Caltech
Student-Faculty Programs

Session J Abstracts

Verifying a continuum approximation for architected materials in three dimensions
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Mentors: Julia R. Greer and Cyrus Fiori

Continuum mechanics theories can be used to model the mechanical response of most solid materials, including how they deform and fail. However, porous materials, such as sponges and aerogels, contain discrete structures and, as a result, cannot be directly modelled as continua. In this project, we employ a theory developed by Cyrus Fiori, my graduate mentor, that asserts that porous materials, such as architected materials, can also be modelled as continua below a critical porosity. Previous work has validated the theory in two dimensions by testing architected samples with varying porosities around this critical value in tension. However, it has not been validated in three dimensions. In order to do so, we designed three-dimensional lattices parametrically with CAD software, fabricated samples using MSLA 3D printing, and performed compression and tensile testing of the lattices to obtain global force-displacement, peak load, and critical strain value data. These data help investigate changes in the mechanical response of the material as the porosity changes, which will help validate the theory and aid engineers and scientists in the use of continuum models to analyse and design porous materials.

Development of a dual-wavelength MSLA platform for spatially controlled photopolymerization of multi-material nanocomposites
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Polymer nanocomposites consist of a polymer matrix and surrounding nanoscale fillers that provide enhanced properties to the material. This dispersion of nanostructures can increase the strength to weight ratio of the material by an entire order of magnitude compared to the base polymer alone. Conventional fabrication is a two step process: nanostructure synthesis followed by dispersion of the nanostructures within the polymer precursor. However, this method is susceptible to poor binding between the matrix and reinforcing phases, in addition to agglomeration and poor dispersion of the nanostructures at high loadings, which can worsen the mechanical behavior of the composite. To address these fabrication challenges, we propose a new dual wavelength additive manufacturing process that will allow for the formation of the nanostructures to occur simultaneously with the polymer matrix, alleviating the need for preformed nanostructures. To realize this new process, we construct a dual-wavelength MSLA platform. Using 405nm and 530nm light sources and an LCD screen driven by custom software, we can selectively cure the matrix and unformed nanofiller phases of a dual-wavelength sensitive photoresin separately. We believe this will improve the network connectivity and overall mechanical performance of the resultant material.

Resin development and monomer synthesis for additively manufactured, architected, glucose-responsive hydrogel microneedles
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The ultimate goal of this project is to design and fabricate architected microneedles for rapid transdermal delivery of glucagon and insulin for people living with Type 1 diabetes. Previous research has demonstrated mold-based fabrication of monolithic hydrogel microneedles, but these suffer from slow insulin release kinetics. This project aims to introduce micron-scale architected structures to enhance the surface area to volume ratio of the microneedles and accelerate insulin release. Our summer objective was to develop a resin formulation that (1) releases insulin in the presence of glucose and (2) can be additively manufactured into architected, mechanically stable cone structures. We accomplished this goal by optimizing the solubilizer composition of the resin and successfully fabricated structurally stable, architected microneedles. Additionally, we developed a scalable two-step synthesis of 2-aminoethyl acrylate hydrochloride (AAH), the resin monomer necessary for insulin binding. We synthesized 2.5 g of AAH, enabling high-throughput resin production for the fabrication of architected, glucose-responsive microneedles.

Reduction pathway control and characterization of HIAM lattices
Ziad Siala
Mentors: Julia R. Greer and Anna Wu

Hydrogel infusion additive manufacturing (HIAM) is a highly modular metal additive manufacturing system that enables high-precision production of metal or ceramic structures. 3D printed hydrogels are infused with metal ions then undergo calcination to produce a metal oxide, which is subsequently reduced to yield a metal structure. This process decouples geometry from material selection, enabling a large range of structure-material combinations. Previous investigations have reported unreduced oxides, porosity, cracking, and significant shrinkage resulting from HIAM thermal treatment. In the first part of this study, a parametric investigation of HIAM reduction was performed to understand how different thermal profiles influence porosity, shrinkage, and cracking. Controlled reduction profiles also enabled synthesis of iron oxide phases; for example, Fe_3O_4 (magnetite), which has applications in electromagnetic interference (EMI) shielding, was obtained using a peak temperature significantly lower than the standard reduction profile. Scanning electron microscopy (SEM), Raman spectroscopy, and energy-dispersive X-ray spectroscopy (EDS) characterized the resulting morphology, oxide phases, and chemical composition. The second part of this study expands previous investigations of HIAM Cu_xNi_{1-x} alloys through focused ion beam (FIB) micropillar compression testing to obtain additional mechanical characterization data. These results will contribute to machine learning models capable of predicting mechanical performance from material-structure combinations.

Design and optimization of adiabatic coupling to focused-ion-beam-fabricated photonic cavities
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Mentors: Andrei Faraon and Emanuel Green

Rare-earth-ion photonic devices are a promising platform for quantum information processing, but their performance is limited by inefficient optical coupling to the devices. In the current $Yb:YVO_4$ platform, light is coupled into focused-ion-beam-fabricated photonic cavities via total internal reflection off 45° angled cuts, achieving efficiencies of only ~30% and motivating the development of improved coupling methods. In this work, we design and optimize an adiabatic coupling scheme between a tapered optical fiber and a tapered waveguide using finite-difference eigenmode (FDE) and finite-difference time-domain (FDTD) simulations. For YVO_4, the optimized design achieves a simulated coupling efficiency of 98.4%, representing a substantial improvement over the existing approach. We further extend the design to $CaWO_4$, a promising alternative host crystal, and to 45°-cut YVO_4 chips, obtaining similarly high simulated efficiencies of 98.1% and 98.2%, respectively. Finally, we evaluate the robustness of the optimized designs to alignment and fabrication errors, demonstrating that they remain efficient under realistic experimental conditions. These results establish the adiabatic coupling scheme as a viable high-efficiency interface for rare-earth-ion photonic devices and provide a foundation for future experimental realization.

Designing a superconducting microwave resonator to magnetically couple to $^{171}Yb^{3+}:CaWO_4$
Nimisha Sivaraman
Mentors: Andrei Faraon and Chengyi Luo

Large ensembles of solid-state spins interacting through cavity-mediated interactions are important systems for both studying collective phenomena and developing quantum technologies, including quantum memory. One promising material platform for studying these collective dynamics is $^{171}Yb^{3+}:CaWO_4$ due to the combination of long intrinsic coherence and a strong microwave transition dipole moment. By coupling a bulk $^{171}Yb^{3+}:CaWO_4$ crystal to a 3D microwave resonator, the Faraon Group has observed extended Ramsey coherence time enabled by the photon-mediated interactions between ytterbium ions. Moving forward, a chip-scale platform with high quality factor microwave resonators strongly coupled to ion ensembles will enable scalable quantum memory. To this end, I have explored multiple 2D resonators using finite element softwares to specifically optimize coupling strength, mode filling factor, and magnetic field homogeneity. After converging on a single design that can be feasibly fabricated, the chip will be used for future experiments.

Spontaneous chiral symmetry breaking of counter-propagating modes via the Kerr nonlinearity within ultra-high-quality factor optical resonators
Avani Ranka
Mentors: Kerry J. Vahala and Haojing Chen

Optical gyroscopes are essential to modern navigation, offering precision and stability unmatched by their mechanical counterparts. Chip-based ring laser gyroscopes are also compact and lightweight with a low lasing threshold. However, at low rotation rates, counter-propagating modes couple via backscattering and lock to a single frequency, making small rotations impossible to measure. We present progress toward a symmetry-based method for breaking this lock-in effect without the external hardware usually required. Our approach uses the Kerr nonlinearity to break chiral symmetry between counter-propagating waves within a silica-based optical resonator, which splits their resonance frequencies. We bidirectionally pumped an ultra-high-quality factor resonator with 1550 nm laser light to form a symmetric standing-wave state. We then swept the laser frequency across modes with quality factors exceeding 100 million at increasing input powers while monitoring the transmitted power in both directions. Current measurements of resonators whose mode spacing precisely matches the Brillouin shift demonstrate counter-propagating modes in the symmetric state even above the predicted threshold, because Brillouin lasing clamps the circulating power. We now intend to use devices with mode spacings detuned from the Brillouin shift and increase the power coupled into the mode until the imbalance between counter-propagating powers is clearly resolvable.

Development of an acoustic bandgap filter for superfluid helium-4 systems
Mitchell J. Agris
Mentor: Keith C. Schwab

Superfluid helium-4 is a promising platform for precision measurements because of its exceptionally low dissipation and long-lived acoustic excitations. However, acoustic energy leakage through fill lines and other supporting structures can significantly reduce the quality factor of superfluid resonators, limiting the performance of a wide range of super-fluid systems and circuits. This project investigates the use of periodically crimped tubing as a one-dimensional phononic crystal that suppresses acoustic transmission through Bragg reflection, thereby reducing unwanted energy loss. A custom crimping tool and experimental measurement system were developed to fabricate and characterize periodically crimped waveguides using frequency response measurements. Preliminary measurements on copper and stainless steel waveguides containing different numbers of periodic crimps revealed clear acoustic bandgaps near the designed Bragg frequency of approximately 12 kHz. The deepest measured bandgap exhibited approximately 60 dB of attenuation relative to an uncrimped waveguide, corresponding to a reduction in transmitted acoustic wave amplitude by roughly a factor of 10^3 and transmitted acoustic power by approximately 10^6. These results demonstrate that periodically crimped waveguides provide an effective method for suppressing acoustic transmission and establish a promising approach for reducing acoustic loss in future superfluid resonators, circuits, and precision sensing technologies.

Dynamic control of solidification conditions via a movable platform for scalable freeze casting
Benjamin D. Porosoff
Mentors: Katherine T. Faber and Wesley D. Patel

Freeze-casting is a materials processing technique that leverages the directional solidification of solutions and suspensions to form porous materials through sacrificial templating. Controlling the temperature gradient (G) and the freezing-front velocity (V) dictate the finished materials properties. This project has focused on making a movable freeze-casting setup which allows the manufacture of much longer samples than previous static freeze-casting setups. The movable setup physically decouples G and V enabling the exploration of freeze-cast materials, crystal morphologies, and properties and regimes that are inaccessible to other freeze-casting apparatuses. After getting the machine operational the samples from the movable machine were validated to be identical in structure to those from the static freeze-casting machine at the same parameters. The machine then allowed exploration of different parts of the G, V graph, exploring the crystal morphologies and material properties at new G-V regimes. It also has allowed the exploration of much larger samples than the static freeze-casting machine can produce, allowing investigation for the potential scalability of freeze-casting in the future. Additionally, the physical decoupling has allowed the machine to form continuously frozen samples while altering the morphology with length.

Dose-controlled In-Ga eutectic delivery for oxide destabilization in additively manufactured ceramic structures

Mark N. Luo

Mentors: Katherine T. Faber and Zachary Chase

Laser powder bed fusion (L-PBF) enables fabrication of architected Al-Al_2O_3-YSZ ceramic composites. Still, the native oxide skin on aluminum particles inhibits wetting, causing molten aluminum to pool rather than infiltrate the pore network during reaction bonding. A liquid Indium-Gallium (In-Ga) eutectic destabilizes this oxide skin. It improves wetting within a critical thermal window, but single-droplet delivery is unreliable on non-flat geometries because the eutectic remains a mobile droplet at room temperature. In this project, a geometric-independent dose-controlled In-Ga strategy was developed. After an initial approach using a porous ceramic sleeve with alumina powder proved difficult, work shifted to surface-coating methods: aluminum-powder pre-layering, In-Ga-coated weighing-paper wraps, and direct brush application tested against single-droplet dosing on staircase-cut coupons. Direct brushing, leveraging the eutectic's strong self-cohesion, produced the most complete surface coverage; coating quality depended on surface finish and moisture, while heating showed no clear effect. Electron probe microanalysis and wavelength-dispersive spectroscopy of staircase coupons revealed reduced indium concentration in regions blocked from direct application, while gallium remained unaffected, suggesting the two elements may not migrate together. Remaining work will confirm this transport behavior and compare coating methods to establish a scalable, geometry-independent In-Ga infiltration framework.