Laser-induced torques in spin spirals

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We investigate laser-induced torques in magnetically non-collinear ferromagnets with a spin-spiral magnetic structure using \textit{ab-initio} calculations. Since spin-spirals may be used to approximate the magnetization gradients locally in domain walls and skyrmions, our method may be used to obtain the laser-induced torques in such objects from a multiscale approach. Employing the generalized Bloch-theorem we obtain the electronic structure computationally efficiently. We employ our method to assess the laser-induced torques in bcc Fe, hcp Co, and L\textsubscript{1}\textsubscript{0} FePt when a spin-spiral magnetic structure is imposed. We find that the laser-induced torques in these magnetically noncollinear systems may be orders of magnitude larger than those in the corresponding magnetically collinear systems and that they exist both for linearly and circularly polarized light. This suggests that laser-induced torques driven by noncollinear magnetic order or by magnetic fluctuations may contribute significantly to processes in ultrafast magnetism.

I. INTRODUCTION

Femtosecond laser-pulses exert effective magnetic fields on the magnetization in collinear ferromagnets, which may be used to tilt the magnetization and to excite magnetization dynamics \cite{1,3}. These effective magnetic fields have been ascribed to the inverse Faraday effect (IFE) and to the optical spin transfer torque (OSTT) \cite{4,6}. The IFE is a key ingredient in several theoretical explanations of magnetization reversal in ferromagnetic thin films \cite{7,8}.

In spintronics, the spin-orbit torque \cite{9} requires spin-orbit interaction (SOI), while the spin-transfer torque \cite{10} does not. The reason is that in collinear ferromagnets the angular momentum can only be transferred to the lattice, which requires SOI, while in non-collinear magnets, spin-valves and magnetic tunnel junctions the angular momentum is transferred between different magnetization directions and between different magnetic layers, which does not require SOI. IFE and OSTT have been studied mostly in collinear magnets and they require SOI.

This comparison between spintronics and laser-induced ultrafast magnetism therefore poses the question if there are additional laser-induced torques in non-collinear magnets or in spin-valves that arise from different mechanisms than the IFE and the OSTT. Indeed, laser-pulses may distort domain walls and excite magnetization dynamics in them \cite{11,12}. Additionally, laser-pulses excite spin currents in spin-valves, which generate spin-transfer torques when they flow between different magnetic layers \cite{13,14}. These laser-induced spin-transfer torques resemble the Slonczewski spin-transfer torque in spintronics. However, in spintronics a second type of torque is known, the so-called non-adiabatic torque \cite{10,15,18}. Therefore, one may expect that not only the Slonczewski torque, but also the non-adiabatic torque should have a laser-induced counterpart in ultrafast magnetism. We will confirm this expectation in this paper.

Strong femtosecond laser-pulses do not only generate effective magnetic fields, but they also trigger ultrafast demagnetization. There are many indications that ultrafast demagnetization in transition metal collinear ferromagnets is not dominated by collapsed exchange but rather by collective excitations \cite{19,21}. Since the magnetization is non-collinear in the presence of collective excitations, one may pose the question if the laser-induced torques that arise from this non-collinearity might contribute to the ultrafast demagnetization itself. Moreover, in order to describe the processes involved in ultrafast magnetism at room temperature properly it is crucial to take the initial thermal fluctuations of the magnetization into account \cite{22,23}. Within the limitations of the frozen magnon approximation our results on spin spirals may also be used to estimate the laser-induced torques on magnons, which therefore provides a valuable asset to understand the torques active in ultrafast magnetism.

Several recent works have added an ultrafast-magnetism perspective to magnetically noncollinear objects such as skyrmions \cite{24,26} and domain walls \cite{11,12}. In order to apply our results for homogeneous spin spirals to such inhomogeneous objects one may locally approximate the magnetization gradients by spin spirals and use a multiscale approach \cite{27}.

This paper is structured as follows. In Sec. \textsection{II} we present our theory and computational formalism of laser-induced torques in spin spirals. In Sec. \textsection{IIA} we introduce basic notations. In Sec. \textsection{IIB} we discuss symmetry properties of laser-induced torques. In Sec. \textsection{IIC} we explain key differences between laser-induced torques on spin spirals and the current-induced torques known from spintronics. In Sec. \textsection{IID} we develop a simple model useful to understand laser-induced torques on spin spirals. In Sec. \textsection{IIE} we describe our computational method. In Sec. \textsection{III} we discuss our \textit{ab-initio} results on the laser-induced torques in bcc Fe, hcp Co, and L\textsubscript{1}\textsubscript{0} FePt. This paper ends with
a summary in Sec. IV

II. THEORY

A. Laser-induced torques on spin-spirals

The magnetization direction $\mathbf{M}$ of spin spirals may be written as

$$\mathbf{M}(r) = \mathcal{R}(\alpha, \beta) \left( \begin{array}{c} \sin(\theta) \cos(q \cdot r + \phi) \\ \sin(\theta) \sin(q \cdot r + \phi) \\ \cos(\theta) \end{array} \right), \quad (1)$$

where $q$ is the spin-spiral wave-vector, $\theta$ is the cone angle of the spin-spiral, and $\mathcal{R}(\alpha, \beta)$ is a proper orthogonal rotation matrix parameterized by the two Euler angles $\alpha$ and $\beta$. When $\alpha = \beta = 0$ we have $\mathcal{R}(0,0) = 1$ and Eq. (1) describes a helical spin spiral when $\theta = 90^\circ$ and when $q$ points into the $z$-direction. When $q$ lies in the $xy$ plane it describes a cycloidal spiral. Non-zero Euler angles are needed in Eq. (1) to describe e.g. a helical spin spiral propagating in $x$ direction, or a cycloidal spin spiral propagating in $z$ direction.

Since torques on the magnetization are perpendicular to it, any torque on the magnetization of a spin spiral may be expressed as

$$\mathbf{T}(r) = \mathcal{R}(\alpha, \beta) [\mathbf{\hat{e}}_\theta(r) T_\theta + \mathbf{\hat{e}}_\phi(r) T_\phi], \quad (2)$$

where the unit vectors $\mathbf{\hat{e}}_\theta(r)$ and $\mathbf{\hat{e}}_\phi(r)$ are given by

$$\mathbf{\hat{e}}_\theta(r) = \left( \begin{array}{c} \cos(\theta) \cos(q \cdot r + \phi) \\ \cos(\theta) \sin(q \cdot r + \phi) \\ -\sin(\theta) \end{array} \right) \quad (3)$$

and

$$\mathbf{\hat{e}}_\phi(r) = \left( \begin{array}{c} -\sin(q \cdot r + \phi) \\ \cos(q \cdot r + \phi) \\ 0 \end{array} \right), \quad (4)$$

respectively.

In spintronics, current-induced contributions to the torque $T_\phi$ are referred to as the adiabatic torque while current-induced contributions to $T_\theta$ are referred to as the non-adiabatic torque [10]. It is nowadays agreed that the terms adiabatic and non-adiabatic are not optimal to describe the mechanisms involved in these current-induced torques. However, these two terms are well established to distinguish the two possible directions of the current-induced torque. When a torque is generated by the application of laser-light, this torque may be decomposed as well into the two components $T_\phi$ and $T_\theta$, which we denote therefore laser-induced adiabatic torque and laser-induced non-adiabatic torque, respectively. However, while borrowing these terms from spintronics we do not suggest that the microscopic origin of laser-induced torques is in any way similar to the microscopic origin of current-induced torques. The analogies between the two, which suggest to use the terms adiabatic and non-adiabatic for both effects, are only in the geometry, i.e., in the directions of these two components, and in the effect of the torques on the magnetization dynamics. The difference in mechanisms is explored in Sec. [11] and Sec. [12] below.

B. Symmetry of laser-induced torques

Consider a flat spin-spiral in the $xy$ plane, i.e., $\theta = 90^\circ$, $\mathcal{R} = 1$, and $q$ along the $x$ direction in Eq. (1). Two subsequent rotations of the spin-spiral firstly by $180^\circ$ around the $x$ axis and secondly by $180^\circ$ around the $z$ axis lead to a simple translation of the entire spin-spiral. However, the application of these rotations to the torque reverses the sign of the torque. Therefore, the laser-induced torques vanish in this case. Generally, for flat spin-spirals, i.e., when $\theta = 90^\circ$, the laser-induced torques vanish. Note that in this symmetry argument we do not consider SOI, because in this work we consider laser-induced torques that arise from the noncollinear magnetic order only. In the presence of SOI the above symmetry argument does not hold because the two rotations are not allowed by symmetry.

Consider a Neel-like spiral with $q$-vector in $x$ direction, cone angle $\theta$, and $\mathcal{R} = 1$ in Eq. (1). When we rotate the spiral around the $z$ axis by $180^\circ$ the $q$-vector changes sign, but the torque is not modified. Consequently, laser-induced torques are even in $q$. When we rotate instead around the $x$ axis by $180^\circ$ the torque changes sign. Therefore, $\mathbf{T}(\theta) = -\mathbf{T}(180^\circ - \theta)$. This suggests that the dependence of the torques on $\theta$ may be described by $\propto \sin(2\theta)$ at the leading order. As a special case it follows that the torque vanishes when $\theta = 90^\circ$, consistent with the result above.

C. Current-induced vs. laser-induced torques on spin-spirals: Different mechanisms

While we borrowed the terms adiabatic and non-adiabatic from spintronics in order to distinguish the two components of the laser-induced torques, the mechanisms responsible for current-induced torques on spin spirals are quite different from those generating the laser-induced torques. In this section we explore some of these differences.

When an electric current propagates along a spin-spiral the spin current is given by

$$Q_i(r) = \frac{\hbar}{2e} P J_i \mathbf{M}(r). \quad (5)$$

Here, the vector $Q_i(r)$ describes the spin current density flowing along the $i$-th cartesian direction. This vector is
parallel to the orientation of the spin polarization of this
spin current. \( J_i \) is the electric current density along the
i-th cartesian direction and

\[
P = \frac{\sigma_1 - \sigma_{-1}}{\sigma_1 + \sigma_{-1}} \tag{6}
\]

is its polarization. \( \sigma_1 \) and \( \sigma_{-1} \) are the respective con-
tributions of the minority and majority electrons to the
electrical conductivity. The resulting torque is given by

\[
T^{\text{adiab}}(r) = \sum_i \frac{\partial Q_i}{\partial r_i}. \tag{7}
\]

In Eq. (6) we assumed that the electron spin follows the
local magnetization direction adiabatically. Therefore, the
torque in Eq. (7) is called the adiabatic torque.

When a laser-pulse is applied to a homogeneous spin-
spiral in a centrosymmetric crystal inversion symmetry
does not allow any spin current to be generated by the
laser-pulse at the second order of the electric field of
the laser light. Of course, if the laser spot has a finite size,
spin current will flow out of the illuminated region, but
we consider here the situation where the entire spiral is
homogeneously illuminated by the pulse. The absence of
spin currents in homogeneously illuminated spin spirals
shows that the microscopic mechanisms of laser-induced
torques have to be different than those of current-induced
torques in spin spirals. Certainly, there are several ex-
periments where laser pulses excite superdiffusive spin
currents, which exert torques on magnets \[13\]. However,
in these experiments two magnets are separated by a non-
magnetic spacer, which is a geometry different to the one
of a homogeneous spin spiral that we consider in this
work.

Since the spin current cannot explain the laser-induced
torque in homogeneous spin spirals, we develop a simple
model in the following section Sec. \[\text{III D}\].

D. Gradient expansion

The Kohn-Sham Hamiltonian of a magnetic system
may be written as

\[
H(r) = H_0(r) - m \cdot \hat{M}(r) \Omega^{xc}(r), \tag{8}
\]

where the first term, \( H_0(r) \), contains kinetic energy
and scalar potential, while the exchange interaction
is described by the second term. Here, \( \Omega^{xc}(r) \)
is the exchange field, i.e., the difference between the po-
tentials of major and minority electrons \( \Omega^{xc}(r) =
\left( V^{\text{eff}}_{\text{minority}}(r) - V^{\text{eff}}_{\text{majority}}(r) \right) \), \( m = -\mu_B \sigma \), \( \mu_B \) is the
Bohr magneton and \( \sigma = (\sigma_x, \sigma_y, \sigma_z)^T \) is the vector of
Pauli spin matrices.

In general the magnetization of a spin spiral Eq. (1)
breaks the translational invariance of the crystal lattice.

In order to obtain at a position \( r_0 \) a local Hamiltonian
that is consistent with the crystal lattice translational
symmetries one may expand the exchange interaction
in \( H(r) \) around \( r_0 \). The expansion of the Hamiltonian
around the position \( r_0 \) is given by

\[
H(r) = H_0(r) - m \cdot \hat{M}(r_0) \Omega^{xc}(r)
- \Omega^{xc}(r) \frac{\partial \{ m \cdot \hat{M}(r_0) \}}{\partial r_0} \cdot [r - r_0]
- \frac{1}{2} \Omega^{xc}(r) \sum_{ij} \frac{\partial^2 \{ m \cdot \hat{M}(r_0) \}}{\partial r_{0,i} \partial r_{0,j}} [r_i - r_{0,i}] [r_j - r_{0,j}] + \cdots. \tag{9}
\]

Consequently, the local Hamiltonian at \( r_0 \) is

\[
\langle H(r) \rangle \simeq H_0(r) - m \cdot \hat{M}(r_0) \Omega^{xc}(r)
- \frac{1}{2} \Omega^{xc}(r) \sum_{ij} \frac{\partial^2 \{ m \cdot \hat{M}(r_0) \}}{\partial r_{0,i} \partial r_{0,j}} \langle [r_i - r_{0,i}] [r_j - r_{0,j}] \rangle, \tag{10}
\]

because \( \langle [r - r_0] \rangle = 0 \) in systems with inversion symme-
try. Here, \( \langle \ldots \rangle \) denotes a suitable averaging.

The second derivative of the magnetization direction
is given by

\[
\frac{\partial^2 \hat{M}(r_0)}{\partial r_{0,i} \partial r_{0,j}} = -q_i q_j \sin \theta \left[ \sin \theta \hat{M}(r_0) + \cos \theta \mathcal{R}(\alpha, \beta) \hat{e}_\theta(r_0) \right], \tag{11}
\]

which leads to an effective magnetic field perpendicular
to the local magnetization:

\[
B_q(r) = -b_q \Omega^{xc}(r) \sin(2\theta) \mathcal{R}(\alpha, \beta) \hat{e}_\theta(r), \tag{12}
\]

where

\[
b_q = \frac{1}{4} \sum_{ij} q_i q_j \langle [r_i - r_{0,i}] [r_j - r_{0,j}] \rangle. \tag{13}
\]

Consequently, the local Hamiltonian may be written as

\[
\langle H(r) \rangle \simeq H_0(r) - m \cdot \hat{M}(r_0) \Omega^{xc}(r) + B_q(r). \tag{14}
\]

We assume that the application of a laser pulse generates
two torques, one in the direction of \( \hat{M} \times B_q \propto \hat{e}_\theta \) and
a second one in the direction of \( \hat{M} \times [\hat{M} \times B_q] \propto \hat{e}_\theta \).

According to Eq. (12) these torques are proportional to
\( \sin(2\theta) \), which is consistent with the symmetry analysis
in Sec. \[\text{III B}\]. According to Eq. (13) these torques are even
in \( q \), which is consistent with the symmetry analysis in
Sec. \[\text{III B}\] and also with our ab-initio results in Sec. \[\text{III I}\].

Thus, the assumption that the interaction of laser-excited
electrons with the effective magnetic field $B_\mathbf{q}(\mathbf{r})$ leads to the laser-induced torques predicts a dependence on $q$ and $\theta$ that agrees to the ab-initio results. Clearly, $B_\mathbf{q}(\mathbf{r})$ exists even without any applied laser-pulse. However, the expectation value $\langle [\mathbf{r}_i - \mathbf{r}_0, \mathbf{r}_j - \mathbf{r}_0] \rangle$ in Eq. (13) is state dependent, and therefore $b_\mathbf{q}$ changes when a laser pulse is applied.

E. Computational formalism

While the laser-induced adiabatic torque does not require SOI, the laser-induced non-adiabatic torque is zero in the full calculation when SOI is not included. By full calculation we mean one that considers both intrinsic and extrinsic contributions. This follows from angular momentum conservation, which is satisfied by the full calculation, provided a conserving approximation [25] is used.

In this work, we compute only the intrinsic contribution, which is nonzero even without SOI. In order to justify this approximation, we briefly recall the theory of the current-induced non-adiabatic torque, which makes use of similar approximations: The current-induced non-adiabatic torque vanishes in the absence of SOI when a conserving approximation is used. Extrinsinc contributions from scattering need to be added to the intrinsic contribution in order to obtain a conserving approximation [15] [16]. Therefore, the intrinsic contribution alone does not vanish in calculations without SOI. However, it has been argued that while SOI is crucial for a non-zero non-adiabatic torque, it does not strongly affect the magnitude of the non-adiabatic torque. Therefore, calculating the intrinsic non-adiabatic torque without including SOI may be useful provided there is a mechanism for angular momentum transfer to the lattice in the real system that one wishes to describe [18].

Since vertex corrections are computationally expensive and numerically tractable expressions for the vertex corrections to the laser-induced torques have not been derived yet, we consider in this work only the intrinsic laser-induced torques without SOI. Not including SOI in the calculation allows us to obtain the electronic structure of spin spirals computationally efficiently based on the generalized Bloch theorem [29]. In order to compute the laser-induced torques we employ the same equations as those used previously for collinear ferromagnets with SOI [6].

When torques are induced by femtosecond laser pulses the torques appear retarded relative to the pulses. Retardation times between 330fs and 3ps have been reported [1] [2]. The expressions that we derived in Ref. [6] and that we use in this work were derived under the assumption of a continuous laser beam rather than a pulse. However, comparison between the experimental assessment of the torques induced by fs laser pulses in Ref. [1] and our theory [6] showed good agreement in the magnitude of the torques. Therefore, we leave the investigation of retardation effects for future work and assess the laser-induced torques assuming a continuous laser beam in this paper.

III. RESULTS

A. Computational details

We obtain the electronic structure of bcc Fe, hcp Co, and L10 FePt selfconsistently using the DFT program FLEUR [30]. The lattice parameters are $a = 5.4235a_0$ (Fe), $a = 4.739a_0$, $c = 7.693a_0$ (Co), and $a = 5.1445a_0$, $c = 7.1489a_0$ (FePt), where $a_0$ is Bohr’s radius. We apply the generalized Bloch theorem to treat the spin-spiral states [29]. In order to evaluate the laser-induced torques we take the expressions given in Ref. [6] and we make use of Wannier interpolation [31] for computational speed-up. For this purpose we disentangle 18 maximally localized Wannier functions per transition metal atom, where we employ our interface [32] between FLEUR and the Wannier90 program [33]. The Green’s function formalism that we developed in Ref. [6] allows us to control disorder through a quasiparticle broadening parameter $\Gamma$, which we set to $\Gamma = 25$meV in this paper. We set the intensity of the laser beam to $I = 10$GW/cm$^2$ and the photon energy to 1.55 eV.

B. bcc Fe

In Fig. 1 we show the laser-induced torques in Fe as a function of cone angle $\theta$ for $q$-vector $\mathbf{q} = (0, -0.023, 0.023)^T/a_0$ and the three linear polarizations $\mathbf{e}_x = (1, 0, 0)$, $\mathbf{e}_y = (0, 1, 0)$, and $\mathbf{e}_z = (0, 0, 1)$. The polarizations $\mathbf{e}_y$ and $\mathbf{e}_z$ yield the same torques, while $\mathbf{e}_x$ yields different torques, because the chosen $q$-vector $\mathbf{q} = (0, -0.023, 0.023)^T/a_0$ lies in the $yz$ plane. For small cone angle $\theta$ both the adiabatic and the non-adiabatic torques increase in magnitude with increasing $\theta$. However, the slope decreases with increasing $\theta$ and in the case of the non-adiabatic torque the magnitude decreases after reaching a maximum close to 20°. This shows that the dependence on $\theta$ is not perfectly described by a simple $\sin(2\theta)$, which describes only the leading order in the expansion with respect to $\theta$ (see Sec. II (B)), and higher-order terms in the angular expansion are important.

In Fig. 2 we show again the laser-induced torques in Fe as a function of cone angle $\theta$ but now for a larger $q$-vector of $\mathbf{q} = (0, -0.115, 0.115)^T/a_0$. In this case the nonadiabatic torque reaches a maximum already close to 5° for the polarizations $\mathbf{e}_y$ and $\mathbf{e}_z$. Compared to Fig. 1 both the adiabatic and the non-adiabatic torque are larger due to the larger $q$. In Ref. [6] we computed the IFE and OSTT.
FIG. 1. Laser-induced torques in Fe vs. cone angle $\theta$ when $q = (0, -0.023, 0.023)^T/a_0$. (a) Adiabatic torque. (b) Non-adiabatic torque.

FIG. 2. Laser-induced torques in Fe vs. cone angle $\theta$ when $q = (0, -0.115, 0.115)^T/a_0$. (a) Adiabatic torque. (b) Non-adiabatic torque.

In bcc Fe and obtained 15 mT and 33 mT, respectively, at the same laser intensity and quasiparticle broadening as in this paper. In comparison, the adiabatic torques in Fig. 2(a) are larger by almost three orders of magnitude.

In order to investigate the $q$-dependence in more detail we show in Fig. 3 the laser-induced torques in Fe as a function of $q$-vector $q = (0, -1.1585Q, 1.1585Q)^T/a_0$ when $\theta = 5.7^\circ$. The torques increase monotonously with $Q$ and they are even in $Q$. For small $Q$ the nonadiabatic torque behaves like $\propto |Q|$, while the adiabatic torque behaves like $\propto Q^2$. This behaviour is consistent with the symmetry analysis in Sec. II B predicting the torques to be even in spin-spiral wave vector $q$.

FIG. 3. Laser-induced torques in Fe vs. $q$-vector $q = (0, -1.1585Q, 1.1585Q)^T/a_0$ when $\theta = 5.7^\circ$. (a) Adiabatic torque. (b) Non-adiabatic torque.

In Fig. 4 we show the laser-induced torques in Co as a function of cone angle $\theta$ for $q$-vector $q = (0, 0, 0.016)^T/a_0$. The in-plane polarizations $\epsilon_x$ and $\epsilon_y$ yield very similar torques, because the $q$-vector points in the $z$ direction and is therefore perpendicular to both polarizations. The slight difference between torques for $\epsilon_x$ and $\epsilon_y$ can be explained by considering that the $x$ and $y$ directions in the hexagonal unit cell are not equivalent. Similar to the case of bcc Fe shown in Fig. 1 the nonadiabatic torque attains a maximum already close to $20^\circ$ and therefore requires higher-order terms in the angular expansion beyond the leading order term $\propto \sin(2\theta)$ for its description.

In Fig. 5 we show the laser-induced torques in Co as a function of cone angle $\theta$ for $q$-vector $q = (0.015, -0.0265, 0)^T/a_0$, which lies in the $xy$ plane. The non-adiabatic torque is now different between the polarizations $\epsilon_x$ and $\epsilon_y$, because the $q$-vector forms different angles with the $x$ and $y$ axes.

C. hcp Co

For the same laser intensity and quasiparticle broadening as used in this paper we determined the IFE and OSTT in Co in Ref. [6] and obtained 118 mT and 0.229 mT, respectively. In comparison, the adiabatic torques shown in Fig. 4(a) and in Fig. 5(a) are orders of magnitude larger.
D. L1_0 FePt

In Fig. 6 we show the laser-induced torques in FePt as a function of cone angle $\theta$ for $q$-vector $q = (0, 0, 0.0176)^T/a_0$. The torques for the polarizations $\epsilon_x$ and $\epsilon_y$ agree, because the crystal axes $a$ and $b$ are equivalent and because the $q$ vector is perpendicular to both of them. At large angles $\theta$ the adiabatic torque for polarization $\epsilon_z$ is strongly suppressed in Fig. 6(a) due to the large anisotropy in the L1_0 structure. Similar to the cases of bcc Fe and hcp Co shown in Fig. 1 and Fig. 4 respectively, the nonadiabatic torque attains a maximum already close to 20° and therefore requires higher-order terms in the angular expansion beyond the leading order term $\propto \sin(2\theta)$ for its description.

In Fig. 7 we show the laser-induced torques in FePt as a function of cone angle $\theta$ for $q$-vector $q = (0.0244, 0, 0)^T/a_0$. In this case the torques are different for the three polarizations $\epsilon_x$, $\epsilon_y$ and $\epsilon_z$: The $x$ and $y$ directions are inequivalent, because $q$ points into $x$ direction, and the $z$ direction is inequivalent to the $y$ direction, because the $c$-axis is longer than the $b$-axis.

For the same laser intensity and quasiparticle broadening as used in this paper we determined the IFE and OSTT in FePt in Ref. 3 and obtained 185 mT and 22 mT, respectively. In comparison, the adiabatic torques shown in Fig. 6(a) and in Fig. 7(a) are more than one order of magnitude larger.

IV. CONCLUSION

We investigate laser-induced torques in homogeneous spin spirals without spin-orbit interaction (SOI) using symmetry arguments and first principles calculations. Symmetry analysis shows that laser-induced torques vanish for flat spirals – at the leading order of an angular expansion the dependence on spiral cone angle is $\propto \sin(2\theta)$ – and that their dependence on the spin-spiral wavevector $q$ is even in $q$. Additionally, it shows that laser-induced torques in homogeneous spin-spirals are not associated with spin currents. Our first-principles calculations show that the laser-induced torques in bcc Fe, hcp Co and L1_0 FePt with an imposed spin-spiral magnetic structure may be orders of magnitude larger than those in the corresponding magnetically collinear systems with SOI. This suggests that these torques may play an important role in ultrafast magnetism phenomena. Within the frozen-magnon approximation our results may also be used to estimate the laser-induced torques on magnons in these materials.

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[5] P. Nemec, E. Rozkotova, N. Tesarova, F. Trojanek, E. De Ranieri, K. Olejnik, J. Zemen, V. Novak, M. Cukr, P. Maly, et al., Nature physics 8, 411 (2012).
[6] F. Freimuth, S. Blügel, and Y. Mokrousov, Phys. Rev. B 94, 144432 (2016).
[7] C.-H. Lambert, S. Mangin, B. S. D. C. S. Varaprasad, Y. K. Takahashi, M. Hehn, M. Cinchetti, G. Malinowski, K. Hono, Y. Fainman, M. Aeschlimann, et al., Science 345, 1337 (2014).
[8] R. John, M. Berritta, D. Hinzke, C. Müller, T. Santos, H. Ulrichs, P. Nieves, J. Walowski, R. Mondal, O. Chubykalo-Fesenko, et al., Scientific Reports 7, 4114 (2017).
[9] A. Manchon, J. Železný, I. M. Miron, T. Jungwirth, J. Sinova, A. Thiaville, K. Garello, and P. Gambardella, Rev. Mod. Phys. 91, 035004 (2019).
[10] D. Ralph and M. Stiles, Journal of Magnetism and Magnetic Materials 320, 1190 (2008).
[11] N. Kerber, D. Ksenzov, F. Freimuth, F. Capotondi, E. Pedersoli, I. Lopez-Quintas, B. Seng, J. Cramer, K. Litzians, D. Lacour, et al., arXiv e-prints arXiv:2002.03971 (2020), 2002.03971.
[12] C. Leveille, E. Burgos-Parra, Y. Sassi, F. Ajejas, V. Chardonnet, E. Pedersoli, F. Capotondi, G. De Ninno, F. Maccherozzi, S. Dhesi, et al., arXiv e-prints arXiv:2007.08583 (2020), 2007.08583.
[13] A. J. Schellekens, K. C. Kuiper, R. J. C. de Wit, and B. Koopmans, Nature Communications 5, 4333 (2014).
[14] G.-M. Choi, C.-H. Moon, B.-C. Min, K.-J. Lee, and D. G. Cahill, Nature physics 11, 576 (2015).
[15] H. Kohno, G. Tatara, and J. Shibata, Journal of the Physical Society of Japan 75, 113706 (2006).
[16] R. A. Duine, A. S. Núñez, J. Sinova, and A. H. MacDonald, Phys. Rev. B 75, 214420 (2007).
[17] I. Garate, K. Gilmore, M. D. Stiles, and A. H. MacDonald, Phys. Rev. B 79, 104416 (2009).
[18] K.-W. Kim, K.-J. Lee, H.-W. Lee, and M. D. Stiles, Phys. Rev. B 92, 224426 (2015).
[19] W. Töws and G. M. Pastor, Phys. Rev. Lett. 115, 217204 (2015).
[20] E. Carpene, H. Hedayat, F. Boschini, and C. Dallera, Phys. Rev. B 91, 174414 (2015).
[21] F. Freimuth, S. Blügel, and Y. Mokrousov, Phys. Rev. B 95, 094434 (2017).
[22] Z. Chen and L.-W. Wang, Science Advances 5 (2019).
[23] S. Ghosh, F. Freimuth, O. Gomonay, S. Blügel, and Y. Mokrousov, Driving spin chirality by electron dynamics in laser-excited antiferromagnets (2020), 2011.01670.
[24] M. Finazzi, M. Savoini, A. R. Khorsand, A. Tsukamoto, A. Itoh, L. Duò, A. Kirilyuk, T. Rasing, and M. Ezawa, Phys. Rev. Lett. 110, 177205 (2013).
[25] S.-G. Je, P. Vallobra, T. Srivastava, J.-C. Rojas-Sánchez, T. H. Pham, M. Hehn, G. Malinowski, C. Baraduc, S. Aufrte, G. Gaudin, et al., Nano Letters 18, 7362 (2018).
[26] P. Olleros-Rodriguez, M. S. Strungaru, S. I. Ruta, P. I. Gavriloaea, P. Perma, R. W. Chantrell, and O. Chubykalo-Fesenko, Non-equilibrium heating path for ultrafast laser-induced nucleation of skyrmion lattices (2020), 2011.06093.
[27] K. M. Seemann, F. Garcia-Sanchez, F. Kronast, J. Miguel, A. Káckay, C. M. Schneider, R. Hertel, F. Freimuth, Y. Mokrousov, and S. Blügel, Phys. Rev. Lett. 108, 077201 (2012).
[28] I. Turek, Phys. Rev. B 93, 245114 (2016).
[29] P. Kurz, F. Förster, L. Nordström, G. Bihlmayer, and S. Blügel, Phys. Rev. B 69, 024415 (2004).
[30] See http://www.flapw.de.
[31] J. R. Yates, X. Wang, D. Vanderbilt, and I. Souza, Phys. Rev. B 75, 195121 (2007).
[32] F. Freimuth, Y. Mokrousov, D. Wortmann, S. Heinze, and S. Blügel, Phys. Rev. B 78, 035120 (2008).
[33] G. Pizzi, V. Vitale, R. Arita, S. Blügel, F. Freimuth, G. Géranton, M. Gibertini, D. Gresch, C. Johnson, T. Koretsune, et al., J. Phys.: Condens. Matter 32, 165902 (2020).