Actual example

Kaken A: subject: **Development and quantitative interpretation of acoustic metamaterial devices from kHz to GHz frequencies.**

Form S-12: Research Proposal Document (forms to be uploaded)

1. Research Objectives, Research Method, etc.

This research proposal will be reviewed in the Medium-sized Section of the applicant's choice. In filling this application form, refer to the Application Procedures for Grants-in-Aid for Scientific Research -KAKENHI-.
In this column, research objectives, research method, etc. should be described within 5 pages.
A succinct summary of the research proposal should be given at the beginning.
The main text should give descriptions, in concrete and clear terms, of (1) scientific background for the proposed research, and the "key scientific question" comprising the core of the research plan, (2) the purpose, scientific significance, and originality of the research project, and (3) what will be elucidated, and to what extent and how will it be pursued during the research period.
If the proposed research project involves Co-Investigator(s) (Co-I(s)), a concrete description of the role-sharing between the Principal Investigator (PI) and the Co-I(s) should be given.

[SUMMARY]

We propose the ***development and quantitative interpretation of acoustic metamaterial devices from kHz to GHz frequencies***, opening new frontiers in this field. We will generate acoustic waves with frequencies ~0.1 kHz-1 GHz and wavelengths from the millimeter scale down to micro- and nano-scales to control bulk, rod, plate and flexural acoustic waves in both fluid and solid metamaterials with the aim to create practical devices. We will investigate ***metamaterial-based acoustic microscopy, metasurfaces for air-water transmission, as well as lightweight single-component metapillars and metaplates for wideband multimode acoustic isolation or sub-diffraction limit focusing***.

[MAIN TEXT]

① **Scientific background:** metamaterials, materials not found in nature that contain artificial sub-wavelength structure, offer exciting opportunities in physics, materials science and technology. Stunning advances in the fundamental science of acoustic metamaterials have led to enormous recent interest [1]. Varieties include inertial acoustic metamaterials, based on low phase-velocity inclusions, and intrinsic acoustic metamaterials, based on mass–spring systems or analogues in the unit cell. As in electromagnetism, many promising applications of metamaterials have been demonstrated in acoustics. For example, negative bulk modulus and density, arising from out-of-phase resonant responses were shown [2]. In particular, single-negative acoustic metamaterials (with one such negative parameter) can be used to attenuate acoustic waves, with important applications in sound and vibration isolation [3]. Double-negative acoustic metamaterials can be used for focusing acoustic waves into tiny areas below the diffraction limit, based on Pendry's original electromagnetic flat superlens idea [4]. Another important development was the demonstration of enhanced acoustic transmission, either using resonances in small sub-wavelength apertures in fluids—a phenomenon known as extraordinary transmission—or using impedance-matched miniature meta-atoms between highly mismatched media [5].

Here we propose to answer two key questions in the field of acoustic metamaterials:
1) Can greatly enhanced transmission via metamaterials be implemented in practical functional devices? and 2) Can one create lightweight simple single-component metaplates or metapillars with useful features such as multimode isolation of vibrations, or superlensing?

[1] S. A. Cummer *et al.*, Nature Rev. 1, 16001 (2016); L. Fok *et al.*, MRS Bulletin, 33, 931 (2008).
[2] S. Lee *et al.*, Phys. Rev. Lett. 104, 054301 (2010).
[3] J. Mei *et al.*, Nat. Comm. 3, 756 (2012); M. Yang *et al.*, Mat. Horizons 4, 67 (2017).
[4] S. Zhang *et al.*, Phys. Rev. Lett. 102, 194301 (2009); J. Pendry, Phys. Rev. Lett. 85, 3966 (2000).
[5] J. J. Park *et al.*, Phys. Rev. Lett. 110, 244302 (2013); B. Eun *et al.*, Phys. Rev. Lett. 120, 044302 (2018).

② **Purpose, scientific significance, and originality:** We aim to show that indeed the above two suggestions are possible:

1) we aim to make scanning acoustic microscopes based on metamaterial extraordinary transmission in air, as well as make a metasurface for efficient acoustic transmission between highly mismatched media, in particular from water to air and vice versa;

2) we aim to create simple lightweight single-component acoustic metamaterials based on pillars or plates engraved with cavities or slits that can stop all modes of vibration over a wide band of frequencies or support plate flexural modes with double-negative behaviour.

CONFIDENTIAL

[1. Research Objectives, Research Method, etc. (continued from the previous page)]

***Enhanced transmission metamaterials*:**

- **Metamaterial-based acoustic microscopy:** extraordinary transmission (ET) is a resonant phenomenon in which more wave energy is transmitted than expected through a sub-wavelength (sub-λ) aperture. Based on our work on record acoustic ET through membranes, we will use in-air ET at kHz frequencies and above for deep sub-λ acoustic imaging for the first time, exploiting the much larger than expected transmission through a small aperture, leading to deep sub-diffraction-limit quantitative scanning acoustic microscopies.
- **Metasurface for air-water acoustic transmission:** sub-λ thickness metasurfaces for acoustic transmission between such different acoustic impedances have not been realized to overcome the tiny power transmission, ~0.1%. We previously showed that such impedance matched meta-atoms can be made with an effective-mass element. We shall construct a working kHz air-water metasurface, with applications in acoustic transduction and sensing.

***Single-component lightweight metamaterials*:**

- **Metapillars and metaplates for broadband multimode vibration isolation:** monolithic, single-material complete-bandgap pillars and plates that block all modes of vibration have never been demonstrated. With a design now verified by trial simulations, we will fabricate such structures with ~0.1-100 kHz multiple-frequency resonators that damp *all* vibrational modes within a broad band. Applications in sound and vibration control will be sought.
- **Flexural metaplates:** double-negative flexural (i.e. A_0 Lamb-wave) metaplates, first proposed by members of our team, have not been created. Such sub-λ thickness structures are analogous to negative index materials and superlenses in electromagnetism. Flexural metaplates will be made using slits in plates down to nanoscale thickness for use up to ~1 GHz. Applications to sub-diffraction-limit focusing with flat superlenses will be sought.

③ **What will be elucidated, and to what extent and how will it be pursued:** This project will elucidate the physics of acoustic metamaterial devices, and demonstrate their use, with the goal of introducing new applications and perspectives in acoustic metamaterials.

1. ***Metamaterial-based acoustic microscopy*:**

- Guided by preliminary in-air simulations and experiments in Hokkaido (Fig. 1), we will make scanning ET-based acoustic microscopes for deep sub-λ imaging, using a loudspeaker placed in a tapered tube closed with a membrane. An outside sub-λ width obstacle causes a change in the acoustic inertance, modifying the acoustic resonance frequency and hence the internal acoustic reflectance. The latter is monitored while the tube is laterally scanned in 2D. Applications in scanning acoustic microscopy will be attempted.

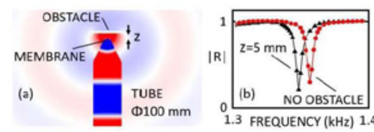

Fig. 1: (a) Our trial simulations of the pressure field for an ET-based acoustic microscope at ~1.34 kHz. Incident waves inside a tapered ϕ100 mm tube pass through a ϕ10 mm membrane and are reflected by a sub-λ width obstacle. The resonance frequency is predicted to negatively shift on introducing the obstacle. Loudspeaker not shown. (b) Preliminary experimental spectrum of in-tube amplitude reflectance |R| with and without a wooden-disc obstacle, demonstrating the expected shift.

- The designs, of different sizes, will be tested and modelled in the 1-100 kHz range (acoustic wavelength λ~cm-200 μm) to achieve λ/20 lateral (*x*-*y*, determined by membrane diameter) and λ/100 depth resolutions (where λ~30 cm to sub-mm).

2. ***Metasurface for air-water acoustic transmission*:**

- Guided by our published experimental work on meta-atoms for impedance matching between air and water, showing 30% acoustic power transmission, as well as simulations for such sub-λ thickness metasurfaces (Fig. 2), we will fabricate and model a macroscopic (>1m^2) metasurface out of square-shaped unit cells for >30% kHz power transmission from air to water and vice versa. Extension to wide-band with multiple-frequency resonators and applications to acoustic transduction are envisaged, since sensitive in-air microphones can be used to detect underwater sound transmitted to air. Extension to efficient air-to-solid transduction will also be investigated.

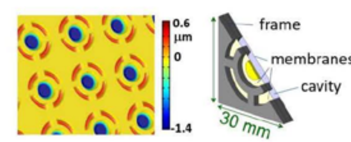

Fig. 2: Left: Our simulations of on-resonance (735 Hz) acoustic displacement field over an air-water impedance matched metasurface. Right: unit cell containing 5 latex rubber membranes. The central one is loaded, and a circular rear membrane (water side) makes an air cavity. For no dissipation, 100% of the acoustic energy is transmitted. In experiment we expect >30%.

[1. Research Objectives, Research Method, etc. (continued from the previous page)]

3. *Metapillars and metaplates for broadband multimode vibration isolation*:

● Guided by our preliminary simulations (Fig. 3) in single-material metapillars containing resonators showing a metamaterial band-gap for all three mode-types, extensional, flexural and torsional, we shall fabricate, model and optimize multiple-resonator-frequency wide-band ($\Delta f/f$=>40%) kHz cm-scale metapillars and metaplates and evaluate dispersion and transmission by frequency-domain acoustic imaging and accelerometers.

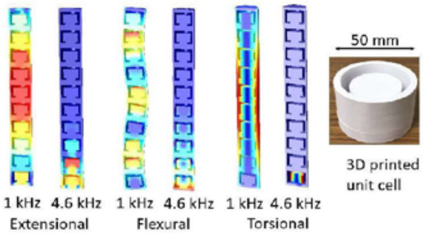

Fig. 3: Our trial simulations of the displacement field inside plastic cylindrical metapillars of 10 unit cells designed with internal resonators. In the metamaterial bandgap at 4.6 kHz, all three modes, extensional, flexural and torsional, are damped out within 1-4 unit cell lengths. Waves are incident from below. A provisionally fabricated unit cell is also shown.

4. *Flexural metaplates for SNG/DNG applications*:

● Based on already-designed metaplates with square- or triangular-lattice spirally-arranged slits (Fig. 4), confirmed by simulation to show negative refraction, we will fabricate and model 10 kHz-1 GHz structures in the form of blocks and prisms, and image their single- or double-negative (DNG) behaviour in the frequency or time domains with optical techniques, characterizing their acoustic dispersion.

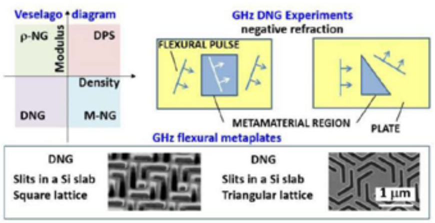

Fig. 4: Veselago diagram for acoustic metamaterials (elastic modulus vs density), some proposed experiments on GHz DNG (double-negative) materials, and already-fabricated two-dimensional GHz acoustic metamaterials. ρ-NG: negative density, M-NG: negative modulus, DPS: double positive. The inset shows our already fabricated trial samples (Si slab thickness: 150 nm, same scales). Simulations show that these structures exhibit negative refraction.

In conclusion, with the advantage of spanning both liquid and solid metamaterials and thus enabling insightful crosstalk between the two approaches, this research will quantitatively interpret and establish key acoustic metamaterial devices and materials over a wide frequency range, and lead to diverse applications, including scanning acoustic microscopy, sound and vibration isolation, and sub-diffraction limit focusing, and should also impact other fields such as electromagnetic metamaterials.

Research Plan and Method 2019-2021 (Outline)

We shall exploit the synergy between my group specialized in acoustics and solid-state physics and four top-ranking groups specialized in nanofabrication and acoustic theory. The ultrafast-optical and audio-acoustic apparatuses are already operational in Hokkaido. Sample fabrication and characterization will take place in Hokkaido, Tokyo and Shizuoka. After validating our basic approaches in 2019, we shall extend our research in 2020-2021 to a fuller range of optimized geometries and samples. Practical applications will also be sought in microscopy, sound and vibration control, and focusing.

2019 Method

● Measurement systems:

GHz frequencies: GHz acoustic experiments are carried out with an existing Ti:sapphire femtosecond pulsed laser producing visible pump optical pulses to locally excite flexural acoustic waves and delayed infrared probe optical pulses to interferometrically detect surface motion. Pump-probe delays are achieved with an existing 0-12 ns mechanical delay line.
Our apparatus contains two scanning systems: 1) a two-axis rotating mirror and 4f lens system

[1. Research Objectives, Research Method, etc. (continued from the previous page)]
for relative scanning of the pump and probe spots, and 2) an existing precision piezo-stage for sample scanning. We chop the pump/probe beams with acousto-optic modulators and use synchronous lock-in detection to achieve sub-pm motion resolution. Includes the use of computers (2019-2021 budget).
kHz frequencies: We shall image in frequency space up to 100 kHz using a laser doppler interferometer (2020 budget) and transducers (in our possession). We shall also make use of accelerometers, hydrophones and speakers (all 2019 budget) and in-air microphones (in our possession), as well as a digital oscilloscope for data acquisition (2019 budget). Includes the use of computers (2019-2021 budget).

● Personnel

Name	Title	Institution	Role
Oliver Wright	Prof.	Hokkaido University	Experiment, analytical theory
Osamu Matsuda	Assoc. Prof.	〃	Experiment, analytical theory
Motonobu Tomoda	Asst. Prof.	〃	Experiment, simulation, fabrication
Postdoctoral researcher	Dr.	〃	Experiment, numerical simulation, sample fabrication, theory
Kentaro Fujita	PhD (D3)	〃	Experiment, simulation, fabrication
Akira Ogasawara	Masters (M2)	〃	Experiment, simulation, fabrication
Junjiro Tokuyama	Masters (M1)	〃	Experiment, simulation, fabrication
Shintaro Ebina	Masters (M1)	〃	Experiment, simulation, fabrication
Genki Sugimoto	Masters (M1)	〃	Experiment, simulation, fabrication
Masahiro Nomura	Assoc. Prof.	University of Tokyo	Sample fabrication, characterization
Hidenori Mimura	Prof.	Shizuoka University	Sample fabrication, characterization
Sam Hyeon Lee	Assoc. Prof.	Yonsei University	Analytical theory
Vitali Gusev	Prof.	CNRS, Le Mans	Analytical theory

● Respective roles:

Our research collaborators have agreed to provide samples: Profs. Nomura (Institute of Industrial Science) and Mimura (Shizuoka University) will make nanostructures and characterize them with scanning-electron microscopy. In Hokkaido we shall use the Hokkaido University Open Facility and the Engineering Faculty Workshop for fabrication (2019-2021 budget) and 3D printing to fabricate in-air and in-solid acoustic devices and materials. Membranes for the enhanced transmission experiments are prepared in Hokkaido on a custom-built rack for stretching to known tensions using calibrated weights.

My group will be involved in experiment, simulation and theory. Profs. Matsuda, Gusev (CNRS, Le Mans, France) and Lee (Yonsei University, Korea) and myself have expertise in the theory of acoustics and acoustic metamaterials. Prof. Tomoda, a postdoctoral researcher and the M/D students perform experiments and simulations, and also make samples. The M/D students, whose projects already involve acoustic metamaterials, will be available for 1-3 years. Further Undergraduate/Masters/Doctors students are expected to join during the project.

● 2019 Plan: 'Basic design, fabrication and validation'

1) **Systems setup:** Audio frequency and GHz setups will be made. For the *Metamaterial-based acoustic microscope* the audio acquisition will be automated for 2D scanning of cm-sized regions in sub-mm steps, for the *Meta-atom for air-water transmission* with a steel square cross-section partially water filled tube with anechoic termination, for the *Metapillars* with accelerometers and a vibrator, and for the *Flexural metaplate* with GHz imaging over ~100-μm^2 sized regions using 0.1 ps/1 µm time/spatial steps. (Wright, Matsuda, Tomoda, M, D, postdoc)
2) **Design and modelling:** With COMSOL and PZFlex finite-element simulations on a workstation (2019 budget), we will optimize designs for both enhanced transmission metamaterials and single-component lightweight metamaterials, including viscous dissipation and dispersion relation evaluation. (Tomoda, M, D, postdoc)
3) **Fabrication:** We fabricate on the nanoscale with e-beam lithography, FIB, dry/wet etching and sputtering, whereas on the macroscale with machining/3D-printing. Fabrication involves a large contrast in elastic properties, and we will use silicon and polymers at GHz frequencies, and rubber membranes, acrylic, aluminium and plastics for audio frequencies (Tomoda, M, D, postdoc, Nomura, Mimura).

[1. Research Objectives, Research Method, etc. (continued from the previous page)]

4) **Audio and GHz experiments:** (Wright, Matsuda, Tomoda, M, D, postdoc)
- **Enhanced transmission metamaterials:** ● kHz imaging with mm lateral resolution for the *Metamaterial-based acoustic microscope* based on a latex rubber membrane will be carried out on trial samples, with the aim to evaluate *xyz* spatial resolutions and sensitivity to acoustic impedance as well as topography variations using test samples of metal, wood and rubber etc. over a range of near-resonance frequencies.
● For the *Metasurface for air-water transmission* we will test the (square) unit-cell effective mass and its normal-incidence acoustic transmission spectrum from water to air at kHz frequencies, aiming for >30% power transmission.
- **Single-component lightweight metamaterials:** ● kHz transmission experiments on cm-scale cylindrical *Metapillars* with identical unit cells will be done by separately exciting the three possible acoustic mode types, aiming for a complete bandgap for all modes. ● GHz time-domain imaging of triangular-lattice slit-based *Flexural metaplates*, for both SNG and DNG geometries, will be done with lithographically-patterned sub-μm Si slabs. Temporal or *xyt* Fourier analysis yield constant-frequency images and dispersion relations, and allow identification of the bandgap regions.

5) **Theory:** Analytical theories based on lumped-elements, equivalent electrical circuits and effective-parameter theory will be developed and compared with experiments and simulations. (Wright, Matsuda, Tomoda, Gusev, Lee, postdoc)

2020-2021 Method and Plan: 'Applications and extension to imaging at kHz frequencies'

1) **Sample fabrication, measurements and setup:** (Tomoda, M, D, postdoc, Nomura, Mimura)

- **Enhanced transmission metamaterials:** ● Extension to a ~100 kHz *Metamaterial-based acoustic microscope* down to sub-mm lateral and ~1 μm vertical resolution will be attempted with miniaturized fabrication and metallic mm to sub-mm diameter membranes. Applications to scanning acoustic microscopes will be explored. ● For the *Metasurface for air-water transmission* we will fabricate a ~0.1-1 m^2 metasurface and test its operation with a water tank and in a swimming pool. The case of non-normal acoustic incidence will also be investigated and characterized. Further design and testing of a wideband multi-resonance frequency metasurface will be carried out, aiming for >30% power transmission with a $\Delta f/f$>40% bandgap, including applications to transduction in air of underwater sound and extensions to the air-solid case for loudspeaker or ultrasonic transducer design.
- **Single-component lightweight metamaterials:** ● We will design, fabricate and test wideband ($\Delta f/f$>40% bandgap) *Metapillars and metaplates* to isolate all vibrational mode types using multiple resonance frequency oscillators in the pillars at sub-kHz frequencies, and investigate practical applications in vibration isolation. We will set up the ~kHz-100 kHz imaging system for metapillars and metaplates by laser doppler interferometry (2020 budget) for dispersion analysis, and explore applications in sound and vibration isolation.
● We will extend the GHz imaging experiments on *Flexural metaplates* to see the effect of 1) 2D lattice type (square, triangular): to optimize and test transmission and sub-diffraction focusing (the latter for DNG), 2) different symmetry cuts and angles of incidence on the metamaterial prism or block faces: to quantify the effects of anisotropy.

2) **Theory and modelling:** (Wright, Matsuda, Tomoda, Gusev, Lee, M, D, postdoc)
We shall continue with numerical simulations and theoretical approaches and their comparison with experiment. The aim is for the simplest possible representations in terms of effective parameter theory to account for the results wherever possible.

Troubleshooting: various pitfalls and their possible solution

A potential problem is the ease of finding the optimum design in each case, for a given operation frequency. One method is to use equivalent-circuit, lumped-element or effective-parameter theory as an intuitive guide. Another is to use iterative geometrical parameter variation by simulation. For this, one must consider viscous damping or ultrasonic attenuation, in air or at GHz frequencies in solids, respectively. An experimental problem is unwanted acoustic back reflections in air or in solids from boundaries or walls. This can be overcome by sound isolation materials or anechoic terminations in air, or by sufficient spacing between, or length of, solid samples. Unwanted whole-structure resonances in all cases should be avoided by iterative design. Experimentally excited acoustic amplitudes should be large enough to mitigate scattering from holes in metaplates, similar to the situation for GHz surface wave imaging of phononic crystals and metamaterials that we have carried out previously.

2. Research Development Leading to Conception of the Present Research Proposal, etc.

In this column, descriptions should be given within 1 page, of (1) applicant's research history leading to the conception of this research proposal and its preparation status, and (2) domestic and overseas trends related to the proposed research and the positioning of this research in the relevant field.

(1) This project is the result of a sustained research effort in the field of ultrafast acoustics as well as audio acoustic metamaterials. Our group has more than 20 years' experience in picosecond ultrasonics, and we are one of the leaders in this field, as evidenced by our journal and review papers in picosecond ultrasonics and in surface-phonon imaging. For the last 6 years we have also specialized in acoustic metamaterials at audio and GHz frequencies, and have published ground-breaking work, including a review paper, in this field. Our work includes acoustic-wave imaging techniques at both extremes of this frequency range. Our relevant experience in metamaterials and phononics is summarized in detail on p. 7-8.

Our previous work on metamaterials involves both devices and materials characterization. This project arose as a result of our work in the field of enhanced acoustic transmission, as well as in the field of acoustic metamaterial imaging and flexural metamaterials. Our work in this field includes record acoustic extraordinary transmission in air, efficient water-to-air acoustic transmission, the proposal of double-negative flexural metamaterials, GHz imaging of surface acoustic waves on acoustic metamaterials, and GHz modulation of electromagnetic metamaterials.

We have done significant preparatory work for this project: initial experiments in extraordinary transmission have been done in our laboratory, including in a microscope geometry, greatly enhanced water-to-air transmission has been demonstrated for a meta-atom and calculated for a metasurface, metapillar damping of all three mode types at the same frequency has been checked by simulations, and negative refraction in our designs of flexural materials has been verified by simulation, and trial samples have been fabricated by Prof. Nomura. We should therefore be able to proceed swiftly with the proposed plan.

(2) The field of acoustic metamaterials is still expanding, with focus on applications becoming more prevalent. There is a lot of activity from USA, Europe, China and Korea. Curiously, apart from our group there do not seem to be any university or government laboratories in Japan with a strong focus on acoustic metamaterials, despite the interest from domestic industries such as those involved in car, tyre or acoustic-technology production.

● Concerning enhanced acoustic transmission, our work on extraordinary transmission (Phys. Rev. Lett. 110, 244302, 2013) represents a record efficiency for airborne acoustic waves, that follows on from pioneering developments in membrane metamaterials in this field in Yonsei University, Korea (S. Lee *et al.*, Phys. Rev. Lett. 104, 054301, 2010). The exploitation of this technology in practical situations is lacking. Recently, a metamaterial scanning microscope based on edge detection was reported (M. Moleron *et al.*, Nat. Comm. 6, 8037, 2015), but with limited lateral resolution. The field is ripe for exploitation of extraordinary transmission for imaging with enhanced lateral resolution.

● In addition, our work on enhanced water-to-air acoustic transmission (Phys. Rev. Lett. 120, 044302, 2018) demonstrated experimentally that this was possible for membrane-based meta-atoms, with a 30% power transmission efficiency, and we predict that meta-surfaces can be fabricated. It is therefore natural that we pursue this goal. Much public and scientific interest was exhibited this year in this subject, and more will be sure to follow.

● Concerning lightweight metamaterials for sound isolation, the subject of metapillars is topical. Recent work from Hong Kong University showed that three-component (steel, silicone, epoxy) metapillars can block all acoustic modes, but in *different* frequency ranges (G. Ma *et al.*, Nat. Commun., 7 13536, 2016). Their structure contains silicone, which is inconvenient in mass production. Our preparatory work shows it is possible to provide complete vibration isolation of *all* modes in the same frequency range with a single, hard material, so we wish to pursue this idea.

● In addition, following our proposal for double-negative (DNG) flexural metamaterials (New. J. Phys. 16, 123053, 2014) many works on single-negative flexural metamaterials have been published, for example in the field of vibration control (J. H. Oh *et al.*, Phys. Rev. Appl. 8, 054034, 2017). It was also recently shown by simulation than active control of a flexural structure could lead to DNG behaviour (J. Chen *et al.*, Mech. Phys. Sols. 105, 179, 2017), but it has not yet been shown in experiment for either passive or active metamaterials.

3. Applicant's Ability to Conduct the Research and the Research Environment

In this column, descriptions of (1) applicant's hitherto research activities, and (2) research environments including research facilities and equipment, research materials, etc. relevant to the conduct of the proposed research should be given within 2 pages to show the feasibility of the research plan by the applicant (PI) (and Co-I(s), if any).

If the applicant has taken leave of absence from research activity for some period (e.g. due to maternity and/or child-care), he/she may choose to write about it in "(1) applicant's hitherto research activities".

(1) Research activities of the PI and Co-I's relevant to the proposed research are as follows:

Work on metamaterials involving sound in air or liquids:

- Metasurface for water-to-air acoustic transmission, enhanced ~160 times, developed at audio frequencies [1] (news in Nature 554, 8, 2018), and interpreted with an analytical model.
  - This forms the groundwork for making a metasurface for air-water acoustic transmission.
- Record extraordinary transmission (enhancement factor ~5700) demonstrated, imaged and analytically modelled at audio frequencies in membrane metamaterials [2] (news in Nature 498, 411, 2013), and also demonstrated for GHz surface acoustic waves by simulation [3]. Negative group velocity shown for an in-air coupled-resonator meta-atom [4].
  - This forms the groundwork for our proposal on metamaterial-based acoustic microscopy.
- Review: acoustic metamaterials [5]. This section's work was in collaboration with Prof. Lee.

Work on metamaterials involving sound in solids:

- Double-negative flexural metamaterials proposed and theoretically modelled [6].
  - This work, done in collaboration with Prof. Gusev, forms the groundwork for our proposal for fabricating a double-negative flexural metamaterial.
- Phonon imaging first demonstrated on bulk GHz metamaterials using the optical pump and probe technique combined with lateral probe scanning [7].
  - This work, directly relevant to our proposed GHz imaging of flexural metamaterials, was done in collaboration with Co-I's Profs. Matsuda and Tomoda, and also with Prof. Gusev. Similar concepts in acoustic imaging will be applicable at lower frequencies for application to metapillars at kHz frequencies with laser doppler interferometry.
- GHz acoustic modulation demonstrated in optical metamaterials with split ring resonators or nanoscale ET holes [8,9]. - This work is peripherally related to our proposal.

Work on ultrafast phonon imaging and picosecond ultrasonics:

- Ultrafast phonon imaging in phononic crystals demonstrated [10].
- Expertise in ultrafast strain generation and detection in solids [11].
  - This work, in collaboration with Profs. Matsuda, Tomoda, and in many cases, Prof. Gusev, will be extended to flexural metamaterials by use of our arbitrary-frequency imaging technique [12] that makes use of high-frequency modulation of the optical beams.

[1] E. Bok *et al.*, Metasurface for Water-to-Air Sound Transmission, Phys. Rev. Lett. 120, 044302, 2018.
[2] J. J. Park *et al.*, Giant acoustic concentration by extraordinary transmission in zero-mass metamaterials, Phys. Rev. Lett. 110, 244302, 2013.
[3] S. Mezil *et al.*, Extraordinary transmission of gigahertz surface acoustic waves, Sci. Rep. 6, 33380, 2016.
[4] I. Yoo *et al.*, Spatiotemporal path discontinuities of wavepackets propagating across a meta-atom, Sci, Rep. 4, 4634, 2014.
[5] S. H. Lee and O. B. Wright, On the origin of negative density and modulus in acoustic metamaterials, Phys. Rev. B 93, 024302, 2016.
[6] V. E. Gusev and O. B. Wright, Double negative acoustic flexural metamaterial, New. J. Phys. 16, 123053, 2014.
[7] P. H. Otsuka *et al.*, Time-domain imaging of gigahertz surface waves on an acoustic metamaterial, New. J. Phys. 20, 013026, 2018.
[8] Y. Imade *et al.*, Gigahertz optomechanical modulation by split-ring-resonator nanophotonic meta-atom arrays, Nano Letters 11, 6684, 2017.
[9] R. Ulbricht *et al.*, Ultrafast optical modulation by gigahertz acoustic perturbation of extraordinary optical transmission, Appl. Phys. Lett. 110, 091910, 2017.
[10] J. Appl. Phys. 117, 245308, 2015, Phil. Trans. Roy. Soc. A 373, 20140364, 2015 (review paper), Sci. Rep. 3, 3351, 2013, Phys. Rev. B 80, 014301, 2009, Phys. Rev. Lett. 97, 055502, 2006.

[3. Applicant's Ability to Conduct the Research and the Research Environment (continued from the previous page)]

[11] Light Sci. Appl. 5, 16082, 2016, Ultrasonics 56, 3, 2015 (review paper), Phys. Rev. Lett. 93, 095501, 2004.
[12] O. Matsuda *et al.*, Time-resolved gigahertz acoustic wave imaging at arbitrary frequencies, IEEE Ultrason. Ferroelectr. Freq. Control 62, 584, 2015.

Other recent related work: Active chiral control of GHz acoustic whispering-gallery modes, Appl. Phys. Lett. 111, 144103, 2017, Upholding the diffraction limit in the focusing of light and sound, Wave Motion 68, 182, 2017, Effect of excitation point on surface phonon fields in phononic crystals in real- and k-space, J. Appl. Phys. 117, 245308, 2015, Imaging arbitrary acoustic whispering-gallery modes in the GHz range with ultrashort light pulses, Opt. Lett. 40, 2157, 2015, Three-dimensional imaging of biological cells with picosecond ultrasonics, Appl. Phys. Lett. 106, 163701, 2015.

Grants awarded to PI (prior to 2007: 科研基盤S, 科研基盤A and JSTさきがけ研究)

1. 2007年-2010年 科学研究費補助金（基盤研究(A)）「ミクロ構造におけるフォノン閉じ込めの可視化とモード制御」 Invited talk at the Phonons conference, 2010, Taipei, Taiwan.
2. 2010年-2012年 科学研究費補助金（基盤研究(A)）「コヒーレントフォノンによる表面プラスモンポラリトン伝播の超高速制御」The imaging apparatus will be used in the present proposal. Invited talks at ICALASE, 2012, Nanjing, Nanometa conference, Seefeld, Austria, 2013, and Plenary Talk at the 3rd International Symposium on Laser Ultrasonics, Yokohama, Japan 2013.
3. 2013年-2015年 科学研究費補助金（基盤研究(A)）「GHz帯音響メタマテリアルの創成とその応用」 This is very relevant to the present proposal. Plenary talks at 15th RIES-Hokudai International Symposium, Japan, 2014, Theo Murphy Int. Scientific Meeting, UK, 2015, invited at META, Singapore, 2014, ISOT, Neuchatel, Switzerland, 2015, WOMA, Sapporo, 2015.
4. 2016年-2018年 科学研究費補助金（基盤研究(A)）「GHzレーザー超音波によるコンピューター断層撮影法」This project is peripherally relevant to the present proposal. Invited talks at 5th Joint Meeting of the Acoustical Society of America and Acoustical Society of Japan, Honolulu, Hawaii, 2016, Phononics, Changsha, China, 2017, META, Incheon, Korea, 2017, International Congress on Ultrasonics Honolulu, Hawaii, 2017, International Conference on Photoacoustics and Photothermal Phenomena, Nanjing, China, 2018, IEEE Ultrasonics Symposium, Kobe, Japan, 2018.

Grants awarded to Co-I's

1. 2008年-2011年 科学研究費補助金（基盤研究(B)） 代表者 松田理「半導体量子構造における音響フォノンを用いた電子・光物性制御」
2. 2013年-2015年 科学研究費補助金（基盤研究(C)） 代表者 友田基信「マイクロ音響レンズを用いたレーザーピコ秒超音波法顕微用技術の開発」
3. 2016年-2017年 科学研究費補助金（挑戦的萌芽研究） 代表者 松田理「２次元撮影素子を用いたGHz表面弾性波の超高速時間分解イメージング」
4. 2016年-2018年 科学研究費補助金（基盤研究(B)）代表者 友田基信「GHz板状フォノニックメタマテリアル及びフォノニックプラズモニック結晶の実現」
5. 2017年-2019年 科学研究費補助金（基盤研究(B)）代表者 松田理「GHz表面弾性波の時間分解イメージング測定と音響カイラリティ制御」

(2) Research environments including research facilities and equipment, research materials, etc. relevant to the proposed research are as follows:

Audio Acoustics: We have a dedicated room with a variety of microphones, acrylic tubes, loudspeakers, anechoic termination materials as well as the necessary signal generators, lock-in amplifiers, amplifiers and oscilloscopes.

GHz Acoustics: We have the necessary Ti:sapphire pulsed lasers with second harmonic crystals to frequency double the beam for visible and infrared probing. Objective lenses and all necessary optical parts are available. We also have set up a common-path Sagnac interferometer system for scanned detection of the sample surface motion. The equipment, including a mechanical delay line, is mounted on optical benches, and computers are available nearby for synchronous lock-in amplifier data acquisition after pump and probe modulation in our arbitrary-frequency acquisition system.

Fabrication facilities: We fabricate on the nanoscale with e-beam lithography, FIB, dry/wet etching and sputtering (all available in Hokkaido, Shizuoka and Tokyo), whereas on the macroscale with machining and with a 3D printer in our possession in Hokkaido.

4. Issues Relevant to Human Right Protection and Legal Compliance

(*cf.* Application Procedures for Grants-in-Aid for Scientific Research)

In case the proposed research involves such issues that require obtaining consent and/or cooperation of the third party, consideration in handling of personal information, or actions related bioethics and/or biosafety (including the laws and regulations and the guidelines in the country/region(s) where the joint international research is to be conducted), the planned measures and actions for these issues should be stated within 1 page.

This applies to research activities that would require approval by an internal or external ethical jury, such as research involving questionnaire surveys, interviews and/or behavior surveys (including personal histories and images) including personal information, handling of donated specimens, human genome analysis, recombinant DNA, and experimentation with animals.

If the proposed research does not fall under such categories, enter "N/A (not applicable)".

N/A

5. Items to be Entered When New Application is Made in the Fiscal Year Previous to the Final Year of the Research Period of an On-Going KAKENHI Project

(For an application that comes under this category, this column is a mandatory entry.

(*cf.* Application Procedures for Grants-in-Aid for Scientific Research))

In this column, the applicant should give within 1 page: (1) the relevant information on the on-going project (for which FY2019 is the final year of the research period) including the original plan at the time of application/adoption and the research accomplishment such as new knowledge acquired, and (2) the reason why he/she is submitting this new proposal for FY2019 on top of the on-going project (in terms of the development of the on-going research, necessity of new research budget, etc.).

If not applicable, leave this page blank. (Do not eliminate the page.)

Research Category	Project Number	Title of the Research Project	Research Period
			FY___ to FY2019

The original plan at the time of application/adoption and the research accomplishment of the on-going project.

The reason for submission of this new proposal.