0)$. We find that the exchange does not
change this dependence a lot.

Phase diagram of spin reversal. – We construct a
phase diagram of spin reversal ($\eta - S_z(0)$) in fig. 3(a) for
thirteen $S_z(0)$’s and two radii of the laser spot, $r = 100$ and
50. For $\eta$ to exceed 50–60%, $S_z(0)$ must be higher than
the critical value of $S_z^c = 0.8\pm 0.2\ h$. The long-
dashed line denotes $S_z^c$. We see that the nickel’s spin
momentum is well below $S_z^c$, which explains why nickel has never been used for AOS. Co is on the threshold. In Co-Pt
granular samples [29], the effective spin magnetic moment
per 3d hole is $0.77\ \mu_0$; since there are 2.49–2.62 holes, the
spin angular momentum is 0.96 $\hbar$, satisfying this criterion.
In the ultrathin ferromagnetic [Co(0.4 nm)/Pt(0.7 nm)]$_3$
films [18], due to the reduced dimensionality, the enhanced
spin moment greatly increases the chance for AOS. The
empty boxes in fig. 3(a) represent the case with $r = 50$
(which is close to the switch limit), where only a small
portion of the sample is exposed to the laser light. We see
that the switchability reduces sharply since the laser flu-
ence on lattice sites away from the center of the laser beam
becomes very weak and is not strong enough to reverse spins on those sites. Since the essence of AOS is rooted in
spin-orbit coupling and all the switchabilities are obtained
at the optimal field amplitude, we do not expect that a
more accurate potential would change the phase diagram
strongly. Our criterion not only applies to ferromagnets,
but also to ferrimagnets. Figure 3(b) illustrates that each
of the major elements in all the 11 GdFeCo and TbFe
alloys [30] has the effective spin above $S_z^c$. This constitutes
strong evidence that our finding has a broader impact on
the ongoing research in all-optical spin switching.

Emergence of optical spin-orbit torque. – While
the effect of the laser field amplitude on AOS is obvi-
ous [31], how the initial spin $S_z(0)$ affects the spin
switching is not obvious. We examine how the spin evolves with

---

**Fig. 2:** (Colour online) (a) Time evolution of the $z$-component of the normalized and system-averaged spin angular momentum for eight initial spin values $S_z(0)$ from $0.2\ h$ to $1.6\ h$. The spin reversal realized starts once $S_z(0)$ is around and above $0.8\ h$. (b) Switchability as a function of spin-orbit coupling. The critical value is around $0.04\ eV/\hbar^2$. (c) Dependence of the final spin on the laser field amplitude for three values of the exchange integral $J_{ex}$. To quantify AOS, we define the spin switchability as $\eta = \frac{S_z(0)}{S_z(0)} \times 100\%$, where $S_z^f$ is the final spin angular momentum. This definition is different from that of Vahaplar et al. [10]. We fix $S_z(0) = 1.2\ h$, but change the spin-orbit coupling $\lambda$. Note that our conclusions are the same for different $S_z(0)$ as far as it is above $S_z^c$. Figure 2(b) shows that a minimum $\lambda = 0.04\ eV/\hbar^2$ is required to reverse spins. Too small a $\lambda$ only leads to a strong spin oscillation, regardless of the laser field amplitude. This indicates a unique role of spin-orbit coupling (SOC) in AOS. The roles of the exchange interaction and laser field amplitude are shown in fig. 2(c), where we fix $S_z(0) = 1.2\ h$, $r = 100$ and $\lambda = 0.06\ eV/\AA^2$. We notice that as $A_0$ increases, $S_z$ sharply increases and reaches its maximum. If we increase it further, $S_z$ is reduced since the spin overshoots, and an asymmetric peak is formed. This constitutes our first criterion that the laser amplitude must fall into a narrow region for AOS to occur. This is consistent with Medapalli et al.’s finding (see fig. 1(c) of their paper [19]); such a helicity-dependent switching also agrees with another study by El Hadri et al. [20]. These agreements do not necessarily validate all the aspects of our model but instead they simply suggest that our model may offer an alternative to the existing models. If we increase $A_0$ further, a second peak appears since the spin re-switching starts. These double peaks do not appear for a smaller $S_z(0)$. We find that the exchange does not change this dependence a lot.

**Fig. 3:** (Colour online) (a) Phase diagram of the spin switchability vs. the initial spin angular momentum $S_z(0)$ at the respective optimal laser field amplitudes. The empty circles and boxes refer to the results with $r = 100$ and $r = 50$, respectively. The long-dashed line denotes the critical spin $S_z^c$. Two thin vertical lines represent the spins for Ni and Fe. Co is on the border line, while Gd and Tb are way above $S_z^c$. (b) Computed experimental effective spin angular momentum for each element in 11 GdFeCo and TbFe alloys [30]. Without exception, all elements have spin larger than $S_z^c$.

---

57003-p3
For a spin at site \(i\), the spin angular momentum \(S\) precedes according to

\[
\frac{dS_i}{dt} = \sum_{j(\neq i)} J_{ij} S_i \times S_j + \lambda (L_i \times S_i),
\]

where the two driving terms on the right-hand side represent two torques. The first is the Heisenberg exchange torque \(\tau_{\text{ex}} = \sum_{j(\neq i)} J_{ij} S_i \times S_j\). Since all the spins are ferromagnetically ordered, this torque is very small. The second one is the spin-orbit torque (SOT), \(\tau_{\text{soc}} = \lambda (L_i \times S_i)\), which may serve as a source term for the inverse Faraday effect [32,33]. Before the laser excitation, \(\tau_{\text{soc}}\) is small, since in solids the orbital angular momentum \(L\) is largely quenched. With the arrival of the laser pulse, \(L\) is boosted sharply [32] (see fig. 4) and helicity dependent, where \(J_{ex} = 1 \text{eV}/\hbar^2\), and \(S_z(0) = 0\). The torque is zero in the beginning. All the torques are in the units of \(\hbar/\text{fs}\). (d) Same as (c) but for \(S_z(0) = 1.2\hbar\) [25].

We choose two initial spin momenta, \(S_z(0) = 0.3\hbar\) and \(1.2\hbar\), with all the spins initialized along the \(-z\)-axis (see the light blue arrows in figs. 5(a) and (b)). Figure 5(a) shows that at \(0.3\hbar\) the spin undergoes strong oscillations and shows many spirals, but does not settle down to the \(+z\)-axis after the laser pulse is gone (see the red arrow). By contrast, at \(1.2\hbar\) the spin flips over from the \(-z\)- to \(+z\)-axis within 110 fs, without strong oscillation (see the solid red arrow). To understand why the initial spin angular momentum has such a strong effect on AOS, fig. 5(c) shows that \(\tau_{\text{soc}}\) at \(0.3\hbar\) is very weak, around 0.01 \(\hbar/\text{fs}\), and more importantly, it rapidly swings between positive and negative values, both of which are detrimental to the spin reversal. At \(S_z(0) = 1.2\hbar\), \(\tau_{\text{soc}}\) is positive and large, which allows the spin to switch over successfully. This suggests that SOT offers an alternative path to AOS (see the bottom part of fig. 1), and it acts like an effective magnetic field, which has been sought after in the literature [10,15] for nearly a decade. At \(1.2\hbar\), we time-integrate the torque from \(-200\) to \(+200\) fs and find that the time-averaged torque corresponds to 65 T of a magnetic field. In spintronics, the spin transfer torque heavily relies on the high electric current [26,36]. Such a large SOT, if implemented in real experiments, should significantly reduce the requirement of huge electric current for spintronics [37], and thus opens a door for rapid applications in storage technology [38].

**Conclusion.** — We have investigated all-optical spin switching in 40000 ferromagnetic spins. We identify that it is the laser-induced optical spin-orbit torque that determines the fate of spin switching. The spin-orbit torque sensitively depends on the value of the initial spin momentum.
of each active element in a sample, regardless of the types of magnets. To switch, each active element must have its effective spin angular momentum larger than \((0.8 \pm 0.2)\hbar\). This means that the switchability in Fe, Gd and Tb is likely to be higher than Co and Ni. PMA observed in various AOS materials \cite{9} seems to be an indication of enhanced spin moment, which is in line with our theory. The ps all-optical spin switching observed in ferromagnets is associated with the weak exchange coupling; in ferromagnets, with a stronger coupling, the switching is much faster. SOT is so large that it will significantly reduce the electric current used in spintronics. After our present study was finished, we noticed a recent publication by Bokor’s group \cite{37} to use a laser to assist magnetization reversal. A combination of photonics and spintronics represents the arrival of photospintronics \cite{39}.

***

We would like to thank Dr. A. Hassdenteufel for sending us the experimental results \cite{30}. This work was solely supported by the U.S. Department of Energy under Contract No. DE-FG02-06ER46304. Part of the work was done on Indiana State University’s quantum cluster and high-performance computers. The research used resources of the National Energy Research Scientific Computing Center, which is supported by the Office of Science of the U.S. Department of Energy under Contract No. DE-AC02-05CH11231. This work was performed, in part, at the Center for Integrated Nanotechnologies, an Office of Science User Facility operated for the U.S. Department of Energy (DOE) Office of Science by Los Alamos National Laboratory (Contract DE-AC52-06NA25396) and Sandia National Laboratories (Contract DE-AC04-94AL85000).

REFERENCES

\[1\] Beaurepaire E., Merle J. C., Daunois A. and Bigot J.-Y., \textit{Phys. Rev. Lett.}, \textbf{76} (1996) 4250.
\[2\] Zhang G. P., Hübner W., Beaurepaire E. and Bigot J.-Y., \textit{Top. Appl. Phys.}, \textbf{83} (2002) 245.
\[3\] Zhang G. P. and Hübner W., \textit{Phys. Rev. Lett.}, \textbf{85} (2000) 3025.
\[4\] Kirilyuk A., Kimel A. V. and Rasing Th., \textit{Rev. Mod. Phys.}, \textbf{82} (2010) 2731.
\[5\] Kimel A. V., Kirilyuk A., Usachev P. A., Pisarev R. V., Balbashov A. M. and Rasing Th., \textit{Nature}, \textbf{435} (2005) 655.
\[6\] Zhang G. P., Hübner W., Lefkidi G., Bai Y. and George T. F., \textit{Nat. Phys.}, \textbf{5} (2009) 499.
\[7\] Stanciu C. D., Hansteen F., Kimel A. V., Kirilyuk A., Tsukamoto A., Itoh A. and Rasing Th., \textit{Phys. Rev. Lett.}, \textbf{99} (2007) 047601.
\[8\] Hassdenteufel A., Hebler B., Schubert C., Liebig A., Teich M., Helm M., Aeschlimann M., Albrecht M. and Bratschitsch R., \textit{Adv. Mater.}, \textbf{25} (2013) 3122.
\[9\] Mangan S., Gottwald M., Lambeth C.-H., Steil D., Uhlik V., Pang L., Hehn M., Alebrand S., Cinchetti M., Malinowski G. et al., \textit{Nat. Mater.}, \textbf{13} (2014) 286.
\[10\] Vahaplar K., Kalashnikova A. M., Kimel A. V., Gerlach S., Hinze D., Nowak U., Chantrell R., Tsukamoto A., Itoh A., Kirilyuk A. et al., \textit{Phys. Rev. B}, \textbf{85} (2012) 104402.
\[11\] Gridnev N. V., \textit{Phys. Rev. B}, \textbf{77} (2008) 094426.
\[12\] Popova D., Bringer A. and Blügel S., \textit{Phys. Rev. B}, \textbf{85} (2012) 094419.
\[13\] Khorsand A. R., Savonin M., Kirilyuk A., Kimel A. V., Tsukamoto A., Itoh A. and Rasing Th., \textit{Phys. Rev. Lett.}, \textbf{108} (2012) 127205.
\[14\] Mentink J. H., Hellsvik J., Afanasiev D. V., Ivanov B. A., Kirilyuk A., Kimel A. V., Eriksson O., Katsnelson M. I. and Rasing Th., \textit{Phys. Rev. Lett.}, \textbf{108} (2012) 057202.
\[15\] Östler T. A., Barker J., Evans R. F. L., Chantrell R. W., Atxitia U., Chubykalo-Fesenko O., El Moussaoui S., Le Guyader L., Mengotti E., Heyderman L. J. et al., \textit{Nat. Commun.}, \textbf{3} (2012) 666.
\[16\] Atxitia U., Östler T., Barker J., Evans R. F. L., Chantrell R. W. and Chubykalo-Fesenko O., \textit{Phys. Rev. B}, \textbf{87} (2013) 224417.
\[17\] Baral A. and Schneider H. C., \textit{Phys. Rev. B}, \textbf{91} (2015) 100402(R).
\[18\] Lambert C.-H., Mangin S., Varaprasad B. S. D. Ch. S., Takahashi Y. K., Hehn M., Cinchetti M., Malinowski G., Honk K., Fainman Y., Aeschlimann M. et al., \textit{Science}, \textbf{345} (2014) 1337.
\[19\] Medapalli R., Afanasiev D., Kim D. K., Quessab Y., Manna S., Montoya S. A., Kirilyuk A., Rasing Th., Kimel A. V. and Fullerton E. E., arXiv:1607.0252v1 (2016).
\[20\] El Hadri M. S., Pirro P., Lambert C.-H., Pettitt-Watelon S., Quessab Y., Hehn M., Montaigne F., Malinowski G. and Mangan S., \textit{Phys. Rev. B}, \textbf{94} (2016) 064412.
\[21\] Soderlund P., Eriksson O., Johansson B., Albers R. C. and Boring A. M., \textit{Phys. Rev. B}, \textbf{45} (1992) 12911.
\[22\] Zhang G. P., \textit{J. Phys.: Condens. Matter}, \textbf{23} (2011) 206005.
\[23\] Zhang G. P. and George T. F., \textit{J. Phys.: Condens. Matter}, \textbf{25} (2013) 366002.
\[24\] Zhang G. P., Bai Y. H. and George T. F., \textit{EPL}, \textbf{112} (2015) 27001.
\[25\] Zhang G. P., Latta T., Babyak Z., Bai Y. H. and George T. F., \textit{Mod. Phys. Lett. B}, \textbf{30} (2016) 1630005.
\[26\] Haney P. M. and Stiles M. D., \textit{Phys. Rev. Lett.}, \textbf{105} (2010) 126602.
\[27\] Wiemhöldt S. et al., \textit{Phys. Rev. B}, \textbf{88} (2013) 020406.
\[28\] Zhang G. P., Si M. S. and George T. F., \textit{J. Appl. Phys.}, \textbf{117} (2015) 17D706.
\[29\] Figueroa A. I., Bartolomé J., Garca L. M., Bartolom F., Bunac O., Stankiewicz J., Ruiz L., Gonzalez-Calbet J. M., Petroff F., Deranlot C. et al., \textit{Phys. Rev. B}, \textbf{90} (2014) 174421.
\[30\] Hassdenteufel A., Schubert C., Hebler B., Helm M., Albrecht M. and Bratschitsch R., \textit{Phys. Rev. B}, \textbf{91} (2015) 104431.
\[31\] Vahaplar K., Kalashnikova A. M., Kimel A. V., Hinze D., Nowak U., Chantrell R.,
[32] JOHN R. et al., arXiv:1606.08723 (2016).

[33] BERRITTA M., MONDAL R., CAIYA K. and OPPENEER P. M., Phys. Rev. Lett., 117 (2016) 137203.

[34] TESAROVA N., NEMEC P., ROZKOTOVA E., ZEMEN J., JANDA T., BUTKOVICOVA D., TROJANEK F., OLEJNIK K., NOVAK V., MALY P. et al., Nat. Photon., 7 (2013) 492.

[35] LINGOS P. C., WANG J. and PERAKIS I. E., Phys. Rev. B, 91 (2015) 195203.

[36] RALPH D. C. and STILES M. D., J. Magn. & Magn. Mater., 320 (2008) 1190.

[37] BOKOR J., private communication. Here the laser-induced spin-orbit torque was used to reverse magnetization.

[38] WOLF S. A., AWSCHALOM D. D., BUHRMAN R. A., DAUGHTON J. M., VON MOLNAR S., ROUKES M. L., CHTCHELKANOVA A. Y. and TREGER D. M., Science, 294 (2001) 1488.

[39] MONDAL P. C., ROY P., KIM D., FULLERTON E. E., COHEN H. and NAAMAN R., Nano Lett., 16 (2016) 2806.