nature portfolio

Peer Review File

Moving magnetic domain walls with sound alone

Corresponding Author: Professor José Prieto

This file contains all reviewer reports in order by version, followed by all author rebuttals in order by version.

Version 1:

Reviewer comments:

Reviewer #1

(Remarks to the Author)
The authors demonstrate that the traveling SAW can move the magnetic domain wall (DW) along the propagation direction of SAW and the mechanism is attributed to a transfer of linear momentum from SAW to the magnetic DW. Although the authors show the micromagnetic simulation results of the time evolution of DW's position along the nanostrip, I am interested in the time evolution of DW under the action of the traveling SAW. Can this evolutionary process be characterized by MFM or other techniques in situ? Of course, the authors also show the experimental evidence of the movement of DW under the action of SAW by carefully measuring the resistance change of the nanostrip due to AMR, but this evidence is not direct. Since the topic of SAW-driven DW motion is now not very novel (many pioneering work have already been published), I cannot recommend publication on Nature Communications.
Also, I found several other discussion points and comments in the present manuscript as following:
1) As the authors mentioned in the Abstract and Introduction, the SAW cannot achieve magnetic switching without the assistance of a magnetic field or a current. But how about these work (such as Phys. Rev. Applied 11, 014045 (2019), J. Phys.: Condens. Matter 30, 244003 (2018) and so on)? In these work, SAW switches the magnetization exclusively. Do you have any comments on these work?
2) I'm interested in the estimation of the current density used to drive DW, which is 4.5*10^4 A/cm^2. Is the Joule heat of the current taken into account in this estimation? Can you give details of the estimation process?
3) As the authors mentioned, the electric current have Joule heat. To avoid any thermal issues associated with the electric current, the authors proposed to use SAW to drive DW. However, SAW can also induce significant thermal effect, such as these work (Phys. Rev. Applied 20, 014002 (2023), Adv. Electron. Mater. 8, 2200593 (2022)). Does the thermal effect induced by the SAW device have any effect on DW motion? Do you have any comments on that?
4) In the second paragraph of the introduction, the authors cited the work by Yang et al. What's the meaning of the comment "this result does not hide a fundamental mechanism…"? Maybe you mean "unhide a fundamental mechanism…".
5) In the Experimental Results, "injection field" H_inj is applied to the SAW device. If H_inj is removed, can SAW still drive DW motion exclusively? What the important role did Hinj play in the DW motion?

Reviewer #2

(Remarks to the Author)
This manuscript investigates the transfer of linear momentum from surface acoustic waves (SAW) to magnetic domain walls (DW). The authors claim that the DW can move in the same direction as the traveling SAW, with anisotropic magnetoresistance (AMR) used as a probe to detect this movement. Their micromagnetic simulations suggest that the efficiency of DW movement improves when the DW width is a quarter of the SAW wavelength. The topic of acoustic wave-driven magnetic textures, such as magnetic DWs, is indeed intriguing within the field of magnon-phonon interactions. However, there are significant experimental gaps that need to be addressed to support the main conclusions of this manuscript. Consequently, I do not recommend the publication of this manuscript in its current form. My major concerns are as follows:

1. The authors present MFM images of the DW in the initial state (Fig. 1), demonstrating their ability to image magnetization in the current DW devices. However, direct imaging data of DW motion are missing. The authors should include MFM or MOKE images of the DW before and after SAW propagation to provide direct visual evidence of DW movement.

2. The manuscript lacks a detailed discussion on the correlation between DW motion and resistance changes. Is it possible

that the SAW reverses the magnetization of NiFe or FeCo, thus altering the magnetoresistance? Additionally, could the resistance change be attributed to SAW-induced phonon-electron coupling? This needs to be clarified.

3. The authors should explain what happens to the injection field when the DW moves. How can it be proven that the moving DW is related to changes in the injection field? A detailed physical explanation is necessary to understand this relationship.

4. The manuscript lacks information about the magnetic multilayers used. The magnetic properties of these multilayers must be characterized. What is the strength of the exchange bias field between NiFe and FeCo? Does the DW exist in FeCo or NiFe? How does NiFe influence the resolution of MFM imaging? Additionally, what are the AMR values for NiFe and FeCo, respectively?

5. The authors claim that the power required for DW motion is 0.2 nW. A detailed explanation of how this power is estimated should be provided to validate this claim.

6. The method used to estimate experimentally the DW motion velocity should be described in detail. This is crucial for assessing the validity of the reported velocities.

7. The manuscript should include details about the physical requirements for the width of the magnetic strip to enable DW movement. A thorough explanation of the underlying physics is necessary.

Minor issue:
The manuscript refers to Fig. 2f, but this figure is missing. Please include Fig. 2f or correct the reference if it was a typographical error.

In summary, while the topic is promising and has the potential to contribute significantly to the field, the manuscript needs substantial revisions to address the experimental and theoretical gaps.

Version 2:

Reviewer comments:

Reviewer #1

(Remarks to the Author)
The authors demonstrate that the travelling SAW can move the magnetic domain wall (DW) along the propagation direction of SAW and the mechanism is attributed to a transfer of linear momentum from SAW to the magnetic DW. But there are still some questions to be answered before publication.
Q1: I am interested in the effect of NiFe on the H_inj, how does NiFe decrease the the propagation field of the strip ?
Q2: Because of the frequency of SAW is of 1.3 GHz, how about the FeCo ferromagnetic resonant field? Will this SAW drive the FMR of FeCo/NiFe which will affect the DW motion?
Q3: Why the DW tends to couple the SAW+ momentum? Is there any effect of ε_xz of Rayleigh wave? Does the helicity matching of magnetization with the SAW propagation direction have any influence? Or the rotational angular momentum of Rayleigh wave has any effect?
Q4: Why the resistance of DW is 0.25 Ω and 0.32 Ω, is there any other DW exist in your strip? How about the DW size?

Reviewer #2

(Remarks to the Author)
I appreciate that the authors have provided additional data on the unidirectional motion of magnetic DWs driven by SAWs in the revised manuscript, I cannot recommend the publication of this paper because claims in the paper are misleading.
The manuscript makes significant claims, specifically that DWs can be driven by SAWs at speeds up to 100 m/s with exceptionally low power consumption (9.6 nW) and without the need for an external magnetic field. However, these claims are derived from simulation results without adequate experimental verification.
The authors have included Kerr microscopy experiments, but these experiments do not provide direct measurements of DW velocities. Moreover, the experiments require an external magnetic field 23 Oe and high SAW power 18 dBm, approximately 60 mW. This contrasts with their low-power simulation claims and their assertion that the mechanism works without any external magnetic fields.
The authors' comparison of the power required for SAW-driven DW motion with current density required for STT-driven DW motion is problematic. The authors should take into account the duration of the SAW or current pulses (for STT).
Given these points, the manuscript currently overstates the significance and reliability of its results. I do not find sufficient evidence to support the claim that this work addresses the challenge of "unveils a reliable mechanism that can move a magnetic texture at sizable speeds in the direction of the SAW, with the potential to do it without the assistance of a magnetic field or electric current," as stated in the introduction. In its present form, this paper is unsuitable for publication in Nature Communications and may be more appropriately considered by more specialized journals after substantial revisions addressing these experimental gaps and overly ambitious claims.

Version 3:

Reviewer comments:

Reviewer #1

(Remarks to the Author)
This work uses the surface acoustic wave alone without the external magnetic field to move the domain wall. The authors have replied all my questions about the materials and mechanism for driving domain wall motion with SAW. They have revised the experimental data and manuscript well. I agree this work to be published.

Reviewer #2

(Remarks to the Author)
I am pleased to see that, in the revised version, the authors have included direct evidence of magnetic DW motion induced by SAWs, as demonstrated through XMCD-PEEM imaging. It is also quite important that they have removed some of the more ambitious claims based on simulation-derived values.

However, several issues remain that need to be addressed:
1. To estimate the DW velocity, the authors used SAW pulses with a 2 μs duration and calculated the velocity by dividing the DW displacement by the pulse duration. In some samples, the extracted velocities appear to vary randomly with applied power. This raises some concerns. Does the DW displacement scale linearly with the number of pulses or with pulse duration? In other words, the authors should provide data showing the DW position as a function of both pulse number and pulse duration. This is quite important for understanding the mechanism of DW motion and for ruling out potential experimental artifacts. Such analysis would also give a more meaningful comparison with the simulation results presented in Fig. 4b.

2. The manuscript currently lacks crucial information on the characterization of the SAW transducer. The authors should include both experimental measurements and simulations of the frequency spectrum. This is particularly important since the electromechanical coupling coefficient was used in their power estimation, but the origin or validation of this value is not provided.

3. In the simulations, the authors show the amplitude of the SAW, whereas in the experiments, only the SAW power is reported. Could the authors estimate the SAW amplitude in experiments? This would enable a more consistent comparison between simulation and experiment.

Minor issue:
1. The presentation of the XMCD-PEEM data, particularly in Fig. 1 and 2, is unclear and somewhat confusing. The primary difference between the two appears to be the side on which the elliptical nucleation pad is placed. However, these figures are not very informative in their current form. Especially, the position of DWs should be labeled. And if fig. 1 and fig. 2 are to offer a direct comparison between configurations, the device dimensions should be kept consistent.

Version 4:

Reviewer comments:

Reviewer #2

(Remarks to the Author)
I appreciate the authors' efforts in providing additional data on the SAW transducers and on the pulse width/power-dependent DW motion to address the questions regarding the SAW amplitude and DW velocity. However, I remain unclear about the pulse-width dependence of the DW motion.

In the revised Fig. S6, pulse widths of 50 μs and 100 μs appear sufficient to fully reverse the stripe, while in Fig. 1, several 500 μs pulses are needed to achieve complete reversal. In both cases, the applied power is 25 dBm. Are there other variables influencing this difference? Additionally, why was the average velocity determined specifically from 2 μs pulses? The authors should provide a summary of velocities obtained for different pulse widths.

Minor Issues
1. The authors use an electromechanical coupling factor from reference papers to determine the acoustic amplitude. However, this value depends on the mode of vibration and the operating frequency. It can be extracted directly from impedance measurements of their SAW devices and should ideally be determined experimentally rather than solely taken from literature.
2. A time-gating analysis should be performed on the S12 data, as the current data show multiple oscillations likely caused by electromagnetic interference.

Prof. José L. Prieto
ISOM-ETSIT
Ciudad Universitaria 30, 28040, Madrid

Monday, 25-ene.-25

We would like to thank the referees for their critical review. Below they can find the detailed answer to their comments. We believe the manuscript has improved significantly thanks to their comments and suggestions.

Reviewer #1 (Remarks to the Author):

Reviewer #*1* Comment: *The authors demonstrate that the travelling SAW can move the magnetic domain wall (DW) along the propagation direction of SAW and the mechanism is attributed to a transfer of linear momentum from SAW to the magnetic DW. Although the authors show the micromagnetic simulation results of the time evolution of DW's position along the nanostrip, I am interested in the time evolution of DW under the action of the travelling SAW. Can this evolutionary process be characterized by MFM or other techniques in situ? Of course, the authors also show the experimental evidence of the movement of DW under the action of SAW by carefully measuring the resistance change of the nanostrip due to AMR, but this evidence is not direct. Since the topic of SAW-driven DW motion is now not very novel (many pioneering work have already been published), I cannot recommend publication on Nature Communications.*

Reply: We are not sure if the Reviewer is asking for a real-time image of the DW movement or additional image evidence of the directional effect of the SAW on the DW movement. As far as we can tell, the first one is not possible, but we provide the second one in this revised version of the manuscript.

A real-time image of the DW as it performs the oscillatory movement described in this work is not possible. We have checked this with experts in different techniques (Synchrotron, Lorentz microscopy, Kerr) and they all believe this is not possible. The reason is that the DW movement is not perfectly repeatable and different switching events are slightly different due to local pinning. Therefore, we cannot do an average of thousands of identical switching events to extract a real-time image.

On the other hand, what is possible is to obtain additional evidence that the DW is moving directionally under the action of the SAW. We evaluated MFM but it is extremely time-consuming. We also applied for beam time at ALBA synchrotron and, although it was granted, this reply would have been delayed at the very least, a few more months. In the end, using a custom-made Kerr microscope with enough resolution to image a 1 μm wide strip with precision, we managed to obtain enough evidence of the directional movement of the DW under the action of the SAW.

We have now included Kerr images (new Figure 3 and Supplementary Material S4) where the unidirectional movement of the DW in the direction of the travelling SAW is clear, repeatable, and it has been measured in different devices. Due to the small size of the devices, a custom-made Kerr device was used for the measurement and, after considerable effort, we obtained clear unmistakable evidence of the effect.

As the referee states, there are several published works on the assisted movement of DWs under the action of the SAW. This article unlocks a different mechanism that allows the movement of a DW in the direction of the travelling SAW. As we describe in the introduction, other groups have already reported SAW-assisted depinning of a DW, reduction of the coercive field, movement of skyrmions, magnetic switching, etc. On the other hand, here we report on a new mechanism that allows the transfer of linear momentum from the SAW to the DW (via accumulation of exchange energy) which, beyond the interest of the mechanism itself, opens new possibilities to design spintronic devices based on DWs.

Reviewer #*1* Comment: 1*) As the authors mentioned in the Abstract and Introduction, the SAW cannot achieve magnetic switching without the assistance of a magnetic field or a current. But how about these work (such as Phys. Rev. Applied 11, 014045 (2019), J. Phys.: Condens. Matter 30, 244003 (2018) and so on)? In these work, SAW switches the magnetization exclusively. Do you have any comments on these work?*

Reply: We have rephrased the relevant sentence in the abstract (we did not find such a statement in the introduction). We are aware of the relevant work of Laura Thevenard and we have observed also local SAW-assisted field free switching (Sci. Reports 10:9413 (2020)). As the reviewer knows, the work mentioned is on magnetic semiconductors and the field-free switching is achieved in some areas of the film, not in the whole device. That is why we did not include this work among our references in the first place. In any case, it is true that the statement in the abstract was strictly incorrect and that this relevant work should have been mentioned. We now include the relevant reference showing the field free switching.

Reviewer #*1* Comment: *2) I'm interested in the estimation of the current density used to drive DW, which is 4.5*10^4 A/cm^2. Is the Joule heat of the current taken into account in this estimation? Can you give details of the estimation process?*

Reply: As it was explained in the previous version of the manuscript, that value was obtained from the current required to produce 0.2 nW of power (the power required to move the DW by springing, although this value was wrong and it has been corrected) in the resistance of the DW. We realize that this is perhaps a poor comparison. Therefore, in the new version of the manuscript, we have included in Suppl. Info. S10, an additional simulation to compare how effective is the movement by springing (driven by a SAW) compared to the movement driven by Spin Transfer Torque. In the same system, the DW velocities obtained by DW springing can be obtained by STT only at current densities that would damage the strip due to Joule Heating. We believe this comparison is now more solid and we have added a few phrases on this point at the end of the Conclusions sections in the main text.

Reviewer #*1* Comment: *3) As the authors mentioned, the electric current have Joule heat. To avoid any thermal issues associated with the electric current, the authors proposed to use SAW to drive DW. However, SAW can also induce significant thermal effect, such as these work (Phys. Rev. Applied 20, 014002 (2023), Adv. Electron. Mater. 8, 2200593 (2022)). Does the thermal effect induced by the SAW device have any effect on DW motion? Do you have any comments on that?*

Reply: By resistive measurements, we have estimated a temperature increase of 10ºC for 19 dBm of the SAW. This is a similar temperature increase as the one reported in the works mentioned by the reviewer. This temperature increase can cause an enhancement of the DW motion in films with Perpendicular Magnetic Anisotropy, where the DW movement is thermally activated but is truly irrelevant in ferromagnetic strips with in-plane anisotropy where the movement of the DW is not thermally activated. We have added this discussion in the last paragraph of the main text.

Reviewer #*1* Comment: *4) In the second paragraph of the introduction, the authors cited the work by Yang et al. What's the meaning of the comment "this result does not hide a fundamental mechanism…"? Maybe you mean "unhide a fundamental mechanism…".*

Reply: We rephrased it as: "Therefore, this result does not seem to unveil a reliable mechanism that can move a magnetic texture at sizable speeds in the direction of the SAW, with the potential to do it without the assistance of a magnetic field or electric current."

Reviewer #*1* Comment: *5) In the Experimental Results, "injection field" H_inj is applied to the SAW device. If H_inj is removed, can SAW still drive DW motion exclusively? What the important role did Hinj play in the DW motion?*

Reply: Experimentally, in most cases, there is no movement without an external field for the mild amplitude of the SAW that we can excite with our generator. As the curves of probability (Fig. 2) are measured with hundreds of injection events, occasionally, we can detect switching without an external magnetic field (or at a very small value), as can be inferred from Fig. S3.2a for instance. But indeed, experimentally, a field-free switching event is improbable. This is not surprising as FeCo has a polycrystalline structure that promotes DW pinning and our experimental set-up is limited to a SAW amplitude of only 19 dBm. The next experimental step is of course to work with materials with less DW pinning and with larger SAW amplitudes.

The unmistakable evidence that the motion of the DW by 'springing' can be done without any field or current, comes from the micromagnetic simulations. There may indeed be a long journey until this is achieved experimentally but, these days, predictions made by micromagnetic simulations often turn later into experimental realities. In this article, we show a very peculiar underlying mechanism with a very particular signature (the DW width to the SAW wavelength). We believe that its optimization until it becomes a reality in a functional device is outside the scope of this, already very lengthy, work.

Reviewer #2 (Remarks to the Author):

We appreciate the positive feedback of the reviewer, in particular, his/her final appreciation "*while the topic is promising and has the potential to contribute significantly to the field, the manuscript needs substantial revisions*". We hope that, with the extensive revision of the manuscript and the new evidence provided with Kerr microscopy, the referee finds the manuscript satisfactory for publication.

Reviewer #2 Comment: *This manuscript investigates the transfer of linear momentum from surface acoustic waves (SAW) to magnetic domain walls (DW). The authors claim that the DW can move in the same direction as the traveling SAW, with anisotropic magnetoresistance (AMR) used as a probe to detect this movement. Their micromagnetic simulations suggest that the efficiency of DW movement improves when the DW width is a quarter of the SAW wavelength. The topic of acoustic wave-driven magnetic textures, such as magnetic DWs, is indeed intriguing within the field of magnon-phonon interactions. However, there are significant experimental gaps that need to be addressed to support the main conclusions of this manuscript. Consequently, I do not recommend the publication of this manuscript in its current form.*

Reply: We hope that the new version of the manuscript with, among other improvements, additional Kerr evidence of the unidirectional movement of the DWs, changes the opinion of the reviewer and he/she recommends publication.

Reviewer #2 Comment: *1. The authors present MFM images of the DW in the initial state (Fig. 1), demonstrating their ability to image magnetization in the current DW devices. However, direct imaging data of DW motion are missing. The authors should include MFM or MOKE images of the DW before and after SAW propagation to provide direct visual evidence of DW movement.*

Reply: Both reviewers and, previously, the editorial team, requested additional evidence of the effect via some imaging technique. We initially resisted this approach because of its difficulty but we realized that, although Fig.2 provides conclusive evidence of a directional SAW-assisted switching, additional evidence was needed to prove the directional movement of the DW due to the SAW. We evaluated MFM but it is extremely time-consuming. We also applied for beam time at ALBA synchrotron and, although it was granted, this reply would have been delayed at the very least, a few more months. In the end, using a custom-made Kerr microscope with enough resolution to image a 1 μm wide strip with precision, we managed to obtain enough evidence of the directional movement of the DW under the action of the SAW.

We have now included Kerr images (new Figure 3 and Supplementary Material S4) where the unidirectional movement of the DW in the direction of the travelling SAW is clear, repeatable, and it has been measured in different devices.

Reviewer #2 Comment: 2. *The manuscript lacks a detailed discussion on the correlation between DW motion and resistance changes. Is it possible that the SAW reverses the magnetization of NiFe or FeCo, thus altering the magnetoresistance? Additionally, could the resistance change be attributed to SAW-induced phonon-electron coupling? This needs to be clarified.*

Reply: The detection of the DW by its AMR signature is a very standard process to detect the presence of the DW, which has been used frequently by us and other teams (possibly pioneered by M. Hayashi during his PhD with Stuart Parkin at IBM). The resistance is measured before and after a few nanoseconds current pulse is delivered through the current line. Nothing else changes. The resistive difference is due exclusively to the presence of a DW, something that we have double-checked with MFM in this and previous works. Note that the magnetization points along the strip due to the shape anisotropy (and a deposition-induced anisotropy in the same direction). Therefore, switching the direction of magnetization from ***+m*** to ***–m*** along the length of the strip does not change the AMR value, as ***m*** is always parallel to the electric current. Only when the DW appears in the strip, there is an area of the strip (the DW) where the magnetization has a component perpendicular to the current and it is detected as a small drop in the resistance. We appreciate the concern of the referee but note that, beyond our previous experience, we have contrasted the resistance changes with MFM images. If there is a resistive change in the range of 0.25-0.3 Ω, we always see a DW by MFM.

About the phonon-electron interaction, we dedicated an entire article to this effect [Sci. Reports 11:8586 (2021)] and we are very aware that the SAW can produce a voltage due to phonon-electron interaction (whose value can change following the magnetization state of the strip). Again, the value of resistance that we attribute to the DW is measured before and after a few nanoseconds current pulse is delivered through the current line. Nothing else changes. The acoustoelectric voltage for the SAW that is present in the device at the moment of nucleation is compensated before the DW injection process begins. But even if it was not compensated, the value would be the same before and after the current pulse and it would not influence the differential value.

We have added a new sentence in the second paragraph of the 'Experimental Set-up' section and we rephrased this paragraph slightly. Hopefully, it should be clearer now.

Reviewer #*2* Comment: *3. The authors should explain what happens to the injection field when the DW moves. How can it be proven that the moving DW is related to changes in the injection field? A detailed physical explanation is necessary to understand this relationship.*

Reply: We do not quite follow this comment. The injection field is set by an external coil (and measured with a Hall probe at the time the DW is injected). The injection field cannot change due to the DW movement, it is set externally. Therefore, we do not understand the reviewer's statement '*explain what happens to the injection field when the DW moves'*. As we have explained in the reply to the Reviewer #1 comments, the injection field is required to achieve DW movement due to the SAW (not always, but most of the time). The key experimental fact (that hopefully is now clearer after the Kerr images) is that, only when the SAW and the field push the DW in the same direction, the DW moves from its pinning point. The SAW is acting directionally, although the injection field is required for the movement (not always, but most of the time). The injection field is required for movement mostly due to two facts: (i) in our experimental setup we can only reach 19 dBm of SAW amplitude and (ii) the FeCo grows polycrystalline, which results in strong pinning points for the DW. This can be optimized using a different material for the strip and increasing the amount of acoustic power that reaches the magnetic strip. We feel though, that all this is outside the scope of this (already extensive) work, which claims the characterization of this peculiar mechanism of transfer of linear momentum from the acoustic wave to the DW.

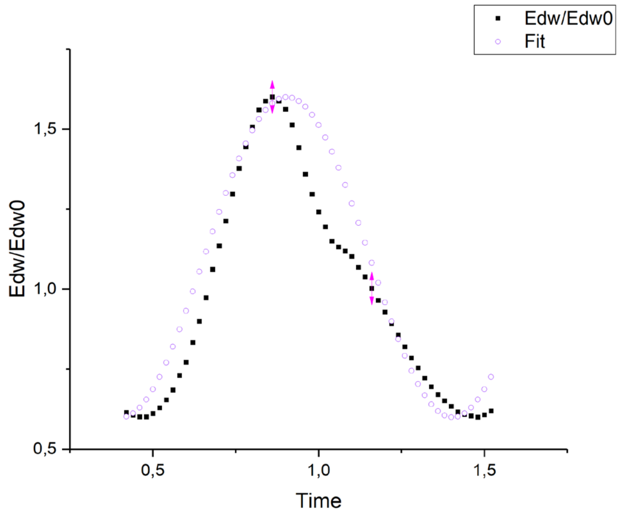
Reviewer #*2* Comment: *4. The manuscript lacks information about the magnetic multilayers used. The magnetic properties of these multilayers must be characterized. What is the strength of the exchange bias field between NiFe and FeCo? Does the DW exist in FeCo or NiFe? How does NiFe influence the resolution of MFM imaging? Additionally, what are the AMR values for NiFe and FeCo, respectively?*

Reply: There is no exchange bias between FeCo and NiFe as they couple through direct exchange because they are both ferromagnetic. Therefore, yes, the DW does exist in both layers. The exchange length in FeCo is several tens of nanometers and larger in NiFe, so there cannot be a significant rotation of the magnetization through the thickness of the two layers. This cannot be seen with the superficial MFM image, but it can be inferred with the micromagnetic simulations. The AMR in both materials is of the order of 2%, dependent on the growing conditions. We realized thought that, in the main text, we phrased wrongly the reason behind adding NiFe to the structure, which is to reduce the propagation field of the strip. We have corrected this mistake.

Reviewer #*2* Comment: *5. The authors claim that the power required for DW motion is 0.2 nW. A detailed explanation of how this power is estimated should be provided to validate this claim.*

Reply: We are very glad the reviewer picked up on this value because it is wrong. The correct value is 9.6 nW, which is still very small in comparison to an equivalent power when the DW moves by spin transfer torque (see also Reviewer 1, question 2). To obtain this value, we measured the energy released by the DW to spring forward. In the figure below, we plot Fig. 5a, the energy of the DW, together with a sinusoidal oscillation (pink circles). After the maximum energy is reached, the DW releases part of the energy by springing forward. This is visible by a fast drop in the energy in the zone marked by two arrows (the same zone marked by a yellow band in Figure 5a). The energy that the DW releases by springing forward is the difference between the sinusoidal behaviour and the real behaviour. This difference can be calculated using different sinusoidal behaviours, but the value is always in the range of 10 nW.

We have corrected this value and added a short explanation in the main text, at the end of the second paragraph in the Discussion and Conclusions section.



Reviewer #2 Comment: 6. *The method used to estimate experimentally the DW motion velocity should be described in detail. This is crucial for assessing the validity of the reported velocities.*

Reply: We have not determined the DW velocity experimentally. The values of velocity are only obtained through micromagnetic simulations. We hope it is clearer in the new version of the manuscript. Performing a real-time measurement of the velocity of the DW is far from easy. This is part of the future work where we may be able to reduce the pinning in the system and make the movement of the DW more reproducible in each switching, so a real-time measurement of the DW velocity can be experimentally achieved by doing an average of thousands of reproducible switching events.

Reviewer #2 Comment: *7. The manuscript should include details about the physical requirements for the width of the magnetic strip to enable DW movement. A thorough explanation of the underlying physics is necessary.*

Reply: A thorough explanation of the importance of the width of the strip to the wavelength of the SAW is included in the Discussion and Conclusions section of the article and section S9 of the Supplementary Material. Does the Reviewer mean anything different to the information already included?

Reviewer #2 Comment: *Minor issue: The manuscript refers to Fig. 2f, but this figure is missing. Please include Fig. 2f or correct the reference if it was a typographical error.*

Reply: We have corrected this typo.

Prof. José L. Prieto
ISOM-ETSIT
Ciudad Universitaria 30, 28040, Madrid

Monday, 20-may.-25

We thank the referees for their critical review. A few days before receiving the second referee report, we had a 6-day access in ALBA synchrotron. During those six days, we collected extensive evidence of the DW movement under the sole action of the SAW, without any external magnetic field. We have prepared the new version of the manuscript. The main changes of the article are listed below:

1.- We removed ALL the previous experimental evidence based on resistive measurements, and we have substituted the first 3 figures with experimental images obtained by XMCD-PEEM, all showing the details of the DW movement with SAW and without any external magnetic field. In the Supplementary Information, we added two more figures with XMCD-PEEM pictures showing that the SAW can move the DW in the direction of wave propagation, even against the opposing pressure of a weak external magnetic field. The simulations were originally done on a single FeCo layer and are still valid (see also the explanation in the main text).

2.- We have changed the title to “Moving magnetic domain walls with sound alone”. This title reflects the (new) experimental evidence: the DW is moved exclusively by an Acoustic Wave and always in the direction of the wave propagation.

3.- We experimentally measured the velocity of the DW by pulsing the SAW and measuring the displacement before and after the SAW pulse (See Fig. 3d). The maximum velocity measured was 12 m/s, and it is always in the range of meters per second.

4.- The power delivered to the IDT in ALBA was 24 to 28 dBm, which is larger than the power used in the previous version of the manuscript. Observing the results of the simulations in Fig. 4d, we realized there is a kind of threshold power from which the effect suddenly becomes larger. We acknowledge that the larger power could cause concerns about the associated heat. Therefore, in Supplementary Information S3, we have added a thermal image to experimentally prove that the increase in temperature in the devices is less than 10ºC, even at the maximum power used in ALBA, 28 dBm.

5.- Regrettably, we have withdrawn the claim regarding the power required to move the DW by springing. Nevertheless, as a matter of pride, we discuss this in further detail in our response to Reviewer#2. The Reviewer compared the power delivered to the IDT (60 mW, which is orders of magnitude larger than the power that arrives to the ferromagnetic strip) with the power obtained with the simulations (9.6 nW), which is the power absorbed exclusively by the DW to move by springing (not by the whole length of the strip, only by the DW).

We hope the Reviewers find the new manuscript suitable for publication in Nature Communications.

Below, we answer one by one the comments and suggestions from the referees

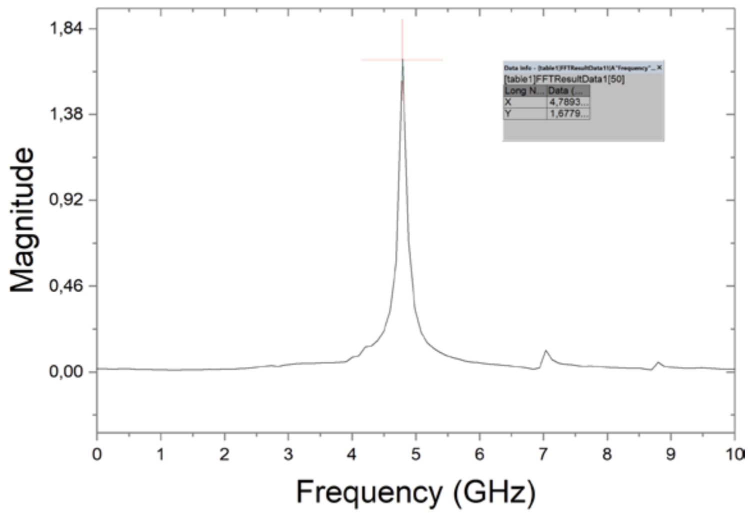
<u>Reviewer #1 (Remarks to the Author):</u>

Reviewer *#1* Comment: *Q1: I am interested in the effect of NiFe on the H_inj, how does NiFe decrease the the propagation field of the strip?*

Reply: We have added section S1 in Supplementary Information, showing the hysteresis loops of the layers involved. The sample used in the new experimental evidence, FeCo/FeCoB/NiFe, has a smaller coercivity thanks to the FeCoB and the NiFe layers. Also, through the resistive measurements shown in the previous versions of the manuscript, we observed that, generally, adding a thin layer of NiFe reduces the stochastic pinning of the DW in the strips. We have also added a phrase in the main text to clarify the effect of each layer.

Reviewer #1 Comment: *Q2: Because of the frequency of SAW is of 1.3 GHz, how about the FeCo ferromagnetic resonant field? Will this SAW drive the FMR of FeCo/NiFe which will affect the DW motion?*

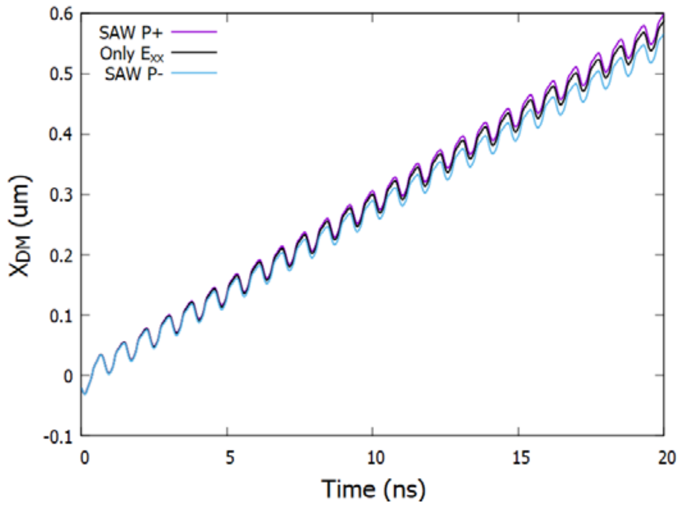
Reply: As the reviewer can see in the figure below, obtained with micromagnetic simulations, the FMR in the FeCo layer is located at 4.78 GHz for zero magnetic field (all the experimental evidence in the new version of the paper is taken at zero external magnetic field). The frequency of the SAW is 1.3 GHz. Therefore, FMR should not play any relevant role in the mechanism reported in the article.



Reviewer #1 Comment: *Q3: Why the DW tends to couple the SAW+ momentum? Is there any effect of ε_xz of Rayleigh wave? Does the helicity matching of magnetization with the SAW propagation direction have any influence? Or the rotational angular momentum of Rayleigh wave has any effect?*

Reply: In Fig. S5 of the supplementary information, we performed a detailed analysis of the domain wall (DW) speed as a function of the SAW propagation direction and DW type. Our results reveal a non-reciprocal DW motion that depends on the SAW wave vector k, and depends on the type of the domain wall, its tilt, and the direction of SAW propagation.

As pointed out in Fig. S6 (supplementary information) it is essentially the longitudinal component eps_xx the one responsible for domain wall motion, whereas the other two components, eps_xz and eps_zz have a negligible contribution. The results shown in the main text, Figs. 4 and 5, were obtained including the three components with clockwise (CW) sense of rotation. Following the referee's comment, we did the simulation changing the sense of rotation (CCW). The comparison between the two is shown in the figure below. As can be observed, the velocity is slightly higher for CW rotation, but it is very small contribution, which is consistent with the fact that the effect of eps_xz is negligible.



Reviewer ***#1*** **Comment:** *Q4: Why the resistance of DW is 0.25 Ω and 0.32 Ω, is there any other DW exist in your strip? How about the DW size?*

Reply: In the new version of the manuscript we have removed any evidence based on resistive results. We have added in Fig. 3e the MFM images of the typical domain walls found in two of the strip widths. So far, even if we include our previous studies, we have only found transversal DWs in these strips. They may have different size, but they are always transversal. The effect of the DW width is discussed in Fig. 5.

Reviewer #2 (Remarks to the Author):

We appreciate the feedback from the reviewer and we understand his/her general position. We hope that, with our new experimental results obtained with XMCD-PEEM at ALBA Synchrotron, we should be able to convince the Reviewer that our claims are now solidly backed with experimental evidence. Below we reply to the specific comments.

Reviewer ***#2*** **Comment:** *The authors have included Kerr microscopy experiments, but these experiments do not provide direct measurements of DW velocities.*

Reply: We now provide XMCD-PEEM experiments and estimates of the effective DW velocity based on the net displacement of a DW during a SAW pulse (Fig. 3d).

Reviewer ***#2*** **Comment:** *Moreover, the experiments require an external magnetic field 23 Oe ….*

Reply: That is not the case now. All the experimental evidence (Figs. 1 to 3 in the main text and section S2 in Suppl. Info. S2) are obtained without any external magnetic field. Still, the SAW moves the DWs in the direction of the wave propagation, even against the opposing pressure of a small external magnetic field (Fig. S2-2).

Reviewer ***#2*** **Comment:** *….and high SAW power 18 dBm, approximately 60 mW. This contrasts with their low-power simulation claims and their assertion that the mechanism works without any external magnetic fields.*

Reply: We think this is an unfair comparison. 60 mW is the power delivered to the IDT, while the 9.6 nW obtained from the simulation is the power absorbed exclusively by the DW (not by the entire strip) to perform the movement by springing. In Suppl. Info. S4, we include a calculation of the energy. For 25 dBm (316 mW), the power delivered to the SAW is $0.5k^2P$, so 8.8 mW. This power is distributed on the 130 µm wide wavefront (the IDT is 130 µm wide), so the power arriving to a strip 1 µm wide is 8.8e-3/130= 68 µW. This is assuming that:

- In the 3mm that the SAW travels from the IDT to the ferromagnetic strip, there is no wave dispersion and no energy is scattered laterally.
- No energy is wasted on heating up the substrate around the IDT (clearly not the case. See Fig. S3).
- All the SAW energy arriving to the ferromagnetic strip is transferred to the ferromagnetic strip.

If all the energy losses are considered, we do not think it is overambitious to think that the energy arriving at the DW is lower than the µW, within the order of magnitude predicted by the simulations.
In any case, as this seems to be a problematic recurrent issue, and obtaining a precise experimental value of the power absorbed by the DW would be a detailed work in itself, we decided to remove this claim from the text.

Reviewer ***#2*** **Comment:** *The authors' comparison of the power required for SAW-driven DW motion with current density required for STT-driven DW motion is problematic. The authors should take into account the duration of the SAW or current pulses (for STT).*

Reply: The simulations for STT and for SAW-induced DW springing are done in the same conditions. If we pulse the current for STT, we should pulse the SAW as well, but the average velocity should be the same, although not the heating involved. In any case, we have rephrased that part of the manuscript and we hope it reads better now. If the Reviewer still thinks this comparison is not fair, we are willing to remove it as well, although we believe it is quite interesting.

Reviewer ***#2*** **Comment:** *Given these points, the manuscript currently overstates the significance and reliability of its results. I do not find sufficient evidence to support the claim that this work addresses the challenge of "unveils a reliable mechanism that can move a magnetic texture at sizable speeds in the direction of the SAW, with the potential* *to do it without the assistance of a magnetic field or electric current," as stated in the introduction. In its present form, this paper is unsuitable for publication in Nature Communications and may be more appropriately considered by more specialized journals after substantial revisions addressing these experimental gaps and overly ambitious claims.*

Reply: Now the manuscript contains undisputable experimental evidence of zero-field SAW-induced movement of the DW and measurements of the DW velocity. Also, we provide experimental evidence of the almost irrelevant thermal increase caused by the SAW and evidence of the influence of the DW width, which is one of the signatures of the mechanism described in this work. We hope the Reviewer finds the work more consistent now.

Prof. José L. Prieto
ISOM-ETSIT
Ciudad Universitaria 30, 28040, Madrid

Monday, 22-jul.-25

We thank the referees for their critical review. Below, we summarize the changes we have implemented in the manuscript to respond to all their comments.

Reviewer #1 (Remarks to the Author):

Reviewer #*1* Comment: *This work uses the surface acoustic wave alone without the external magnetic field to move the domain wall. The authors have replied all my questions about the materials and mechanism for driving domain wall motion with SAW. They have revised the experimental data and manuscript well. I agree this work to be published.*

Reply: We thank the reviewer for his/her effort reviewing the manuscript.

Reviewer #2 (Remarks to the Author):

We appreciate the feedback from the reviewer and, in general, we understand his/her position. We have replied to his/her comments and added the necessary experimental evidence to answer all his/her questions

Reviewer #*2* Comment: *1. To estimate the DW velocity, the authors used SAW pulses with a 2 μs duration and calculated the velocity by dividing the DW displacement by the pulse duration. In some samples, the extracted velocities appear to vary randomly with applied power. This raises some concerns.* ***Does the DW displacement scale linearly with the number of pulses or with pulse duration?*** *In other words, the authors should provide data showing the DW position as a function of both pulse number and pulse duration. This is quite important for understanding the mechanism of DW motion and for ruling out potential experimental artifacts. Such analysis would also give a more meaningful comparison with the simulation results presented in Fig. 4b.*

Reply:
We have added Figure S4 in Supplementary material showing a sequence in which the DW moves a measurable distance after each of the four 6 μs SAW pulses.
We have added Figure S5 with sequences in which the DW moves under the action of a SAW pulse of increasing width.
We have added Figure S6 with the DW displacement versus the amplitude of the SAW. For an amplitude smaller than 25 dBm, we have not observed any DW displacement. For amplitudes larger than 25 dBm, there is a clear enhancement of the DW mobility with the amplitude of the SAW.
An explanatory note for all these figures has been added at the end of the first paragraph on page 3 of the main text.

In the figure reporting the estimation of velocity that concerns the reviewer (now Figure 2d), there is a clear increase in velocity with increasing SAW amplitude (see also Figure S7 in the Supplementary Information). Nevertheless, there is also some variability in the results. In most of the experimental images presented in this work, it is evident that DW displacement exhibits a degree of stochastic behaviour, possibly due to the polycrystalline nature of the ferromagnetic strip and lithographic imperfections. This stochastic behaviour is also predicted by our micromagnetic simulations (see Figure 3d in the main text) and it is the very nature of the displacement of a DW in a ferromagnetic element. We hope that with the three additional figures added to the Supplementary Information, the nature of the experiment is now clearer.

Please note that an accurate determination of the DW velocity as a function of the length or amplitude of the SAW pulse would require a dedicated study. This would involve using longer strips—to prevent full magnetization reversal when applying longer or higher-amplitude SAW pulses—and performing measurements across many strips to gather sufficient statistics and account for the inherent stochasticity of DW motion. Such work would likely require using a Kerr microscope with enough spatial resolution (as synchrotron-based imaging is inherently slow), with automated image recognition. We believe this would constitute a separate experiment in its own right and falls outside the scope of the present work. The main claim of this article is SAW-driven displacement of the DW in the direction of SAW propagation with zero external magnetic field. This claim is well supported by experimental evidence and corroborated by micromagnetic simulations.

We have added the following phrase in the middle of the second paragraph on page 4.
"Although Figure 2d shows a clear increase in velocity with increasing SAW amplitude (see also Figure S7 in the Supplementary Information), there is some variability in the results. In most of the experimental images presented in this work, it is evident that DW displacement exhibits a degree of stochastic behaviour, possibly due to the polycrystalline nature of the ferromagnetic strip and lithographic imperfections. This stochastic behaviour is also predicted by our micromagnetic simulations discussed later."

Reviewer #*2* Comment: *2. The manuscript currently lacks crucial information on the characterization of the SAW transducer. The authors should include both experimental measurements and simulations of the frequency spectrum. This is particularly important since the electromechanical coupling coefficient was used in their power estimation, but the origin or validation of this value is not provided.*

Reply: We have now included in Supplementary Information (Figure S1 a-c) the experimental S parameters of one of the IDTs used in the measurements presented in the manuscript (the characteristics of the other reflectors used in this work are very similar). The measurements were taken with a VNA network analyser directly connected to the IDT. S11 shows a very sharp minimum at a frequency of 1.286 GHz, which corresponds to the fundamental frequency of the Rayleigh mode.

The three authors, experts in SAW transducers, have revised the estimation of the strain wave amplitude using the S12 parameter.

Reviewer #*2* Comment: *3. In the simulations, the authors show the amplitude of the SAW, whereas in the experiments, only the SAW power is reported. Could the authors estimate the SAW amplitude in experiments? This would enable a more consistent comparison between simulation and experiment.*

Reply: We hope this point may be settled with the response to the previous point. A measurement of the amplitude of the acoustic wave is possible by interferometry and other techniques. Nevertheless, a meaningful measurement would only make sense if performed at the set-up in ALBA Synchrotron, which is impossible as ALBA does not have this possibility. The estimation of the amplitude of the strain wave using the calibration of the reflectors (Supplementary Information, section S1), results in a value quite close to the one used in the simulations. Note also that, by assuming a simple 1D wave model, the amplitude is overestimated because not all the energy goes to excite the longitudinal wave, the one inducing the displacement of the DW.

Our micromagnetic simulations were done independently from the experiments, without any feedback from the experiment. The measurements in ALBA were done in April 2025, much later than the first submission of this manuscript (May 2024), where the simulations were included to justify our first experimental results based on electric measurements. In the simulations, for a polycrystalline sample, there is only a limited DW movement for an amplitude smaller than 150 ppm (see figure 3d in the main text). Then, nearly a year later, in our measurements at ALBA, we did not observe any DW movement without an external magnetic field for powers below 25 dBm, which, following the calibration shown in Suppl. Info. S1, corresponds to an amplitude of 170 ppm. Therefore, in our view, everything indicates that our micromagnetic simulations consistently capture the mechanism involved in the zero-field DW movement in the direction of the travelling wave.

Reviewer #*2* Comment: *Minor Point. The presentation of the XMCD-PEEM data, particularly in Fig. 1 and 2, is unclear and somewhat confusing. The primary difference between the two appears to be the side on which the elliptical nucleation pad is placed. However, these figures are not very informative in their current form. Especially, the position of DWs should be labeled. And if fig. 1 and fig. 2 are to offer a direct comparison between configurations, the device dimensions should be kept consistent.*

Reply: We appreciate the comment from the referee. Not using the same strip width in Figure 2 was an attempt to squeeze more information using strips of different widths in the minimum number of figures. But we agree that it is perhaps somehow confusing. In Figure 2, we have added the sequence for a strip 900 nm wide and transferred this figure to Supplementary Information, now Figure S7. With this change, we believe the text becomes clearer.

Prof. José L. Prieto
ISOM-ETSIT
Ciudad Universitaria 30, 28040, Madrid

Monday, 8-sep.-25

We thank the referee for his/her critical review. Below, we answer his/her questions.

Reviewer Comment: *, I remain unclear about the pulse-width dependence of the DW motion.*

In the revised Fig. S6, pulse widths of 50 µs and 100 µs appear sufficient to fully reverse the stripe, while in Fig. 1, several 500 µs pulses are needed to achieve complete reversal. In both cases, the applied power is 25 dBm. Are there other variables influencing this difference? Additionally, why was the average velocity determined specifically from 2 µs pulses? The authors should provide a summary of velocities obtained for different pulse widths.

Reply: The strip in Figure 1 of the main text is 900 nm wide, while the width of the strip in Fig. S6 is 1 µm wide. Our experimental results (Fig. 2) and simulations (Fig. 4g-h) show that strips 1 µm wide should allow a better SAW-driven DW mobility than stripes 900 nm wide. Of course, as we explain in the text and on the previous round of comments, there is an intrinsic stochasticity in the movement of the DW. For instance, if one strip has a strong pinning point, this would likely affect our quasi-static velocity measurement.

Why is the velocity determined with 2 µs pulses? This is the minimum pulse width we could apply at ALBA Synchrotron. To the best of our knowledge, ALBA is the only Synchrotron in Europe (possibly in the world) that can excite the Acoustic Wave at such a high frequency (1.3 GHz) and such a large power (+28 dBm). The maximum field of view of the XMCD-PEEM microscope is 50 µm. Therefore, when we got granted beamtime at ALBA, we designed the devices with a maximum length that could fit in the field of view of the XMCD-PEEM microscopy, as shown in Fig. 1. According to our simulations, we were expecting DW speeds of the order of tens of meters per second. Therefore, with a pulse width larger than 2 µs, we could expect full reversal of the strip. That is why we initially planned the velocity study with the minimum possible pulse width we could apply at ALBA. As we explain in the next paragraph, once you start the study at a fixed pulse width, there is not much margin to change things within the allocated beamtime.

Please allow us also to provide some details on the synchrotron measurement. Each XMCD-PEEM photograph takes around 10 minutes (the noise level is high because we had to reduce the acceleration voltage to 10kV to reduce the risk of arcs that would destroy the device. We had to take many photographs for each beam polarization to reduce noise, resulting in a long acquisition time). In ALBA, every time a new device is wire-bonded and reintroduced in the chamber, there is a delay of about 6h without measurements (degassing, realigning, etc). As the referee can see, the velocity study, performed only for 2 µs pulses, took days. In 6 days of beamtime, we also characterized the influence of the strip width and other experiments that the referee can see in the article and in the Suppl. Info. We hope it becomes clear that the Synchrotron is not the optimum tool to perform a statistical study of the DW velocity.

In our view, beyond the technical problems of performing a study of the velocity at shorter pulses than 2 µs, the experimental evidence shown in the article proves beyond doubt the effect of DW acoustic motion without any external field or electric current, and the effect is well characterized with the micromagnetic simulations. Although a more thorough study of the velocity of the DW could be interesting, we believe it is outside the scope of the article, and we hope that, after the above explanation, the referee shares this view with us.

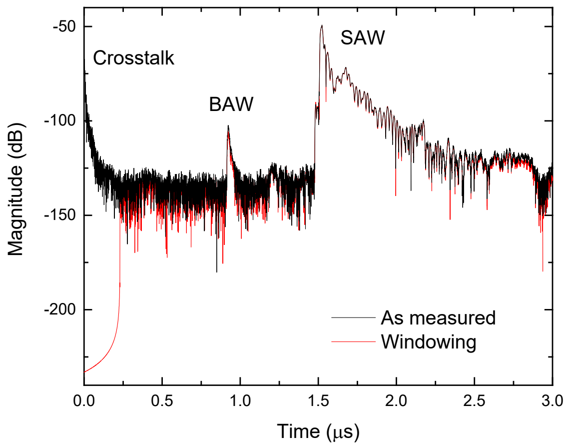
Minor Issues

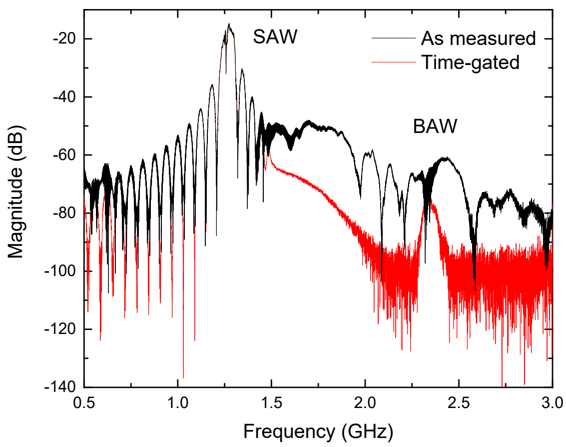
Reviewer Comment: *1. The authors use an electromechanical coupling factor from reference papers to determine the acoustic amplitude. However, this value depends on the mode of vibration and the operating frequency. It can be extracted directly from impedance measurements of their SAW devices and should ideally be determined experimentally rather than solely taken from literature.*

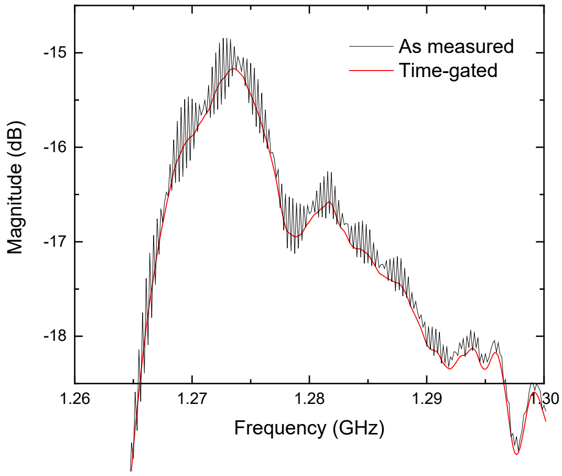
Reply: In a bulk substrate, the value of the electromechanical coupling factor K^2 of the vibration modes does not depend on the frequency, as the wavelength is much smaller than the substrate thickness. The substrate used in this work, 128°-rotated Y-cut X-propagating $LiNbO_3$, is a very well-known material designed to provide an optimum Rayleigh mode while effectively suppressing bulk spurious modes [1]. Thus, the Rayleigh mode is the only mode used here, and it has a very well tabulated K^2 value.

Reviewer Comment: *A time-gating analysis should be performed on the S12 data, as the current data show multiple oscillations likely caused by electromagnetic interference.*

Reply: The following graphs show the time-gating analysis of the S_{21} parameter. The ripple shown in the passband of the Rayleigh mode (SAW) is indeed caused by the crosstalk or electromagnetic interference, which is cancelled out windowing the signal in the time domain that is much faster than the SAW and bulk (BAW) modes. In addition, the effective suppression of bulk modes, mentioned above, is clearly seen here, with the BAW magnitude at around -75 dB.







[1] Optimum cut for rotated Y-cut $LiNbO_3$ crystal used as the substrate of acoustic-surface-wave filters, K. Shibayama, K. Yamanouchi, H. Sato, and T. Meguro. Proceedings of the IEEE Vol. 64, Issue 5, Pages 595 – 597 (1976).