

# Localized topological states beyond Fano resonances via counter-propagating wave mode conversion in piezoelectric microelectromechanical devices

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A variety of scientific fields like proteomics and spintronics have created a new demand for on-chip devices capable of sensing parameters localized within a few tens of micrometers. Nano and microelectromechanical systems (NEMS/MEMS) are extensively employed for monitoring parameters that exert uniform forces over hundreds of micrometers or more, such as acceleration, pressure, and magnetic fields. However, they can show significantly degraded sensing performance when targeting more localized parameters, like the mass of a single cell. To address this challenge, we present a MEMS device that leverages the destructive interference of two topological radiofrequency (RF) counter-propagating wave modes along a piezoelectric Aluminum Scandium Nitride (AlScN) Su-Schrieffer-Heeger (SSH) interface. The reported MEMS device opens up opportunities for further purposes, including achieving more stable frequency sources for communication and timing applications.

Emerging needs in proteomics have created a necessity to sense parameters localized within a few tens of micrometers or less. This is crucial for studying biological processes at a single-cell scale<sup>1-7</sup>, identifying protein biomarkers associated with specific diseases<sup>8-12</sup>, achieving atomic-scale resolutions in mass spectrometry<sup>13-19</sup>, and more; similar needs have emerged even in other fields of study<sup>20</sup>. For instance, being able to sense spin waves transduced in strongly localized regions<sup>21</sup> can lead to higher bit densities and improved energy efficiency in high-frequency spintronic memory devices. Similarly, highly localized acoustic modes of vibration in piezoelectric films can provide a path toward robust Quantum State Transfer (QST) between remote superconducting qubits<sup>22</sup> and their successful read-out.

Over the past fifteen years, nano and microelectromechanical systems (NEMS/MEMS) have been extensively utilized for sensing parameters (magnetic field<sup>23–25</sup>, acceleration<sup>26–29</sup>, pressure<sup>30–36</sup>, etc.)

that exert nearly uniform forces across hundreds of micrometers along their frequency-setting dimension. However, these devices are significantly limited in their ability to monitor parameters localized within a few tens of micrometers or less (i.e., in their ability to achieve a high “spatial sensing resolution”). In fact, to enable high responsivity in such scenarios, the size of NEMS/MEMS must be shrunk to confine their mode of vibration within an area matching closely the one where the targeted parameter exerts its force. However, shrinking the size of the current MEMS/NEMS, particularly along their frequency-setting dimension, results in a notable reduction of their quality factor ( $Q$ ) and dynamic range<sup>14</sup>, which inevitably impacts the achievable sensing performance<sup>37</sup>.

Several physical phenomena have been exploited to enhance the spatial sensing resolution of NEMS/MEMS while preserving a high-quality factor. These include internal-resonance<sup>38-40</sup>, phase-

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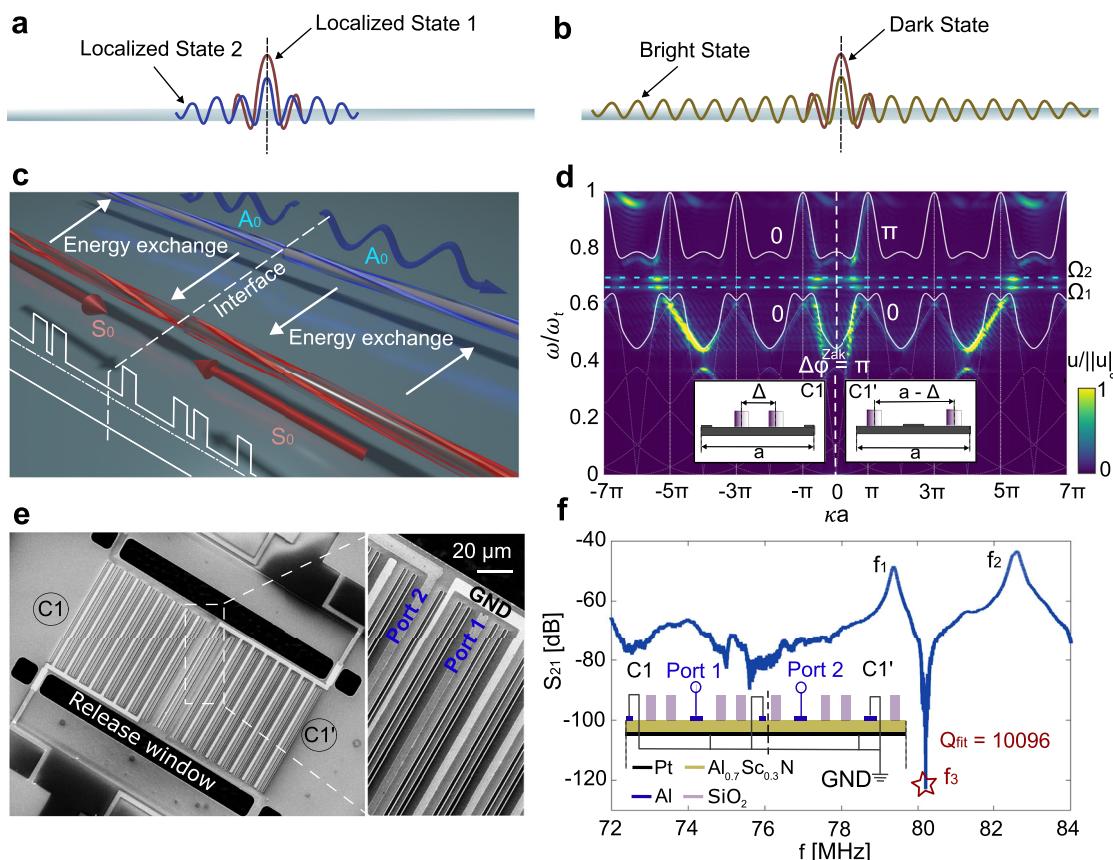
synchronization<sup>41–43</sup>, phonon-cavity<sup>44–47</sup>, and mode-localization<sup>48–50</sup>. Most of these phenomena originate from the nonlinear interaction between multiple mechanical modes. As a result, they necessitate precise control of these modes' driving conditions. Harnessing these phenomena also requires the use of amplitude read-out schemes, which are inherently more susceptible to accuracy degradations caused by electrical noise than the frequency read-out schemes typically used for linear NEMS/MEMS<sup>51</sup>.

In this Article, we demonstrate that both a strong mode-localization and a high-quality factor can be simultaneously achieved in a MEMS device operating in a linear regime by leveraging the destructive interference of two topologically protected states. This interference is achieved by leveraging a unique design strategy based on the creation of a SSH interface supporting counter-propagating symmetric  $S_0$  and antisymmetric  $A_0$  Lamb waves<sup>52</sup>. The counter-propagation of the  $S_0$  and  $A_0$  waves is key to the ultimate high  $Q$  factors we obtain and is achieved along the topological SSH interface by breaking the spatial symmetry of an elastic layer, i.e. by corrugating the upper surface of the AlScN layer. This creates two localized states in a one-dimensional wave propagation problem but without using

in-plane symmetry breaking which would be the usual approach to create topological states in acoustics or elasticity<sup>53,54</sup>. These states, from now on labeled *State-1* and *State-2* (Fig. 1a), show comparable lifetimes. Also, they are both localized around an interface, which marks a significant difference between the dark and bright states (Fig. 1b) forming a Fano resonance (i.e. the bright state approaches a continuum state and the dark state is a localized state)<sup>55,56</sup>.

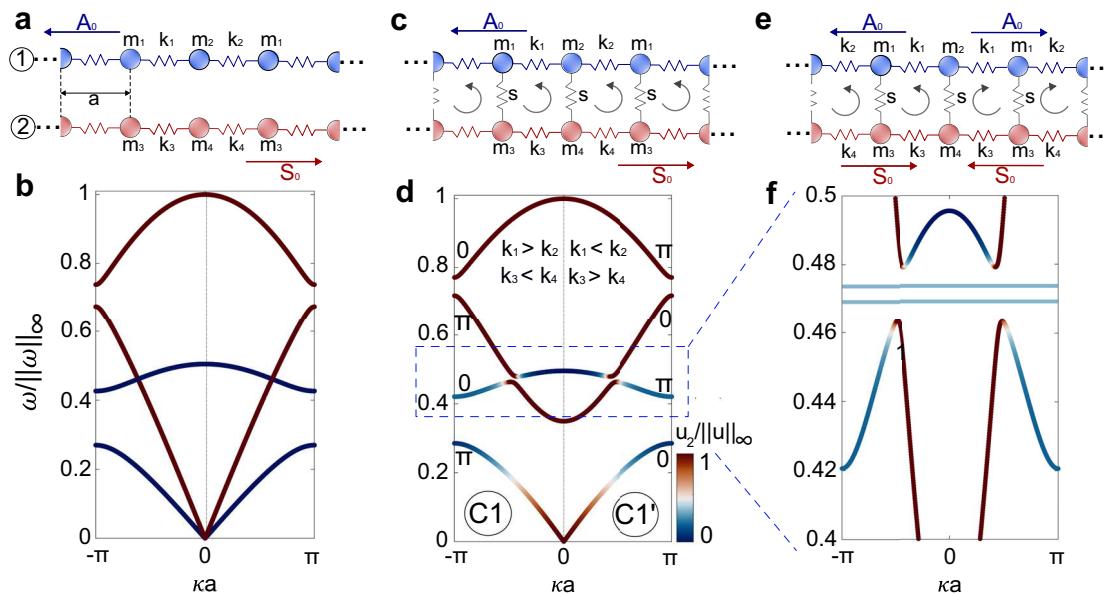
The interference between State-1 and State-2 is described by coupling counter-propagating symmetric  $S_0$  and antisymmetric  $A_0$  Lamb waves<sup>52</sup> at a topological interface in an elastic waveguide (Fig. 1c).

To verify the generation of States-1-2 we have built a MEMS device operating in the radiofrequency range that uses a piezoelectric Aluminum Scandium Nitride (AlScN) layer (Fig. 1e). This device reconstructs an elastic version of the SSH model<sup>57</sup>, where an interface is encountered between two periodic structures referred to as  $C1$  and  $C1'$ . The unit cells of each structure share the same periodicity  $a$ , but have corrugated elements separated by  $\Delta$  and  $a - \Delta$ , respectively. This creates two topological interface states with distinct Zak phases and different wavenumbers, as shown in the numerically computed dispersion curves reported in Fig. 1d.



**Fig. 1 | Schematic of the physics and the reported MEMS device, aided by theoretical and experimental results.** a Strong wave localization is achieved by leveraging the interference of two topologically protected localized states, named as State-1 and State-2. b This scenario differs from the conventional Fano resonance, wherein the dark and bright states have very different lifetimes, i.e. the bright state approaches a continuum state and the dark mode is a localized state. c 3D rendering of the schematized topological problem: the interference between State-1 and State-2 is described by coupling, at a topological interface, counter-propagating symmetric ( $S_0$ ) (red) and antisymmetric ( $A_0$ ) (blue) Lamb waves each with distinct Zak phases. d Such wave coupling is achieved, in one-dimensional wave propagation, by breaking the horizontal spatial symmetry, i.e. by corrugating one side of the surface of an elastic plate. This structure is then combined with an elastic version of the SSH model, where an interface is encountered between two

periodic structures ( $C1$  and  $C1'$ ). The unit cells of each structure share the same periodicity  $a$ , but have corrugated elements separated by  $\Delta$  and  $a - \Delta$  respectively. This creates two topological interface states with distinct Zak phases and different wavenumbers, as shown by the 2D Fast Fourier Transform of wavefield from numerical simulations. Refer to Table S1 in the supplementary material for a description of all variables included in the plot. e We report a piezoelectric MEMS prototype using Aluminum Scandium Nitride as a piezoelectric material, Silicon Oxide to form the periodic corrugations of  $C1$  and  $C1'$ , and Aluminum strips to form the electrical ports. f The experimental electrical transmission of this MEMS device, expressed in terms of the  $S_{21}$  scattering parameter, shows the existence of two interface states that lie within a complete bandgap. At their destructive interference, marked with a red star, strong localization is achieved, as well as a record-high  $Q$  for MEMS devices using AlScN films as piezoelectric layers.



**Fig. 2 | The creation of topological interface states via counter-propagating wave mode conversion is analytically described using a spring-mass model.** **a** Chain 1 (blue) models the propagation of antisymmetric  $A_0$  waves while chain 2 (red) models the propagation of symmetric  $S_0$  waves. **b** When the chains are disconnected, no coupling occurs and band crossing is observed. **c** The introduction of elastic connections couples the two modes, opening a complete bandgap (**d**) where distinct Zak phases guarantee the existence of non-trivial topological states.

**e** The introduction of an interface between the initial chain, having stiffness  $k_1$ ,  $k_2$ ,  $k_3$ ,  $k_4$  and its mirrored counterpart, i.e.  $k_2$ - $k_1$ ,  $k_4$ - $k_3$ , enables two topological states, here demonstrated from a supercell dispersion analysis (**f**). The color map of the dispersion curves shows the relative polarization of the waves, with blue points corresponding to vertical (out-of-plane) polarization, while red refers to horizontal (in-plane) polarization, i.e.  $A_0$  and  $S_0$  waves.

We also show that the interaction between State-1 and State-2 creates an interference state (State-3) even more localized than both State-1 and State-2. In fact, the majority of the energy stored by the device when transducing State-3 is confined within less than  $21\ \mu\text{m}$  along the frequency setting dimension. The stronger localization of State-3 enables a significant reduction in radiation losses (also known as anchor losses for NEMS/MEMS devices<sup>58</sup>) towards the surrounding silicon substrate. As a result, State-3 exhibits a  $Q$  substantially higher than States-1,2.

The  $Q$  factor of AlScN resonators is usually affected by various dissipation mechanisms, including thermoelastic damping<sup>59</sup>, interfacial losses<sup>60</sup>, ohmic losses, and anchor losses<sup>61</sup>. The anchor losses—caused by acoustic energy leaking into the resonator's surroundings—are dominant when the effective cavity size of AlScN resonators is reduced along the frequency-setting dimension<sup>62</sup>, and this effective size reduction is initially suggestive of similar leakage in the MEMS device reported in this work. Previous studies have attempted to mitigate anchor losses in AlScN resonators by using reflectors<sup>63,64</sup>, however it is notable that the AlScN device reported here demonstrates a  $Q$  at the resonance frequency of State-3 (Fig. 1f) that is five times higher or more than any previously reported device made from a thin AlScN film. An additional advantage of the MEMS device is that States-1-3 exist within a topologically protected bandgap; this provides immunity to the typical defects<sup>65,66</sup> relaxing required tolerances for the microfabrication of chip-scale devices.

## Results

The MEMS device demonstrated in this study consists of two periodic structures (i.e., C1 and C1') formed by SiO<sub>2</sub> grooves deposited atop a suspended thin bilayer plate. This plate embodies a piezoelectric AlScN layer and a platinum (Pt) layer. C1 and C1' have the same pitch of the unit cell ( $a$ ) but the position of their SiO<sub>2</sub> grooves is shifted by an amount equal to  $\Delta$  and  $a - \Delta$  respectively, as shown in the inset of Fig. 1d. This allows us to synthesize an elastic version of the SSH-model. Two 100 nm-thick Al metallic strips are used to piezoelectrically excite

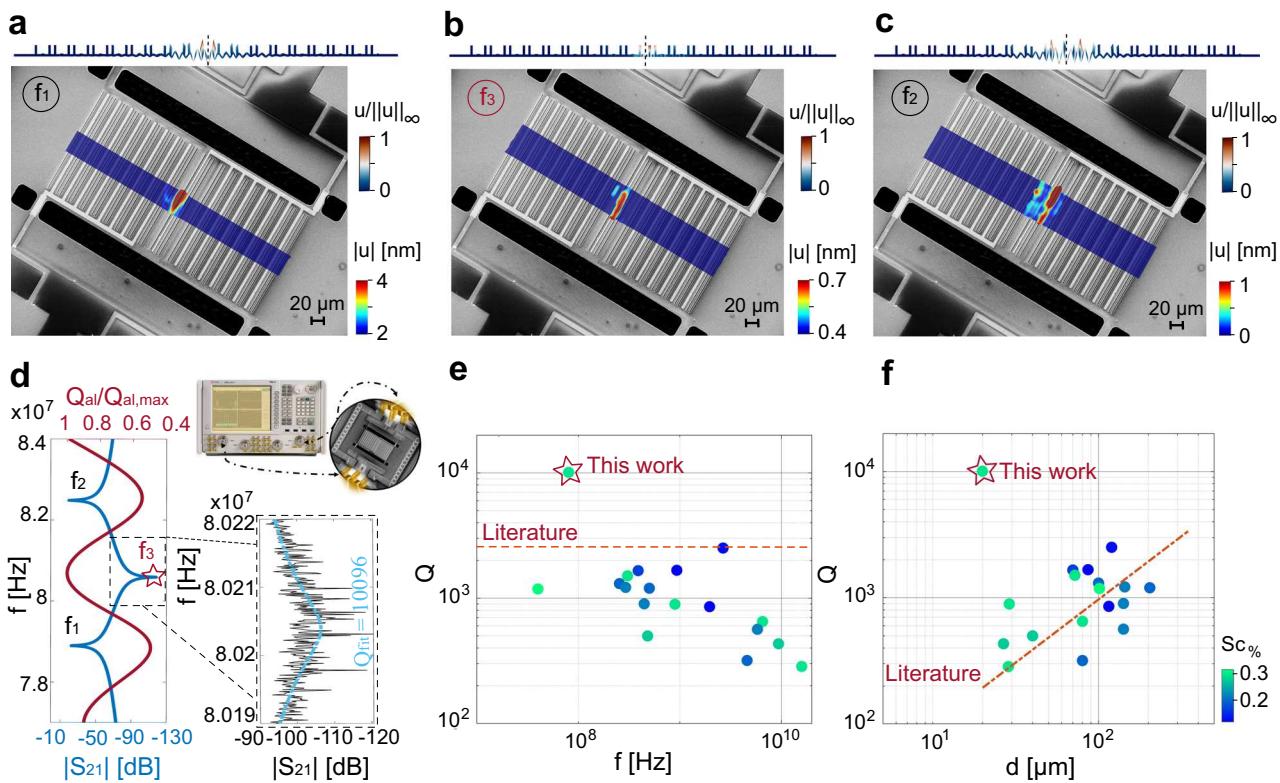
the device. These strips, each one forming an electrical port (Port-1 or Port-2), have been positioned near the interface of C1 and C1' to ensure strong enough piezoelectric transduction efficiency to successfully validate the presence of States-1-3 from the extraction of the device's electrical scattering parameters (i.e., the S-parameters). Other grounded Al strips have been inserted across the device to preserve the same dispersion characteristics for all unit cells. Four anchors are used to support the fabricated device after its structural release (i.e., after the removal of the silicon underneath the device to generate a suspension). A Scanned Electron Microscope (SEM) picture of the fabricated device is reported in Fig. 1e while the device's electrical transmission (i.e., its  $S_{21}$  scattering parameter) is anticipated in Fig. 1f.

The physics of the  $S_0$ - $A_0$  counter-propagating wave mode conversion in the reported AlScN device can be conceptually idealized by coupling two distinct elastic waveguides supporting  $S_0$  and  $A_0$  wave modes, as usually done to describe wave locking<sup>67</sup> (Fig. 1c). Both waveguides can be modeled as independent periodic chains (Fig. 2a) including a set of masses and springs (i.e.,  $m_1$ ,  $m_2$ ,  $k_1$ ,  $k_2$  and  $m_3$ ,  $m_4$ ,  $k_3$ ,  $k_4$  respectively). These chains mimic the propagation of the  $A_0$  and  $S_0$  wave modes when no coupling between them occurs. The solution to the wave-equation for the system in Fig. 2a can be found by solving the time-independent Schrödinger equation for any possible Bloch state:

$$\hat{H}_\kappa |\Psi_{\kappa n}\rangle = E_{\kappa n} |\Psi_{\kappa n}\rangle. \quad (1)$$

In Eq. (1),  $E_{\kappa n}$  identifies a time-independent eigenvalue relative to the wavevector  $\kappa$  for a specific propagating  $n$ th mode. Similarly,  $|\Psi_{\kappa n}\rangle$  denotes the solution to the wave-equation for the  $n$ th mode and wavevector  $\kappa$ .

The solution of Eq. (1) for the independent chains in Fig. 2a is reported in Fig. 2b in terms of dispersion curves relating frequency and wavenumber. In order to model the coupling between the  $A_0$  wave and the  $S_0$  wave in our structure, we add connecting springs between the



**Fig. 3 | Experimental displacement field and Q factor of the reported MEMS device.** Measured displacement magnitude for the midsection of the reported MEMS device when operating at  $f_1$  (a),  $f_2$  (b) and  $f_3$  (c). The measurements were performed through a high-frequency vibrometer. Also, corresponding FEM simulated cross-sectional displacement modeshapes are reported above each one of these measured plots. d The fabricated MEMS device was electrically tested by probing its input and output ports through two RF GSG probes and by using a Vector Network Analyzer (VNA). We report the FEM calculated frequency distribution of the device transmission ( $S_{21}$ , in blue), together with a trend of the normalized quality term associated to anchor losses (in red) vs. frequency.

Also, a zoomed-in picture of the measured  $S_{21}$  around  $f_3$  is also reported, together with the analytical fitting line we have generated to quantify the MEMS device's  $Q$  at  $f_3$ . e A comparison of the  $Q$  achieved by the reported MEMS device (see the red star) with those previously reported by state-of-the-art AlScN devices. f The same pool of devices has been also used to analyze the  $Q$  attained by our reported device vs. the size of its resonant cavity (i.e.,  $d$ ) with the corresponding values for each previously reported resonator listed in e. Evidently, the MEMS device reported in this work not only shows a superior quality factor, but also demonstrates the capability of overruling the current strict correlation of  $Q$  with the effective size of the resonant cavity in AlScN MEMS devices.

two chains, as shown in Fig. 2c. The resulting dispersion curves are reported in Fig. 2d, where a complete bandgap appears due to the coupling of the two modes. The full  $\hat{\mathbf{H}}$  matrix, its perturbation and the model parameters for the case study described in Fig. 2 are reported in the analytical section of the Supplementary Material.

Next, we can look at the case where an SSH model is reconstructed from the two chains described in Fig. 2a, c. To do so, we connect each chain in Fig. 2c with a mirrored version forming the C1' structure (Fig. 2e). The calculation of the Zak phase<sup>68</sup> for both C1 and C1' allows us to verify that non trivial interface states localized at the common interface exist, and these states are topologically protected, being the bandgaps of C1 and C1' endowed with distinct Zak phases. Details about this calculation are reported in the analytical section of the Supplementary Material. The dispersion curves of the supercell, reported in Fig. 2f for the system shown in Fig. 2e clearly demonstrate the existence of two interface states inside the topological bandgap. As both states have mixed polarizations and store their entire elastic energy within few unit cells around the same interface discontinuity, they can interfere. As a result, an interference state arises, as expected (see Fig. S1) from the analysis of the spring-mass chain system shown in Fig. 2e. The modal characteristics of the interference state have been investigated both numerically and experimentally for the MEMS device built in this work, as described in the following.

We characterized the electrical response of the MEMS device demonstrated in this work by measuring its  $S_{21}$  transmission from

60 MHz to 110 MHz using a Vector Network Analyzer. The device's  $S_{21}$  trend shows two peaks and one notch in its electrical transmission (i.e., in its  $S_{21}$ ). The two peaks correspond to States-1,2 while the notch corresponds to State-3. From our measured  $S_{21}$  vs. frequency trend, we extracted the  $Q$  value of State-3. We found the  $Q$  of State-3 to be higher than 10,000, as shown in Fig. 1f. We characterized the localization of States-1–3 by direct measurement of the reported device's displacement through a high-frequency vibrometer (Fig. 3a–c). We found the measured displacement for State-3 to be localized within an effective cavity width ( $d$ , calculated along the frequency setting dimension) of 21  $\mu\text{m}$ . Such a  $d$  value was attained by identifying the width of the region around the interface characterized by displacement magnitudes higher than  $\frac{1}{e} \cdot \mu_{\max}$ , where  $\mu_{\max}$  is the maximum displacement and  $e$  is the Neper number. In turn, States-1,2 exhibit a lower  $Q$  (approximately 700) and show a more spread modal energy distribution, with State-1 being more localized than State-2. These findings have been confirmed numerically through additional FEM simulations (see in the top insets of Fig. 3a–c the FEM simulated cross-sectional modeshapes of the total displacement for States-1–3).

The strong localization of State-3 allows to obtain an exceptionally high- $Q$ , being the leakage of elastic energy into the surrounding silicon substrate minimized. To confirm this, we simulated the device's response through Finite Element Methods (FEM), extracting its  $S_{21}$  trend at various frequencies (see Fig. 3d) as well as the trend of its  $Q$  term ( $Q_{al}$ ) associated to anchor losses. Our FEM simulations

further confirm the presence of States-1,3. Also, they show a significant enhancement in the simulated  $Q_{al}$  value for frequencies approaching the resonance frequency of State-3 ( $f_3$ ), as shown in Fig. 3d.

## Discussion

We have demonstrated a topological microacoustic device using a suspended AlScN thin-film. This device leverages the interaction of two interface states with hybrid polarizations and comparable localization properties. This allows us to generate an interference state simultaneously exhibiting a strong mode-localization and a high quality factor. We compare in Fig. 3e the  $Q$  achieved at  $f_3$  by the built MEMS device with the  $Q$  value of other recent AlScN thin-film MEMS devices operating in the RF range. Evidently, the MEMS device demonstrated in this work shows a quality factor exceeding by more than five times anything reported previously for AlScN MEMS devices. Furthermore, we report in Fig. 3f the trend of the measured  $Q$  value vs. the size of the region where the modal energy is confined along the frequency setting dimension (i.e.,  $d$ ) for each one of the AlScN MEMS device reported in Fig. 3e. The  $d$  values for all the devices listed in Fig. 3f have been extracted from reported modeshape distributions. Evidently, a reduction in  $Q$  typically occurs for devices showing a lower  $d$  value. However, the MEMS device reported in this work overcomes this limitation by exhibiting a  $Q$  value more than one order of magnitude higher than what reported for AlScN MEMS devices with comparable  $d$  values. Due to its record high  $Q$ , the MEMS device reported in this work also promises to create a pathway to achieve MEMS sensors with a lower limit-of-detection (LoD). In fact, the minimum LoD of any MEMS/NEMS sensors is constrained by thermomechanical noise-induced fluctuations of their resonance frequency<sup>37,69,70</sup>. These fluctuations decrease inversely with  $Q$ , which underscores the importance of achieving a higher  $Q$  in order to improve the achievable LoD. Furthermore, the high- $Q$  achieved by the reported MEMS device at  $f_3$  also creates a path to achieve ultra-stable MEMS-based frequency synthesizers for timing and frequency conversion<sup>71</sup>, which can be manufactured with conventional semiconductor processes.

## Methods

The fabrication process of the reported MEMS device starts with the deposition of an AlN/Pt/AlScN stack, which is implemented by reactive co-sputtering in the same multi-target chamber, without breaking the vacuum. Then, we etch the AlN/Pt/AlScN stack to form "release windows". This step is key as it gives direct access to silicon, which is required to be able to etch the silicon under the device through a XeF<sub>2</sub> isotropic etching step (ensuring its suspension). Wet-etching of AlScN is then processed to create vias, allowing to electrically ground the bottom Pt layer. Then we sputter and pattern a 2  $\mu$ m-thick  $SiO_2$  layer via Plasma-enhanced chemical vapor deposition (PECVD) to form the surface corrugations, which have the longest dimension along the out-of-plane direction (i.e., along the anchors' direction). Etching of the  $SiO_2$  layer to form the corrugations is implemented through a reactive-ion etching (RIE) step. The Al strips are attained by sputtering and patterning a 150 nm-thick aluminum (Al) layer.

Finally, we deposit a 300 nm-thick gold (Au) layer through evaporation to cover the vias, routing lines and probing pads, ensuring lower ohmic losses. A process flow chart is provided in the supplementary material, together with the definition of the experimental setup.

## Data availability

The numerical and experimental data supporting our findings are available, under a Creative Commons Attribution 4.0 International License, on the Zenodo repository as MATLAB figure (.fig) files, accessible at the following <https://doi.org/10.5281/zenodo.13850960>.

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J.M.D.P. and X. Z. contributed equally to the paper; C.C., R.V.C., J.M.D.P., X.Z. and R.A. developed the research plan; J.M.D.P. and L.I. conceived the initial design, the physical concept, and developed analytical and numerical models; X.Z. and C.C. designed, modeled through FEM, and fabricated the device; J.M.D.P., L.I. and R.V.C developed the theory and the physical interpretation; X.Z., T.M., B.D, M.C. and C.C. contributed to the design of experiments; All the authors contributed in writing the paper.

## Competing interests

The authors declare no competing interests.

## Additional information

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