

Document Version

Final published version

Licence

CC BY

Citation (APA)

Wang, Q., Zhao, X., Krishna Ghatkesar, M., & Manzaneque, T. (2026). Acoustic delocalization sensing by scattering of surface acoustic waves. *Journal of Micromechanics and Microengineering*, 36(8), Article 085016.
<https://doi.org/10.1088/1361-6439/ae97ee>

Important note

To cite this publication, please use the final published version (if applicable).
Please check the document version above.

Copyright

In case the licence states "Dutch Copyright Act (Article 25fa)", this publication was made available Green Open Access via the TU Delft Institutional Repository pursuant to Dutch Copyright Act (Article 25fa, the Taverne amendment). This provision does not affect copyright ownership.
Unless copyright is transferred by contract or statute, it remains with the copyright holder.

Sharing and reuse

Other than for strictly personal use, it is not permitted to download, forward or distribute the text or part of it, without the consent of the author(s) and/or copyright holder(s), unless the work is under an open content license such as Creative Commons.

Takedown policy

Please contact us and provide details if you believe this document breaches copyrights.
We will remove access to the work immediately and investigate your claim.

PAPER • OPEN ACCESS

Acoustic delocalization sensing by scattering of surface acoustic waves

To cite this article: Qiuxuan Wang *et al* 2026 *J. Micromech. Microeng.* **36** 085016

View the [article online](#) for updates and enhancements.

You may also like

- [Tunnelling and Capacitive Displacement Transducers for Acoustic Detection of Particles](#)
G. Carugno, E. Conti and R. Onofrio
- [Finite size effect on nanomechanical mass detection: the role of surface elasticity](#)
Mai Duc Dai, Chang-Wan Kim and Kilho Eom
- [A high-performance lab-on-a-chip liquid sensor employing surface acoustic wave resonance: part II](#)
K Kustanovich, V Yantchev, A Olivefors et al.



PAPER

OPEN ACCESS

RECEIVED

17 March 2026

REVISED

24 July 2026

ACCEPTED FOR PUBLICATION

11 August 2026

PUBLISHED

25 August 2026

Original content from this work may be used under the terms of the [Creative Commons Attribution 4.0 licence](#).

Any further distribution of this work must maintain attribution to the author(s) and the title of the work, journal citation and DOI.



Acoustic delocalization sensing by scattering of surface acoustic waves

Qiuxuan Wang¹ , Xiaoxi Zhao¹ , Murali Krishna Ghatkesar^{2,3} and Tomás Manzaneque^{1,3,*} ¹ Department of Microelectronics, Delft University of Technology, Delft, The Netherlands² Department of Precision and Microsystems Engineering, Delft University of Technology, Delft, The Netherlands³ Equal contribution.

* Author to whom any correspondence should be addressed.

E-mail: t.manzanequegarcia@tudelft.nl**Keywords:** acoustic device, surface acoustic wave, particle sensing, wave scatteringSupplementary material for this article is available [online](#)

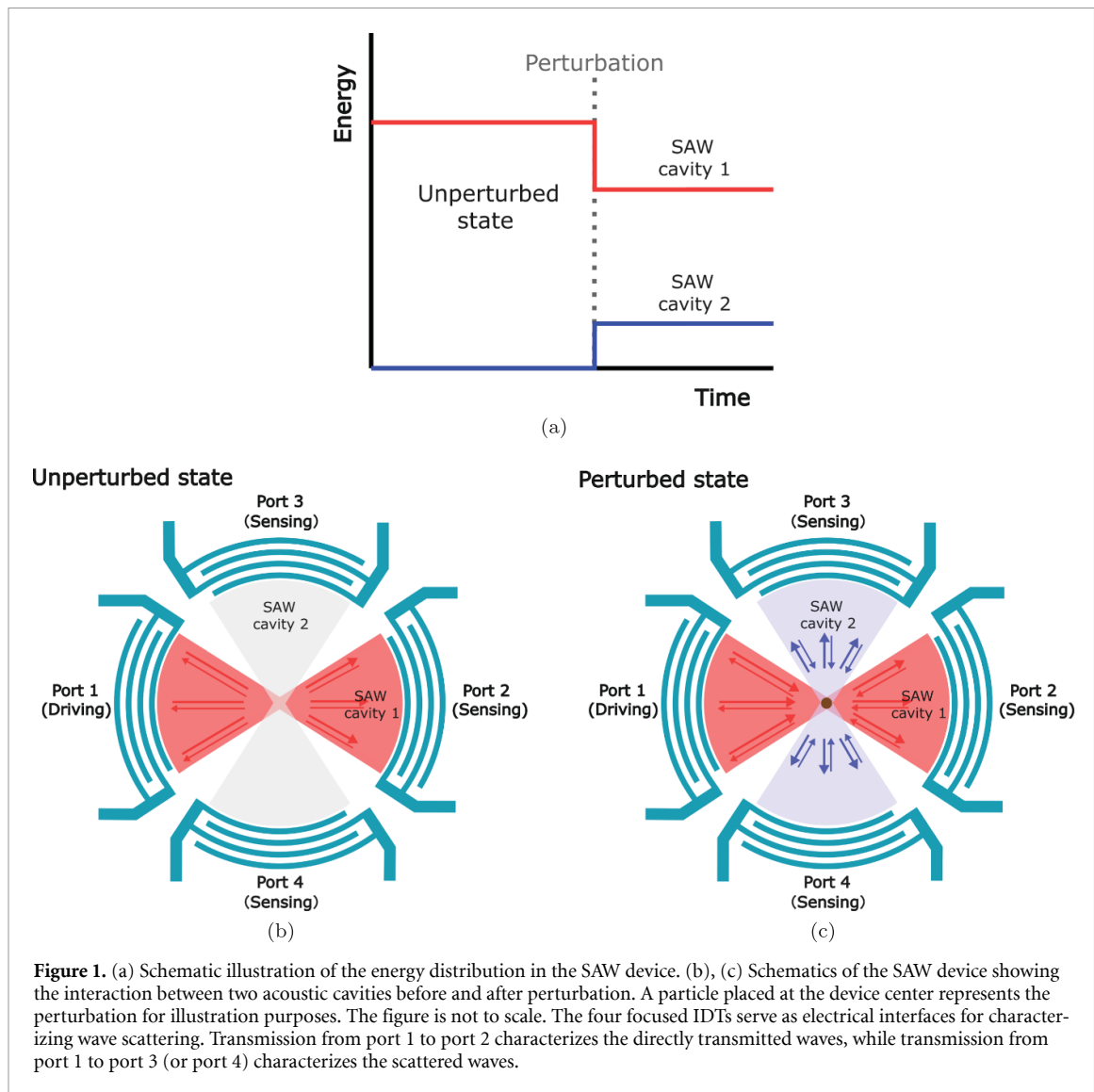
Abstract

Micro- and nanomechanical resonators are widely used for chemical and biological detection. Mode localization sensing, based on the distribution of energy between two or more coupled resonators, has demonstrated enhanced sensitivity with respect to the conventional frequency shift method. In contrast, this work introduces an alternative sensing concept based on acoustic delocalization, where energy redistribution is induced in initially uncoupled surface acoustic wave (SAW) cavities by particle-triggered acoustic scattering. We implement this concept using two orthogonally arranged SAW resonators operating with a center frequency of around 415 MHz. Particle adsorption at the intersection region generates wave scattering that effectively couples the resonant cavities. This scattering-driven interaction leads to a redistribution of acoustic energy that was initially confined to a single cavity, enabling detection through the signal emerging in the non-driven cavity and providing information on the mechanical properties of the particles. Devices were fabricated to validate the proposed mechanism and demonstrated the detection of particle arrays. Finite element simulations agree well with experimental results and further reveal how the acoustic scattering coefficient depends on the mechanical properties of the particles and their spatial distribution. These results demonstrate the feasibility of acoustic delocalization sensing using SAW scattering and highlight its potential for robust and sensitive detection of micro- and nanoparticles.

1. Introduction

Mechanical resonators at the microscale represent a powerful concept for the detection of small amounts of analytes. Devices based on this approach have become an established tool for chemical and biological detection, including quartz crystal microbalance [1], surface acoustic wave (SAW) resonators [9], and suspended microstructures [7]. In their most basic realization, resonant sensors rely on a single mechanical degree of freedom whose resonance frequency shifts in response to changes in device mass [3] or stiffness [14]. The pursuit of enhanced sensitivity has led to the miniaturization of resonators to scale down their mass and scale up their resonance frequency [4]. However, the normalized sensitivity of the resonance frequency to the mass in resonant sensors of one-degree-of-freedom is limited to 1/2 [10], and miniaturization increases susceptibility to temperature drifts and other environmental fluctuations.

A compelling alternative has gained traction in the last years to mitigate these limitations through the use of mode-localized sensors [20]. These devices exploit the large redistribution of vibrational energy among nearly identical weakly coupled resonators induced by small perturbations. In such systems, a perturbation caused by mass adsorption on one resonator is detected through the resulting asymmetric energy redistribution, rather than through a shift in resonance frequency. Recent developments have further expanded the application of mode localization sensing. For example, mode-localized



resonators have been employed for gas sensing in combination with gas absorption films [18]. In addition, blue-sideband excitation has been exploited to drive both interresonator and intermodal modes of mode-localized resonant sensors, leading to enhanced sensitivity and reduced noise floor [17]. Overall, mode localization sensing offers significant improvements in sensitivity for a given resonator size by several orders of magnitude [13], and inherent rejection of disturbances affecting both resonators, such as temperature variations [11,16]. Despite these advantages, widespread adoption of this sensing principle is hindered by the need for system parameter identification [20], and vulnerability to asymmetries introduced by fabrication tolerances [15].

This work builds on the simultaneous use of two resonators for sensing by introducing a novel approach termed acoustic delocalization sensing. Unlike previously demonstrated mode-localized sensors, which rely on weak intrinsic coupling between resonators, our method begins with completely uncoupled acoustic resonant cavities sharing the same material platform. Upon analyte adsorption, SAW scattering by the analytes induces coupling between two SAW cavities, redistributing acoustic energy that was initially confined to a single cavity. While SAW scattering from elastic inhomogeneities (dots) has previously been visualized using scanning acoustic force microscopy [8], here we investigate this scattering from the perspective of scattered power, quantified through electrical measurements at interdigitated transducers (IDTs). This approach establishes acoustic delocalization as a promising sensing mechanism that combines enhanced sensitivity with improved robustness and implementation simplicity.

We present a realization of this concept through a device composed of two SAW cavities arranged in a mutually orthogonal geometry, see figure 1. Each cavity is formed by two focusing IDTs, and they intersect at the shared focal point. In the unperturbed state, the cavities are effectively decoupled, i.e. acoustic excitation in one does not yield a detectable acoustic wave in the other. When analytes are

adsorbed at the focal intersection, the SAWs are scattered, redirecting part of the acoustic energy from one propagation axis into the orthogonal axis. For analyte sensing, one cavity is driven by an applied signal, while the generated signal in the orthogonal cavity is monitored as the sensor output. The chosen geometry with focusing IDTs creates a localized scattering region with high energy concentration, offering superior sensitivity per unit of active area compared to conventional SAW devices with straight IDTs. Our method aims to exploit the advantages of mode localization sensing without imposing stringent requirements on system symmetry, weak coupling strength, and operation in the immediate vicinity of the localization transition point, thereby potentially improving fabrication tolerance and extending the measurement range. Submicrometer-sized particles deposited on the substrate were used in this work to induce wave scattering, mimicking the adsorption of analytes such as airborne engineered nanoparticles.

2. Method

2.1. SAW device design and fabrication

SAW devices were implemented on a 1 μm -thick AlN film deposited on a 500 μm Si substrate, with four sets of interdigital transducers (IDTs) oriented at 90° angles, as shown in figure 2. The IDT fingers were designed in a 60° circular arch shape to focus SAWs, in contrast to conventional straight IDTs. The 60° angle was selected to ensure sufficient acoustic transmission by increasing the IDT finger length, while maintaining adequate separation between neighboring ports. The geometric focal length, defined as the distance from the IDT center to the geometric focal point, was set to 1 mm. This results in a finger overlap length ranging from 0.895 mm to 1.105 mm. The IDTs were based on a conventional bi-directional design, with finger width and spacing equal to a quarter of the designed wavelength, $\lambda = 12 \mu\text{m}$. The duty cycle of the fingers is fixed to 50%, which results in a finger width $w = \lambda/4 = 3 \mu\text{m}$. The acoustic wave velocity (v) in 1 μm -thick AlN on Si(1 0 0) is estimated as 4920 m s^{-1} [2]. The designed center frequency was therefore designed as $f = v/\lambda = 410 \text{ MHz}$.

The SAW devices were fabricated through a sequence of AlN deposition, photolithography, aluminum evaporation, and lift-off processes. The AlN film was deposited on a Si(100) substrate by reactive sputtering with a set thickness of 1 μm . Trikon Sigma 204 sputtering machine was used with a pulsed DC magnetron sputtering technique. The deposited AlN thin film was initially measured using a Woollam ellipsometer, yielding a thickness of approximately 850 nm. A more accurate thickness measurement was obtained from an SEM cross-section image, which gave a thickness of 975.8 nm, as shown in figure 3. For IDT fabrication, 200 nm-thick aluminum was deposited on top of AlN using a CHA Solution e-beam evaporator and subsequently patterned through a lift-off process in an ultrasonic bath using acetone.

2.2. Nanoparticle deposition

Arrays of cylindrical-shaped nanoparticles were deposited at the focal point of the SAW devices for perturbation using focused ion beam induced deposition (FIBID) with an FEI Helios G4 CX system. Trimethyl platinum precursor gas was introduced through the MultiChemGIS system, resulting in platinum deposition on the device substrate. An ion beam current of $2 - 6 \text{ pA } \mu\text{m}^{-2}$ and a dwell time of 200 ns, were used. For a target deposition diameter set as 0.5 μm , an ion beam current of 1.1 pA was selected. Due to wear of the ion beam aperture, the actual beam current deviated from the selected value and was measured to be 1.80 pA. A 2×2 array of FIBID platinum cylinders was deposited on one device, with measured heights of $818.5 \text{ nm} \pm 62 \text{ nm}$ and diameters of $656.5 \text{ nm} \pm 13.3 \text{ nm}$. A 3×3 array of FIBID platinum cylinders was deposited on another device, with measured heights of $947 \text{ nm} \pm 66 \text{ nm}$ and diameters of $653.8 \text{ nm} \pm 13.7 \text{ nm}$, as shown in the inset of figure 2 for illustration. In both arrays, the cylinders were deposited with a center-to-center spacing of 5 μm .

2.3. Experimental setup

Four SAW devices were investigated in this work fabricated using identical design parameters. Two devices, without nanoparticles, served as unperturbed references, while the other two were modified by depositing localized nanoparticle arrays at the acoustic focal region. Specifically, one device was perturbed by the 2×2 nanoparticle array and the other by the 3×3 nanoparticle array, and are hereafter referred to as perturbed device 1 and perturbed device 2, respectively. A microscopic image of perturbed device 2 is shown in figure 2 as an example. This set of devices enables a systematic comparison of the acoustic response between the reference devices and devices subjected to two different perturbation conditions.

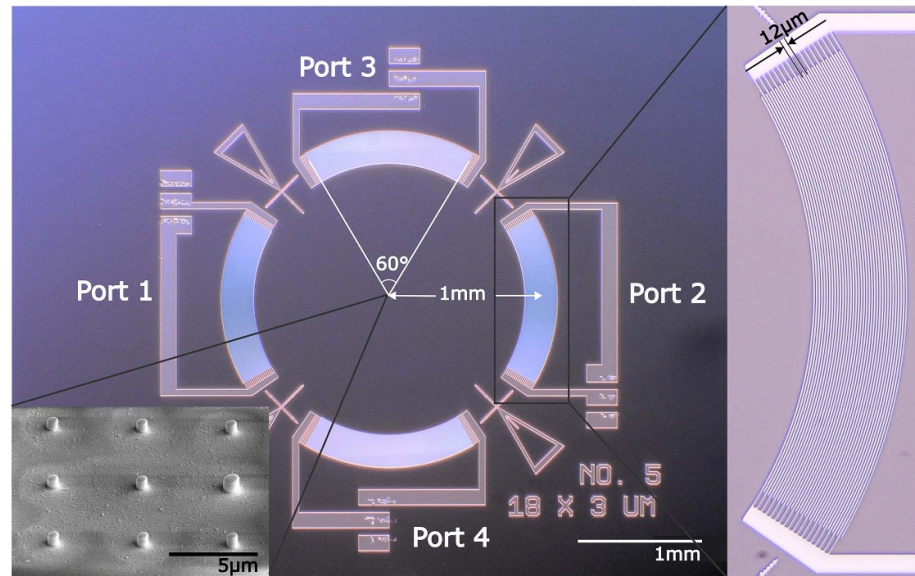


Figure 2. Microscope top-view picture of one of the fabricated SAW devices (perturbed device 2). The device features IDTs with a finger width of $3\ \mu\text{m}$ and a pitch of $12\ \mu\text{m}$. The nanoparticle array consists of cylindrical particles with diameters of $\sim 650\ \text{nm}$ and heights of $\sim 950\ \text{nm}$, arranged with a center-to-center spacing of $5\ \mu\text{m}$. Left inset: SEM image of the FIBID Pt nanoparticle array. Right inset: magnified view of the port 2 IDT.

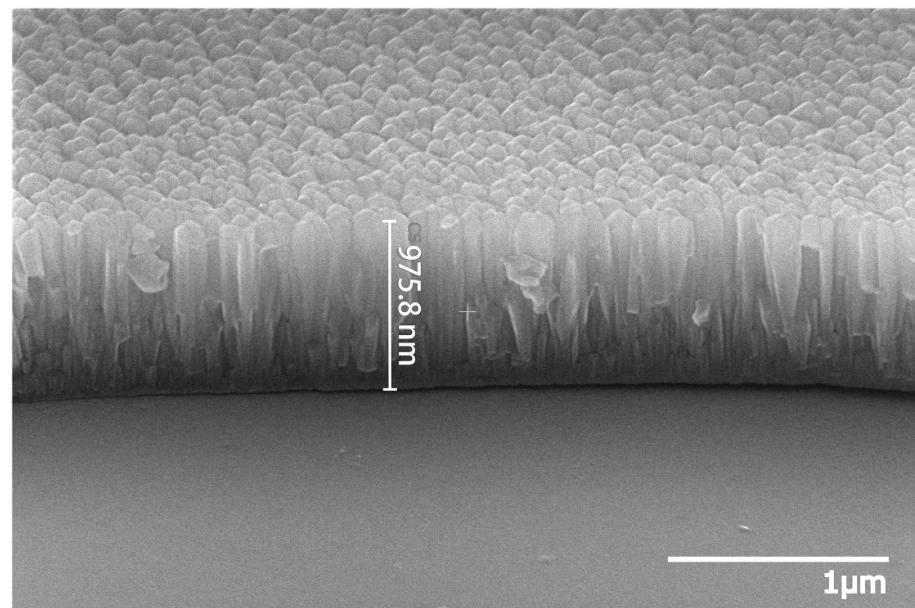


Figure 3. Cross-sectional SEM image of the deposited AlN film on the Si substrate acquired at a tilted angle. The AlN film thickness, corrected according to the tilt angle, is labeled in the figure.

S-parameter measurements were conducted on these SAW devices with a probe station and a vector network analyzer. The acoustic transmissions were measured pairwise between both coaxial IDTs (direct transmission, e.g. from port 1 to 2) and orthogonal IDTs (orthogonal transmission, e.g. from port 1 to 3 or from port 1 to 4), characterizing the directly transmitted waves (S_{21}) and scattered waves (S_{31} , S_{41}) for each device.

2.4. Simulation setup

The effects of particle mass and spatial distribution on the ability to scatter SAW into the orthogonal direction were investigated through the finite element method performed in COMSOL Multiphysics.

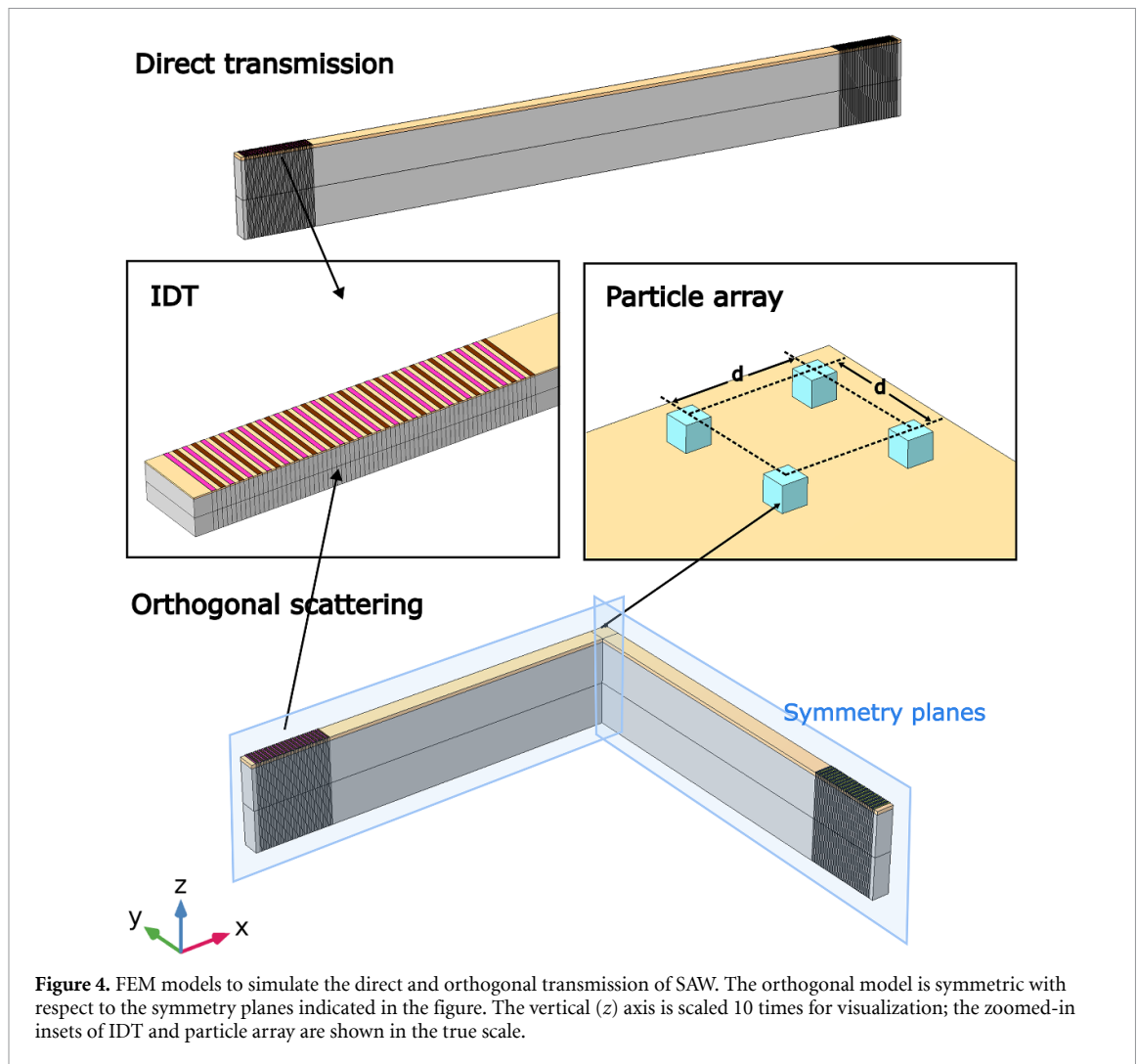


Figure 4. FEM models to simulate the direct and orthogonal transmission of SAW. The orthogonal model is symmetric with respect to the symmetry planes indicated in the figure. The vertical (z) axis is scaled 10 times for visualization; the zoomed-in insets of IDT and particle array are shown in the true scale.

To calculate the acoustic scattering by the nanoparticles, models for direct and orthogonal transmissions were implemented, as shown in figure 4. Straight IDTs with a pitch of $12\ \mu\text{m}$ and a width of $100\ \mu\text{m}$ were modeled using a $200\ \text{nm}$ Al layer on a $1\ \mu\text{m}$ AlN film on a Si substrate, matching the material stack and thickness of the fabricated devices. To reduce the computational burden, the large focused IDTs used in the experiments were replaced by narrow straight IDTs in the simulations. Orthogonal scattering was modeled using a configuration consisting of two straight SAW devices crossing at the center. Owing to the geometric symmetry, only one quarter of the structure in an L-shaped domain was included in the model, with symmetry boundary conditions applied to the two faces, as illustrated in figure 4. The Si substrate was assigned a thickness of one SAW wavelength, with an additional layer of one wavelength thickness at the bottom implemented as a perfectly matched layer (PML) to absorb outgoing waves and thus eliminate reflections. At both ends of the IDTs, the domains were laterally extended by one wavelength and also assigned as PML. All remaining side walls in both simulation models were applied with low-reflecting boundary conditions. In the orthogonal scattering model, nanoparticle arrays consisting of 2×2 , 3×3 , and 4×4 particles with an inter-particle spacing d were placed at the intersection region, respectively. Each particle was represented as a $1\ \mu\text{m}^3$ cube and modeled as pure platinum with a density of $21.45\ \text{g cm}^{-3}$ and a Young's modulus of $168\ \text{GPa}$. In the simulations investigating the effect of particle mass density, a 3×3 particle array with an inter-particle spacing of $6\ \mu\text{m}$ was used. The particle density was swept from $10\ \text{g cm}^{-3}$ to $40\ \text{g cm}^{-3}$ while the particle volume was fixed at $1\ \mu\text{m}^3$. The mesh size in all simulations was chosen to be smaller than one-eighth of the SAW wavelength to ensure numerical accuracy.

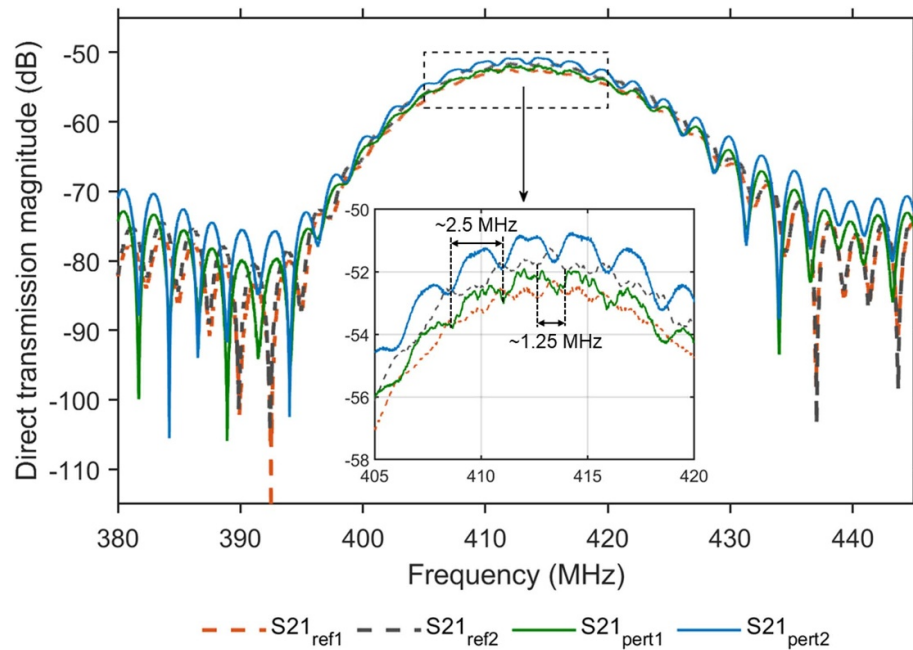


Figure 5. Measured direct transmission of the reference and perturbed devices. The inset shows the Fabry–Pérot resonance ripples in a zoomed-in region around the device center frequency.

3. Results

3.1. Experimental measurements

The direct transmissions of the two perturbed devices and two independently fabricated but identical reference devices are shown in figure 5. The measured S21 responses show transmission bands of these devices with a center frequency f_c of around 415 MHz and a 3 dB bandwidth ranging approximately from 406 MHz – 421 MHz. Outside the 3 dB bandwidth, the device still exhibits sufficient transmission, resulting in a usable bandwidth of 400–430 MHz. From the zoomed-in inset, the ripple characteristics of the reference devices differ from those of the perturbed devices. The reference devices exhibit highly consistent ripple locations and widths with a spacing of approximately 1.25 MHz, whereas the perturbed devices show similarly consistent ripples but with a spacing of approximately 2.5 MHz, which is twice that of the reference devices. These ripples in the transmission curves originate from reflections within the SAW cavities, and the frequency location of each ripple peak can be described by the Fabry–Pérot cavity resonance $f_n = (nv_{\text{SAW}})/(2l)$, where n is an integer and l is the cavity length. For the reference devices, the SAW cavity length is approximately the distance between the midpoints of the two opposing IDTs, which is about 2 mm. When nanoparticles are introduced at the center of the perturbed devices, additional reflections occur between the particles and the IDTs, effectively forming a new cavity with an effective length of half the original one. As a result, the ripple spacing increases by a factor of two. These direct transmission measurements confirm the formation of new SAW cavities and coupling between the two orthogonal SAW modes induced by the nanoparticles. From the inset of figure 5, the changes in transmission magnitude induced by the particle perturbations are comparable to the device-to-device variations. Consequently, little information about the particles can be extracted from the direct transmission response.

To characterize wave scattering by nanoparticles, figures 6(a)–(c) compare the measured direct and orthogonal transmissions for perturbed device 1 and perturbed device 2, with 2×2 and 3×3 nanoparticle arrays at the focal area, respectively, to those of a reference device. The corresponding nanoparticle array distributions are shown in the insets. As shown in figure 6(c), the orthogonal transmission of perturbed device 2 shows distinct ripples, compared to the smooth orthogonal transmission curve of the reference device (figure 6(a)). These ripples can be explained by the scattering of the acoustic waves from the driving cavity (1–2) to the orthogonal sensing cavity (3–4) by the nanoparticles. Although the scattered portion represents only a small fraction of the total acoustic power and therefore produces negligible changes in the direct transmission S21, it leads to a pronounced emergence of a frequency-dependent pattern in the orthogonal transmission, which is otherwise nearly absent in the reference device. The ripples exhibit a frequency spacing of approximately 2.5 MHz, which is consistent with

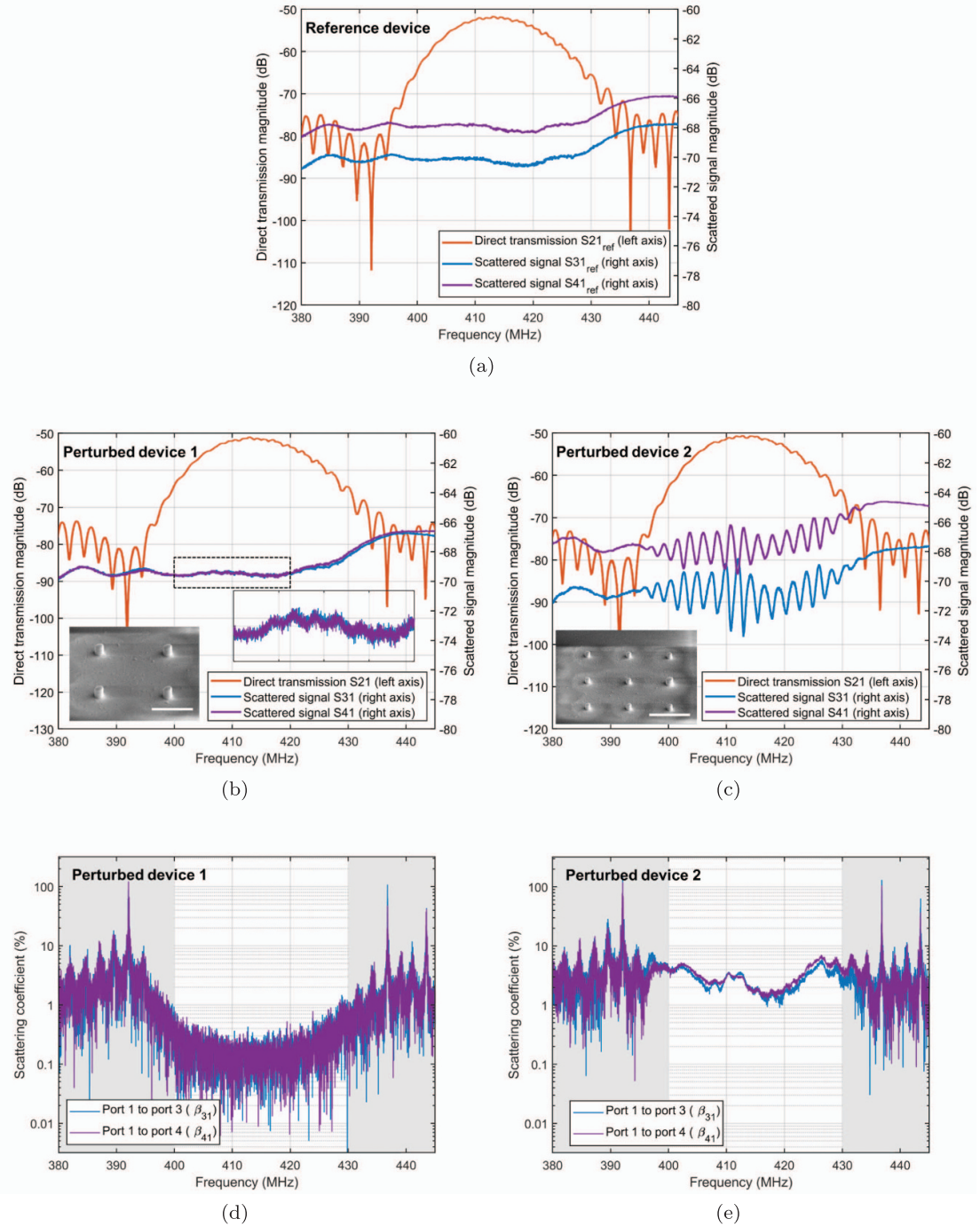


Figure 6. Measurement results of SAW scattering by particle arrays. (a)–(c) Measured raw data of the direct transmission and orthogonal scattering of the reference device and two perturbed devices. (d), (e) Extracted scattering coefficients for perturbed devices 1 and 2. Only the central high-transmission band of the SAW device is considered in the analysis; frequency regions outside this band are shaded in gray. Insets in (b) and (c) show SEM images of the particle arrays on perturbed devices 1 and 2, with scale bars of $3\ \mu\text{m}$ and $5\ \mu\text{m}$, respectively.

the spacing observed in its direct transmission and consistent with the frequency difference associated with standing waves at the SAW cavity. Using the SAW phase velocity found from the device response $v_{\text{SAW}} = \lambda f_c = 4980\ \text{m s}^{-1}$ and considering the distance between the particles and the IDTs, $l = 1\ \text{mm}$, the expected frequency spacing is $\Delta f = v_{\text{SAW}}/(2l) = 2.49\ \text{MHz}$ at the center of the transmission band. This confirms that the ripples arise from standing waves in the cavity formed between the nanoparticles and IDTs 3 and 4. As figure 6(b) shows, the orthogonal transmission of perturbed device 1 also exhibits ripples, although much less pronounced than for perturbed device 2. This observation suggests a much smaller scattering effect for the 2×2 array than for the 3×3 array.

As observed in figure 6(a), the reference device shows significant and unexpected orthogonal transmission in the range of -71 dB to -66 dB, despite the absence of wave scatterers. Although the orthogonal transmissions S_{31} and S_{41} measured along different directions are theoretically expected to be identical, discrepancies of a few dB are observed between them. This parasitic signal might arise from IDT crosstalk effects, unrelated to acoustic wave scattering. To further analyze the acoustic scattering of nanoparticles, the S -parameters measured for perturbed devices 1 and 2 were processed to eliminate the crosstalk effects. For that, the measured S_{31} and S_{41} were smoothed to obtain the baseline transmissions without ripples, S_{31_0} and S_{41_0} . Then, these baselines were subtracted from the measured orthogonal transmissions, and the results were normalized by the direct transmission coefficient of the reference device, $S_{21_{\text{ref}}}$. A comparison of the original, smoothed, and corrected orthogonal transmission is shown in Supplementary Information figure S1. This calculation results in the scattering coefficient of the nanoparticles toward ports 3 and 4:

$$\beta_{31} = \frac{S_{31} - S_{31_0}}{S_{21_{\text{ref}}}} \quad (1)$$

$$\beta_{41} = \frac{S_{41} - S_{41_0}}{S_{21_{\text{ref}}}}. \quad (2)$$

The scattering coefficients defined in equations (1) and (2) are introduced specifically for the acoustic delocalization sensing proposed in this work to quantify the scattering strength of particles through the scattering-induced coupling between orthogonal SAW cavities. Figures 6(d), show the scattering coefficients of the nanoparticles, β_{31} (from port 1 to port 3) and β_{41} (from port 1 to port 4), for the perturbed devices. The increased fluctuations in the scattering coefficient outside the 400–430 MHz range (gray shaded regions) arise from the weak SAW transmission in these frequency regions, where the measured signals approach the system noise floor. For perturbed device 1 with the 2×2 particle array, the scattering coefficients exhibit relatively low values within the device bandwidth. Given the low ripples found in S_{31} and S_{41} for this device, the obtained values for the scattering coefficient might be determined only by measurement noise. Still, it can be concluded that the scattering coefficients are below 0.1% for the 2×2 particle array. For perturbed device 2 with the 3×3 particle array, the obtained coefficients, ranging from 1% to 7% across the device bandwidth, show nearly identical scattering to directions 3 and 4 ($\beta_{31} \approx \beta_{41}$). At the measured device center frequency (415 MHz), the 3×3 particle array scatters approximately 2% of the incident waves. The calculated scattering coefficient across the device frequency band exhibits variations, likely influenced by the parasitic signals observed in the orthogonal transmissions. To minimize errors introduced by these parasitic signals and other sources, the scattering coefficient value at the device center frequency, where the SAW transmission is strongest, is used for comparison with the simulation results in the subsequent analysis.

3.2. FEM simulations

To elucidate the experimental results, particularly the large difference found in the scattering coefficients of the fabricated 2×2 and 3×3 nanoparticle arrays, numerical simulations were performed using COMSOL. Finite element simulations were used to investigate how the particle mass and spatial distribution affect the ability to scatter acoustic waves into the orthogonal direction. Two simulation models were implemented, as shown in figure 4. The models' geometries were simplified while retaining the dominant device features in order to ensure computational feasibility. The first model simulates the direct transmission of a reference device without nanoparticles and the second model simulates the orthogonal scattering in which an array of n particles separated by distance d is situated at the intersection. The simulated direct transmission of the reference device, together with the orthogonally scattered signals of the reference device and a perturbed device, are shown in figure 7. The simulation results exhibit a center frequency and bandwidth comparable to those observed experimentally. Because the simulations are performed in an ideal, noise-free environment, even extremely weak signals can be resolved. As a result of the geometrically simplified model employed to ensure computational feasibility, small but unavoidable scattering signals appear in the simulated orthogonal transmission of the reference device, with magnitudes below -120 dB. The presence of nanoparticles on the perturbed device leads to substantially stronger orthogonally scattered signals. Near the center frequency, the direct transmission exhibits ripples with a spacing of approximately 1.25 MHz, whereas the orthogonally scattered signals show ripples with a spacing of approximately 2.5 MHz. This behavior is consistent with the experimental observations and confirms that the scatterers effectively form a new SAW cavity with half the original cavity length. The scattering coefficient is extracted using the same definition as in the experiments

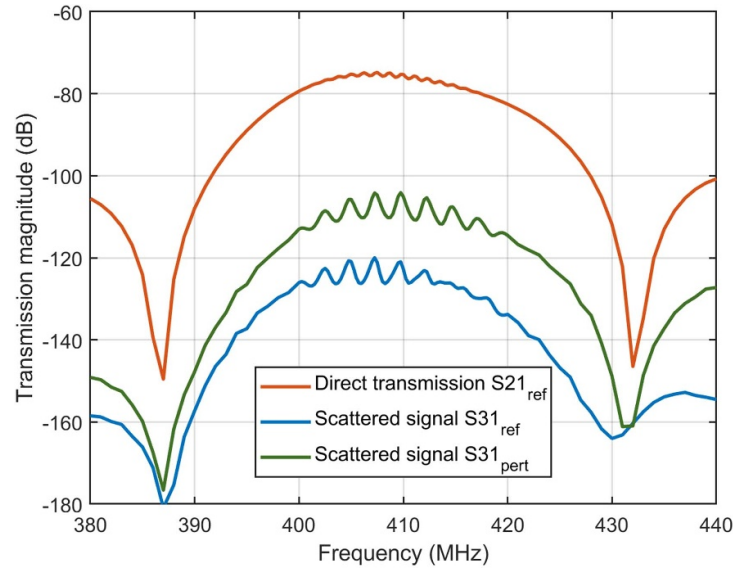


Figure 7. Simulated direct transmission of the reference device and orthogonal transmissions of the reference and perturbed devices. The perturbed device is modeled with a 3×3 particle array with an interparticle spacing of $d = 5 \mu\text{m}$.

(equations (1) and (2)), with $S31_0$ and $S41_0$ replaced by $S31_{\text{ref}}$ and $S41_{\text{ref}}$. The simulations were performed to quantify the dependence of the orthogonal scattering coefficient on the number of particles n , the inter-particle spacing d , and the particle mass m .

The effect of particle number and spatial distribution was first investigated by sweeping the center-to-center inter-particle spacing d in 2×2 , 3×3 , and 4×4 particle arrays. Simulations were performed with nanoparticle arrays as the spacing d was varied from $1 \mu\text{m}$ to $13 \mu\text{m}$. At the minimum spacing of $1 \mu\text{m}$, the particles form a single block. As the spacing increases to $12 \mu\text{m}$, it approaches one wavelength of the SAW at the simulated device center frequency (410 MHz). The calculated scattering coefficients as a function of the inter-particle spacing are shown in figure 8(a). For each particle configuration, the frequency-dependent scattering coefficient was evaluated over a frequency range of ± 10 MHz around the center frequency and condensed into a single representative value by averaging over this band. This averaging was performed because the simulated transmissions clearly showed strong Fabry–Pérot cavity resonances, as shown in figure 7. These resonances produced oscillations in both the transmissions and the scattering coefficients derived from them, superimposed on their respective envelopes. The open circles indicate the averaged scattering coefficients, while the error bars represent the variation across the frequency range. For all three arrays with different numbers of particles, the orthogonal scattering coefficient peaks when the inter-particle spacing approaches either the minimum feasible value ($d = 1 \mu\text{m}$) or one wavelength ($d = 12 \mu\text{m}$), in agreement with Bragg’s law. At $d = \lambda$, the peak values also increase with the number of particles, from 17.4% for a 2×2 particle array, to 34.6% for a 3×3 particle array, and 52.1% for a 4×4 particle array. These results are explained by the cumulative effect of particles on scattering strength when the waves scattered by each particle interact constructively. It is worth noting that the propagation path difference between waves scattered by different particles is approximately equal to the distance between the particles, as the particle size and spacing are substantially smaller than the overall SAW cavity length. The propagation path associated with each particle is illustrated in figure 8(c) using the 3×3 array as an example. For clarity, the particle array is shown at an enlarged scale relative to the overall device, and the propagation path length associated with each particle is labeled in the figure. This propagation path difference explains the different spacing-dependent trends observed in the scattering coefficients of the three particle arrays. At half-wavelength spacing ($6 \mu\text{m}$), destructive interference between waves scattered by adjacent particles in the 2×2 and 4×4 arrays results in low scattering coefficients, hence the dips observed in the top and bottom panels of figure 8(a) at $d = 6 \mu\text{m}$. However, for the 3×3 array, the scattered waves do not fully cancel out due to the odd number of rows in the array, resulting in a small peak in the scattering coefficient at half-wavelength spacing. The locations of the peaks and dips obtained from the simulations match the mathematical predictions for the maxima and minima of amplitude resulting from the superposition of $n \times n$ waves with the corresponding phase, as shown in figure 8(b).

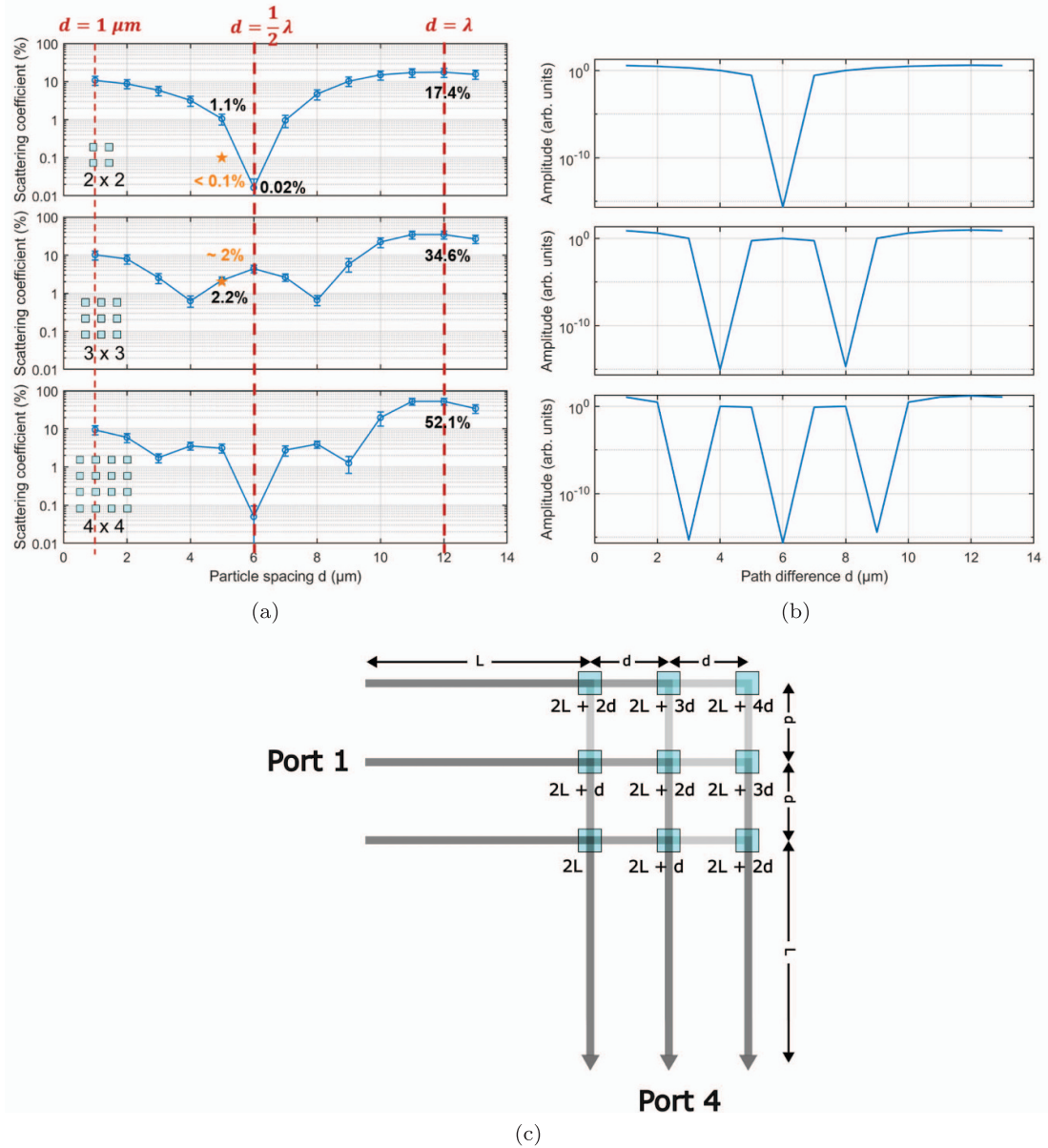
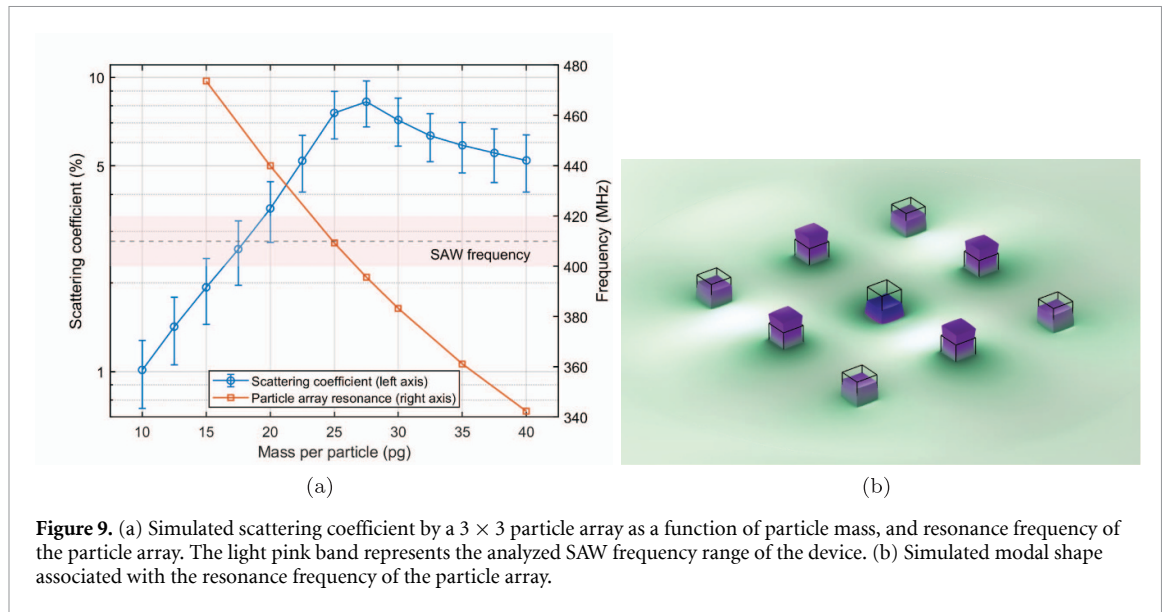


Figure 8. (a) Simulated orthogonal scattering coefficient by 2×2 , 3×3 , and 4×4 particle arrays as a function of particle spacing. Orange stars denote measured results. (b) Mathematical calculation showing the superposition of 2×2 , 3×3 , and 4×4 sinusoidal waves, each with unit amplitude and with wavelength and phase corresponding to the simulation. The x-axis parameter path difference is equivalent to the particle spacing shown in (a). To avoid zero values in logarithmic representation, a small positive constant ϵ ($\epsilon = \text{eps}$ in MATLAB) is added to all values. (c) Wave scattering paths to the orthogonal direction in a 3×3 particle array.

The values of the scattering coefficients at the device center frequency from the experimental measurements are indicated by the orange stars in figure 8(a) for comparison. The simulated scattering coefficients on the frequency domain at particle spacings $5 \mu\text{m}$ and $6 \mu\text{m}$ are shown in Supplementary Information figures S2 and S3. The simulations predict a scattering coefficient of 1.1% for the 2×2 particle array with $5 \mu\text{m}$ spacing, while the experimental result indicated a value below 0.1%. For the 3×3 particle array with $5 \mu\text{m}$ spacing, the simulation predicts a scattering coefficient of 2.2%, and the experimental result indicated a value of about 2% at the center frequency. Both the simulations and experiments show reduced scattering for the 2×2 array near half-wavelength spacing and enhanced scattering for the 3×3 array near the half-wavelength spacing, following the expected rules of constructive and destructive interference. The measurement and simulation results are therefore in qualitative agreement, with the simulations providing support for the experimental observations.

To investigate the effect of particle mass density on SAWs scattering, simulations were performed in which the particle density was varied while the particle volume was kept constant. The simulation results are shown in figure 9(a). For low mass values, the ability of the particles to scatter acoustic waves



increases almost linearly with their mass, up to a particle mass of 25 pg. Above that value, the scattering coefficient decreases with mass. To elucidate this observation, an eigenfrequency analysis was performed on the particle array. The results show that one of the resonance frequencies of the array falls closely to the SAW frequency used in this study. The vibration shape associated with this resonance corresponds to the out-of-plane vibrations of the particles in opposite phases, as illustrated in figure 9(b). The resonance frequency of the 3×3 particle array near the device operating frequency was simulated and plotted as a function of the particle mass, shown by the orange curve on the right axis. As observed, the peak of the scattering coefficient at 25 pg coincides with the particle mass at which the particle array exhibits a resonance frequency of 409 MHz. This resonance frequency falls approximately at the center of the SAW frequency range analyzed. When the particle mass is lower than 25 pg, the SAW operating frequency is much lower than this resonance frequency of the particles. According to Gil-Santos *et al* [6], this lies in the inertial regime, where the particles act as static mass loading. As the resonance frequency of the particle array approaches the SAW frequency, the acoustic waves interact with the resonance of the particle array, entering the coupling regime. The turnaround in the mass-dependent trend can be attributed to the coupling between the SAW and the particle resonances. When the particle mass increases further, the SAW frequency becomes higher than the particle resonance frequency, entering the insensitive regime. In this regime, the device becomes less sensitive to particle variations, resulting in a slower decrease in the scattering coefficient.

4. Discussion

Conventional resonant mass sensors for particle detection primarily rely on monitoring the resonance frequency shift induced by mass loading. In contrast, the present work explores an alternative sensing mechanism based on the scattering of SAWs by particles. The proposed approach employs two crossing SAW cavities to directly measure particle-induced acoustic scattering. In this configuration, analytes interact directly with the propagating SAWs, allowing particle characteristics to be extracted without using resonators as intermediate sensing elements. The experimental and simulation results suggest that the orthogonally scattered waves carry information about particle mass and spatial distribution, indicating the feasibility of extracting particle characteristics through scattering responses.

In the proposed device, two orthogonal SAW cavities are used as actuating and sensing channels. Particles located at the intersection region scatter acoustic energy from the actuating cavity into the sensing cavity, generating signals that are otherwise absent in the unexcited cavity. Because the sensing mechanism relies on the redistribution of acoustic energy from the actuating cavity to the sensing cavity, the system shares the advantage of sensitivity enhancement observed in mode localization method, where small perturbations lead to pronounced energy redistribution between coupled resonators. Meanwhile, the coupling between the two cavities is established through particle-induced scattering rather than

structural coupling. Therefore, the two cavities do not require precise matching, which significantly relaxes the design constraints and fabrication tolerances of the device.

The preliminary experimental measurements, although limited to two representative data points, qualitatively support the simulated trend between particle distribution and scattering intensity. These results serve as an initial proof-of-concept demonstrating the feasibility of detecting the particle scattering coefficient in the proposed configuration.

The numerical simulations indicate that the scattering coefficient of the particles increases with particle mass when particle resonances are not involved. This trend can be understood from the enhanced perturbation of the local SAW field caused by larger inertial loading. In addition to particle mass, the simulations also reveal a dependence of the particle array scattering coefficient on the inter-particle spacing and the size of periodic particle arrays. This behavior originates from the interaction between scattered waves generated by neighboring particles, which can lead to constructive or destructive interference depending on their separation, analogous to Bragg's law. Consequently, both the number of particles and their spacing influence the total scattered intensity received at the orthogonal port. The number of scattered waves contributing to the superposition, together with their phase relationships determined by their propagation paths, leads to alternating enhancement and suppression of the scattered intensity, producing peaks and dips in the scattering coefficient as the particle spacing varies.

In this work, the particle arrays are regularly arranged at the center of the SAW device, which does not reflect the random distribution typically encountered in real analyte measurements. However, such periodic particle or pillar configurations can be beneficial for biosensing and chemical sensing applications, where increased surface area and controlled adsorption sites are essential. One advantage is that regularly arranged pillars can serve as effective carriers to improve analyte capture efficiency with increased surface-to-volume ratio [19], thereby improving sensing performance by utilizing collective effects rather than individual analyte responses. Periodic pillars can also enhance interactions between analytes and the substrate by increasing cell and tissue adhesion [12], and can be used as biointerfaces for sensing the intracellular environment, cellular traction forces, and other biological parameters [5]. Furthermore, building on this work, using regularly positioned particles or pillars as analyte carriers could enhance sensing performance by intentionally localizing analytes in regions of strong acoustic wave interaction.

The results from this work suggest that the proposed scattering-based sensing approach using acoustic delocalization between SAW cavities, may provide access not only to particle mass information but also to spatial information about particle distributions. The present study focuses on demonstrating the feasibility of acoustic delocalization sensing through scattering-induced coupling between orthogonal SAW cavities. Several factors that may influence the scattering response remain to be investigated, including irregular particle attachment configurations and different particle materials such as non-metallic and biological analytes. Understanding how these factors affect the scattering strength and mechanism will be important for extending the applicability of the proposed sensing approach. In addition, the experimental validation presented in this work is limited to a relatively small set of particle configurations. Future studies should include a larger experimental dataset covering a wider range of particle numbers and inter-particle spacing to establish a more comprehensive understanding of the relationship between particle distribution and scattering response. Furthermore, the current work establishes the fundamental sensing principle but does not address key sensor performance metrics, such as sensitivity and limit of detection, which will be the subject of future studies toward the development of a complete sensing platform. In the present work, the sensing information is obtained from a single orthogonal sensing cavity, which limits the amount of spatial information that can be extracted. Future device layout incorporating additional sensing cavities crossing at different angles could provide multiple channels to capture waves scattered in different directions. For example, additional IDT ports could be introduced at 30°, 45°, or 60°, in addition to the existing ports at 90°. This would primarily result in a linear increase in the VNA measurement and subsequent data processing effort. Such a configuration may enable reconstruction of particle distributions at the device center, potentially solving for the number of particles and their relative positions.

5. Conclusion

In conclusion, based on the above experiments and simulations, the feasibility of using SAW scattering to detect an array of particles adhered to a substrate has been demonstrated. Our results reveal a complex relationship between the scattering coefficient and the properties of the particle array, including the

particle number, spacing, and mass density. The number of particles and spacing determine the overall scattering coefficient of the array, as a result of the constructive/destructive interference of scattered waves by the individual particles. The scattering coefficient is maximized for a spacing of an integer number of wavelengths, corresponding to maximum constructive interference, and increases with the number of particles. For half wavelength spacing, 2×2 and 4×4 arrays result in destructive interference, but 3×3 array provide significant scattering. The experimental results on 2×2 and 3×3 particle arrays with particle spacings close to half SAW wavelength agree with the trends observed in simulations. Furthermore, the resonance frequency of the particles plays an important role. For SAW frequency below the resonance, the scattering coefficient increases with the particle mass. However, the observed inverted trend near the particle resonance frequency represents an important limitation of the proposed sensing approach for wide-range mass sensing. In this regime, the relationship between scattering coefficient and particle mass is no longer monotonic, making it difficult to uniquely determine particle mass from the measured scattering response. Therefore, practical sensor designs should ensure that the operating frequency range remains sufficiently separated from particle resonance modes that can be excited by the SAW. These findings showcase the suitability of SAW scattering to detect particles in small areas and characterize their mechanical properties.

Data availability statement

All data that support the findings of this study are included within the article (and any supplementary files).

Supplementary information available at <https://doi.org/10.1088/1361-6439/ae97ee/data1>.

ORCID iDs

Qiuxuan Wang  0009-0007-7282-4323

Xiaoxi Zhao  0000-0001-6198-5876

Murali Krishna Ghatkesar  0000-0001-8423-3159

Tomás Manzaneque  0000-0002-1738-4261

References

- [1] Alanazi N, Almutairi M and Alodhayb A N 2023 *Sens. Imaging* **24** 10
- [2] Assouar M, Elmazria O, El Hakiki M and Alnot P 2006 *Integr. Ferroelectr.* **82** 45–54
- [3] Ekinci K, Huang X and Roukes M 2004 *Appl. Phys. Lett.* **84** 4469–71
- [4] Ekinci K L and Roukes M L 2005 *Rev. Sci. Instrum.* **76** 0034–6748
- [5] Elnathan R et al 2022 *Nat. Rev. Mater.* **7** 953–73
- [6] Gil-Santos E, Ruz J J, Malvar O, Favero I, Lemaître A, Kosaka P M, García-López S, Calleja M and Tamayo J 2020 *Nat. Nanotechnol.* **15** 469–74
- [7] Hajjam A, Wilson J C, Rahafrroz A and Pourkamali S 2010 Detection and mass measurement of individual air-borne particles using high frequency micromechanical resonators (*SENSORS, 2010 IEEE*) pp 2000–4
- [8] Hesjedal T and Behme G 2001 *Appl. Phys. Lett.* **78** 1948–50
- [9] Mujahid A and Dickert F L 2017 *Sensors* **17** 1424–8220
- [10] Puchkawade V 2021 *IEEE Sens. J.* **21** 8751–79
- [11] Pandit M, Zhao C, Sobreviela G and Seshia A 2020 *IEEE Sens. J.* **20** 6818–25
- [12] Piergallini C et al 2025 *Biomater. Sci.* **13** 6918–31
- [13] Spletzer M, Raman A, Wu A Q, Xu X and Reifenberger R 2006 *Appl. Phys. Lett.* **88** 0003–6951
- [14] Tamayo J, Ramos D, Mertens J and Calleja M 2006 *Appl. Phys. Lett.* **89** 0003–6951
- [15] Thiruvengatanathan P, Yan J, Lee J Y and Seshia A 2009 Enhancing parametric sensitivity using mode localization in electrically coupled mems resonators (*TRANSDUCERS 2009 - 2009 International Solid-State Sensors, Actuators and Microsystems Conf.*) pp 2350–3
- [16] Thiruvengatanathan P, Yan J and Seshia A A 2009 Common mode rejection in electrically coupled mems resonators utilizing mode localization for sensor applications 2009 *IEEE Int. Frequency Control Symp. Joint With the 22nd European Frequency and Time Forum* pp 358–63
- [17] Wang L, Wang Y, Zhang P, Mak P I, Martins R P, Wu X and Wang C 2025 *IEEE Trans. Electron Devices* **72** 1345–51
- [18] Xiang J, Xia C, Lin S, Zhao Z, Zhang L, Xia Y, He L, Wang D F and Wang Z 2024 *IEEE Sens. J.* **24** 9734–43
- [19] Xu J, Setiono A and Peiner E 2020 *ACS Appl. Nano Mater.* **3** 6609–20
- [20] Zhao C, Montaseri M H, Wood G S, Pu S H, Seshia A A and Kraft M 2016 *Sens. Actuators A: Phys.* **249** 0924–4247