Coupled ferromagnetic-resonance modes and frequency enhancement in Py/FeMn bilayers under magnetic proximity effect

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Ferromagnetic resonance (FMR) in exchange-coupled ferromagnet-antiferromagnet bilayers commonly shows only one resonance mode corresponding solely to the excitation of the ferromagnetic component. Here we report an observation of a simultaneous excitation of both the ferromagnetic and antiferromagnetic films in a Py/FeMn bilayer, observed as two coupled FMR modes. These modes are explained as due to a dynamic interplay between the magnetization of Py and the proximity-induced magnetization in an ultra-thin layer of nominally antiferromagnetic FeMn. We find that this proximity induced magnetization of FeMn increases with decreasing the thickness of FeMn. A concomitant increase in the FMR frequency toward the sub-THz range is observed for the bilayer with FeMn as thin as 3 nm. We explain the results as due to a competition between the intrinsic antiferromagnetic order in the FeMn film and the magnetic proximity effect induced by the Py layer. As a result, the structure transforms into a relatively strongly-coupled ferromagnetic bilayer, with a completely different FMR spectrum, particularly near the Néel temperature of the antiferromagnetic film. Our results show that combining materials with strong and weak anti/ferromagnetic ordering can be promising for high-speed spintronic applications, which can potentially close the notoriously difficult GHz-THz gap.

The significant difference in the magnetization dynamics of ferromagnetic (FM) and antiferromagnetic (AFM) materials leads to a wide gap between the respective resonance frequencies, reaching several orders of magnitude. This frequency gap is due to drastically different intrinsic fields acting on the spins in FMs and AFMs under FMRs. The spins in FMs are in the effective field of the magnetic anisotropy, which is usually not larger than a kOe (100 mT) for ferromagnetic 3d-metals and their alloys. On the contrary, the spins belonging to one of the FM spin sublattices in an AFM material experience a strong exchange field (\(\gtrsim 100\) T) from the other (antiparallel) sublattice. This 1000-fold factor between the intrinsic effective fields governing the FMR in FMs and AFMs leads to a corresponding GHz-THz frequency gap.

The idea to enhance the ferromagnetic-resonance (FMR) frequencies by combining FM and AFM materials, e.g. in thin-film multilayers, meets difficulties in practice, which arise from typically weak exchange coupling at FM/AFM interfaces. This problem is well known and well-studied in relation to exchange bias, widely used in spintronic applications for creating the so-called exchange pinning of FM layers. The latter manifests as relatively weak unidirectional magnetic anisotropy (typically \(< 1\) kOe), which can offer only a weak enhancement of the FMR frequency.

In this work, we report on coupled magnetization dynamics and a considerable FMR frequency enhancement in thin-film bilayers of Ni\(_{50}\)Fe\(_{20}\)/Fe\(_{50}\)Mn\(_{50}\) (Py/FeMn). Despite the fact that Py/FeMn is one of the most studied exchange-bias systems, the magnetization dynamics of this and similar bilayers, specifically near the Néel temperature of the AFM layer, \(T_N\), had received little attention, since the focus with exchange-pinning is on the relevant magnetic properties at \(T \ll T_N\). The main thesis of this work is that the magnetization dynamics of Py/FeMn should be strongly modified near \(T_N\) due to the pronounced magnetic proximity effect of Py on FeMn. When approaching \(T_N\) from bellow, AFM ordering in FeMn becomes weaker, while the exchange-field from Py penetrates into FeMn and re-aligns the AFM spins ferromagnetically. Such magnetic proximity effect has been observed for Ni/FeMn/Co trilayers and shown to decrease \(T_N\) of the FeMn layer. The strength of the proximity-exchange is known to drop exponentially with depth into adjacent weakly magnetic layers, making the effect most pronounced for nanometer thin layers. On the other hand, FeMn has an fcc lattice with random chemical occupation of the sites and a noncollinear spin structure, which together can result in an uncompensated magnetic moment in a thin film. The spin structure of FeMn in Py/FeMn is aligned with the FM moment (of Py), \(M_{24,25}\) one can assume that the proximity effect can induce and stabilize a non-zero net magnetic moment, \(M_{b}\), in thin FeMn layers (Fig. 1). The dynamic interplay between \(M\) and \(M_{b}\) can then lead to coupled FMR modes. We indeed observe two coupled FMR modes in Py/FeMn near the effective \(T_N\) of the AFM layer and a 3-fold enhancement of the FMR frequency.

The FMR frequency for an exchange-coupled bilayer for the in-plane orientation of the external magnetic field can be expressed as:

\[
f_{\text{FMR}} = \frac{\gamma}{2\pi} \sqrt{H_{\text{eff}}(H_{\text{eff}} + 4\pi M_{\text{eff}})}.
\]

where \(\gamma\) is the gyromagnetic constant; \(H_{\text{eff}}\) is the effect-
FIG. 1. Schematic of a two-layer exchange-coupled system: “high-$T_f$ ferromagnet / low-$T_N$ antiferromagnet” (F/AF), under in-plane FMR with external magnetic field $\mathbf{H}$ oriented in the film plane. In the vicinity of $T_N$, non-zero magnetic moment ($\mathbf{M}_b$) in AF is induced by the strong magnetic proximity effect from F. $\mathbf{M}_b$ is exchange coupled to the magnetic moment of F ($\mathbf{M}$), which results in coupled, acoustic and optical, FMR modes.

tive field, combining the external magnetic field and any intrinsic in-plane magnetic anisotropy field; $4\pi M_{\text{eff}}$ is the thin-film demagnetizing field proportional to the saturation magnetization ($M_{\text{eff}} \approx M_s$). The latter term can include out-of-plane anisotropy terms, which cannot be distinguished from the demagnetization in (1).

In expression (1), the interlayer exchange coupling contributes mainly to $H_{\text{eff}}$. Our expectation detailed above is that the Py/FeMn bilayer should combine the properties of F/AF exchange-biased and F/F*-like proximity-coupled systems. These two types of exchange coupling are described by different $H_{\text{eff}}$. The first, F/AF exchange bias, is commonly manifest as unidirectional anisotropy in F and, thus, is described as $H_{\text{eff}} = (H - H_b \cos \varphi)$, where $\varphi$ is the in-plane orientation of $M$ with respect to the pinning direction ($\varphi = 0^\circ$). $H_b$ is the effective field of the exchange-bias, which can be determined from the angle profile of the resonance field, $H_{\text{res}}$, as the half-difference between $H_{\text{res}}(0^\circ)$ and $H_{\text{res}}(180^\circ)$. On the other hand, exchange coupled F/F* bilayers usually exhibit two coupled FMR modes corresponding to different $H_{\text{eff}}$: the acoustic mode, when the magnetic moments of both F layers are precessing in phase, has $H_{\text{eff}} = H$ (for simplicity, we disregard possible in-plane anisotropy); and the optical mode, when the moments are precessing in antiphase, has $H_{\text{eff}} = (H \pm H_{\text{ex}})$, with $H_{\text{ex}}$ being the effective field of the FM-like (“+””) or AFM-like (“−”) interlayer coupling. As a result, the acoustic mode is usually observed at the same resonance field as that for the corresponding single F film, whereas the optical mode is shifted by $H_{\text{ex}}$ down (up) from the position of the acoustic mode in the case of the FM-like (AFM-like) interlayer coupling.

As discussed above, $M$ and $M_b$ in our Py/FeMn system should exchange couple (F/F*) and both experience exchange pinning (F/F*/AF). Therefore, the system’s dynamics can be described by (1) with $H_{\text{eff}} = (H - H_b \cos \varphi)$ for the acoustic mode and $H_{\text{eff}} = (H - H_b \cos \varphi + H_{\text{ex}})$ for the optical mode. It should be stressed that $H_b$ and $H_{\text{ex}}$ are different quantities: $H_{\text{ex}}$ reflects the strength of the exchange coupling at the interface between Py and FeMn, whereas $H_b$ describes the effective exchange pinning in the system. Indeed, $H_b$ is determined by the strength of the interlayer exchange coupling ($H_{\text{ex}}$) as well as the other factors affecting the exchange pinning mechanism, e.g., the magnetic anisotropy in FeMn. Consequently, an FMR study can distinguish between $H_{\text{ex}}$ and $H_b$, which is not possible by using other methods, such as magnetometry, which yield only $H_b$.

A series of multilayers Ta(5)/Py(5)/FeMn($t = 0, 3, 5$ and $7 \text{ nm}$)/Al(4) were deposited on thermally oxidized Si substrates using magnetron sputtering. To induce exchange pinning, a magnetic field of $\lesssim 1$ kOe was applied in the film plane during deposition. The FMR measurements were carried out in a temperature interval of 200–320 K using an X-band ELEXSYS E500 spectrometer (Bruker) at a constant operating frequency of 9.46 GHz. The FMR spectra were measured for varying in-plane orientation of the external field and using reverse field sweeping from 5 kOe to zero. Temperature-dependent measurements were performed after cooling in a magnetic field applied along the pinning direction.

Figure 2 shows select FMR spectra for Py/FeMn bilayers with different thickness $t$ of FeMn, measured at room temperature and with varying in-plane orientation of the applied field (angle $\varphi_H$). Depending on the thickness of FeMn, the spectra can be grouped into two categories [Fig. 2(b)–(d)]. First, the bilayers with the thicker FeMn ($t = 5$ and $7 \text{ nm}$) exhibit two resonance lines, both with the resonance field, $H_{\text{res}}$, dependent on $\varphi_H$. This angular dependence reflects the exchange pinning in the system, as detailed above, and indicates that the thicker FeMn layers have a significant antiferromagnetic character with $T_N$ higher than the measurement (room) temperature. In contrast, the bilayer with the thinnest FeMn ($3 \text{ nm}$) shows only one resonance mode. The corresponding resonance line is independent of $\varphi_H$ and has a large offset ($\sim 600$ Oe) from the position of the free-Py line (L$_{\text{Py}}$) [Fig. 2(a)]. This difference between the two types of FMR behavior is explained below in terms of a transformation of the interlayer exchange coupling near $T_N$.

We associate the observed two resonance lines for the structures with $t = 5$ and $7 \text{ nm}$ with the acoustic and optical resonance modes arising from a dynamic interaction of the Py’s magnetization and the FeMn’s proximity-induced magnetic moment. Line L$_A$ is recognized as the acoustic mode since its average position is very close to $H_{\text{res}}$ of the reference Py film [Fig. 3]. From the angle profile of L$_A$, the effective field of exchange pinning is $H_b = 300–400$ Oe. The other line, L$_O$, observed at lower fields is attributed to the optical mode arising from the FM-like coupling at the Py/FeMn interface. The difference between $H_{\text{res}}$ of L$_A$ and L$_O$ yields, using the above effective-field expression, the strength of the interlayer exchange coupling, $H_{\text{ex}} = 700–900$ Oe. The obtained
difference in values for $H_{ex}$ and $H_{b}$ illustrates the two distinct manifestations of the same interlayer exchange effect, only one of which contributes to the observed optical resonance mode.

Both acoustic and optical FMR modes carry information about the effective magnetization, $M_{\text{eff}}$, contained in the $4\pi M_{\text{eff}}$ term in (I). The gap between the $L_A$ branches in Fig. 3 reflects an increase in $M_{\text{eff}}$ on decreasing the thickness of FeMn from $t = 7$ nm to 5 nm. Interestingly but not surprisingly, $M_{\text{eff}}$ for $t = 5$ nm is even higher than the saturation magnetization of the reference Py film (details below). Such increase in $M_{\text{eff}}$ is expected from an induced magnetic moment in FeMn, which should increase in magnitude with decreasing $t$ as a result of the magnetic proximity effect from Py overcoming the weakening AFM order in FeMn.

The FMR behavior of the Py/FeMn bilayer with $t = 3$ nm exhibits only one FMR mode, which we interpret as acoustic and mark $L_A$. Performing the measurements at different temperatures reveals the key properties of $L_A$ (Fig. 4). Being essentially angle-independent at room temperature, $L_A$ shows unidirectional anisotropy at lower temperatures, as seen in $H_{\text{res}}$-vs-$\varphi_H$ [Fig. 4(b)]. This unidirectional anisotropy indicates the presence of exchange pinning in the system and therefore sufficiently strong AFM-ordering in the thin FeMn layer. As seen in Fig. 4(d), the exchange pinning vanishes completely at $T \gtrsim 300$ K and is significantly suppressed (with a relatively low $T_N$) compared with the thicker-FeMn structures, where FMR reveals exchange pinning in the whole temperature interval [see Suppl. Material].

Reduction of effective $T_N$ was reported for similar exchange-coupled systems and explained by the competition of the magnetic proximity effect and intrinsic AFM ordering in the AF layers. Since the magnetic proximity effect is relatively short range (a few nm), the reduction of $T_N$ is more pronounced for thinner AF layers, for which the finite-size effect can also take place. This explains the relatively large difference in $T_N$ for the structures in our series.

The temperature dependence of $M_{\text{eff}}$ obtained from the FMR data using (I) and shown in Fig. 4(a) helps to explain the pronounced difference in dynamic properties between the structures with different $t$. With increasing temperature, $M_{\text{eff}}$ decreases for the structure with the 7-nm FeMn, which is typical for ferromagnetic materials. In contrast, $M_{\text{eff}}$ for the structure with the 5-nm FeMn has an unconventional upturn at high temperatures. This can be explained by an increase in the net magnetic moment of the 5-nm FeMn, since its AFM order weakens and the magnetic proximity effect becomes more pronounced at higher temperatures.

The temperature behavior of $M_{\text{eff}}$ for the structure with the 3-nm FeMn cannot be explained in the same fashion as for the other structures. The reason is that the obtained values for $M_{\text{eff}}$ are larger than the maximum possible magnetization of the bilayer or even that
of a corresponding Fe film [Fig. 5(a)]. This large enhancement in $M_{\text{eff}}$ is unlikely to arise from the presence of some “easy-plane” magnetic anisotropy, which can contribute to the $4\pi M_{\text{eff}}$ term in \(\mathcal{H}^{\text{eff}}\), because the required strength would be $\sim 100$ kG – too high for any 3d transition-metal system. On the other hand, such a high value can be an indication of its magnetic-exchange origin and thus be attributed to some dynamic effective field, $H_{\text{AF}}$, arising from the interaction of the FM subsystem with the AFM component in FeMn. The characteristic frequencies of the AFM excitations near $T_N$ are close to the ferromagnetic excitations range (low GHz), which should enable the energy transfer between the FM and AFM subsystems. With decreasing temperature, the AFM order becomes stronger, which is verified by a strengthening exchange-pinning. At the same time, the resonance frequency of the bilayer increases significantly, trending toward the sub-terahertz range characteristic of the AFM resonance, as shown in Fig. 5(b).

Coupled FMR modes in exchange-biased F/AF systems have not, to the best of our knowledge, been reported before. The two FMR modes we observe cannot be attributed to standing spin wave modes, which have been reported for similar systems with much thicker Py (>40 nm)[21]. We explain our findings in terms of a dynamic interplay between the magnetization of Py and the proximity-induced magnetic moment in FeMn. Along with the fact that a nonzero magnetization of FeMn is typical for similar bilayers[22,23], we highlight the importance of the magnetic proximity effect[18] for the induced magnetic moment in FeMn, concentrated in the vicinity of the interface. Our data show that the proximity exchange from Py acts as a ferromagnetic bias in FeMn, with the induced magnetic moment becoming greatly enhanced as the AFM ordering becomes weaker at elevated temperatures.

Analyzing the observed acoustic and optical FMR modes we are able to distinguish between the exchange-pinning field, $H_b$, and the exchange-coupling field, $H_{\text{ex}}$, which characterize different aspects of the studied exchange-coupled system. Importantly, $H_{\text{ex}}$ is impossible to determine by using commonly employed quasistatic methods, which yield $H_b$ typically determined as the field-offset of the hysteresis loop[21,22]. Due to the dynamic nature of the FMR technique, $H_{\text{ex}}$ appears as the
field offset between the acoustic and optical modes of the bilayer. $H_b$ is still present and reflects the static properties, i.e. the unidirectional anisotropy. Distinguishing between $H_{ex}$ and $H_b$ adds a greater detail and a better understanding of the exchange-bias effect. Particularly, our results show that the strength of the exchange pinning ($H_b \approx 400$ Oe) in our Py/FeMn is limited by the factors intrinsic to the AFM (relevant for exchange-pinning) rather than by the strength of the interfacial exchange coupling per say ($H_{ex} \approx 1000$ Oe).

The considerable frequency enhancement we observe for the structure with the thinnest FeMn in the series demonstrates an alternative way for designing magnetic nanostructures operating in the high-GHz frequency range. In contrast to the conventional approach to enhancing the FMR frequency by tailoring the magnetic anisotropy, e.g. by using exchange bias, we show that the frequency can be significantly increased by employing coupled FMR modes in the proximity-magnetized regime of the AFM near its Néel temperature, where the frequency gap between the spin excitations in the two materials becomes sufficiently narrow. This approach can potentially result in a new class of ferromagnetic-like materials operating at sub-THz frequencies, important for a variety of high-speed applications.

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1. A. G. Gurevich and G. A. Melkov, Magnetization Oscillations and Waves (CRC Press, 1996).
2. R. C. O’Handley, Modern Magnetic Materials: Principles and Applications (Wiley-IEEE Press, 2000).
3. B. Viala, G. Visetin, and P. Gaud, “AF-biased CoFe multilayer films with FMR frequency at 5 GHz and beyond,” IEEE Transactions on Magnetics 40, 1996–1998 (2004).
4. C. Pettiford, A. Zelser, S. Yoon, V. Harris, C. Vittoria, and N. Sun, “Effective anisotropy fields and ferromagnetic resonance behaviors of CoFe/PtMn/CoFe trilayers,” IEEE Transactions on Magnetics 42, 2993–2995 (2006).
5. Y. Lamy and B. Viala, “NiMn, IrMn, and NiO exchange coupled CoFe multilayers for microwave applications,” IEEE Transactions on Magnetics 42, 3332–3334 (2006).
6. N. N. Phuoc, F. Xu, and C. K. Ong, “Ultrawideband microwave noise filter: Hybrid antiferromagnet/ferromagnet exchange-coupled multilayers,” Applied Physics Letters 94, 092505 (2009).
7. N. N. Phuoc, L. T. Hung, and C. Ong, “Ultra-high ferromagnetic resonance frequency in exchange-biased system,” Journal of Alloys and Compounds 506, 504–507 (2010).
8. N. N. Phuoc and C. K. Ong, “Diluted antiferromagnet effect on magnetic and microwave characteristics of exchange-biased multilayered thin films,” Journal of Applied Physics 111, 093919 (2012).
9. N. N. Phuoc, H. Y. Chen, and C. K. Ong, “Effect of antiferromagnetic thickness on thermal stability of static and dynamic magnetization of NiFe/FeMn multilayers,” Journal of Applied Physics 113, 063913 (2013).
10. B. Peng, N. N. Phuoc, and C. Ong, “High-frequency magnetic properties and their thermal stability in diluted IrMn–al2o3/FeCo exchange-biased multilayers,” Journal of Alloys and Compounds 602, 87–93 (2014).
11. G. W. Paterson, F. J. T. Gonçalves, S. McFadzean, S. O’Reilly, R. Bowman, and R. L. Stamps, “Magnetic characteristics of a high-layer-number NiFe/FeMn multilayer,” Journal of Applied Physics 118, 205903 (2015).
12. Nogués and J. K. Schuller, “Exchange bias,” Journal of Magnetism and Magnetic Materials 192, 203–232 (1999).
13. J. Nogués, J. Sort, V. Langlais, V. Skumryev, S. Surinach, J. Muñoz, and M. Baró, “Exchange bias in nanostructures,” Physics Reports 422, 65–117 (2005).
14. R. Hempstead, S. Krongelb, and D. Thompson, “Unidirectional anisotropy in nickel-iron films by exchange coupling with antiferromagnetic films,” IEEE Transactions on Magnetics 14, 521–523 (1978).
15. C. Tsang, N. Heiman, and K. Lee, “Exchange-induced unidirectional anisotropy at FeMn-ni80fe20 interfaces,” Journal of Applied Physics 52, 2471–2473 (1981).
16. C. Schlenker, S. Parkin, J. Scott, and K. Howard, “Magnetic disorder in the exchange bias bilayered FeNi/FeMn system,” Journal of Magnetism and Magnetic Materials 54-57, 801–802 (1986).
17. G. Choe and S. Gupta, “High exchange anisotropy and high blocking temperature in strongly textured NiFe(111)/FeMn(111) films,” Applied Physics Letters 70, 1768–1768 (1997).
18. K. Lenz, S. Zander, and W. Kuch, “Magnetic proximity effects in antiferromagnet/ferromagnet bilayers: The impact on the Néel temperature,” Physical Review Letters 98, 237201 (2007).
19. A. Hernando, I. Navarro, and P. Górriz, “Iron exchange-field penetration into the amorphous interphase of nanocrystalline materials,” Physical Review B 51, 3281–3284 (1995).
20. I. Navarro, M. Ortnino, and A. Hernando, “Ferromagnetic interactions in nanostructured systems with two different Curie temperatures,” Physical Review B 53, 11665–11666 (1996).
21. H. Wijn, ed., Magnetic Properties of Metals (Springer-Verlag Berlin, 1991).
22. D. Schmitz, E. Schierle, N. Darowski, H. Maletta, E. Wescle, and M. Gruyters, “Unidirectional behavior of uncompensated orbital moments in exchange-biased Co/Fe/Mn(300),” Physical Review B 81, 224422 (2010).
23. D. Kaya, P. N. Lapa, F. Jayathilaka, H. Kirby, C. W. Miller, and I. V. Roschchina, “Controlling exchange bias in FeMn with Cu,” Journal of Applied Physics 113, 17D117 (2013).
24. W. J. Antel, F. Perjeru, and G. R. HARP, “Spin structure at the interface of exchange-biased FeMn/Cu bilayers,” Physical Review Letters 83, 1439–1442 (1999).
25. T. Mohanty, A. Persson, D. Arvanitis, T. Temst, and C. V. Haesendonck, “Direct observation of frozen moments in the NiFe/FeMn exchange bias system,” New Journal of Physics 15, 033016 (2013).
26. C. Kittel, “On the theory of ferromagnetic resonance absorption,” Physical Review 73, 155–161 (1948).
27. Z. Zhang, L. Zhou, P. E. Wigen, and K. Omadjela, “Angular dependence of ferromagnetic resonance in exchange-coupled co/ru/co trilayer structures,” Physical Review B 50, 6094–6112 (1994).
28. Y. Chen, X. Fan, Y. Zhou, X. Xie, J. Wu, T. Wang, S. T. Chui, and J. Q. Xiao, “Designing and tuning magnetic resonance with exchange interaction,” Advanced Materials 27, 1351–1355 (2015).
29. Similar gap is also observed for the Lq branches, which, however, are incomplete at small $\phi$ due to the measurement limitations; we therefore focus the following in-depth analysis predominantly on the Lq mode.
30. V. Golosovsky, G. Salazar-Alvarez, A. López-Ortega, M. A. González, J. Sort, M. Estrader, S. Surinach, M. D. Baró, and J. Nogués, “Magnetic proximity effect features in antiferromagnetic/ferromagnetic core/shell nanoparticles,” Physical Review Letters 102, 217201 (2009).
31. J. C. Scott, “Ferromagnetic resonance studies in the bilayer system ni0.80fe0.20/ma11.50fe0.50: Exchange anisotropy,”
1. Sample Fabrication and Methods

A series of multilayers Ta(5)/Py(5)/FeMn(\(t = 0, 3, 5 \text{ and } 7\) nm)/Al(4) were deposited on oxidized Si substrates at room temperature using a dc magnetron sputtering system (AJA Inc.). The thicknesses of individual layers were controlled by setting the deposition time using the respective rate calibrations. In order to induce exchange pinning, all multilayers were deposited in a magnetic field of \(\lesssim 1\) kOe applied in the film plane. For temperature-dependent measurements, the samples were cooled down in a magnetic field applied in the same direction as during the deposition. The magnetic properties were initially characterized at room temperature using a vibrating-sample magnetometer (Lakeshore Cryogenics). The FMR measurements were carried out in a temperature interval of 200–320 K using an X-band ELEXSYS E500 spectrometer (Bruker) at a constant operating frequency of 9.46 GHz and sweeping the external magnetic field in the film plane. The field sweeping was performed in the reverse direction, from 5 kOe to zero, in order to prevent FMR signals due to possible domain formation at low fields (below \(\sim 100–200\) Oe).

2. Temperature-dependent FMR behavior of bilayers with thicker FeMn

The structures with the thicker FeMn layers (\(t = 5\) and 7 nm) have much higher \(T_N\) than the maximum temperature available experimentally in our FMR measurements (\(T \leq 320\) K). With decreasing temperature, the unidirectional anisotropy observed in \(H_{\text{res}}\)-vs-\(\varphi_H\) for line \(L_A\) increases [Fig. A1(a)]. The corresponding effective exchange filed \(H_{\text{ex}}\) can be derived from the temperature dependence of \(H_{\text{res}}(0^\circ)\) and \(H_{\text{res}}(180^\circ)\) [Figs. A1(b),(c)]. A pronounced temperature dependence of \(H_{\text{ex}}\) is typical for exchange-biased systems [\textit{J. Magn. Magn. Mater.} \textbf{192}, 203–232 (1999)]. The highly unusual result is that the derived effective magnetization is 10–20 % larger than that for the reference Py film [Fig. A1(a)]. This additionally confirms the origin of \(L_A\) as due to coupled dynamics in the system, discussed in the main text.

**Figure A1.** Temperature-dependent resonance field for the Py/FeMn bilayer with a thicker FeMn (\(t = 5\) nm; \(T_N\) well above room temperature). (a) Angle profiles of the resonance field of the \(L_A\) line versus temperature. (b) Temperature dependence of the resonance field along (0\(^\circ\)) and against (180\(^\circ\)) the exchange pinning direction. (c) Exchange field vs temperature derived from the data in panel (b).