Received 13 November 2024; accepted 14 April 2025. Date of publication 5 May 2025;
date of current version 22 May 2025. The review of this article was arranged by Associate Editor S. Bandyopadhyay.

Digital Object Identifier 10.1109/OJNANO.2025.3567022

Nanomagnetic Gears With Electrically Controlled Transmission Ratio

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This work was supported in part by the Italian factory of micromagnetic modelling and spintronics under Projects PRIN 2020LWPKH7 and PRIN20222N9A73, in part by SKYrmion-based magnetic tunnel junction to design a temperature SENSor—SkySens under Grant PRIN_20225YF2S4, in part by Magneto-Mechanical Accelerometers, Gyroscopes and Computing based on nanoscale magnetic tunnel junctions—MMAGYC, in part by the Italian Ministry of Research under Project Number 101070287, in part by SWAN-on-chip—HORIZON-CL4- 2021-DIGITAL EMERGING-01 under Project PE0000021, in part by Network 4 Energy Sustainable Transition – NEST, and in part by the European Union – NextGenerationEU, through the National Recovery and Resilience Plan (NRRP), Mission 4 Component 2 Investment 1.3 - Call for tender No. 1561 of 11.10.2022 of Ministero dell'Università e della Ricerca (MUR) under Grant CUP C93C22005230007.

ABSTRACT Magnetic gears offer a reliable and vibration-free alternative to traditional mechanical gears. At the micro- and nanoscale, electrical manipulation of magnetic domains can further enhance the performance and versatility of these gears. In this work, we introduce the concept of electrically tunable magnetic nanogears and propose a nanomagnetic gear design that operates at the mesoscopic scale and exploits the electrical manipulation of magnetic textures and stray field coupling to achieve precise, contactless and tunable torque transmission. This device concept is scalable and offers a continuously adjustable electrical transmission ratio between two gears by exploiting the spin-orbit torque observed in nanomagnetic devices. We have analyzed the coupling of magnetic domains in two parallel circular nanotracks, each serving as a rotor in the gear system, using experimentally realistic material parameters. By exploiting the current-driven motion of the magnetic domains, we derive an ideal transmission ratio given by $\omega_2/\omega_1 = 1 + \omega_d/\omega_1$ where ω_2 and ω_1 are the mechanical angular velocities of the driven (output) and driving (input) rotors, respectively, and $\omega_d(J)$ is the current-driven angular velocity of the magnetic domains valid when the two rotors are fully coupled via stray fields. Numerical calculations show that this nanogear can work up to current densities J of 4.10^{12} A/m^2 and distances of 30 nm. This work paves the way for the development of a new generation of highly tunable nanomagnetic gears with potential applications in nano-actuators, micromachines and other nanoscale devices.

INDEX TERMS Magnetic gear, mechanical torque, spintronics.

I. INTRODUCTION

Magnetic gears offer a compelling scalable alternative solution to conventional mechanical gears, providing reliable, low maintenance, efficient and vibration-free torque transmission [1], [2], [3], [4] . Current designs use permanent magnets to achieve contactless transmission, enabling the transfer of high torque without the drawbacks of noise, vibration or physical wear on moving parts [5], [6], [7]. These advantages have led to a growing interest in the potential of magnetic gears to replace traditional mechanical gears in various commercially and industrial relevant applications [8], [9], [10]. While their use has been explored at sub-cm scale, the approach is promising for developing potential solutions at micro- and nanoscale.

One possibility is to use spintronic systems, which allow for manipulating nanoscale magnetic textures, such as domain walls, with electric currents, voltage gates and strain, fosters a path to the design and realization of innovative concepts for micro- and nanomagnetic gears with electrically controlled transmission properties [11], [12], [13], [14], [15], [16]. Current proposals for spintronic-based actuation mechanisms exploit effects such as the Einstein-de Haas and Bardeen effects to couple magnetization to mechanical motion, offering promising ways to improve mechanical transmission [17], [18], [19], [20]. While these couplings are critical at the nanoscale, they tend to be relatively weak and have limited utility in high-torque applications. In contrast, electric currents offer a low-power approach to manipulate magnetic domains via spin-orbit coupling, which has been shown experimentally to drive fast domain wall motion at low current densities [21], [22], [23].

Here, we demonstrate how recent advances in the electrical manipulation of nanoscale magnetic textures, combined with optimized geometric design, enable the development of nanoscale magnetic gears with high-precision, tunable transmission rates and sufficiently large torque transmission[24], [25]. The key principle relies on the low-power electrical control of magnetic textures—an approach already established in spintronic devices for racetrack memories—to move domains that, through their stray fields, couple the driving and driven rotors without physical contact. These nanoscale gears are particularly promising for applications in nano-actuators, micro/nano machines, and soft robotics, where precision, compactness, and reliability are critical [26], [27], [28].

II. MAGNETIC NANOGEAR CONCEPT AND WORKING PRINCIPLE

Fig. 1(a) illustrates one example of the conventional design for magnetic gears in which magnetic coupling between driven and driven rotors enables efficient, contactless power transmission. Conventional magnetic gears typically use rare earth permanent magnets with high saturation magnetization, often around 1 MA/m, to enhance robust magnetic interactions and coupling [1], [2] [5], [6], [7] [8]. At the nanoscale, the magnetization patterns of these materials can be precisely manipulated by electrical means with minimal power input, using current and voltage-controlled gates [25], [29], [30]. Recent studies on CoFeB thin films, which also exhibit saturation magnetization values close to 1.2 MA/m, have shown that the motion of magnetization textures within these films can be effectively driven by low current densities, as low as 1 MA/m^2 [11], [31]. This current-driving control of magnetic textures opens up new possibilities for nanomagnetic gears. In conventional magnetic gears, as schematically shown in Fig. 1(a), the transmission ratio is determined by the number permanent magnets in the driving and driven rotors and the flux concentrator design and it is fixed for a given design and realization[2].

Our nanogear concept is shown in Fig. 1(b) and proposes a fully electrically tunable magnetic driven and driven rotors that exploits current-driven domain wall motion in nanoscale ferromagnets to control the relative mechanical angular velocity of the driven and driving rotors. In this approach, the magnetic domains in one gear, the driven, are pinned by material and geometric design, or by an additional applied current which can enhance the pinning force at large mechanical torque. Whereas the domains in the other magnetic gear, driving, are allowed to move in response to an applied current. The stray field coupling between the domains in the two magnetic

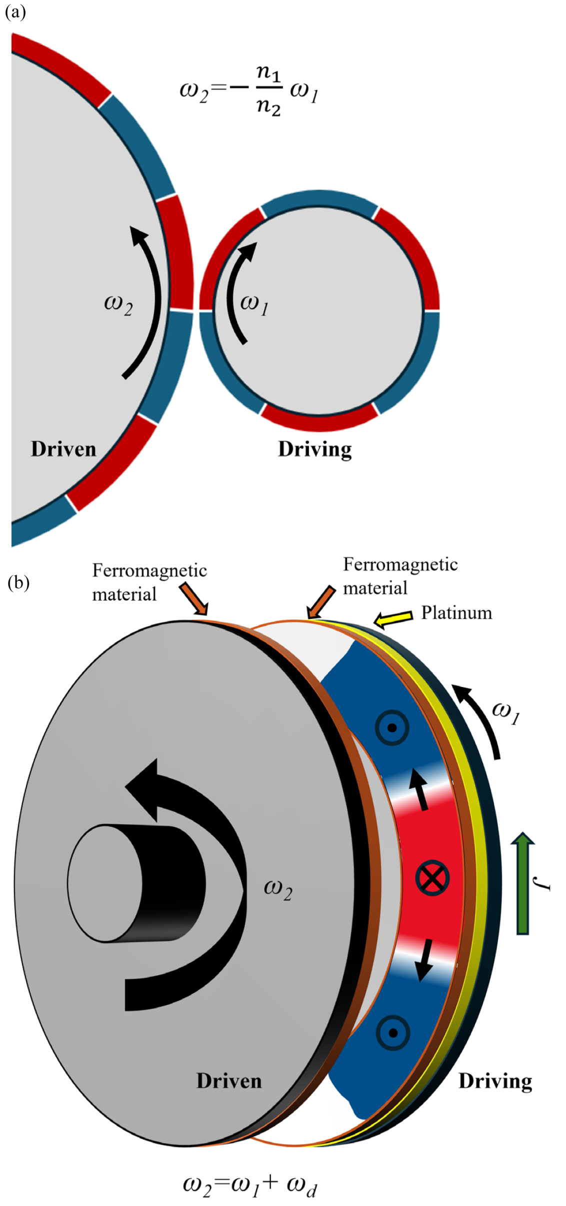

FIGURE 1. Magnetic gears: (a) Conventional magnetic gear design in which the gear ratio is determined by the ratio of permanent magnets in each gear. (b) Proposed electrically tunable magnetic gear, in which the gear ratio is influenced by both the speed of the gear and the speed of the magnetic domains, which are driven by an applied electric current. In gear 1 (driving rotor), the magnetic domains in the ferromagnetic layer (orange) are driven by the spin-polarized current generated in the adjacent platinum layer (yellow). In gear 2 (driven rotor), the magnetic domains are pinned, resulting in mechanically induced rotation due to stray field coupling with the rotating domains in gear 1. In both (a) and (b), the mechanical angular velocity of each gear is given by ω_i (where i refers to gear 1 or 2), and in (b), ω_d is the current-driven magnetic domains velocity.

layers provides the physical mechanism for torque transmission. The first step of the design is the optimization of the number of domains to maximize the magnetic coupling. Such magnetic configuration should be ideally the global minimum in the energy landscape defining the magnetic configuration of the coupled driving and driven rotors.

Recent experimental studies have shown that the ground state of magnets coupled to neighboring materials with strong spin-orbit coupling, such as platinum, is governed by a chiral energy term known as the Dzyaloshinskii–Moriya interaction (DMI) [21], which enables control over the number of magnetic domains by tuning the spatial periodicity of oppositely oriented domains [32]. By adjusting the geometrical parameters and the composition of both the magnetic layer and the adjacent material with strong spin-orbit-coupling, it is possible to tailor the DMI strength and thus control the domain periodicity. This approach enables scaling of magnetic gears to smaller dimensions, as it eliminates the need for separate permanent magnets to spatially separate magnetic domains. Furthermore, recent demonstrations of voltage-controlled DMI provide a means to fine-tune the number of domains even after fabrication, enhancing the magnetic coupling strength [33], [34]. An additional advantage of placing the magnetic layer on a material with strong spin-orbit coupling is that an applied electric current generates a large spin-polarized current that exerts sufficient torque on the magnetic texture to drive its motion.

The working principle of this nanomagnetic gear can be summarized as follows: A mechanical torque drives the driving at a velocity ω_1. When the domains are fixed, the two rotors move at the same mechanical velocity $\omega_2 = \omega_1$. When an electric current is applied to the driving, the magnetic texture moves at a velocity ω_d whose direction can be the same or opposite to the mechanical rotation velocity ω_1 depending on the direction of the applied current. This enables continuous tuning of the mechanical transmission ratio, with the final velocity of the driven gear being $\omega_2 = \omega_1 + \omega_d$ for a given fixed geometry.

III. MODELLING AND DESIGN

At the micro- and nanoscale, the magnetization configuration of magnetic materials can be controlled using external fields, electric currents, and voltage gates. This allows for the formation of various magnetic patterns - such as domain walls, skyrmions, and vortices - as well as the creation, annihilation, and manipulation of these structures [35], [36], [37]. In particular, domain wall dynamics have been studied extensively due to their potential applications in racetrack memory technology [35], [36].

The width of domain walls (Δ_{DW}) is determined by the exchange stiffness constant (A) and the uniaxial anisotropy constant (K_u), following the relationship $\Delta_{DW} = \sqrt{A/(K_u - 0.5\mu_0 M_S^2)}$, where M_S is the saturation magnetization. In rare-earth materials, domain walls typically span only a few nanometers. In materials characterized by a strong spin-orbit coupling, an antisymmetric exchange contribution, known as DMI, emerges, which imposes a preferred chirality for the domain walls and resulting in higher current-driven mobility [21], [23], [38]. In this work, we consider interfacial DMI due to the presence of the adjacent Platinum acting as material with large spin orbit coupling.

In materials with strong DMI - where the DMI strength D exceeds $4\sqrt{A(K_u - 0.5\mu_0 M_S^2)}/\pi$ - a periodic arrangement of domain walls naturally emerges, with periodicity determined by DMI strength [32]. This periodic domain configuration is ideal for designing magnetic gears with strong and intrinsically stable magnetic coupling being a global minimum of the magnetic energy landscape. In addition, the current-driven dynamics of these domain walls allows for continuous tuning of the transmission ratio between the two rotors of the gear as anticipated in the previous section and as will be discussed quantitatively in the next session.

The field and current driven magnetization dynamics in those systems is well-described by the Landau-Lifshitz-Gilbert-Slonczewski equation [39],

$$\frac{d\mathbf{m}}{d\tau} = -\left(\mathbf{m} \times \mathbf{h_{eff}}\right) + \alpha_G \left(\mathbf{m} \times \frac{d\mathbf{m}}{d\tau}\right) + \sigma \mathbf{m} \times (\mathbf{m} \times \mathbf{p}) \tag{1}$$

where α_G is the Gilbert damping and is associated to the magnetic losses, $\mathbf{m} = \boldsymbol{M}/M_S$ is the normalized magnetization vector, and $\tau = \gamma_0 \, M_S \, t$ is the dimensionless time, with γ_0 being the gyromagnetic ratio. The effective field $\mathbf{h_{eff}}$, includes the field contributions related to the exchange, DMI, uniaxial anisotropy, magnetostatic (both self and given by the other magnetic layer) energies. Moreover, $\sigma = g\mu_B J\theta_H \, / \, 2eh\gamma_0$ where μ_B, g, J, θ_H and e are the Bohr magneton, the Lande factor, the applied current density, the spin Hall angle, and the electric charge, respectively. $\mathbf{p}$ is the direction of the spin-polarization [21], [40], [41].

The first term on the right-hand side of (1) describes the precessional motion of the magnetization, while the second term represents the dissipation term, which favors the alignment of the magnetization with the applied effective field. The last term captures the coupling between the magnetization and spin-polarized currents, allowing the description of current-driven creation, annihilation, and motion of domain walls through the spin-orbit torque (SOT) created in the material with large spin orbit coupling.

Stray fields, due to the magnetostatic given by the magnetostatic configuration of the other layer – driven for the driving and *vice versa* - mediate the long-range interaction between magnetic dipoles and the potential energy resulting from the interaction between two dipoles, $\mathbf{m}_1$ (magnetic configuration of the driving) and $\mathbf{m}_2$ (magnetic configuration of the driven), is given by [38]

$$\begin{aligned} H_{stray1,2} = &-\frac{\mu_0}{4\pi\,|\mathbf{r}|}\left[3\left(\mathbf{m}_1 \cdot \hat{\mathbf{r}}\right)\left(\mathbf{m}_2 \cdot \hat{\mathbf{r}}\right) - \mathbf{m}_1 \cdot \mathbf{m}_2\right] \\ &- \frac{2\mu_0}{3}\mathbf{m}_1 \cdot \mathbf{m}_2 \delta\left(\mathbf{r}\right) \end{aligned} \tag{2}$$

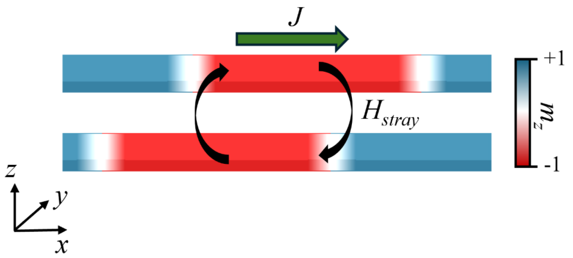

FIGURE 2. Magnetic domains coupling: The configuration consists of two parallel magnetic materials where the magnetic domains of one material are driven by an applied electric current. The stray magnetic field (H_{stray}) generated by the first material couples to the second material, causing its magnetic domains to follow the motion of the current-driven domains.

where $\mathbf{r}$ is the vector distance between the two dipoles, and $\delta(x)$ is the Dirac delta function. Stray fields couple magnetic domains between different gears with magnetic forces.

In this work, we assume that the motion of the magnetic domains can be converted into mechanical motion of the gear. Due to intrinsic[42] or engineered pinning sites [43], the current-driven motion of domains in the driving can induce mechanical rotation in the driven gear, even without any additional mechanical torque. In this case, the pinning potential in the driven gear converts magnetic forces into mechanical forces, allowing it to respond to the magnetic fields generated by the adjacent moving domains [44], [45], [46]. If the stray field coupling is strong enough, any relative displacement of the magnetic domains will generate mechanical motion to keep the domains aligned. By electrically controlling the motion of the magnetic domains and leveraging the stray field coupling and pinning strength, a differential mechanical speed can be generated between the two gears when both mechanical torque and current are applied to the driving This concept is explored in detail in the next section.

IV. RESULTS

A. PARALLEL STRIPES

To investigate the coupling between magnetic domains, we first analyzed a simple configuration with two parallel nanostripes oriented along the $\hat{x}$-direction. Fig. 2 schematically illustrates the micromagnetic simulation setup. A current was applied to the top stripe with spin polarization $\mathbf{p}$ in the $\hat{y}$-direction, generating domain motion along the $+\hat{x}$-direction. Micromagnetic simulations revealed that, although no current was applied to the bottom stripe, its magnetic domain followed the motion of the top stripe's domain. When the current exceeded the Walker breakdown threshold, we observed strong oscillations in domain wall motion, which impacted the coupling between the domains [47], [48], [49]. However, if the oscillation amplitude remained significantly smaller than the domain size, the domains remained strongly coupled. As a result, a 1-to-1 velocity relationship was maintained between the two domains.

In these simulations, we modeled two nanowires with dimensions of 1 μm × 10 nm × 1 nm, with domains pointing in the $\pm z$-direction, and separation distances ranging from 1 to 30 nm. Here we will focus on results obtained with the following material parameters $A = 10^{-12}$J/m, $D = 10^{-3}$ J/m^2, $K_u = 8{\times}10^5$ J/m^3, $M_S = 1.1$ MA/m, $\alpha_G = 0.01$, $\theta_H = 0.1$, but qualitative similar results have been observed for a wide range of parameters. Currents densities up to $4{\times}10^{12}$ A/m^2 were applied.

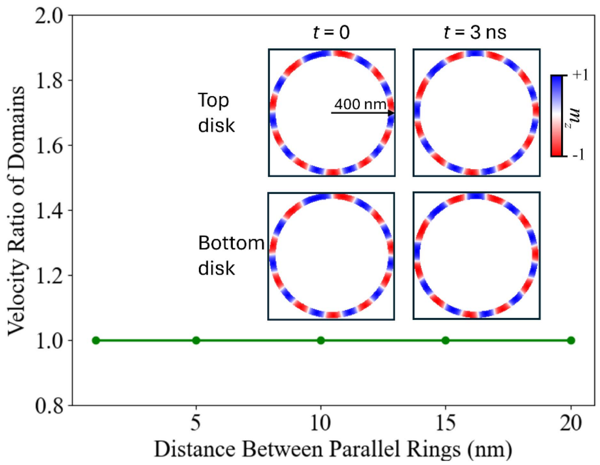

FIGURE 3. Velocity ratio of magnetic domains in parallel rings: This plot shows the velocity ratio between the global velocities of magnetic domains in two concentric parallel rings. The magnetization motion in the upper ring is driven by a spin-polarized current, while the magnetization motion in the lower ring results solely from stray field coupling with the upper ring. The inset shows the magnetization configurations of both rings at two different times with a separation of 10 nm. It is noteworthy that although the upper ring is directly driven by the current, the magnetization motion in the lower ring closely mirrors that of the upper ring.

B. PARALLEL RINGS

Building on the results obtained with two parallel nanostrips, we designed the nanogear and performed simulations with two parallel nanorings acting as magnetically coupled layers of the gears. The micromagnetic simulations used rings with an outer radius of 200 nm and an inner radius of 190 nm, using the same material parameters for consistency. Similar results have been observed for an inner radius of 180 nm. This setup is simulated with a finite difference scheme having a cell size of 1 nm^3. We introduced numerical pinning at the domain walls, which can emulate the defects induced in nanofabrication patterned, resulting in more pronounced non-uniform motion of the domain walls. With this cell discretization, rings with smaller radii were strongly affected by numerical pinning, and no significant domain wall motion was observed at experimentally achievable current densities. We considered a spatially non-uniform radial polarization direction for the spin current, which is applied only to the top ring. Radial spin polarization can be created by passing a current through the platinum underlayer in either a clockwise (positive currents) or counterclockwise (negative currents) direction. The material parameters were the same as for the parallel stripe simulations.

Fig. 3 shows the plot of the ratio of the velocity between the domains as a function of the distance between the parallel rings. The inset shows the magnetization configuration of the

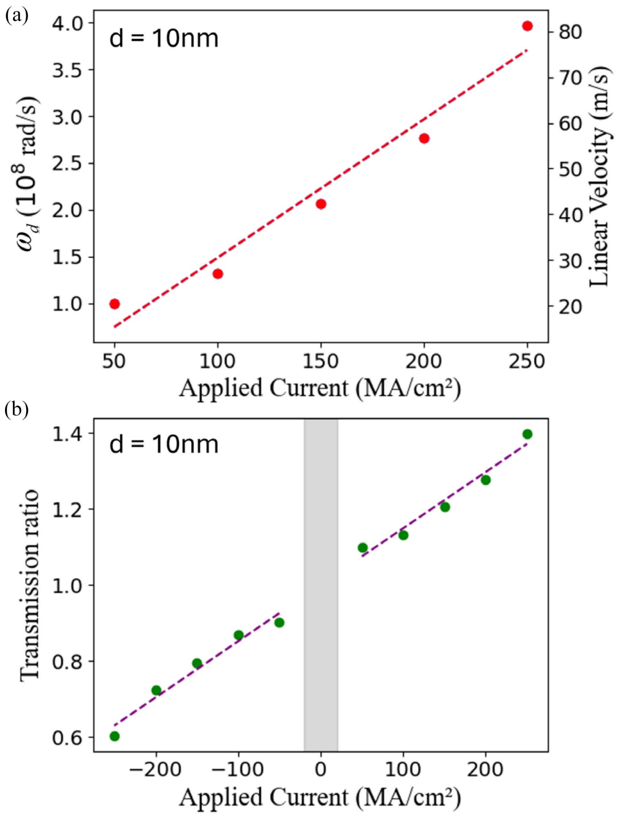

FIGURE 4. **Tunable transmission ratio. (a) The angular and linear velocities of the magnetic domains as a function of the applied current to the top gear. (b) The transmission ratio, defined as the ratio of the angular velocity of the bottom gear to the angular velocity of the top gear, as a function of the applied current to the top ring. In both figures, the distance between the gears is set to 10 nm. In panel (b), we assume that the top gear moves with a constant mechanical angular velocity of 10^9 rad/s. The gray region in (b) indicates the current range below the pinning threshold, where the transmission ratio is expected to be 1, as the magnetic domains are pinned, and no relative motion occurs between the mechanical rotation and the electrical motion of the domain wall.**

upper and lower rings at two different time steps. Despite the non-uniform domain wall behavior, a strong coupling between the magnetic domains persisted, with the system favoring configurations that minimize the total stray field energy. As a result, the overall motion of the domains in the non-current-driven ring closely followed the motion of the current-driven domains, demonstrating robust coupling. By changing the current applied to the top ring, one can change the velocity of the rotation of the magnetic domains. It is important to note that the electrical velocity of the domain walls can be much greater than the mechanical rotation of the gears. Notably, the coupling of the gears, as well as the tunability of the gear ratio, depend on gear characteristics such as geometry, moment of inertia, and strength of the magnetic coupling. In addition, the mechanical velocity of the gears and the current-driven velocity of the magnetic domains must be of the same magnitude.

C. TUNABILITY OF TRANSMISSION RATIO

Building on the previous results, we observe that the magnetic domains tend to remain aligned in a stable configuration due to stray field coupling. Considering two mechanically rotating gears, driving the magnetic domains in one ring with an electric current allows us to tune the speed ratio between the two gears. This behavior is the key property of the proposed nanogear, where the rotational inertia of the disks is small, allowing an electrically tunable gear ratio.

Considering the orientation of the magnetic domains, we can deduce that for two rotating gears with mechanical angular velocities ω_i (where i refers to gear 1 or 2 for top and bottom gears), and magnetic domains current-driven velocity ω_d applied to the top gear, the gear transmission ratio is given by

$$\frac{\omega_2}{\omega_1} = 1 + \frac{\omega_d\,(J)}{\omega_1} \tag{3}$$

This relationship allows for precise and continuous tuning of the transmission ratio.

Fig. 4(a) shows the domain angular velocity ω_d as a function of the current applied to the top as obtained from micromagnetic simulations. The data show a linear dependence of the domain wall velocity on the applied current. Fig. 4(b) shows the expected transmission ratio as a function of current, assuming perfectly aligned magnetic domains. We show that the transmission ratio can be tuned linearly with the applied current, enabling both speed multiplication and reduction depending on the current's direction. Over a range of mechanical velocities and applied currents, we also expect to be able to reverse the direction of rotation of the driven gear relative to the driving gear. In practical conditions, we expect the transmission ratio to be close to 1:1 for small currents below the pinning threshold.

V. CONCLUSION

In this work, we propose a novel concept for a nanoscale magnetic gear that leverages spintronics, enabling electrical manipulation of magnetic domains to achieve precise and continuously adjustable gear transmission ratio. Our approach involves generating current-driven motion of magnetic domains in the driven and driving rotors, allowing fine control of the transmission ratio. Micromagnetic simulations show that for current densities up to 4x10^{12} A/m^2 and distances up to 30 nm, the magnetic domains remain strongly coupled via stray fields. Moreover, we obtained that for currents above the depinning threshold, the transmission ratio varies linearly with the applied current, allowing for speed multiplication or reduction according to the sign of the applied current. To induce the motion of the magnetic domains, the magnetic ring is coupled with a material with large spin-orbit coupling, such as platinum [21]. The range of applied currents is determined by the mechanical properties of driven and driving rotors. In addition, the number of magnetic domains can be controlled by voltage gating the DMI for optimizing the magnetic coupling between the rotors [32], [33]. This work paves the way for a new generation of highly tunable nanomagnetic gears for applications in nano-actuators and other nanoscale devices where mechanical torques should be transmitted with a different ratio.

ACKNOWLEDGMENT

The authors are with the Petaspin TEAM and thank the support of the PETASPIN association (www.petaspin.com).

REFERENCES

[1] K. Ikuta, S. Makita, and S. Arimoto, "Non-contact magnetic gear for micro transmission mechanism," in *Proc.. IEEE Micro Electro Mech. Syst.*, 1991, pp. 125–130, doi: 10.1109/MEMSYS.1991.114782.

[2] Y. Wang, M. Filippini, N. Bianchi, and P. Alotto, "A review on magnetic gears: Topologies, computational models, and design aspects," *IEEE Trans. Ind. Appl.*, vol. 55, no. 5, pp. 4557–4566, Sep./Oct. 2019, doi: 10.1109/TIA.2019.2916765.

[3] P. M. Tlali, R.-J. Wang, and S. Gerber, "Magnetic gear technologies: A review," in *Proc. IEEE Int. Conf. Elect. Mach.*, 2014, pp. 544–550, doi: 10.1109/ICELMACH.2014.6960233.

[4] B. Yan, X. Li, X. Wang, and Y. Yang, "A review on the field-modulated magnetic gears: Development status, potential applications, and existent challenges," *Int. Eng. Technol. Electric Power Appl.*, vol. 18, no. 1, pp. 1–19, 2024, doi: 10.1049/elp2.12365.

[5] K. Atallah and D. Howe, "A novel high-performance magnetic gear," *IEEE Trans. Magn.*, vol. 37, no. 4, pp. 2844–2846, Jul. 2001, doi: 10.1109/20.951324.

[6] F. T. Joergensen, T. O. Andersen, and P. O. Rasmussen, "The cycloid permanent magnetic gear," in *Proc. Conf. Rec. IEEE Ind. Appl. Conf. 41st IAS Annu. Meeting*, 2006, pp. 373–378, doi: 10.1109/IAS.2006.256549.

[7] C.-C. Huang, M.-C. Tsai, D. G. Dorrell, and B.-J. Lin, "Development of a magnetic planetary gearbox," *IEEE Trans. Magn.*, vol. 44, no. 3, pp. 403–412, Mar. 2008, doi: 10.1109/TMAG.2007.914665.

[8] P. O. Rasmussen, T. O. Andersen, F. T. Jorgensen, and O. Nielsen, "Development of a high-performance magnetic gear," *IEEE Trans. Ind. Appl.*, vol. 41, no. 3, pp. 764–770, May/Jun. 2005, doi: 10.1109/TIA.2005.847319.

[9] K. T. Chau, C. C. Chan, and C. Liu, "Overview of permanent-magnet brushless drives for electric and hybrid electric vehicles," *IEEE Trans. Ind. Electron.*, vol. 55, no. 6, pp. 2246–2257, Jun. 2008, doi: 10.1109/TIE.2008.918403.

[10] A. Meo et al., "Magnetomechanical accelerometer based on magnetic tunnel junctions," *Phys. Rev. Appl.*, vol. 20, no. 3, Sep. 2023, Art. no. 034003, doi: 10.1103/PhysRevApplied.20.034003.

[11] G. S. D. Beach, M. Tsoi, and J. L. Erskine, "Current-induced domain wall motion," *J. Magnetism Magn. Materials*, vol. 320, no. 7, pp. 1272–1281, 2008, doi: 10.1016/j.jmmm.2007.12.021.

[12] M. Hayashi, L. Thomas, R. Moriya, C. Rettner, and S. S. P. Parkin, "Current-controlled magnetic domain-wall nanowire shift register," *Science*, vol. 320, no. 5873, pp. 209–211, Apr. 2008, doi: 10.1126/science.1154587.

[13] F. Schlickeiser, U. Ritzmann, D. Hinzke, and U. Nowak, "Role of entropy in domain wall motion in thermal gradients," *Phys. Rev. Lett.*, vol. 113, no. 9, pp. 1–5, 2014, doi: 10.1103/PhysRevLett.113.097201.

[14] H. Sohn et al., "Electrically driven magnetic domain wall rotation in multiferroic heterostructures to manipulate suspended on-chip magnetic particles," *Amer. Chem. Soc. Nano*, vol. 9, no. 5, pp. 4814–4826, 2015, doi: 10.1021/nn5056332.

[15] S. Bandyopadhyay, "Straintronics: Digital and analog electronics with strain-switched nanomagnets," *IEEE Open J. Nanotechnol.*, vol. 1, pp. 57–64, 2020, doi: 10.1109/OJNANO.2020.3011637.

[16] D. Kumar et al., "Domain wall memory: Physics, materials, and devices," *Phys. Rep.*, vol. 958, pp. 1–35, 2022, doi: 10.1016/j.physrep.2022.02.001.

[17] A. A. Kovalev, G. E. W. Bauer, and A. Brataas, "Current-driven ferromagnetic resonance, mechanical torques, and rotary motion in magnetic nanostructures," *Phys. Rev. B*, vol. 75, no. 1, Jan. 2007, Art. no. 014430, doi: 10.1103/PhysRevB.75.014430.

[18] W. Izumida, R. Okuyama, K. Sato, T. Kato, and M. Matsuo, "Einstein–de Haas Nanorotor," *Phys. Rev. Lett.*, vol. 128, no. 1, Jan. 2022, Art. no. 017701, doi: 10.1103/PhysRevLett.128.017701.

[19] S. Tateno, Y. Kurimune, M. Matsuo, K. Yamanoi, and Y. Nozaki, "Einstein–de Haas phase shifts in surface acoustic waves," *Phys. Rev. B*, vol. 104, no. 2, Jul. 2021, Art. no. L020404, doi: 10.1103/PhysRevB.104.L020404.

[20] M. Matsuo, E. Saitoh, and S. Maekawa, "Spin-Mechatronics," *J. Phys. Soc. Jpn.*, vol. 86, no. 1, Jan. 2017, Art. no. 011011, doi: 10.7566/JPSJ.86.011011.

[21] S. Emori, U. Bauer, S. M. Ahn, E. Martinez, and G. S. D. Beach, "Current-driven dynamics of chiral ferromagnetic domain walls," *Nature Mater.*, vol. 12, no. 7, pp. 611–616, 2013, doi: 10.1038/nmat3675.

[22] E. Martinez, S. Emori, and G. S. D. Beach, "Current-driven domain wall motion along high perpendicular anisotropy multilayers: The role of the Rashba field, the spin Hall effect, and the Dzyaloshinskii-Moriya interaction," *Appl. Phys. Lett.*, vol. 103, no. 7, 2013, Art. no. 072406, doi: 10.1063/1.4818723.

[23] K. S. Ryu, L. Thomas, S. H. Yang, and S. Parkin, "Chiral spin torque at magnetic domain walls," *Nature Nanotechnol.*, vol. 8, no. 7, pp. 527–533, 2013, doi: 10.1038/nnano.2013.102.

[24] I. Žutić, J. Fabian, and S. D. Sarma, "Spintronics: Fundamentals and applications," *Rev. Mod. Phys.*, vol. 76, no. 2, pp. 323–410, Apr. 2004, doi: 10.1103/RevModPhys.76.323.

[25] A. Hirohata et al., "Review on spintronics: Principles and device applications," *J. Magnetism Magn. Materials*, vol. 509, 2020, Art. no. 166711, doi: 10.1016/j.jmmm.2020.166711.

[26] Z. Wang et al., "Design, fabrication and application of magnetically actuated micro/nanorobots: A review," *Nanotechnology*, vol. 33, no. 15, Apr. 2022, Art. no. 152001, doi: 10.1088/1361-6528/ac43e6.

[27] Q. Wang and L. Zhang, "Ultrasound imaging and tracking of micro/nanorobots: From individual to collectives," *IEEE Open J. Nanotechnol.*, vol. 1, no. 1, pp. 6–17, 2020, doi: 10.1109/OJ-NANO.2020.2981824.

[28] M. A. Rahman and A. T. Ohta, "Micromanipulation with microrobots," *IEEE Open J. Nanotechnol.*, vol. 2, pp. 8–15, 2021, doi: 10.1109/OJ-NANO.2021.3050496.

[29] S. A. Wolf et al., "Spintronics: A spin-based electronics vision for the future," *Science*, vol. 294, no. 5546, pp. 1488–1495, Nov. 2001, doi: 10.1126/science.1065389.

[30] B. Dieny et al., "Opportunities and challenges for spintronics in the microelectronics industry," *Nature Electron.*, vol. 3, no. 8, pp. 446–459, 2020, doi: 10.1038/s41928-020-0461-5.

[31] O. Boulle, G. Malinowski, and M. Kläui, "Current-induced domain wall motion in nanoscale ferromagnetic elements," *Materials Sci. Eng. R Reports*, vol. 72, no. 9, pp. 159–187, Sep. 2011, doi: 10.1016/j.mser.2011.04.001.

[32] R. Knapman, D. R. Rodrigues, J. Masell, and K. Everschor-Sitte, "Current-induced H-shaped-skyrmion creation and their dynamics in the helical phase," *J. Phys. D. Appl. Phys.*, vol. 54, no. 40, pp. 1–14, 2021, doi: 10.1088/1361-6463/ac0e5a.

[33] T. Srivastava et al., "Large-voltage tuning of Dzyaloshinskii–Moriya interactions: A route toward dynamic control of Skyrmion chirality," *Nano Lett.*, vol. 18, no. 8, pp. 4871–4877, Aug. 2018, doi: 10.1021/acs.nanolett.8b01502.

[34] R. Moukhader et al., "Manipulation of 2D and 3D magnetic solitons under the influence of DMI gradients," *IEEE Open J. Nanotechnol.*, vol. 5, pp. 68–79, 2024, doi: 10.1109/OJNANO.2024.3484568.

[35] D. Atkinson, D. A. Allwood, G. Xiong, M. D. Cooke, C. C. Faulkner, and R. P. Cowburn, "Magnetic domain-wall dynamics in a submicrometre ferromagnetic structure," *Nature Mater.*, vol. 2, no. 2, pp. 85–87, Feb. 2003, doi: 10.1038/nmat803.

[36] G. Catalan, J. Seidel, R. Ramesh, and J. F. Scott, "Domain wall nanoelectronics," *Rev. Mod. Phys.*, vol. 84, no. 1, pp. 119–156, Feb. 2012, doi: 10.1103/RevModPhys.84.119.

[37] Y. Zhou, S. Li, X. Liang, and Y. Zhou, "Topological spin textures: Basic physics and devices," *Adv. Mater.*, vol. 37, Jul. 2024, Art. no. 2312935, doi: 10.1002/adma.202312935.

[38] G. Finocchio, F. Büttner, R. Tomasello, M. Carpentieri, and M. Kläui, "Magnetic skyrmions: From fundamental to applications," *J. Phys. D. Appl. Phys.*, vol. 49, no. 42, Oct. 2016, Art. no. 423001, doi: 10.1088/0022-3727/49/42/423001.

[39] A. Giordano, G. Finocchio, L. Torres, M. Carpentieri, and B. Azzerboni, "Semi-implicit integration scheme for Landau–Lifshitz–Gilbert-Slonczewski equation," *J. Appl. Phys.*, vol. 111, no. 7, Apr. 2012, Art. no. 07D112, doi: 10.1063/1.3673428.

[40] G. Finocchio, M. Carpentieri, E. Martinez, and B. Azzerboni, "Switching of a single ferromagnetic layer driven by spin Hall effect," *Appl. Phys. Lett.*, vol. 102, no. 21, pp. 10–15, 2013, doi: 10.1063/1.4808092.

[41] R. Tomasello et al., “Micromagnetic understanding of the skyrmion Hall angle current dependence in perpendicularly magnetized ferromagnets,” *Phys. Rev. B*, vol. 98, no. 22, Dec. 2018, Art. no. 224418, doi: 10.1103/PhysRevB.98.224418.

[42] T. Koyama et al., “Observation of the intrinsic pinning of a magnetic domain wall in a ferromagnetic nanowire,” *Nature Materials*, vol. 10, no. 3, pp. 194–197, Mar. 2011, doi: 10.1038/nmat2961.

[43] V. Jeudy, R. Díaz Pardo, W. S. Torres, S. Bustingorry, and A. B. Kolton, “Pinning of domain walls in thin ferromagnetic films,” *Phys. Rev. B*, vol. 98, no. 5, Aug. 2018, Art. no. 054406, doi: 10.1103/PhysRevB.98.054406.

[44] R. A. Duine and C. M. Smith, “Creep of current-driven domain-wall lines: Effects of intrinsic versus extrinsic pinning,” *Phys. Rev. B - Condens. Matter Materials Phys.*, vol. 77, no. 9, 2008, Art. no. 094434, doi: 10.1103/PhysRevB.77.094434.

[45] E. Martinez, G. Finocchio, and M. Carpentieri, “Stochastic resonance of a domain wall in a stripe with two pinning sites,” *Appl. Phys. Lett.*, vol. 98, no. 7, pp. 3–5, 2011, doi: 10.1063/1.3556314.

[46] C. Burrowes et al., “Role of pinning in current driven domain wall motion in wires with perpendicular anisotropy,” *Appl. Phys. Lett.*, vol. 93, no. 17, pp. 3–5, 2008, doi: 10.1063/1.2998393.

[47] A. Mougin, M. Cormier, J. P. Adam, P. J. Metaxas, and J. Ferré, “Domain wall mobility, stability and Walker breakdown in magnetic nanowires,” *Europhys. Lett.*, vol. 78, no. 5, Jun. 2007, Art. no. 57007, doi: 10.1209/0295-5075/78/57007.

[48] S. Glathe, R. Mattheis, and D. V. Berkov, “Direct observation and control of the Walker breakdown process during a field driven domain wall motion,” *Appl. Phys. Lett.*, vol. 93, no. 7, pp. 23–25, 2008, doi: 10.1063/1.2975181.

[49] M. Yan, C. Andreas, A. Kákay, F. García-Sánchez, and R. Hertel, “Fast domain wall dynamics in magnetic nanotubes: Suppression of Walker breakdown and Cherenkov-like spin wave emission,” *Appl. Phys. Lett.*, vol. 99, no. 12, Sep. 2011, Art. no. 122505, doi: 10.1063/1.3643037.

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