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(54) Title: ACOUSTIC APPARATUS FOR CONTACTLESS EXCITATION OF TRANSVERSE PIEZO-ACOUSTIC PHONONS

(57) Abstract: A quantum acoustic apparatus (114) for contactless excitation of transverse piezo-acoustic phonons is provided. In another aspect, a device and method couples between free-space electromagnetic waves in the radio frequency and microwave frequency range to transverse bulk phonon modes in a piezoelectric material over a wide range of temperatures, from room temperature to cryogenic temperatures, in a contactless fashion. The quantum acoustic apparatus (114) determines if a mechanical mode of the substrate (100) is excited based on a change in amplitude and a shift in the applied signal. The apparatus includes a substrate (100) with electrodes (102) fabricated on top disposed within a resonant cavity (104).



ACOUSTIC APPARATUS FOR CONTACTLESS EXCITATION OF TRANSVERSE PIEZO-ACOUSTIC PHONONS

CROSS-REFERENCE TO RELATED APPLICATIONS

[0001] The present application claims priority to U.S. Provisional Application No.

5 63/526,272, filed on July 12, 2023. The entire disclosure of the above application is incorporated herein by reference.

STATEMENT OF GOVERNMENT SUPPORT

[0002] This invention was made with government support under Grant No.

10 ECCS-2142846 awarded by the National Science Foundation. The government has certain rights in this invention.

BACKGROUND AND SUMMARY

[0003] The present disclosure relates to phonons and in particular, contactless excitation of transverse piezo-acoustic phonons.

15 **[0004]** Quantum acoustic systems where superconducting qubits are interfaced with mechanical degrees of freedom provide a platform for applications in quantum information science. Prior quantum acoustic systems have not understood and controlled the multiple natural mechanical modes existing in such devices, each of which depend on the geometry and boundaries of a substrate and device layout. Understanding and
20 controlling the existence of these natural modes at the level of device design allows for simultaneous coupling to multiple distinct types of phononic excitations in a single architecture. When the modes are not understood and controlled, they can act as unwanted decoherence channels for the quantum systems of interest and degrade device performance. Optimizing the device geometry allows for the mitigation of these
25 unwanted couplings and methods for improving the coherence of quantum acoustic systems and enhancing the performance of quantum acoustic-based devices for quantum sensing, communication, and information processing. Moreover, if the devices can be operated over a wide range of temperature these devices, and their optimized geometry, can also be utilized for classical applications in sensing and signal processing.

30 **[0005]** In accordance with the present disclosure, a quantum acoustic system in which superconducting qubits are interfaced with mechanical degrees of freedom offering a platform for quantum information science, as mechanical resonators, can be

fabricated having a small spatial footprint and long coherence times. By engineering hybrid quantum systems of the present application, it is possible to design quantum memory protocols, implement microwave-to-optical transduction schemes, and operate the qubit, as well as the mechanical modes, as a sensor. The ability to leverage

5 mechanical degrees of freedom at the level of single or few phonons allows for quantum information processing, with experimental results demonstrating the creation of phononic Schrodinger cat states, the joint entanglement of high-frequency mechanical oscillators, and the ability to simulate open quantum acoustic systems.

[0006] The present disclosure provides a single integrated quantum acoustic device that couples a superconducting transmon qubit to both an engineered surface phonon resonator as well as natural transverse bulk substrate phonons. The transverse bulk phonon modes are excited via their free-space coupling to the resonator cavity (e.g., three-dimensional microwave cavity) in which the device is housed and at low temperatures where they exhibit coupling to the qubit with an interaction strength

10 comparable to the decay rate of the hybrid system. Additionally, similar devices in which the qubit and surface phonon resonator are removed, enable contactless coupling to these naturally occurring transverse modes with a coupling that resists to room temperature.

[0007] In accordance with the present disclosure, a quantum acoustic apparatus for contactless excitation of transverse piezo-acoustic phonons is provided. In another aspect, a device and method couples between free-space electromagnetic waves in the radio frequency and microwave frequency range to transverse bulk phonon modes in a piezoelectric material over a wide range of temperatures, from room temperature to cryogenic temperatures, in a contactless fashion. The quantum acoustic apparatus

20 determines if a mechanical mode of the substrate is excited based on a change in amplitude and frequency or phase shift in the applied signal.

[0008] As such, this technology is suitable for both classical and quantum piezoelectric sensing. The strong coupling of these transverse phonon modes to superconducting qubits at low temperatures allows this technology to alternatively be

30 used for quantum metrology. Furthermore, integrating optical signals by free-space or optical fibers allows these devices to function for classical and quantum microwave-to-optical transduction protocols.

[0009] The fundamental technology consists of a substrate (e.g., piezoelectric YZ-lithium niobate substrate) with electrodes (e.g., metallic antenna pads) fabricated

onto the surface. To excite the piezoelectric modes of the quantum acoustic apparatus, the quantum acoustic apparatus is housed inside a resonant cavity (e.g., three dimensional microwave cavity), which allows the electromechanical coupling between the resonant cavity excitations and the electrodes to generate the transverse bulk phonon modes. When the electric field of the resonant cavity impinges on the electrodes, which constitute a dipole moment, the charges in the electrode screen the external field and polarize the substrate. The magnitude of the field is proportional to the capacitance between the electrodes and the internal walls of the resonant cavity. As a consequence of the piezoelectric effect, the field creates phononic excitations within the substrate. If the frequency of the applied oscillating electromagnetic field is resonant with a natural mechanical frequency of the geometry of the substrate, the phonon mode will resonate within the bulk of the material with extremely high quality-factor. The transverse modes of the bulk phonon modes oscillate along the direction of the electrode.

[0010] Rotation of the antenna of the surface of the substrate relative to the electric field within the cavity decouples the transverse modes and the electromagnetic excitations, which shows the sensitivity of the device with respect to the electric field direction. The excitation of the transverse modes is shown to persist to room temperature but become more pronounced as the temperature of the system is cooled. While a microwave line is needed to excite the resonant cavity, no other wires are attached to the device, possibly making it suitable for applications that require compact space. Additionally, because of the wide range of temperature operation, both classical and quantum sensing and signal processing applications are possible as is operation in environmentally challenging conditions (e.g., high temperature, caustic gases/liquids). Moreover, at cryo-temperatures, these transverse modes can be made to couple strongly with superconducting qubits when the qubit chip and the substrate are arranged in a flip-chip configuration or connected via on-chip coupling circuits.

[0011] Further areas of applicability will become apparent from the description provided herein. The description and specific examples in this summary are intended for purposes of illustration only and are not intended to limit the scope of the present disclosure.

DRAWINGS

[0012] Figure 1 is a schematic diagram showing the architecture of the present quantum acoustic apparatus;

5 [0013] Figure 2 is a perspective view showing a resonant cavity of the present apparatus;

[0014] Figure 3 is a graph illustrating the induced voltage on the surface of a substrate when the present apparatus is driven at the same frequency as the induced transverse strain;

[0015] Figure 4 is an electrical diagram of the present apparatus;

10 [0016] Figures 5A and B are graphs illustrating a relationship associated with frequency and transmission of the present apparatus for two angles of the electric cavity relative to the device dipole;

[0017] Figures 6A and B are graphs illustrating a relationship of frequency versus flux tuning current associate with the present apparatus;

15 [0018] Figure 7A is a graph depicting a measurement of the resonant cavity of the present apparatus, at large input powers where the transmission is independent of the state of the qubit;

[0019] Figure 7B is a graph depicting extracted coupling strength between the hybrid qubit-cavity system for five avoided crossings of the present apparatus; and

20 [0020] Figure 8 is a diagram showing a method of contactless excitation of phonons for the present apparatus.

DETAILED DESCRIPTION

[0021] A preferred embodiment of a multimode integrated quantum acoustic apparatus and method is expected to enhance quantum information science, such as
25 quantum piezoelectric sensing, quantum metrology, quantum microwave-to-optical transduction protocols, etc. Specifically, a quantum acoustic apparatus comprising a resonator cavity, a substrate, one or more electrodes, and a controller. The device further couples a superconducting qubit hosting both surface and bulk phonon modes in the substrate is probed via the transmission through the resonant cavity. Using finite
30 element modeling (FEM), the bulk phonons excited by the cavity field have a transverse polarization with a shear velocity. The coupling between the transverse phonons and the electric field in the cavity depends on the relative orientation of the lithium niobate crystal axes and the cavity field, with the coupling persisting to room temperature. At

cryogenic temperatures, the shear phonon modes couple to a flux tunable superconducting qubit with strength comparable to the decay rate of the qubit-cavity system.

[0022] The flux tunable superconducting qubit is fabricated on high-resistivity silicon. The system is mounted in a 3D electromagnetic copper cavity with a measured energy decay rate of $\kappa/(2\pi) = 11$ MHz at cryogenic temperatures. A superconducting wire is wound around the cavity to apply an external magnetic field that tunes the resonant frequency of the qubit. Large antenna pads of dimension (250 μm) on either substrate that form a set of parallel plate capacitors when the devices are vertically aligned and adhered together using standard flip-chip techniques. The antenna pads serve a dual purpose in enabling the coupling between the devices as well as serving as a coupling mechanism between the electric field in the microwave cavity and either device independently.

[0023] More specifically, Figure 1 depicts an example architecture of a quantum acoustic apparatus 114. The example architecture of Figure 1 depicts the orientation of the oscillating electric field which couples to the dipole moment of the hybrid quantum acoustics systems. The quantum acoustic apparatus 114 is generally comprised of a substrate 100, an electrode 102, a resonant cavity 104, a controller 106, power 108, a VNA (vector network analyzer) 110, a cryogenic cooling system 120, and a superconducting wire 118. Each of these components is further described below. It is to be understood that only the relevant components of the system are discussed in relation to Figure 1, but other components may be needed to control and manage the overall operation of the system.

[0024] Substrate 100 is a piezoelectric material that includes lithium niobate, specifically Y cut lithium niobate. Substrate 100 can alternatively be gallium arsenide, quartz, zinc oxide, barium titanate, barium, barium strontium titanate, strontium titanate etc. Electrode 102 is preferably a metallic antenna/aluminum pad fabricated onto the surface of substrate 100. The electrodes 102 are fabricated by first cleaning the substrate 100 and then performing positive photolithography. The substrate 100 is cleaned by use of PG remover, acetone, IPA, and O₂ plasma etcher. Other suitable forms of fabrication of the electrodes are available, such as an etching process. The electrodes 102 have dimension (250 μm) and the pair of electrodes 102 are parallel with one another.

[0025] Resonant cavity 104 may be a three-dimensional microwave resonator, a two-dimensional microwave resonator, a three-dimensional waveguide, two-dimensional waveguide, or a suitable resonator cavity. The three-dimensional microwave resonator is the preferred resonator cavity 104. Substrate 100 and electrodes 102 are disposed within resonator cavity 104 as depicted in Figure 2. The substrate 100 sits on a lip within the resonant cavity 104 such that the substrate 100 sits directly in the middle of the resonant cavity 104. In alternate embodiments, the substrate 100 could be sit at other positions inside the cavity, which would allow for variable coupling to the acoustic modes.

[0026] Controller 106 is a microprocessor that runs programmed software instructions stored in non-transient memory, such as RAM or ROM. During operation, controller 106, applies a variable frequency electromagnetic signal that ranges from 100 megahertz to 10 gigahertz. The optimal range for the signal is from 4-8 gigahertz. Referring to Figures 1 and 4, power supply 108 provides DC or AC voltage to the quantum acoustic apparatus 114. Furthermore, VNA 110 is a test instrument configured to detect a reduction in amplitude and a shift in the phase of the transmitted signal. Cryogenic cooling system 120 is configured to maintain the inside and outside of the resonant cavity 104 at cryogenic temperatures. The cryogenic cooling system 120 is attached to the resonator cavity 104. Alternatively, the cryogenic cooling system 120 could provide cooling to the resonant cavity 104 through cryogenic pipes that extend to the resonant cavity 104 from the cryogenic cooling system 120. The superconducting wire 118 is a metal wire wrapped around the outside of the resonant cavity 104 to provide an external magnetic field that tunes the resonant frequency of the superconducting qubits coupled to the acoustic device on the substrate 100.

[0027] The signal being applied to resonant cavity 104 creates an electric field 112 disposed within resonant cavity 104. When the electric field 112 impinges on the electrodes, the charges in the electrodes 102 screen the electric field 112 and polarize the substrate 100. The magnitude of the electric field 112 is proportional to the capacitance between the electrodes 102 and the internal walls of the resonant cavity 104. As a consequence of the piezoelectric effect, the electric field 112 creates phononic excitations within the substrate 100 depicted in Figure 1. Figure 3 depicts a diagram of an induced transverse strain S_{yz} in the substrate when a resonant frequency of the fundamental transverse phonon mode is achieved. Figure 3 depicts a diagram of

the induced voltage on the surface of the substrate 100 when the quantum acoustic apparatus 114 is driven at the same frequency as the induced transverse strain S_{yz} .

[0028] If the frequency of the applied oscillating electric field 112 is resonant with a natural mechanical frequency of the geometry of the substrate 100, the phonon mode will resonate within the bulk of the substrate 100. Because the electric field 112 can excite the phonon mode and is perpendicular to the direction of the phonon propagation, transverse phonon modes are generated in the substrate. The transverse phonon modes oscillate along the Y direction of the substrate 100 having a resonant frequency dictated by the speed of the sound and thickness of the water. The resonant frequency is determined by the below Equation 1:

$$f_n = nv/2t, \quad (1)$$

where n is the mode number, v is the speed of sound, and $t = 500 \mu\text{m}$ is the thickness of the water. The speed of sound within the bulk material can be calculated via Hooke's Law:

$$C_{44} = \rho v^2, \quad (2)$$

where $C_{44} = 5.95 \times 10^{10} \text{ Pa}$ is an elastic constant of the material and $\rho = 4647 \text{ kg/m}^3$ is the material density. For YZ lithium niobate (i.e., the substrate 100), the speed of transversely polarized bulk sound can be calculated to be 3578 m/s , leading to a free spectral range for the quantum acoustic apparatus 114 of $\Delta f_n = 3.578 \text{ MHz}$. COMSOL Multiphysics (or other suitable simulation package) is used to find the mechanical eigenmodes of the substrate 100. By applying boundary conditions which enforce the natural symmetries of the system, the frequency of the fundamental transverse Y mode is calculated to be $f_1 = 3.5784 \text{ MHz}$, which is consistent with the theoretical predictions.

[0029] The coupling of the resonant cavity 104 to odd-indexed transverse modes of the substrate 100 is verified by fabricating a control sample. The control sample consists of a Y cut lithium niobate (i.e., the substrate 100) containing only the capacitor pads (i.e., the electrodes 102) corresponding to the quantum acoustic apparatus 114 measuring the transmission through a three-dimensional microwave cavity (i.e., the resonant cavity 104).

[0030] Figure 5A and 5B illustrate dependence of the generation of bulk phonon modes on the dipole dependence of the quantum acoustic apparatus 114. Figure 5A depicts when the dipole moment of the quantum acoustic apparatus 114 is parallel to the electric field 112, coupling is observed between the cavity mode and the mechanical modes of the substrate. Figure 5B depicts when the substrate 100 is

oriented such that the dipole moment is perpendicular to the electric field 112, no coupling between the two systems is observed. The shift in the cavity frequency is attributed to the large anisotropy of the lithium niobate substrate (i.e., the substrate 100).

5 **[0031]** The coupling between the electromagnetics and the mechanical modes is apparent breaks in the transmission spectrum of the resonator cavity 104, with free spectral range of $\cong 7.9$ MHz, consistent with the prediction of $2 \times f_n = 7.1566$ MHz. Furthermore, the coupling is verified by measuring the transmission through the cavity with the dipole antenna of the control sample rotated by 90° relatives to the electric field 112 within the resonant cavity 104, so that the dipole moment is perpendicular to the electric field 112. In the scenario $\vec{E} \cdot \vec{D} = 0$, the breaks in the cavity spectra are no longer apparent, indicating that there is no electromechanical coupling.

15 **[0032]** To determine the importance of the family of resonant phonon modes in the quantum acoustic systems, measurement of transmission through an identical microwave cavity at low input power ($P_{\text{input}} \approx -110$ dBm) is taken. As the resonant frequency of the qubit is tuned across an entire flex quantum, the hybrid qubit-cavity system undergoes an avoided crossing, which can be fit to the Jaynes-Cummings Hamiltonian revealing coupling strength of $g/(2\pi) = 74 \pm 2$ MHz. Figure 6A and 6B depict a hybrid system spectra coupling to mechanical modes depicted by horizontal breaks in microwave transmission and are independent of external magnetic flux. Figure 6A depicts spectroscopic data over a smaller frequency range where clear avoided crossings between the qubit-cavity system and the phonon modes are clear. Figure 6B depicts a spectroscopy of the hybrid qubit-cavity system as the qubit frequency is tuned via the magnetic flux through an external superconducting coil. The qubit cavity system is coupled with an interaction strength of $g/(2\pi) = 74 \pm 2$ MHz. Additional coupling between the hybrid system and bulk mechanical modes is observed as features at constant features which are largely independent of external magnetic flux. The fit is to a coupled oscillator model with the coupling strengths depicted in Figure 7A and 7B.

25 **[0033]** Figure 7A depicts a measurement of the resonant cavity 104 at large input powers where the transmission is independent of the state of the qubit. Coupling to the acoustic modes is clear as breaks in the cavity transmission. The bare cavity transmission ($P_{\text{input}} \approx -60$ dBm) is displayed in Fig. 7A with the coupling to mechanical modes present. Figure 7B depicts extracted coupling strength between the hybrid qubit-

cavity system for five avoided crossings, where the coupling strength is largely independent of mode number.

5 **[0034]** Referring now to Figure 8, a flowchart depicts a method of operating the present apparatus, including contactless excitation of phonons. Control may begin with 202 where the controller 106 applies the signal (i.e., the variable frequency electromagnetic (EM) signal to the resonant cavity (e.g., three-dimensional microwave cavity) 104. At 204, the signal generates the electric field 112 (i.e., a free-space signal) that will excite the substrate 100 (i.e., a piezoelectric material). At 206, the signal will resonate with a mechanical mode of the substrate 100. At 208, the VNA 110 will detect
10 a reduction of amplitude and a shift in the phase of the transmitted signal through the cavity.

[0035] While various implementations of the present disclosure have been disclosed herein, additional implementations may be employed with the quantum acoustic apparatus and method.

15

CLAIMS

What is claimed is:

1. A acoustic apparatus comprising:

(a) a resonant cavity;

5 (b) a substrate, including an electroactive material, located within the resonant cavity;

(c) one or more electrodes located on the substrate; and

(d) a controller configured to:

- 10 i. apply a signal to the resonant cavity;
- ii. detect a reduction of amplitude and a shift in the phase of the applied signal through the resonant cavity; and
- iii. determine if the signal is resonant with a mechanical mode of the substrate based at least in part, on the reduction of amplitude and the shift in the phase.

- 15 2. The apparatus of claim 1 further comprising a cryogenic cooling system configured to maintain the inside and outside of the resonant cavity at cryogenic temperatures below 20 millikelvin.

- 20 3. The apparatus of claim 1, wherein the signal is a variable frequency electromagnetic signal that ranges from 100 megahertz to 10 gigahertz.

4. The apparatus of claim 1 further comprising a superconducting wire coupled to the resonant cavity and configured to apply an external magnetic field that tunes
25 the resonant frequency on the substrate.

5. The apparatus of claim 1, wherein the resonant cavity is a three-dimensional resonant cavity, a two-dimensional resonant cavity, a three-dimensional waveguide, or a two-dimensional waveguide.

- 30 6. The apparatus of claim 1, wherein the substrate is a Y cut lithium niobate substrate.

7. The apparatus of claim 1, wherein the signal creates an electric field inside the resonant cavity.
- 5 8. The apparatus of claim 7 wherein when the electric field interacts with the one or more electrodes, the substrate is polarized.
9. The apparatus of claim 7, wherein the electric field excites the substrate through the mechanical mode.
- 10 10. The apparatus of claim 7, wherein the electric field creates phonic excitations within the substrate.
11. A quantum acoustic apparatus comprising:
- 15 (a) a resonant cavity;
- (b) a substrate, wherein the substrate is an electroactive material and located within the resonant cavity;
- (c) electrodes coupled to the substrate;
- (d) a cryogenic cooling system configured to maintain the inside and outside of the resonant cavity at cryogenic temperatures; and
- 20 (e) a controller configured to:
- i. apply a signal to the resonant cavity, the signal is a variable frequency electromagnetic signal that ranges from 100 megahertz to 10 gigahertz;
- 25 ii. detect a reduction of amplitude and a shift in the phase of the applied signal through the resonant cavity; and
- iii. determine if the signal is resonant with a mechanical mode of the substrate based on the reduction of amplitude and the shift in the phase.
- 30 12. The apparatus of claim 11 further comprising a superconducting wire coupled to the resonant cavity and configured to apply an external magnetic field that tunes the resonant frequency on the substrate.

13. The apparatus of claim 11, wherein the resonant cavity is a three-dimensional resonant cavity, a two-dimensional resonant cavity, a three-dimensional waveguide, or a two-dimensional waveguide.
- 5 14. The apparatus of claim 11, wherein the substrate is a Y cut lithium niobate substrate.
15. The apparatus of claim 11, wherein the signal creates an electric field inside the resonant cavity.
- 10 16. The apparatus of claim 15, wherein when the electric field interacts with the one or more electrodes, the substrate is polarized.
17. The apparatus of claim 15, wherein the electric field excites the substrate through the mechanical mode.
- 15 18. The apparatus of claim 15, wherein the electric field creates phonic excitations within the substrate.
- 20 19. A method of contactless excitation of a lithium niobate substrate, the method comprising:
- (a) applying a signal to a resonant cavity;
 - (b) detecting a reduction of amplitude of the applied signal;
 - (c) detecting a shift in the phase of the applied signal;
 - 25 (d) automatically determining if the signal is resonant with a mechanical mode of the lithium niobate substrate based on the reduction of amplitude and the shift in the phase of the applied signal; and
 - (e) automatically determining if transverse modes of the lithium niobate substrate are excited by an electric field created by the applied signal.
- 30 20. The method of claim 19, wherein the inside and outside of the resonant cavity is maintained at cryogenic temperatures below 20 millikelvin by a cryogenic cooling system.

21. The method of claim 19, wherein the signal is a variable frequency electromagnetic signal ranging from 100 megahertz to 10 gigahertz.
- 5 22. The method of claim 19, wherein the resonant frequency of the lithium niobate substrate is tuned by an external magnetic field, the external magnetic field is applied by a superconducting wire.
- 10 23. The method of claim 19, wherein the resonant cavity is a three-dimensional resonant cavity, a two-dimensional resonant cavity, a three-dimensional waveguide, or a two-dimensional waveguide.
24. The method of claim 19, wherein the signal creates an electric field inside the resonant cavity.
- 15 25. The method of claim 24, wherein when the electric field impinges on one or more electrodes disposed on the lithium niobate substrate, the lithium niobate substrate is polarized.
- 20 26. The method of claim 24, wherein the electric field excites the lithium niobate substrate through the mechanical mode.
27. The method of claim 24, wherein the electric field creates phonic excitations within the lithium niobate substrate.

25

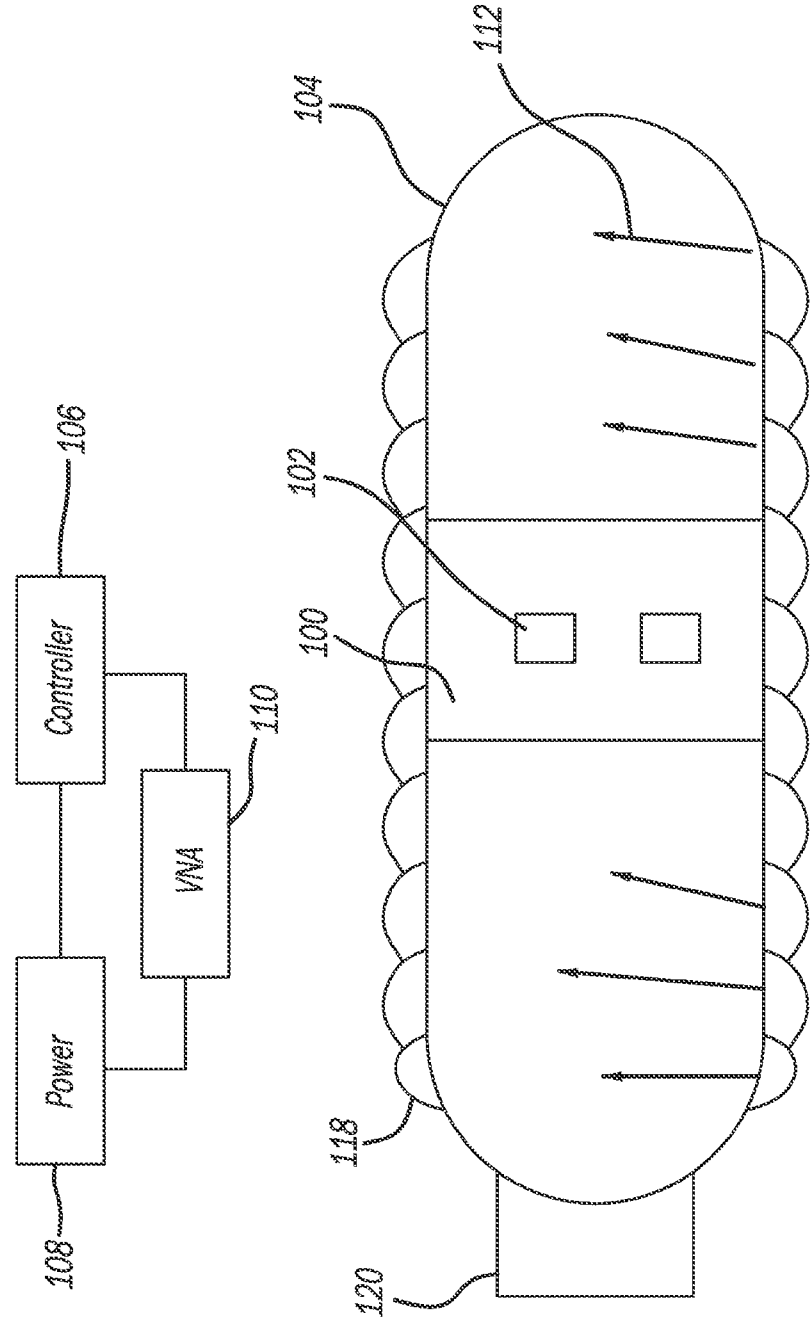


FIG. 1

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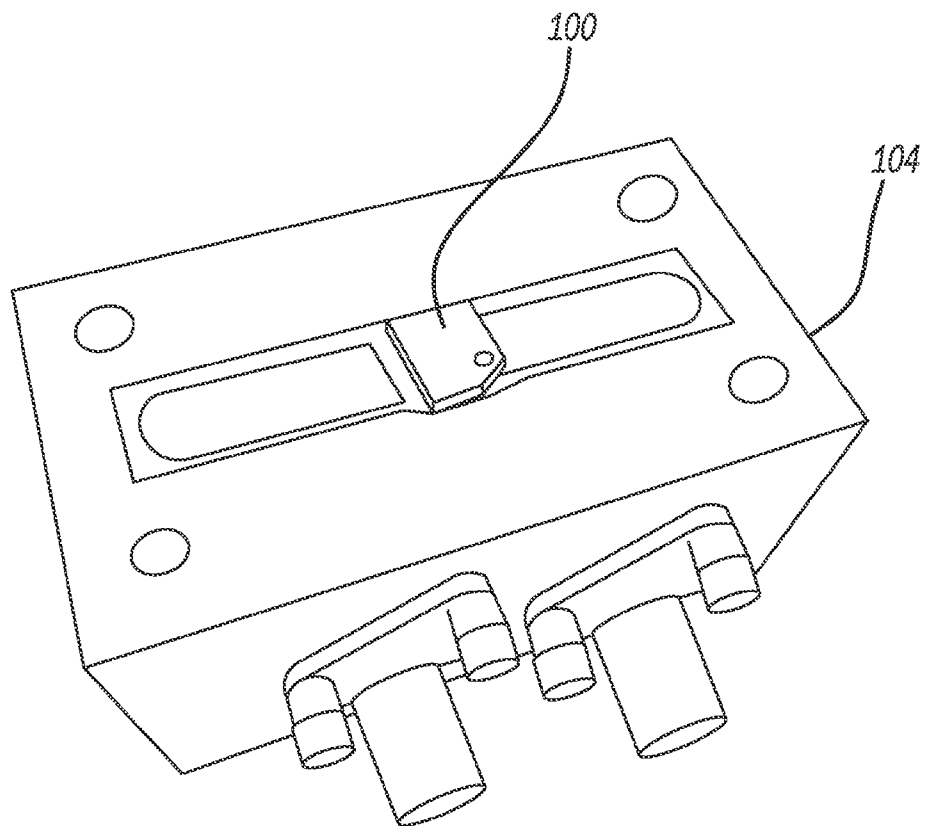


FIG. 2

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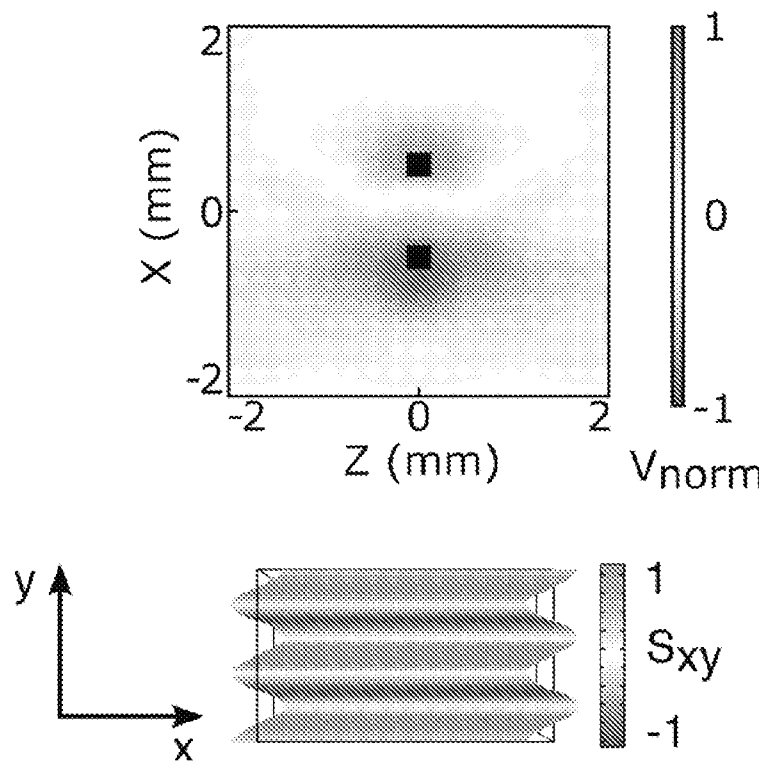


FIG. 3

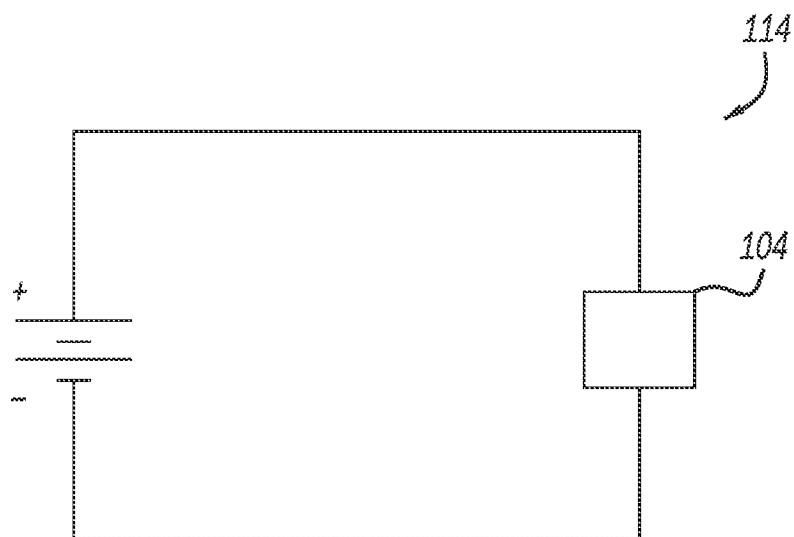


FIG. 4

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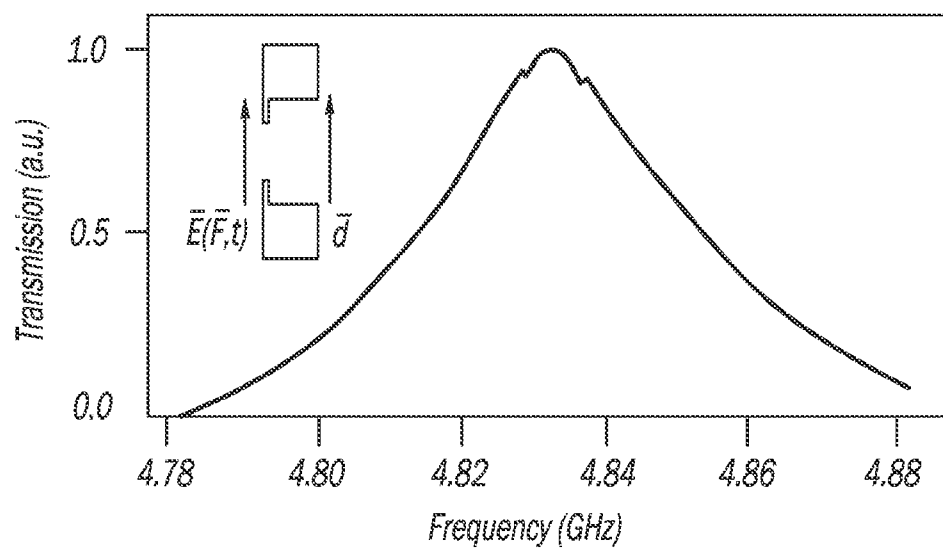


FIG. 5A

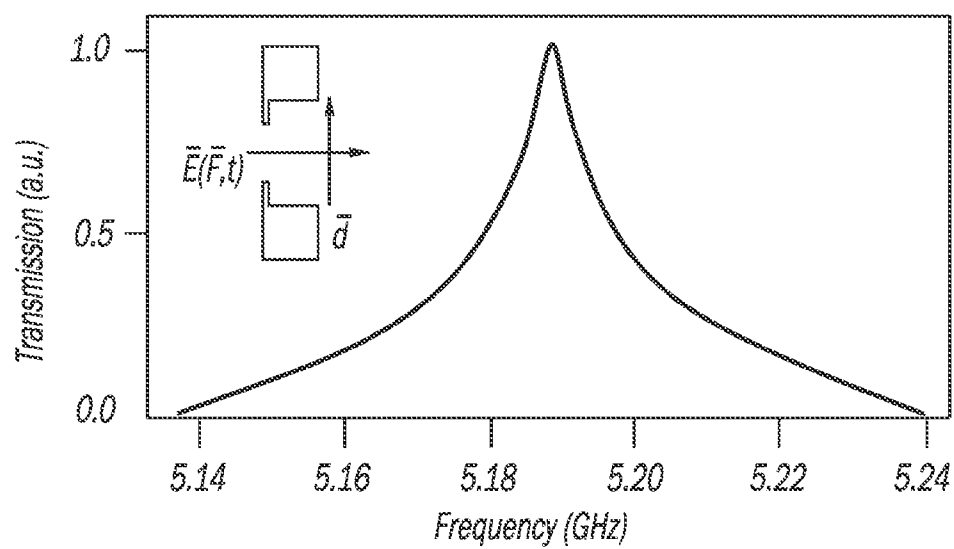


FIG. 5B

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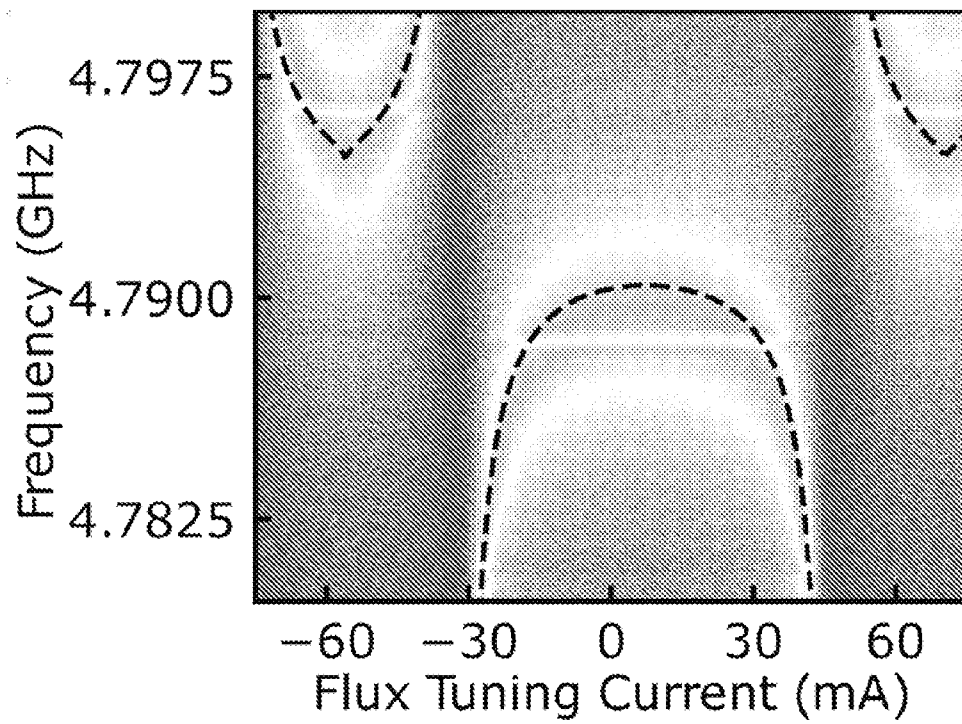


FIG. 6A

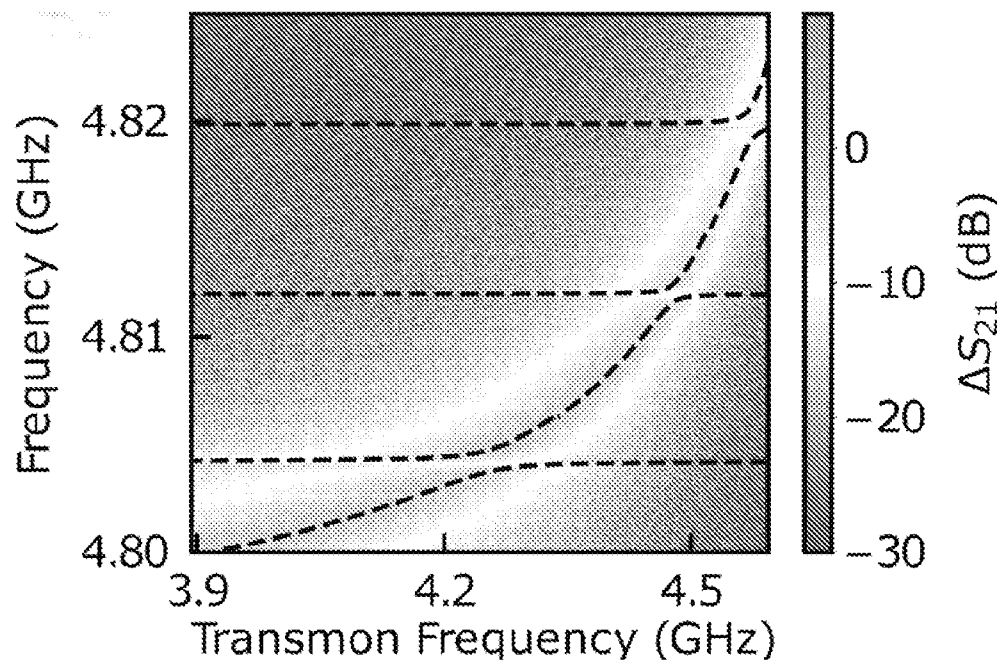


FIG. 6B

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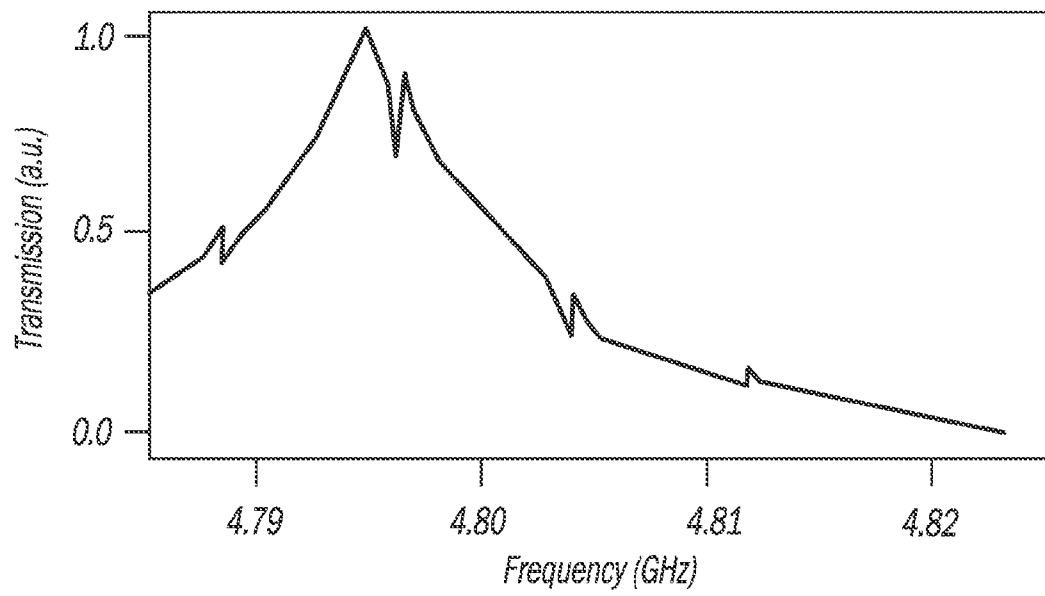


FIG. 7A

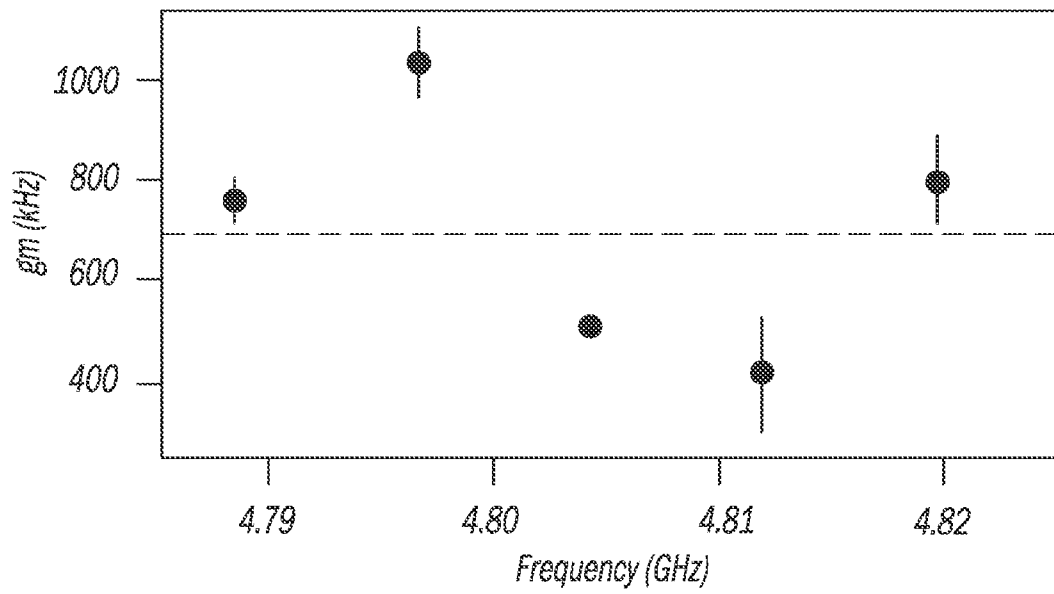


FIG. 7B

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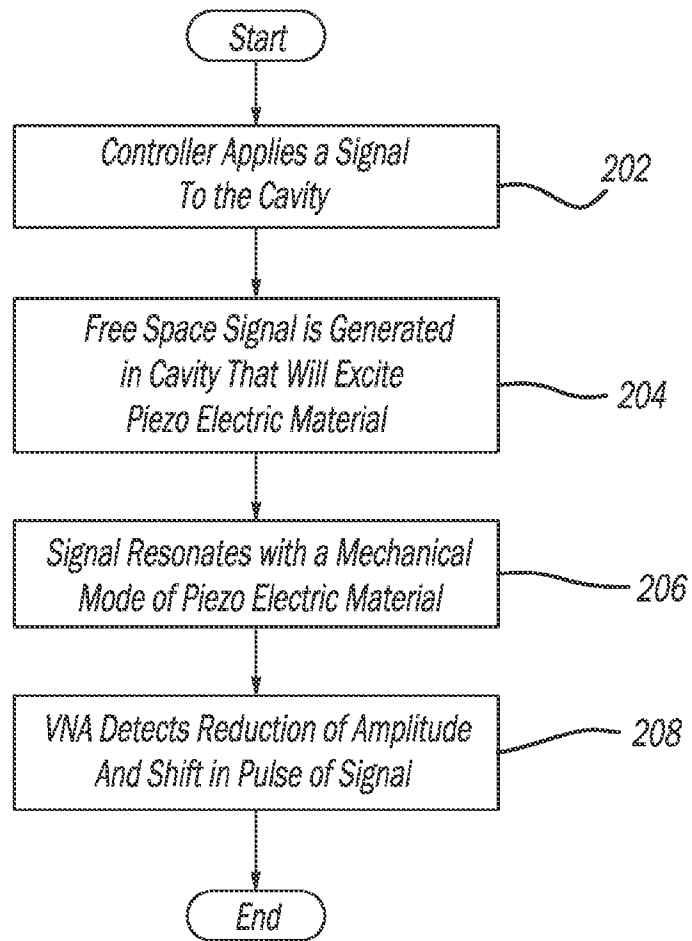


FIG. 8

INTERNATIONAL SEARCH REPORT

International application No.

PCT/US2024/037579

A. CLASSIFICATION OF SUBJECT MATTERIPC: **H03H 9/42** (2024.01); **G10K 11/36** (2024.01); **H03H 3/04** (2024.01); **H03H 9/02** (2024.01)CPC: **H03H 9/42**; **H03H 9/02559**; **G10K 11/36**; **H03H 3/04**; **H03H 2003/0414**

According to International Patent Classification (IPC) or to both national classification and IPC

B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)

See Search History Document

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched

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Electronic data base consulted during the international search (name of data base and, where practicable, search terms used)

See Search History Document

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
X	WO 2022/115392 A1 (PRESIDENT AND FELLOWS OF HARVARD COLLEGE et al.) 02 June 2022 (02.06.2022)	19-21, 23, 24, 26, 27
Y	entire document	1-3, 5-18, 25
Y	US 11,509,277 B2 (HRL LABORATORIES LLC) 22 November 2022 (22.11.2022)	8, 16, 25
Y	entire document	
A	US 10,160,061 B2 (THE AEROSPACE CORPORATION, et al.) 25 December 2018 (25.12.2018)	1-27
A	entire document	
Y	KITZMAN et al. Phononic bath engineering of a superconducting qubit. Nat Commun 14, 3910 (2023). 3 July 2023 [retrieved 1 September 2024]. Retrieved from the internet <https://doi.org/10.1038/s41467-023-39682-0> entire document.	1-3, 5-18
A		4, 22



Further documents are listed in the continuation of Box C.



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Date of the actual completion of the international search

03 September 2024 (03.09.2024)

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INTERNATIONAL SEARCH REPORT

International application No.

PCT/US2024/037579

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
A	KITZMAN et al. Surface acoustic wave Fano interference in the quantum regime. Physical Review A 108, L010601 (2023). 2 February 2023 [retrieved 1 September 2024]. Retrieved from the internet < https://doi.org/10.48550/arXiv.2302.01271 > entire document.	1-27