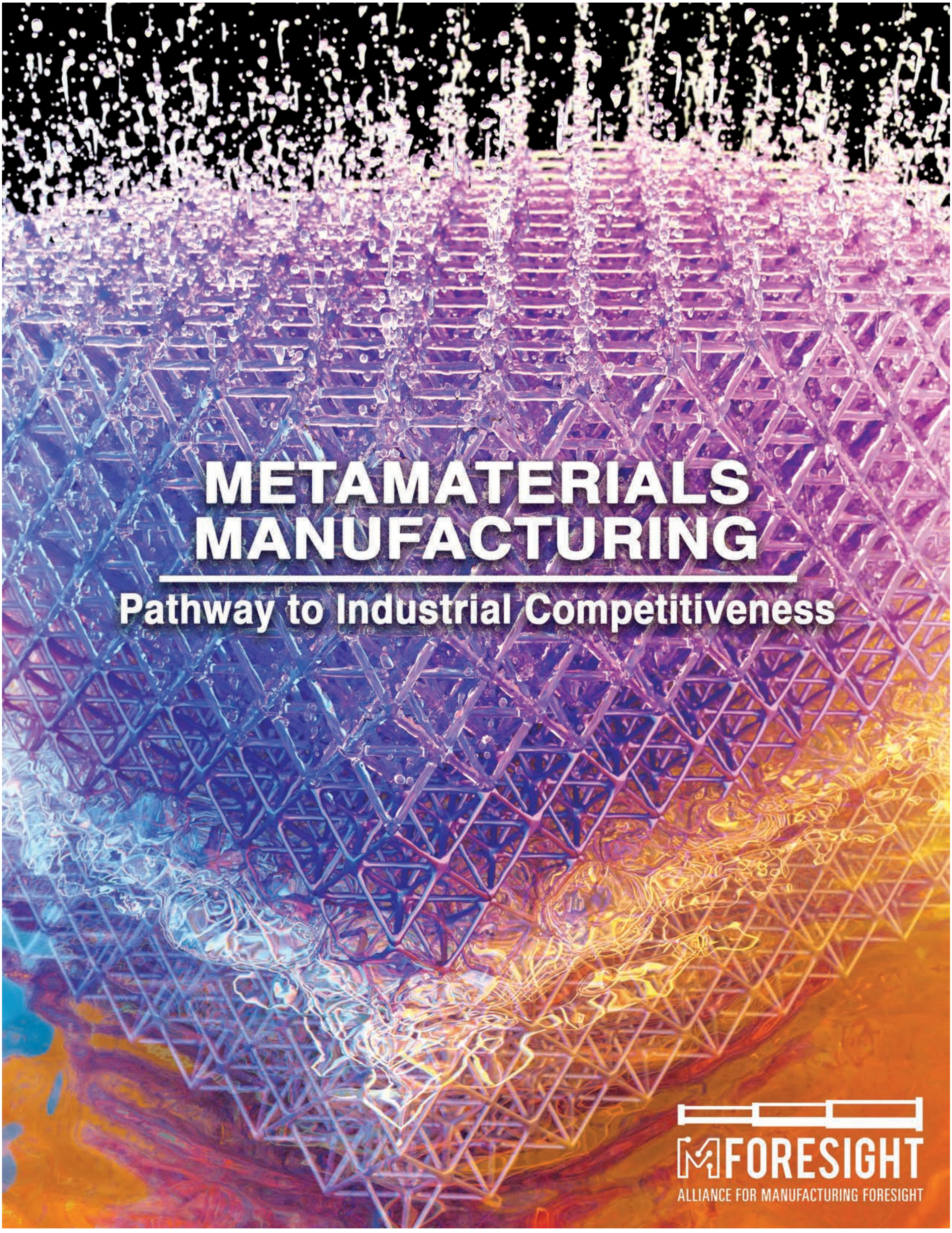

METAMATERIALS MANUFACTURING

Pathway to Industrial Competitiveness

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Metamaterials Manufacturing

Pathway to Industrial Competitiveness

April 2018

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*Cover image by Ryan Chen (Lawrence Livermore National Laboratory).

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MForesight: Alliance for Manufacturing Foresight serves as the voice of the national advanced manufacturing community, providing government, academia, and industry with information and analyses about emerging technologies, workforce training, and opportunities for public-private partnerships that strengthen U.S. competitiveness.

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Executive Summary

Metamaterials are artificially structured materials with the promise to remove performance constraints associated with conventional materials, redefining the boundaries of materials science and offering a wealth of new opportunities for innovation and economic growth.

The prospects are powerful. National security applications of metamaterials range from enhanced stealth technology to improved military communication to higher-quality reconnaissance imaging to next-generation body armor. Health implications range from greatly improved medical imaging and research tools to superior injury protection products. Metamaterials also have promising energy applications in transportation light-weighting, as well as energy generation and storage technologies. By 2025, it is estimated that metamaterials manufacturing will be a multi-billion-dollar market.

The United States has invested heavily in the potential of metamaterials, and U.S. experts and research facilities lead the world in publications, citations, and intellectual property related to this emerging field. Realizing the true benefits of these emerging technologies—and return on federal investments—will require advancing metamaterials from prototypes to products manufactured at scale. Manufacturing of these materials at the volume and quality needed for practical applications requires process innovation and establishment of a strong supporting ecosystem. **This report examines the challenges and opportunities facing metamaterials manufacturing and presents a set of actionable recommendations for realizing the promised impact.**

MForesight: Alliance for Manufacturing Foresight, a national consortium focused on enhancing U.S. manufacturing competitiveness, convened experts from academia, government, federal labs, and industry to gather insights on the key challenges and opportunities facing metamaterials manufacturing. The experts defined a range of recommendations for U.S. stakeholders seeking to establish a competitive advantage for U.S. metamaterials manufacturing.

Key Actionable Recommendations

Establish a National Metamaterials Manufacturing Research Initiative. This coordinated, multi-agency federal effort should focus on a number of precompetitive translational research topics to address critical barriers to scaled metamaterials manufacturing:

- Scaling of enabling process technologies for metamaterials manufacturing, including nanoimprint lithography, pattern transfer, additive manufacturing, self-assembly, and associated high-throughput roll-to-roll and stepping processes.

- Technologies for manufacturing metamaterials from disparate materials, which includes processes to shape and join disparate materials, as well as the development of new materials that are more conducive to joining.
- Integrated and stand-alone metrology solutions that can evaluate at high resolutions, across multiple scales and dimensions.
- Simulation and design tools relevant to the design and manufacture of metamaterials including those capable of addressing 3D, multi-scale, periodic structures, design for manufacturability, and manufacturing process modeling.

Increase access to current federal facilities and experts to accelerate process innovation through the following actions:

- Encourage existing outward-facing federal facilities to address metamaterials manufacturing challenges and engage the U.S. metamaterials community.
- Instantiate new, and extend existing, federal programs that link industry researchers and needs with federal experts and key national resources, such as high-end equipment and high-performance computing.

Enhance federal support for critical feedstocks. To enable metamaterials manufacturing technologies to be practically scaled, critical nanomaterials and substrates need to be made available and supported through a number of actions:

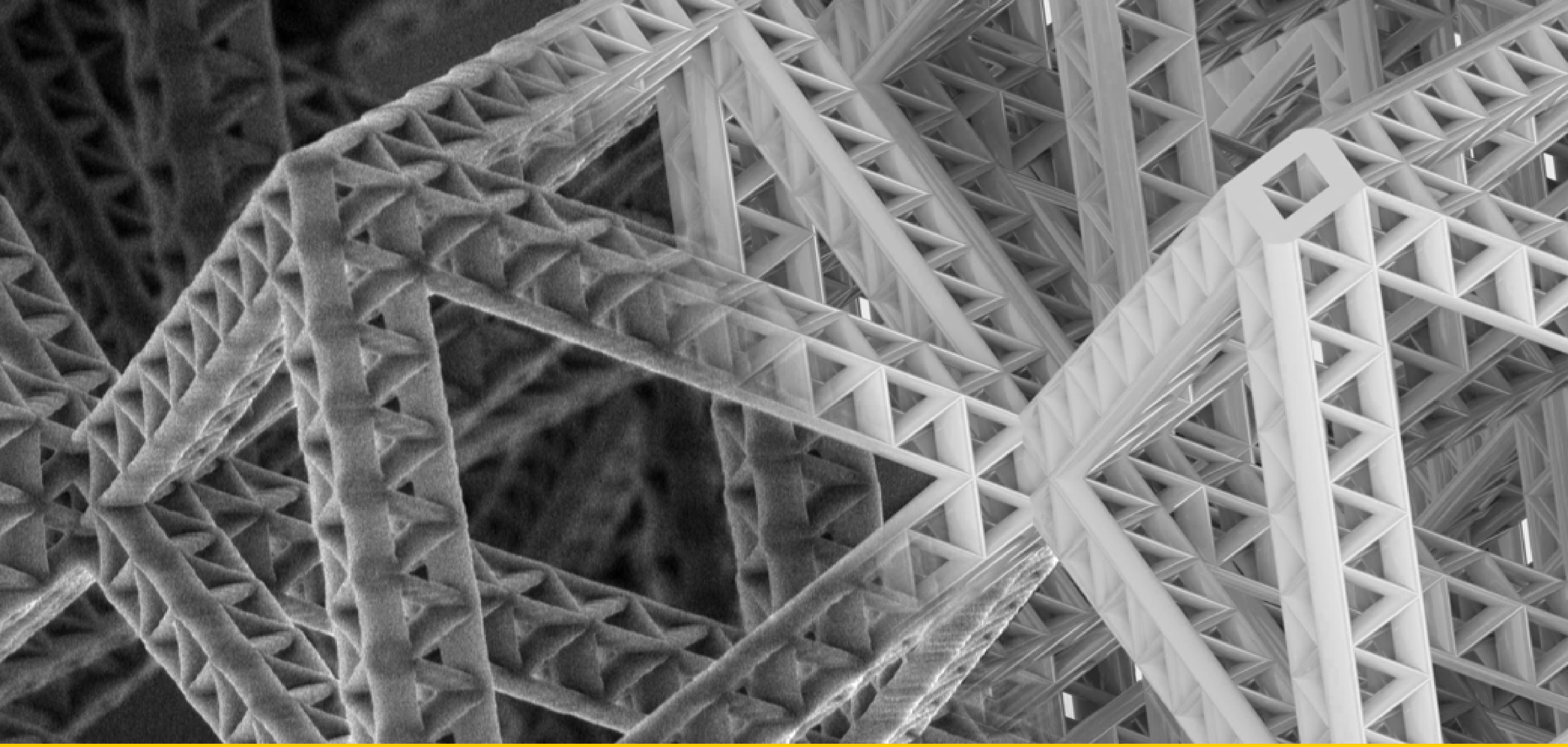
- Temporarily co-fund resources to scale and manufacture feedstocks critical to scaling metamaterials manufacturing in the United States.
- Align existing federal nanomanufacturing R&D efforts with feedstocks critical to metamaterials manufacturing and expand relevant characterization tools, standards, and certifications.
- Fund research to develop and process novel nanomaterials and substrates to enhance metamaterial manufacturability and functionality.

Establish an interdisciplinary advisory group. The advisory group should be tasked with providing real-time insights on emerging opportunities and challenges relevant to metamaterials manufacturing. In the near term, this group should address the following tasks:

- Lead efforts in roadmapping metamaterials manufacturing technology research and development priorities, and track progress on overcoming technical barriers. Opportunities should be prioritized to ensure that manufacturing and technology implementation are primarily capitalized on by the U.S. manufacturing industry.
- Provide policy guidance on issues such as intellectual property classifications that could either hinder or accelerate progress.

Create a National Center of Excellence. Funded through a public-private partnership, the Metamaterials Manufacturing Center of Excellence will play the essential role of coordinating efforts to secure American technological leadership and enhance U.S. manufacturing competitiveness in metamaterials manufacturing. The center will support the national effort through the following actions:

- Coordinate industry participation and needs.
- Support and accelerate collaborative research.
- Provide shared manufacturing equipment and computational resources.
- Generate shared intellectual property for precompetitive technologies.
- Create and facilitate workforce training programs.



Opportunities and Challenges for Metamaterials Manufacturing

Metamaterials are an advanced class of materials offering unique and superior performance. They are defined by an artificial structure, precisely engineered to overcome the limitations of bulk materials. This structure typically consists of small repeating unit cells. Advances in metamaterials continue to redefine the boundaries of materials science, offering new opportunities for economic growth and essential technologies to address national priorities in security, health, and energy.

Cross-Cutting Potential

Metamaterials have the potential to enable breakthrough advances across a broad set of applications from radical advancements in communications, imaging, cloaking, and solar efficiency, to high-performing noise mitigation and ultra-lightweight structural materials.

Acoustic metamaterial prototypes suggest that the resolution of sonography used for medical imaging, underwater sonar, and nondestructive evaluation could be improved by a factor of 50,[1,2] while novel damping metamaterials may provide 500% better acoustic attenuation per weight over conventional options.[3] In electromagnetics, antennas based on metamaterials show an ability to utilize subwavelength structures to boost signal and create novel mechanism-free beam steering and shaping (Figure 1). A similar approach on a much smaller scale could be used to create super-resolution optical lenses. Such technology could enable real-time filming

FIGURE 1: A beam shaping and steering radio frequency antenna enabled by metamaterials.

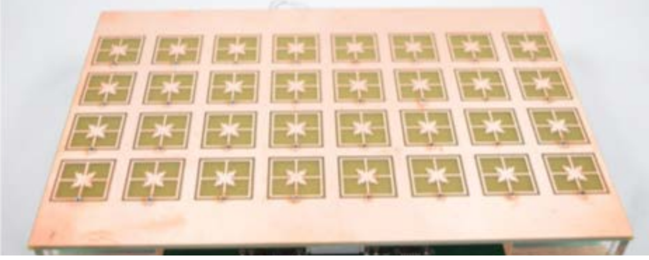


Image courtesy of Metawave

**Top image courtesy of Julia R. Greer (Caltech). The transition from design to manufacturing of nano-architected metamaterials.*

FIGURE 2: A metamaterial wavelength selective mirror.

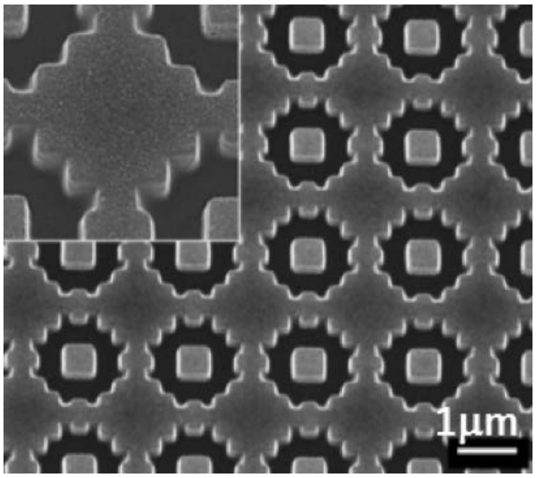


Image courtesy of Clara Rivero-Baleine (Lockheed Martin)

of molecules in action to, for example, observe the interaction of pharmaceuticals with a virus.[4] A metamaterial prototype of a wavelength-selective mirror (Figure 2) provides nearly perfect reflection (99.76%),[5] which could enable high-performance optical filters and sensors for next-generation devices. Theoretically, metamaterial mirrors could also increase photocurrent generation in solar cells by 20%,[6] while metamaterials with nearly perfect absorption could improve the efficiency of concentrated solar power receivers by 10%.[7] Metamaterials also have the potential to make invisibility cloaking a reality[8,9] for important advancements in defense applications such as radar cross-section reducing structures and stealth technology. For example, an acoustic metamaterial prototype (Figure 3) can render objects underneath it "invisible" to sound waves. It can redirect and alter the trajectory and speed of waves coming from any direction. Optical cloaking with metamaterials is possible in principle, but fabrication methods with improved resolution and alignment are needed to create devices in practice.[10]

FIGURE 3: 3D broadband omnidirectional acoustic ground cloak.

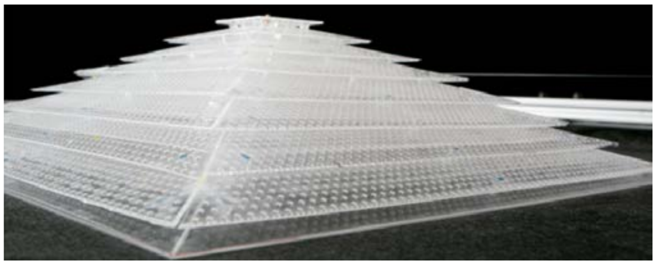


Image courtesy of Bogdan Popa (University of Michigan)

Beyond the ability to amplify, mitigate, redirect, and/or modify acoustic and electromagnetic waves, metamaterials also enable extraordinary and unusual mechanical properties. For example, brittle materials such as ceramics used in turbine blades could be more damage resistant with internal nanolattice metamaterials that recover after greater than 50% compression without a sacrifice in strength or stiffness (Figure 4).[11,12] Athermal metamaterials can resist volumetric changes due to temperature fluctuations, a property critical for laser and other optical systems that must maintain precise alignment. Negative stiffness and negative Poisson's ratio metamaterials can theoretically absorb and redirect impact for applications such as blast-mitigating helmets and military equipment.[13] Mechanical metamaterials can also provide enhanced seismic protection through periodic unit cells with tuned stiffness that can disperse and dissipate seismic waves.[14] Metamaterials can also be ultra-lightweight while preserving or even improving mechanical performance (Figure 5),[15,16] an important aspect for achieving increased energy efficiency in automotive and aerospace applications. For example, a metamaterial can potentially be four times stronger than structural steel while having a

FIGURE 4: Ceramic metamaterial with hollow tubes to enable ductile-like behavior from the normally brittle aluminum oxide.

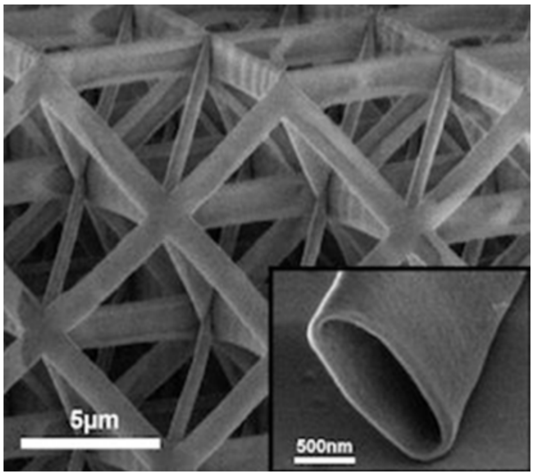


Image courtesy of Julia R. Greer (Caltech)

FIGURE 5: A lightweight metamaterial microlattice that is 99.99% air – the world's lightest material when announced.

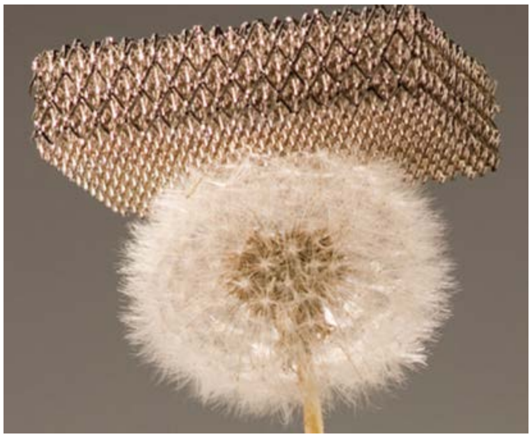


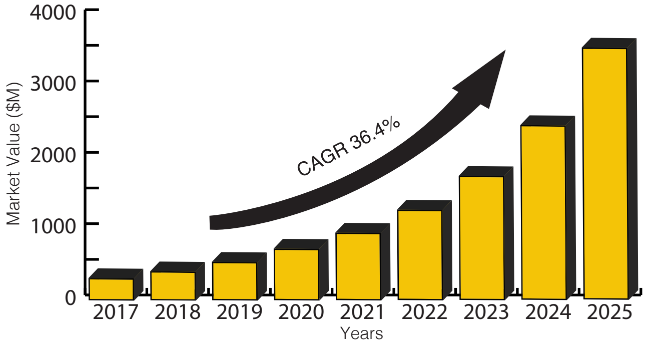
Image courtesy of HRL Laboratories, LLC

density less than most plastics.[17] And this is just the beginning of the potential performance and impact that metamaterials are poised to deliver.

Metamaterials also represent a significant economic opportunity. They comprise a rapidly expanding market segment (Figure 6)[a] with market size estimates of $2.5B[18] to $4.6B[19] by 2025, and associated CAGR (compound annual growth rate) estimates of 22.3% to 63.1%.

Despite this wide range of opportunities, metamaterials have yet to be broadly adopted to address practical applications and deliver societal and economic value. Although researchers have fabricated many promising prototypes with boutique processes, these methods do not readily lend themselves to devices and products manufactured at scale. **Realizing the potential of metamaterials relies on translating these scientific discoveries to scaled metamaterials manufacturing.** This will require process innovation and a robust, supporting ecosystem.

FIGURE 6: Global metamaterials market size by year from 2017 to 2025.



Barriers to Metamaterials Manufacturing

By definition, metamaterials are geometrically complex. To achieve their desirable performance characteristics, manufacturing process technologies must be able to reliably and affordably produce multi-scale architectures. This includes upwards of 1 million repeated unit cells per layer, equating to square meters for radio frequency[20] and square centimeters for optical applications.[21] Repetition in the vertical dimension varies widely across applications. Further, process technologies for metamaterials are needed for a broad range of constituent materials including metals, polymers, semiconductors, ceramics, and multi-material systems. Traditional manufacturing processes do not readily provide high-throughput solutions to manufacture critical nanoscale and macroscale features within a single structure or allow for precise alignment of small unit cells in three dimensions across large volumes. **Novel scalable process technologies are needed.**

Metrology tools to monitor and evaluate these complex, multi-scale geometries are also not readily available, especially at the speed, cost, and reliability needed for scaled production. Similarly, current modeling and simulation tools are limited in their ability to design metamaterials for manufacturability and model processes across multiple scales. **Manufacturing metamaterials at the scale and quality needed for practical applications requires innovation in metrology and modelling**.

Developing metamaterials manufacturing processes will require a suite of advanced tools. However, the advanced manufacturing

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[a] Estimates are a linear average of available professional market estimates, with CAGR-based interpolation used to determine years without data.

equipment, metrology instrumentation, and computational tools most relevant to the challenge are often prohibitively costly for individual research labs, start-ups, or pilot programs. **Improved access to the most relevant equipment, tools, and experts is needed to accelerate process innovation for metamaterials manufacturing researchers and start-ups.**

Metamaterials manufacturing is also plagued by insufficient and unreliable supply chains. **New process technologies can only deliver value if the supply of high-quality feedstocks is consistent and affordable.** Nanomaterials and advanced substrates are increasingly becoming commercially available, yet their quality is either unknown or inadequate for dependable metamaterial performance. Processes could be developed and improved to provide these critical feedstocks, but industry is unlikely to act without sufficient market demand. However, researchers need access to these feedstocks to create prototypes and justify pilot-scale experimentation that will ultimately generate this market demand. It is a recursive challenge in need of public-private partnerships.

The interdisciplinary nature of metamaterials requires a coordinated, collaborative, and focused approach to addressing these challenges. The breadth of applications, expertise, and priorities has lent itself to siloed and uncoordinated efforts. Communication across the broad metamaterials community, especially related to the transition to scaled manufacturing, is largely missing in the United States. The metamaterials manufacturing community has yet to identify and agree upon "killer applications" and coordinate resources to drive innovation. This lack of coordination not only inhibits technological advancements and competitive advantage, but also makes it difficult to appropriately prepare a skilled workforce for metamaterials manufacturing. Coordinated action is needed.

Opportunities for U.S. Leadership

The United States is uniquely positioned to address the challenges of scaled metamaterials manufacturing and reap the benefits of U.S.-based production and technological superiority. The U.S. government has invested heavily in metamaterials research (both basic and applied) through an array of federal science and technology agencies and divisions (Table 1). For example, the Center for Metamaterials, a National Science Foundation Industrial/University Cooperative Research Center, provides a multi-university facility to research, design, fabricate, and test electromagnetic metamaterial prototypes.[b] These research investments have significantly advanced the state of the art in metamaterials. U.S. researchers have produced nearly a quarter of all relevant academic publications, which have received nearly half of all citations (Figure 7).[c] U.S. researchers have also developed world-class intellectual property. Worldwide, the number of metamaterials patents granted per year continues to increase, with the United States largely leading the way (Figure 8).[c] In the past decade, the number of U.S. originated patents granted per U.S. publication has increased eightfold as industry has identified financial motivations to protect metamaterial-related technologies.

Research-focused companies, such as HRL Laboratories, LLC, are developing platform technologies for metamaterials, while a range of start-ups, many spun out of U.S. universities and labs, have emerged in the United States to focus on commercializing key metamaterials technologies. These include Echodyne, Kymeta, Metawave, Evolv Technology, and Pivotal Commware.[d] The United States also has a strong manufacturing base composed of key companies with interest, expertise, and equipment critical

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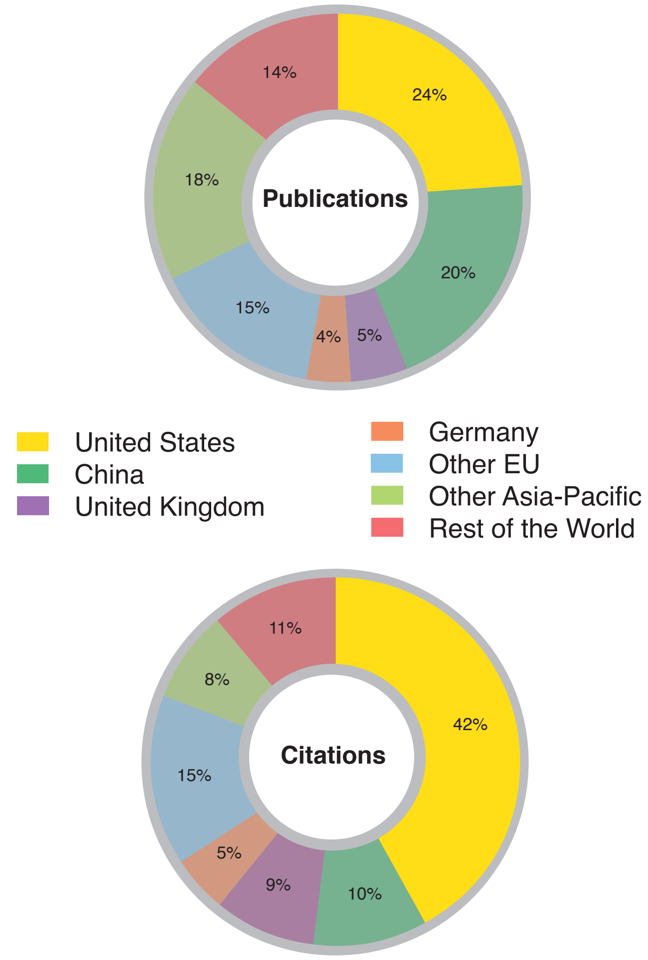
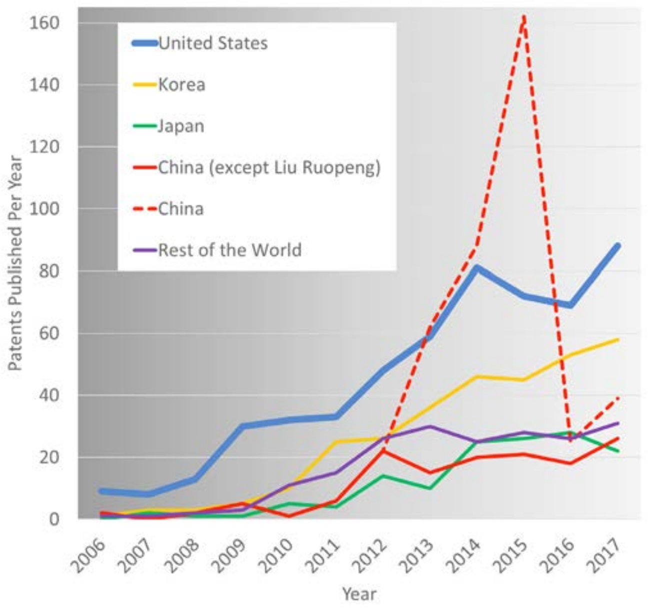
b centerformetamaterials.org
c Methodologies can be found in Appendix 1.
d echodyne.com
kymetacorp.com
metawave.co
evolvtechnology.com
pivotalcommware.com

FIGURE 7: Total metamaterial article and conference proceedings publications and citations by country of residence of last author.



to scaled metamaterials production. This includes roll-to-roll technologies, wafer and lithography-based fabrication, 3D printing, and a range of bottom-up methods. Examples of these manufacturers include Lockheed Martin, Raytheon, 3M, Kodak, and General Motors. Finally, with a strong industry base in market sectors key to metamaterials, such as defense, aerospace, scientific equipment, gaming, communications, and medical devices, the United States is poised to lead in bringing metamaterial-based products to the world.

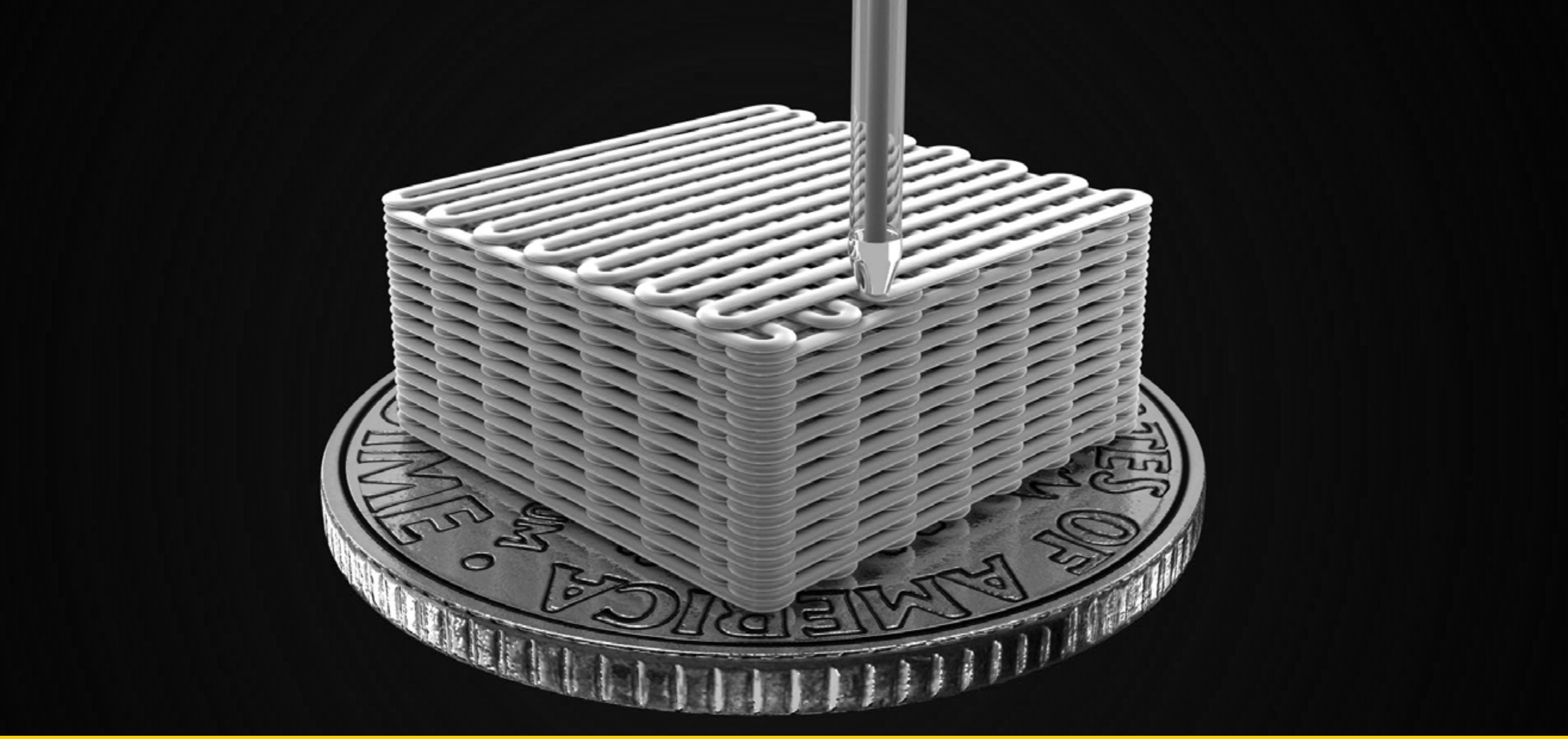
FIGURE 8: Metamaterials patents published per year by country of origin. Note: China is shown inclusive and exclusive of inventor Liu Ruopeng.



However, to ensure that America's scientific discoveries and engineering inventions in metamaterials result in the creation of new economic opportunities and technical superiority, strategic investment and coordination is needed. MForesight convened and gathered the insights of metamaterials manufacturing experts from academia, government, federal labs, and industry to begin this effort. Led by a steering committee chaired by Chris Spadaccini (Lawrence Livermore National Laboratory), metamaterials experts defined and prioritized the cross-cutting challenges and explored opportunities for coordinated action from public and private stakeholders. The remainder of this report examines the challenges and opportunities facing metamaterials manufacturing and delivers five actionable recommendations for enhancing U.S. manufacturing competitiveness in metamaterials. A complete list of contributors and the workshop agenda can be found in Appendices 2 and 3.

TABLE 1: Federal Metamaterials Research Funding

Air Force	• Air Force Research Laboratory – Materials and Manufacturing Directorate • Air Force Office of Scientific Research – Physical Science Division
Navy	• Naval Research Laboratory – Acoustic Signal Processing and Systems Branch • Office of Naval Research – Naval Materials Division • Office of Naval Research – Ship System and Engineering Research Division
Army	• Army Research Laboratory - Sensors and Electronic Devices Directorate
Defense Advanced Research Projects Agency (DARPA)	• Extreme Optics and Imaging (EXTREME) program • Atoms to Product (A2P) program • Materials with Controlled Microstructural Architecture (MCMA)
National Science Foundation (NSF)	• Electrical, Communications and Cyber Systems (ECCS) Division • Civil and Mechanical and Manufacturing Innovation (CMMI) Division • Chemical, Bioengineering, Environmental, and Transport Systems (CBET) Division • Industry – University Cooperative Research Centers
Department of Energy (DOE)	• Office of Basic Energy Sciences • Lawrence Livermore National Laboratory • Lawrence Berkeley National Laboratory • Los Alamos National Laboratory • Sandia National Laboratory • Argonne National Laboratory • Ames Laboratory
National Aeronautics and Space Administration (NASA)	• Space Technology Mission Directorate • NASA Glenn Research Center • NASA Ames Research Center
National Institute of Standards and Technology (NIST)	• CNST Nanofabrication Research Group



Establish a National Metamaterials Manufacturing Research Initiative

Process Technologies for Scaled Manufacturing

Early successes in manufacturing metamaterial devices at scale have come as two-dimensional metamaterials (metasurfaces) with unit cells large enough to be compatible with printed circuit board manufacturing processes. At this scale, Lockheed Martin, in partnership with Penn State University, lined a horn antenna with a metal metasurface to deliver improved radiative power per weight (Figure 9). Similarly, Kymeta, a U.S. metamaterials start-up, creates metasurfaces with glass-on-glass microfabrication techniques to direct Ku-band electromagnetic waves for satellite communications. However, to achieve enhanced performance at smaller wavelengths, such as within the lucrative optical range, the smaller unit cell dimensions quickly become challenging to manufacture. Construction of such a near perfect repeating structure at the nanoscale over a large two-dimensional area is nontrivial. When moving beyond metasurfaces to 3D metamaterials, the manufacturing complexity is compounded further.

FIGURE 9: A horn antenna lined with an electromagnetic metamaterial for enhanced radiated power.

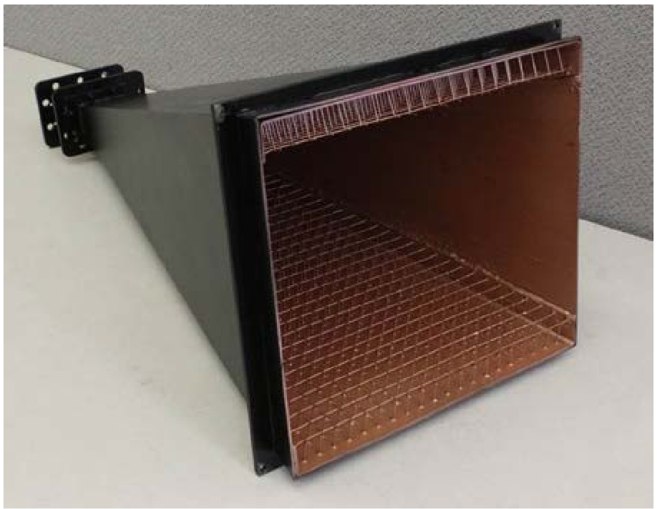


Image courtesy of Erik Lier (Lockheed Martin)

**Top image courtesy of Marcus Worsley and Ryan Chen (Lawrence Livermore National Laboratory). Direct ink write additive manufacturing enables an aerogel metamaterial with both nano and micro scale features.*

Methods such as two-photon lithography, e-beam lithography, and traditional semiconductor processes (e.g., chemical vapor deposition (CVD), chemical etching) have been used to make promising prototypes that demonstrate metamaterial structures and scientific principles. However, these processes are not practical for scaled manufacturing of metamaterials. They are slow, applicable only over small areas, and expensive. Alternatively, nanoimprint lithography, pattern transfer, additive manufacturing, and self-assembly methodologies are laboratory processes that show greater promise for scalability, for example through large-scale parallelization. Focused translational research efforts are needed to develop these potentially enabling technologies into scaled manufacturing processes relevant to metamaterials. Specific areas of precompetitive research that would benefit the U.S. manufacturing sector are discussed below.

Nanoimprint Lithography

Nanoimprint lithography (NIL) is a hot embossing process that uses a nanopatterned stamp, combined with heat and pressure, to create patterns in a polymer substrate. Researchers, including those at NASCENT,[e] have made promising developments toward scaling nanoimprint lithography with roll-to-roll technologies;[22,23,24] however, further increases in processing speed are needed. Challenges also remain in delivering the necessary dimensional tolerances, achieving precise alignment when stacking films to create 3D structures, and patterning a broader material set. The following research areas are promising starting points for addressing these challenges:

- **Thermal and ultraviolet-assisted NIL** can increase imprinting speeds through thermal pre-heating or in-situ ultraviolet cross-linking of the substrate. These versatile processes enable the creation of features as small as 10nm and can be applied to wafer-based, sheet-based, and roll-to-roll platforms.

- **NIL features as etch masks** can eliminate multiple processing steps and pieces of equipment, providing enhanced speed and affordability.

- **Metallized NIL patterned surfaces** provide opportunities to obtain metallic metamaterials in otherwise difficult to produce patterns. The process utilizes the benefits of NIL scalability and precision, while overcoming NIL's limitations in patterning metal.

- **New NIL compatible material sets,** including nanoparticle-based inks,[25] will broaden the range of metamaterials that can be directly manufactured using NIL.

Pattern Transfer

Pattern transfer involves the creation of elements on a compatible substrate before transferring them onto the desired substrate. For example, nanocrystal superlattices can be manufactured by first using liquid-interfacial forces to create an assembly, transferring the assembly onto a topologically structured mold using the Langmuir-Schaefer technique,[f] and then moving the structured assembly to a final substrate with transfer printing techniques.[26] Scaling pattern transfer to enable high-throughput manufacturing of 3D metamaterials will require further investigation into the following research topics:

- **Layer alignment methods** are needed for large-area and high-throughput processes. This includes the development of fiducial markers for registration and alignment of subsequent layers or processing.

- **Residual strain compensation and mitigation** must be addressed for substrates that deform with changes in temperature and humidity, such as polymer-based substrates. New sheet-based processes with nondeforming substrates could also be a viable solution.

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[e] NSF Nanosystems Engineering Research Center for Nanomanufacturing Systems for Mobile Computing and Mobile Energy Technologies.

[f] The Langmuir-Schaefer technique transfers material on the surface of a liquid to a substrate using immersion.

Additive Manufacturing

Additive manufacturing has advanced rapidly over the past decade and has served as a valuable tool for prototyping metamaterials. For many metamaterial applications, the current additive manufacturing methods and available equipment do not provide the throughput needed for commercial production. However, promising areas for further research exploit the periodic nature of metamaterials to enable scalable additive manufacturing:

- **Multi-nozzle arrays** can enable direct write technologies with fixed nozzle spacing that deposit and pattern slurries at accelerated rates, especially when integrated with roll-to-roll techniques.[27,28]

- **Self-propagating feature guides,** such as HRL Laboratory, LLC's photopolymer waveguide technology, can rapidly generate a structure with self-propagating waveguides produced during photopolymerization of the material.[29] This technology should be expanded to additional material sets, smaller feature sizes, and thicker parts.

- **Massively parallel shaping** in which entire layers or volumes are sintered, polymerized, or bound together at once can improve processing times. For example, diode-based additive manufacturing[30] enables one-step layer melting in metal additive manufacturing.

Self-Assembly Processes

Bottom-up fabrication methods offer the promise of direct 3D fabrication, rather than a layer-by-layer approach, by using DNA,[31] block copolymers,[32] and other chemistries[33] to organize and assemble nanoparticles or form complex structures for templating. High-throughput processing using these approaches is limited by defects, slow assembly kinetics, and insufficient models. The following research topics will enable and accelerate self-assembly processes for metamaterials manufacturing:

- **Bottom-up processes that are size-agnostic** can enable rapid assembly of multi-component systems. Block copolymers with brush-like architectures show specific promise in this area.[34,35]

- **Tools for guided assembly,** such as topological features printed with nanoimprint lithography, can aid in obtaining consistent metamaterial unit cells.

- **Models for self-assembly processes and disorder** will accelerate both discovery and optimization of low-defect self-assembly techniques.

- **Novel bottom-up processing methods** that inherently reduce defects over large areas would provide further opportunities for self-assembly in manufacturing metamaterials.

High-Throughput Methods for Periodic Structures

Across the wide variety of metamaterial applications, periodic 3D lattice architectures composed of identical repeating geometric unit cells are ubiquitous. This repetitive nature provides opportunities to apply "step and repeat" technologies. Like the "stepper" tool widely used in semiconductor fabrication, these technologies create repeated structures by repeatedly stepping the manufacturing tool, part, or projection path by a set increment across the area of the part. In addition to discrete steps, techniques such as light-based scanning could be coupled with roll-to-roll processing for enhanced throughput, similar to the method a laser printer uses to pattern toner.

Alignment is one of the greatest challenge for these technologies, especially at the micro- and nanoscale and in three dimensions. Misalignment could result, for example, in electrical shorts degrading the performance of electromagnetic metamaterials or unconnected struts and nodes reducing the strength and stiffness of mechanical metamaterials. Although high-precision alignment technologies can be leveraged from the semiconductor fabrication industry, the alignment challenge becomes more difficult to overcome in the vertical dimension. Key research challenges for realizing high-throughput periodic structures include the following:

- **Step and repeat technologies** need to be adapted for metamaterials manufacturing, with a focus on extending these technologies into the third dimension. Emerging technologies for 3D integrated circuits serve as a potential starting point.

- **Rapid, real-time sensing and adjustment technologies** will allow for precision nanoscale alignment of metamaterial features in three dimensions.

- **Self-aligning technologies** for existing and emerging manufacturing methods will help to overcome alignment challenges. An example of this is 3D self-aligned imprint lithography (SAIL).[36]

- **Approaches to combine repetition with variation** will enable functionally graded metamaterials, which are especially critical for acoustic metamaterials.[37]

Metamaterials from Disparate Materials

Many important classes of metamaterials rely on processing and joining disparate materials into intricate 3D architectures. For instance, manufacturing electromagnetic waveguides relies on successfully joining electrical conductors with insulators. Similarly, the functionality of negative thermal expansion metamaterials relies on joining two materials with significantly different coefficients of thermal expansion. Figure 10 shows a model of a negative thermal expansion metamaterial.[38] Here the red material has a higher coefficient of thermal expansion than the gray material, meaning it will expand more than the gray material when heated. This difference, combined with the strategic structural layout of the two materials, will result in a net contraction (negative expansion) when heated; a property largely unavailable in bulk materials.

Handling and shaping disparate material while also ensuring joint robustness across length scales and in three dimensions has proven to be particularly challenging. Although some promising new developments are relevant to metamaterial geometries, they still have significant limitations. For example, laser-based direct deposition techniques can be used to generate metal composite structures;[39] however, the metals must be somewhat similar, and the composite is limited to layer-by-layer material variation in the vertical dimension. Microstereolithography methods can be used to create partially cured photopolymer structures that can be flushed with another material before curing completely to create multi-material structures.[40] Similarly, Stratasys PolyJet printers allow material stiffness to be varied across a part through slight changes in composition, but only within a limited set of polymer systems. The following research areas will further expand the opportunities for manufacturing metamaterials from disparate materials:

- **Efficient multi-material manufacturing processes** that reduce wasted material resulting from unwanted mixing or fluid flushing will help enable commercially viability.

- **Novel material agnostic processes** for manufacturing metamaterials are needed. This could include refined bottom-up fabrication methods that excel at pattering multiple materials, including functional materials.

FIGURE 10: A negative thermal expansion metamaterial unit cell design with multiple materials in 3D.

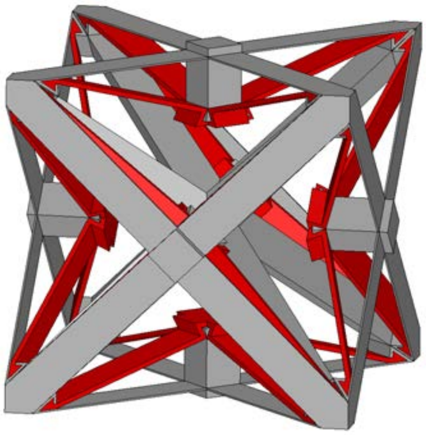


Image courtesy of Jonathan Hopkins (UCLA)

- **Technologies for joining disparate materials,** such as metals to ceramics or to polymers, are needed to design and manufacture specialized interfaces. For example, functionalizing materials for better adhesion at interfaces or creating designed material gradients rather than sharp step changes may lead to more robust interfaces and joints.

- **Joining conducive materials** could be identified through molecular design or new alloy development. If the other properties of the materials are not radically degraded, there may be room for materials designed specifically for joining.

Metrology

As the process technologies to manufacture the complex, multi-scale, and 3D geometries typical of metamaterials mature, there will be an increasing need for metrology to ensure that the strategically designed shapes and tolerances are precisely replicated across the part. Consider, for example, the mechanical metamaterial shown in Figure 11. It consists of unit cells with walls 60 nanometers thick and repeated several times over to comprise a macroscale component.[41] For this part to provide optimal functionality, each of these nanoscale walls need to be precisely manufactured and verified to be sized, aligned, and connected properly. This is especially challenging for geometries where many of the relevant features are obscured by other parts of the structure, which is typical for metamaterials. For scaled metamaterials manufacturing, such metrology must also be fast and inexpensive. The following research directions in metrology will be critical to the success of metamaterials manufacturing:

FIGURE 11: Hierarchical metamaterial with nano- and microscale features in a macroscale component. This metamaterial provides high (>20%) tensile elasticity not found in its constituent materials.

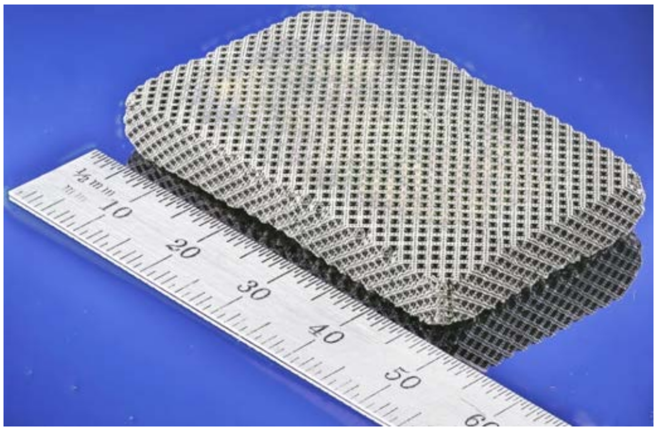


Image courtesy of Chris Spadaccini (Lawrence Livermore National Laboratory)

- **Advanced multi-scale metrology methods** that can resolve features down to the nanoscale over many-centimeter scale areas and volumes are needed. Existing nondestructive evaluation methods[42] should be adapted for metamaterials manufacturing. This includes laser-based (holographic and laser profilometry), magnetic, radiographic (computed tomography), thermal/infrared, ultrasonic, and acoustic methods.

- **Evaluation methods for multi-material structures** will also be important for distinguishing disparate materials at interfaces and small length scales (micro to nanoscale).

Simulation and Design

Metamaterials present a unique set of challenges for process simulation and design for manufacturing. These challenges arise from the multi-scale, multi-dimensional nature of metamaterials that can also include disparate materials and, in some cases, require solutions to more than one set of physics. From surface quality to dimensional tolerance to alignment, manufacturing parameters affect metamaterials in ways that substantially alter their performance. The inability to adequately model manufacturing process parameters, constraints, and/or limitations can restrict the ability to manufacture metamaterials with optimal functionality. It also restricts the ability to deliver tools that can design for manufacturability.

An additional challenge is the speed at which the design of metamaterials can be performed. Most existing tools approximate, analyze, and modify designs iteratively, rather than using inverse (or “top-down”) design methods that could algorithmically synthesize nonintuitive, high-performance metamaterial designs in a single computational run. To address these challenges, the following research areas require additional attention:

■ **Multi-scale simulation capability** for both electromagnetic and mechanical metamaterials is critical. Many emerging metamaterial designs are hierarchical in nature, with features as small as tens of nanometers within structures as large as meters.

■ **Design and simulation codes for periodic** structures will enable enhanced design complexity without the associated computational burden. Expanding these efforts to multi-material and gradient systems will further facilitate novel designs.

■ **Process technology models,** including sensitivity analysis and integration with design tools, will facilitate precise designs with known tolerance limitations.

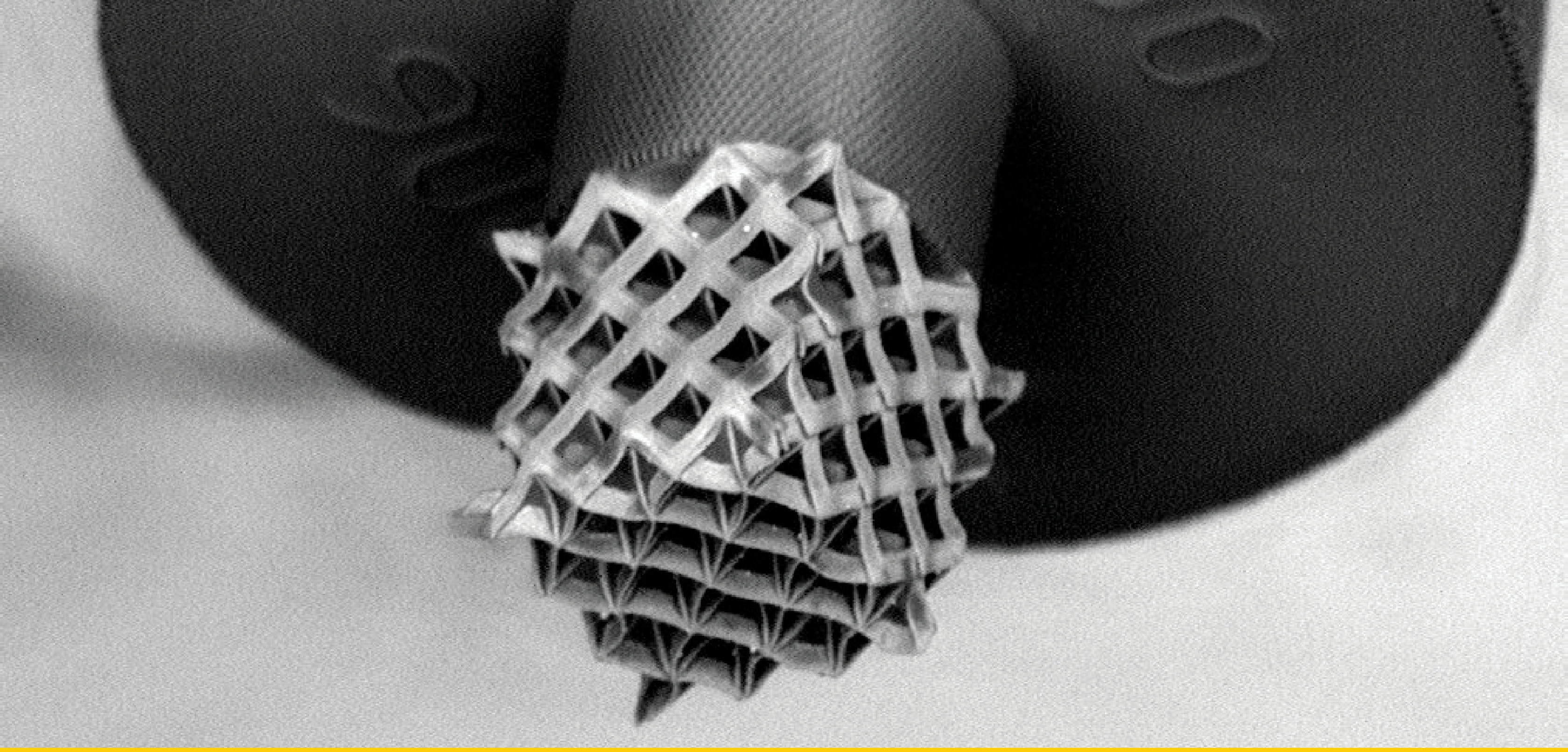
■ **Codes that design for manufacturability** will enable designs that can be fabricated with existing manufacturing methods and will greatly reduce the design-build iteration loop.

■ **Multi-physics computing codes** that are scalable to moderate to large high-performance computing clusters, while also able to solve problems on single multi-core machines, will be beneficial.

■ **Efficient inverse (“top-down”) design methods** for all relevant physics will be a key enabler for nonintuitive metamaterial design.

Recommendation 1: Establish a National Metamaterials Manufacturing Research Initiative. This coordinated, multi-agency federal effort should focus on a number of precompetitive translational research topics to address critical barriers to scaled metamaterials manufacturing:

- Scaling of enabling process technologies for metamaterials manufacturing including nanoimprint lithography, pattern transfer, additive manufacturing, self-assembly, and associated high-throughput roll-to-roll and stepping processes.
- Technologies for manufacturing metamaterials from disparate materials. These include processes to shape and join disparate materials and the development of new materials that are more conducive to joining.
- Integrated and stand-alone metrology solutions that can evaluate at high resolutions, across multiple scales and dimensions
- Simulation and design tools relevant to the design and manufacture of metamaterials including those capable of addressing 3D, multi-scale, periodic structures, design for manufacturability, and manufacturing process modeling.



Increase Access to Current Federal Facilities and Experts

Many of the pioneers in metamaterials manufacturing operate with limited access to resources such as the most advanced manufacturing equipment, rare characterization tools, and complex modeling and simulation capabilities with the associated computing power. For start-ups and small manufacturers, these resources are otherwise cost-prohibitive to obtain. For example, a small start-up company working to develop a new electromagnetic metamaterial may not have the sophisticated and expensive characterization tools required to validate that their manufactured structures meet geometric specifications. They may also lack the computing power and expertise to design the next version of their product to be manufactured in the United States. **Fortunately, many of these resources exist at federally funded research and development facilities. Increased access to these resources, and the experts most familiar with them, will accelerate industry's ability to competitively move metamaterials toward broad-based applications.**

Outward-Facing Federal Facilities

Several existing outward-facing federal facilities can be leveraged to advance metamaterials manufacturing. Researchers at these facilities should be encouraged to engage with the metamaterials community to address the key technical barriers outlined in this report. Similarly, industrial and academic experts working on translational metamaterials research should take advantage of existing outward-facing federal facilities and mechanisms for gaining access. Relevant facilities include the following:

- The Advanced Manufacturing Laboratory (AML) at the Lawrence Livermore National Laboratory (LLNL), which resides in the Livermore Valley Open Campus (LVOC), is intended for joint LLNL-industry and/or LLNL-

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**Top image courtesy of James Oakdale and Sourabh Saha (Lawrence Livermore National Laboratory). The creation of a metamaterial with submicron features on top of a solid base smaller than a human hair.*[43]

academic partnership projects where advanced manufacturing is central to the mission. Industry and LLNL staff work side-by-side on projects of joint interest using advanced and prototype manufacturing technologies that are not otherwise publicly available.

- Highly powerful and expensive beam-lines residing in national labs could be used by industry for detailed characterization of metamaterials. Some examples of these facilities include the Stanford Linear Accelerator (SLAC), the Advanced Light Source (ALS) at Lawrence Berkeley National Laboratory (LBNL), the Advanced Photon Source (APS) at Argonne National Laboratory, and the Spallation Neutron Source (SNS) at Oak Ridge National Laboratory (ORNL).

- The Molecular Foundry at LBNL consists of one of the world's best suites of nanofabrication tools. This collection of high-end fabrication techniques is ideally suited for metamaterials manufacturing process development.

- The Center for Integrated Nanotechnologies (CINT), which is jointly operated by Sandia and Los Alamos National Laboratories (SNL and LANL), houses various unique fabrication and characterization tools highly applicable to metamaterials manufacturing.

- The Manufacturing Demonstration Facility (MDF) at ORNL houses an array of advanced manufacturing technologies including one of the world's broadest suites of additive manufacturing tools. Many of these systems are ideal for the complex geometries associated with metamaterials.

Many of these resources are open to researchers in both academia and industry. In most cases, access is provided through a competitive peer-reviewed application process. In some cases, expedited access is provided for time-sensitive projects. Most of these federal resources require companies to pay for access or to keep their data private, which may create barriers to entry, especially for small companies and start-ups.

Programs to Connect Industry with Federal Resources and Experts

To enhance access to outward-facing federal facilities including high-performance computing (HPC), explicit federal programs that fund efforts to directly work with industrial partners should be created and/or continued. The HPC4Manufacturing[g] is an example of a successful program. In this program funded by the Department of Energy (DOE), industry needs are paired with national lab computing resources and personnel through a proposal process. A typical successful proposal seeks to solve a key industrial manufacturing problem through the use of HPC. The industrial partner works with national lab researchers and HPC assets, including both codes and machines, to develop a solution. The national lab researcher's interaction and computing time is funded directly by DOE while the industrial partner covers its own cost of the interaction.

Another example of a federal program that pairs industry with national labs is the DOE Small Business Vouchers (SBV) pilot.[h] SBV seeks to "facilitate access to the DOE national labs for American small businesses, enabling them to tap into the intellectual and technical resources they need to overcome critical technology challenges." Like HPC4Manufacturing, this program pairs small businesses with national lab resources ranging from characterization tools to manufacturing systems. This program, along with others like it, should be extended or created to address the challenges facing metamaterials manufacturing and widespread application. Requirements for access, such as fees and licensing agreements, should be managed to maximize the contribution of all facilities to the overall national objective.

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[g] hpc4mfg.llnl.gov/
[h] sbv.org/

Similar to connecting industry to federal resources, federal programs specifically focused on linking industrial researchers with relevant federal experts are needed. While the SBV and HPC4Manufacturing programs certainly accomplish this indirectly, some existing programs, such as the DOE Technologists in Residence Program,[i] specifically target valuable personnel interactions. In this federally funded program, industry and national lab researchers spend time in residence at each other's organizations to learn their respective challenges and capabilities, and work together to find viable solutions. This program, along with others like it, would have a substantial impact on delivering the manufacturing innovation needed to realize scaled metamaterials manufacturing in the United States.

Recommendation 2: Increase access to current federal facilities and experts to accelerate process innovation through the following actions:

- Encourage existing outward-facing federal facilities to address metamaterials manufacturing challenges and engage the U.S. metamaterials community.
- Instantiate new, and extend existing, federal programs that link industry researchers and needs with federal experts and key national resources, such as high-end equipment and high-performance computing.

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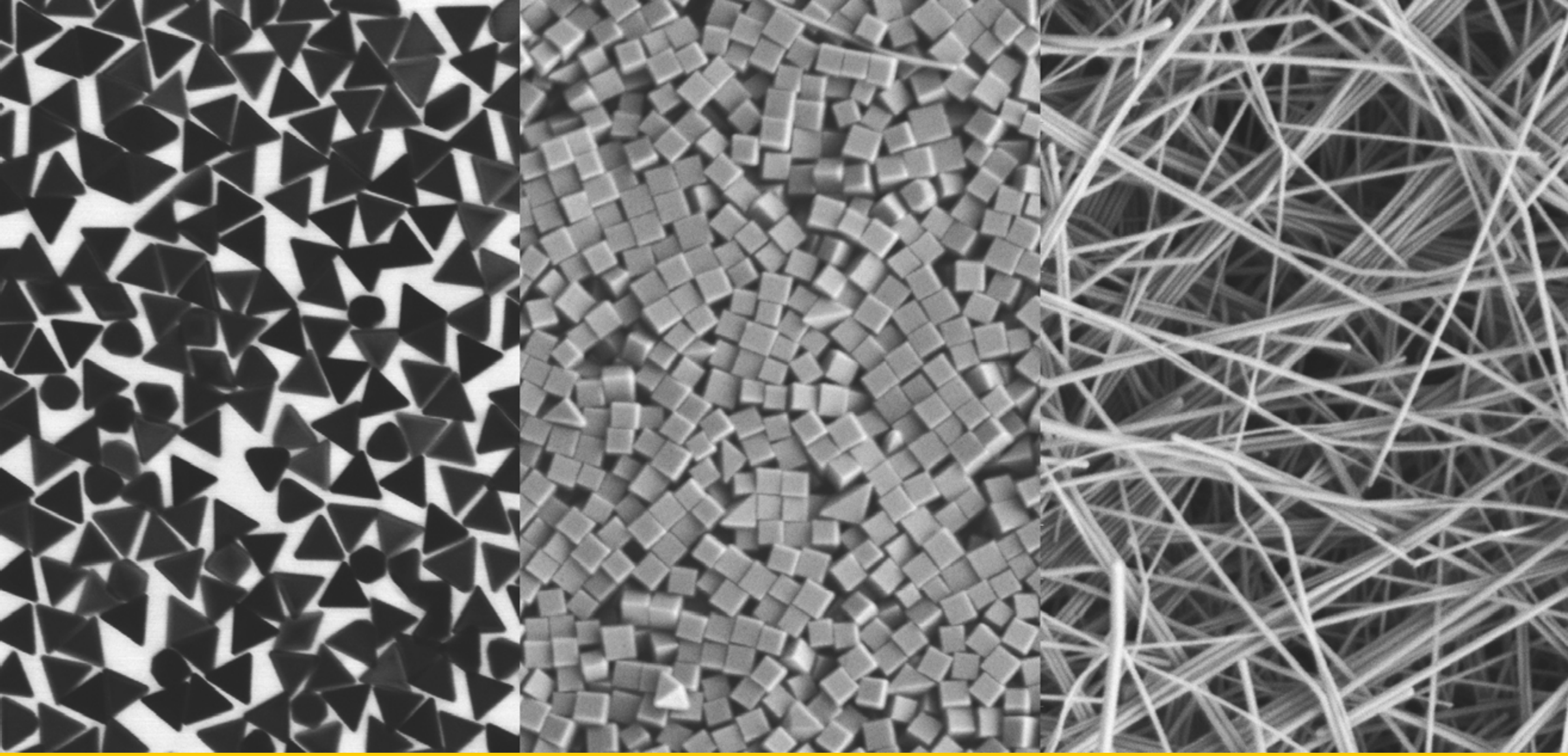
[i] energy.gov/eere/cemi/technologist-residence-program



Enhance Federal Support for Critical Feedstocks

Scaled Production of Critical Feedstocks

A reliable and affordable supply of high-quality nanomaterials and substrates is needed to achieve scaled metamaterials manufacturing in the United States. While nanomaterials are slowly becoming available commercially for other applications, the quality is largely below the specifications needed to reliably deliver the novel material performance capabilities of metamaterials. **Nanomaterials for metamaterial production must be of the highest purity with consistent composition, morphology, and surface features.** To develop metamaterial prototypes under these constraints, researchers typically use nanomaterials produced at milligram quantities in laboratories. When it comes time to scale production quantities to kilograms (and more) the quality can suffer dramatically.

Most metamaterials manufacturing approaches also employ substrates. **The planarity, uniformity, and surface quality of the substrate is critical to the accuracy, precision, and ultimate success of the manufacturing processes.** Maintaining precise control over the topmost surface quality is critical, because imperfection directly leads to dislocations, defects, poor adhesion, and a general inability to control the subsequent fabrication of metamaterial structures. While silicon, GaAs, and InP reaped the benefits of steady military and consumer electronics investment, nontraditional substrates that are key to enabling metamaterials manufacturing, such as sapphire and zinc oxide, have not received the same attention and consequently suffer from poor quality and limited sizing.

Further, without access to feedstocks at the necessary purity and quality, it is challenging for researchers to create functional prototypes, justify pilot-scale experimentation, and ultimately drive demand for feedstocks. This situation

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**Top image courtesy Image courtesy of T. Yong Han (Lawrence Livermore National Laboratory). Nanomaterials used in metamaterial manufacturing.*

creates a recursive challenge where the absence of high-volume demand prevents suppliers, especially domestic suppliers, from giving these needs appropriate attention, which in turn prevents the development and scaling of metamaterials manufacturing, which would drive demand. This ultimately leads to critical nanomaterials and substrates being unavailable to the metamaterials community, or only available as expensive custom batch productions.

Federally Co-Funded Feedstock Production

One approach to addressing the challenge of feedstock availability is to create a facility or facilities that focuses on scaled nanomaterial and substrate processing as related to the needs of metamaterials manufacturers. The primary focus of this effort is to provide U.S. manufacturers and researchers with a stable and affordable supply of the necessary feedstocks to advance metamaterial applications through their development and nascent stages of production. **Scale-up and production of critical feedstocks could be accomplished through the support of government co-funding until market demand reaches a point where subsidies are no longer necessary.**

The metamaterials community would need to prioritize which feedstocks would draw partial funding from private stakeholders and would provide the greatest return on investment. Potential priority areas include high refractive index nanostructures, ultraviolet optical materials, functionalized metal nanoparticles, nanorods, core-shell particles, and other hybrid nanomaterials. Nontraditional substrates of interest include sapphire, zinc oxide, flexible glasses, polyimide materials, heavily doped semiconductors, and noble metals such as silver and gold. Large format substrates and substrate preparation at the length scales required for metamaterial applications would also be a valuable addition.

Alignment with Federal Nanomanufacturing Efforts

Multiple nanomanufacturing efforts are funded by various federal agencies that can be leveraged to address the nanomanufacturing challenges specific to metamaterials manufacturing. These include institutes at universities, centers, and laboratories such as the Center for Nanoscience and Technology (CNST) Nanofabrication Research Group at the National Institute of Standards and Technology (NIST) that has performed relevant research in modeling, fabrication, and testing methods. **The existing research efforts, equipment, and expertise resulting from federal nanomanufacturing efforts could be leveraged to more rapidly advance metamaterials manufacturing** through realignment of priorities or funding of additional efforts where appropriate. Where possible, federal nanotechnology research funding should place emphasis on feedstocks critical to metamaterials.

Building on these efforts, a variety of enhanced tools, standards, and certifications would further enable quality processes, feedstocks, and resulting products:

- Standards and certifications for measuring and reporting size distribution of nanoparticles, especially nonspherical nanoparticles;
- Refinement of models that predict particle size and size distribution in large volume nanoparticle production;
- Continued development of methods for sorting particles by size;
- Extended tools, standards, and certifications for measuring thin film thickness and surface roughness, especially for substrates and thin films made from nontraditional materials; and
- Establishment of characterization methods for multi-material particles, such as metal-semiconductor or semiconductor-insulator, including bonding quality at the interface.

Enhanced Manufacturability and Functionality

For some of the most unique and attractive metamaterials, the challenge is not yet in producing known feedstocks at scale but remains in discovering novel materials and processes to enable manufacturability and deliver unprecedented functionality.

Novel Nanomaterial Opportunities

Nanomaterials designed for manufacturability are a viable solution to some of the barriers to metamaterials manufacturing. For instance, the creation of nanomaterials containing two or more disparate materials provides a practical route to precisely align and securely bond challenging material combinations within a complex 3D geometry. Similarly, nanomaterials designed to resist degradation throughout the manufacturing process and in end-use conditions would enable the production of metamaterials with more reliable and repeatable performance characteristics. For example, plasmonics[j] is a promising area of metamaterials limited by the challenges associated with integrating metal nanomaterials and films such as silver or gold with silicon manufacturing technologies. In the case of silver, it can lead to inconsistent films and degradation in air. A novel material designed to enable the functionality of metal-based plasmonics without the challenges of metal manufacturing would expand opportunities for scaled manufacturing. Looking forward, the next generation of metamaterials will be increasingly active and responsive with the ability to dynamically change shape, properties, and/or function. These functionalities will also rely on the development of novel constituent materials. Specific research areas to enable these opportunities include the following:

- **Novel low-loss plasmonic materials** such as titanium nitride[44] could provide plasmonic function equivalent to metals without the manufacturing challenges.

- **Nanoscale cold bonding** and other methods[45] are needed to enable hybrid nanomaterials that combine diverse materials to be produced at scale.

- **Environmentally robust nanomaterials** are essential to ensuring that metamaterials maintain performance in a variety of manufacturing and working conditions.

- **Materials for active and reconfigurable metamaterial structures** such as phase change materials and novel materials for varactor diodes[k] will enhance opportunities for the next generation of metamaterials.

Novel Substrate Opportunities

Enhancing the surface properties of widely available substrates is a practical approach for obtaining novel substrates for metamaterials manufacturing. Epitaxial growth is a promising method for creating an outer single crystal layer on lower cost bulk substrates. Single crystal substrates are important for achieving optimized electrical and optical functionality in metamaterials, and, in some cases, the difference in material between the epitaxy layer and the substrate may be used functionally in the device (e.g., to create a band gap). In addition, dopant patterning or patterning of chemical functional groups can be used to selectively modify a substrate to aid in precise metamaterials manufacturing.

Curved substrates also offer exciting opportunities for metamaterials. They enable metamaterials appropriately shaped for curved applications such as lenses and aircraft nose cones. They also enable metamaterials with final shapes that provide added functionality such as paraboloid antennas. The most relevant 3D substrates will need prescribed complex curvatures with sub-micron precision. Curved metamaterials have proven to be quite difficult to

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[j] Plasmonics is the interaction of light with surface electromagnetic waves. This physical phenomenon is critical to enabling novel properties in a range of electromagnetic metamaterials.

[k] Varactors are electronic components with a capacitance that varies with applied voltage.

manufacture, in large part due to the absence of not only available substrates, but also methods for transforming planar manufacturing methods to curved substrates without damaging or distorting the pattern. An alternative approach could be new design and post-processing methods to reliably translate metamaterials prepared on planar substrates to functional metamaterials on curved substrates. Key research areas for enabling novel substrate opportunities include the following:

- **Nanoscale selective epitaxial growth and dopant patterning** needs to be further advanced to create surface films for metamaterials manufacturing.

- **Patterned functionalized surfaces** has advanced rapidly as a means to interface substrates with biological elements; however, metamaterials manufacturing applications have yet to be widely explored.

- **Extending traditional processes to nontraditional substrates,** such as noble metals (silver and gold), heavily doped semiconductors, zinc oxide, sapphire, flexible glasses, and polyimide materials, is needed to enable application of these substrates.

- **Curved substrates** with appropriate manufacturing processes or transfer methods will offer exciting applications for curved metamaterials.

Recommendation 3: Enhance federal support for critical feedstocks. To enable metamaterials manufacturing technologies to be practically scaled, critical nanomaterials and substrates need to be made available and supported through a number of actions:

- Temporarily co-fund resources to scale and manufacture feedstocks critical to scaling metamaterials manufacturing in the United States.
- Align existing federal nanomanufacturing R&D efforts with feedstocks critical to scaling metamaterials manufacturing and expand characterization tools, standards, and certifications.
- Fund research to develop and process novel nanomaterials and substrates to enhance metamaterial manufacturability and functionality.

Establish an Interdisciplinary Advisory Group

This report aims to provide timely insights and recommendations from the metamaterials manufacturing community on the most pressing barriers to metamaterials manufacturing today. However, the situation is evolving and dynamic. Looking forward, **an interdisciplinary advisory group will be needed to actively monitor progress toward development of metamaterials manufacturing in the United States and to provide up-to-date insights on evolving opportunities and challenges.** The group should include members from industry, academia, federal labs, and government agencies. They should represent equipment vendors, manufacturers, end-users, program managers, and researchers spanning the fields of chemistry, physics, materials science, and engineering. While the role of the group should evolve based on the needs of the U.S. metamaterials manufacturing community, pressing issues include roadmapping exercises for manufacturing research and development priorities, and preemptive guidance for a growing intellectual property portfolio.

Metamaterials Manufacturing Roadmapping

One of the greatest barriers to metamaterials manufacturing innovation in the United States is the lack of a focused and coordinated technology development strategy. Metamaterials is a broad field, with the potential to offer promising solutions to a wide range of critical challenges facing industry and federal agencies. Aligning these application opportunities to emerging and nascent technologies, and mapping priorities to focus and accelerate manufacturing innovation, is a non-trivial task. It will require collaboration and understanding between metamaterials manufacturing research and development leaders, end-users, and technologists from industry, academia, and government. The proposed advisory group of metamaterials manufacturing experts should be tasked to assist industry and government stakeholders

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**Top image courtesy of Ross Brindle (Nexight Group). MForesight Metamaterials Manufacturing workshop participants.*

by developing and updating metamaterials manufacturing technology and implementation roadmaps. This task should include the following actions:

- Identify and highlight the most promising and advanced (close-to-production) process technologies for scalability.
- Match specific emerging manufacturing technology solutions with targeted application areas of national priority (e.g., defense, energy, and health) and interest.
- Develop long-term strategies to coordinate resources and accelerate innovation.
- Collect and provide timely intelligence on the progress of metamaterials technology and manufacturing roadmaps.

Throughout these activities the advisory group should place specific emphasis on technologies and opportunities on which the U.S. manufacturing sector is uniquely positioned to capitalize.

Intellectual Property Workshop

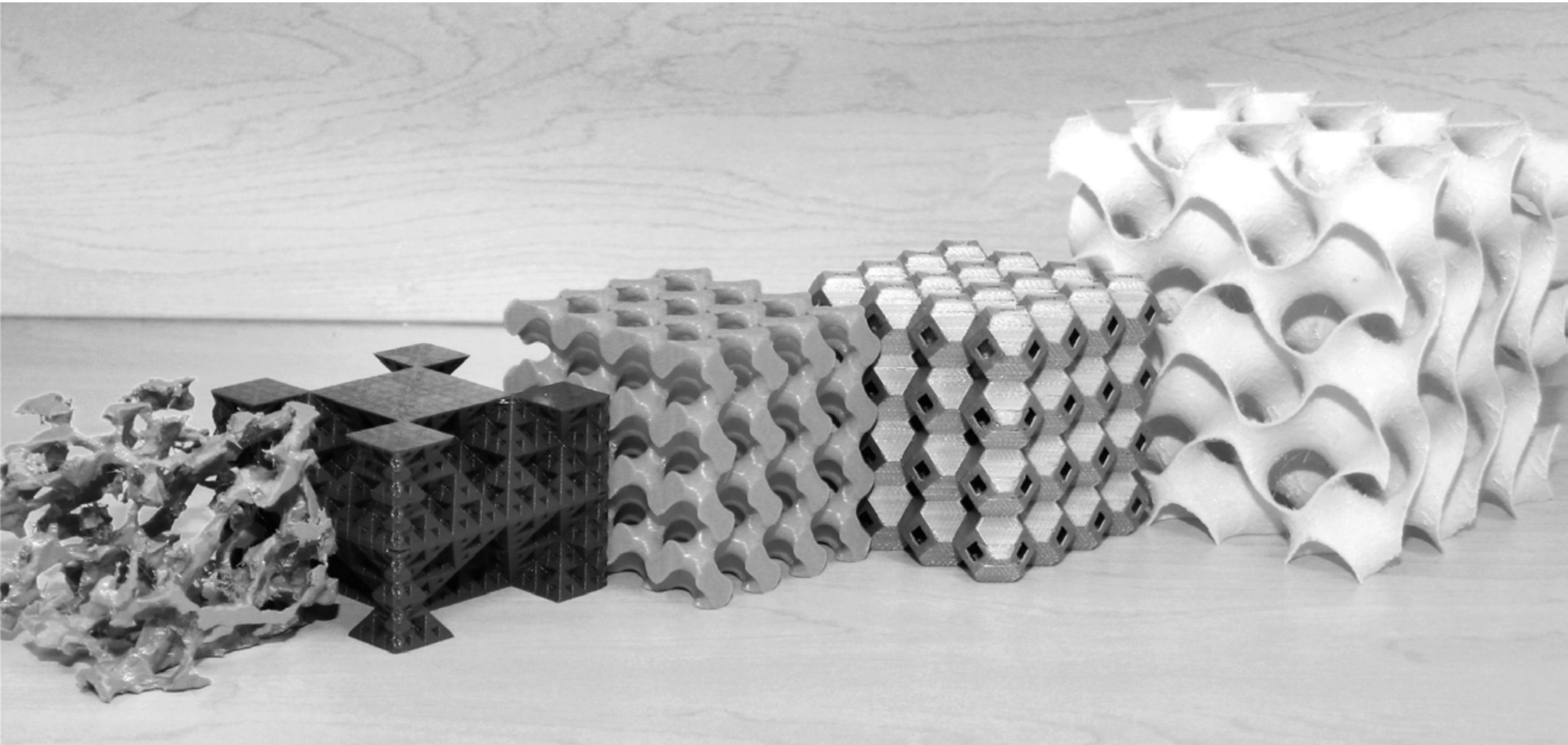
Metamaterial researchers are expected to patent their inventions at an ever-increasing rate as the community continues to understand and apply the basic principles of metamaterials to new applications and engineering challenges. Although the United States Patent and Trademark Office (USPTO) has considerable experience in effectively classifying new technologies and identifying relevant prior art, metamaterials present unique difficulties. Currently, there is no USPTO category for metamaterials as a class. Rather, the USPTO generally classifies new metamaterial-based or metamaterial-enabled inventions in line with existing classes of physics, electromagnetics, acoustics, and mechanics, in addition to classes associated with the enabled technologies. Although this approach may work for single-physics applications of metamaterials (e.g., electromagnetic filters), more complex multi-physics applications (e.g., steerable antennas) may suffer from insufficient classification, and as a result not all relevant prior art may be brought to light during examination, leaving any patent disputes to be resolved with potentially lengthy and expensive court proceedings.

The history of patenting in the nanotechnology field is a cautionary tale. Here the lack of categorization and a consistent approach has presented an unprecedented challenge for patent law.[46,47] Early nanotechnology patents became overly broad, over-claimed, and effectively irrelevant in the service of stimulating commercial development. Patent disputes, licensing arrangements, and the large set of overlapping patents across many nanotechnology domains have made it difficult for start-up technologies to flourish.[48,49]

Early engagement with the USPTO and other interested world-wide bodies to identify appropriate classification schemes for both prior art and pending applications would aid in preventing such patent thicket issues in the metamaterials manufacturing space. The interdisciplinary advisory group should convene a workshop to cover the basics of metamaterials, how scientific classification is made, multi-physics and geometrical optimization, technological applications, and emerging areas. For relatively little investment, the USPTO would become able to better understand this emerging technology area and to make better determinations when allowing patent claims.

Recommendation 4: Establish an interdisciplinary advisory group. The advisory group should be tasked with providing real-time insights on emerging opportunities and challenges relevant to metamaterials manufacturing. In the near term, this group should focus on the following tasks:

- Lead efforts in roadmapping metamaterials manufacturing technology research and development priorities and track progress on overcoming technical barriers. Here opportunities should be prioritized to ensure that manufacturing and technology implementation are primarily capitalized on by the U.S. manufacturing industry.
- Provide policy guidance on issues such as intellectual property classifications that could either hinder or accelerate progress.



Create a National Center of Excellence

The aforementioned recommendations stand to significantly enhance the ability of the U.S. research and manufacturing community to advance the manufacturing readiness level of metamaterials in this country. However, a Metamaterials Manufacturing Center of Excellence would play an essential role as a sustained central hub for coordinating communication and collaborative efforts. As a public-private partnership similar to the Manufacturing USA Institutes, the center will sponsor and host events and activities that bring together academia, government, federal labs, large manufacturers, potential customers, equipment providers, and small and medium manufacturers to address the barriers to scaled metamaterials manufacturing. As highlighted in Figure 12, the center will focus on six key attributes to drive collaborative efforts toward delivering the utmost potential of metamaterials technologies.

Coordination of Industry Participation and Needs

The center will house and expand upon the previously proposed interdisciplinary advisory group to coordinate the needs of manufacturers by bringing together manufacturers of all sizes to identify, prioritize, and invest in precompetitive translational research challenges. A sustained mechanism to provide guidance to academic researchers on the challenges that are most important to manufacturers in metamaterials will be put in place. Topics of interest include key applications, engineering limitations, performance specifications, process bottlenecks, integration challenges, and key material needs. Although funding for metamaterials has focused thus far on mainly scientific fundamentals, these activities will provide a continuous feedback loop for decision makers to understand the evolving

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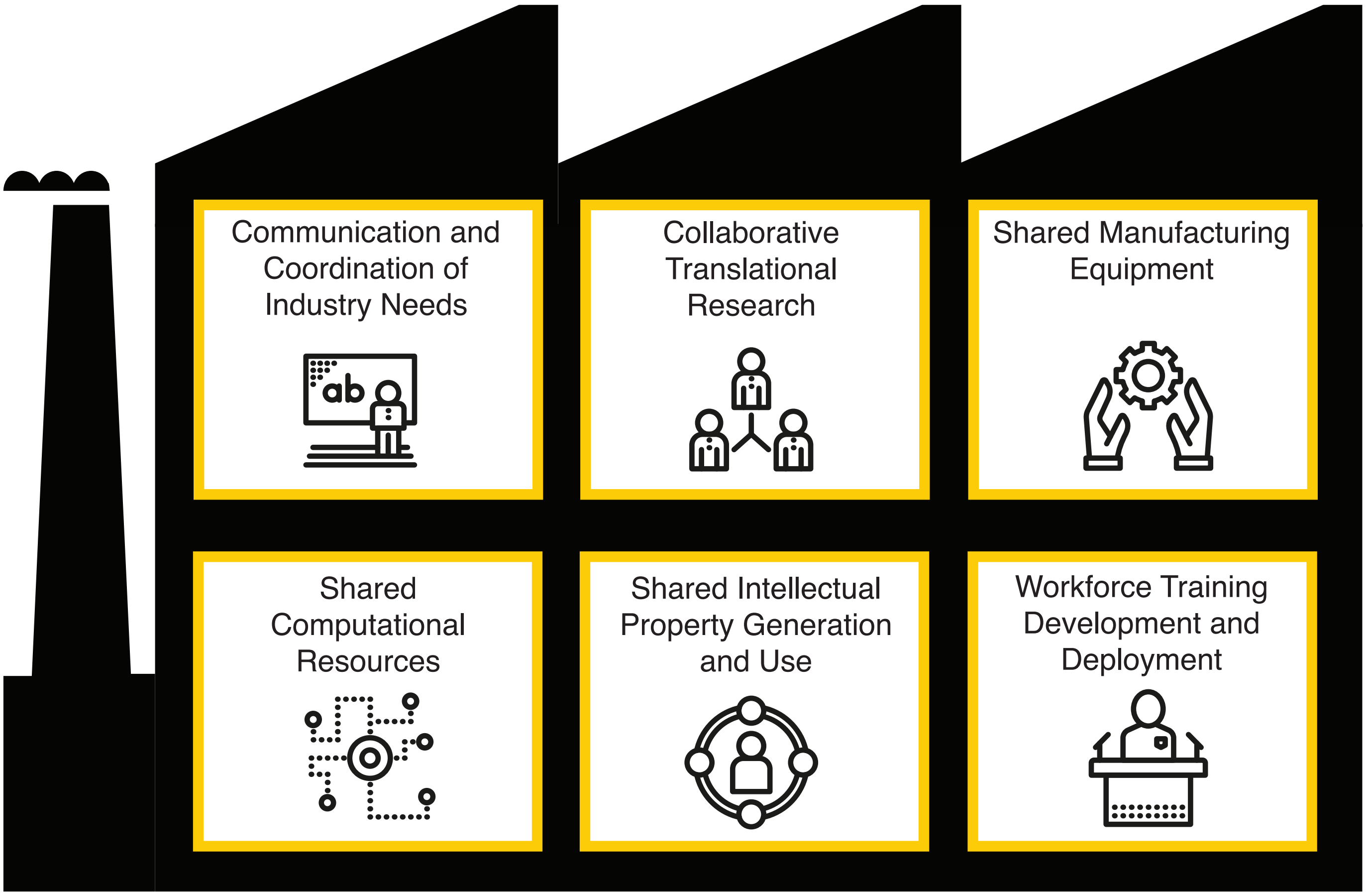
**Top image courtesy of Hamid Seyyedhosseinzadeh (Rowan University). A range of metamaterials with orthopedic applications, exhibiting properties that match the human body.*

FIGURE 12: Six key thrusts of the Metamaterials Manufacturing Center of Excellence.



needs of manufacturers and the funding needs for critical precompetitive translational research. These challenges should guide not only the focus of the center, but also the broader national research agenda.

Collaborative Translational Research

Improving and accelerating communication and collaboration across the broad metamaterials community will be essential to the technological advancements needed to translate metamaterials to scaled manufacturing. The interdisciplinary nature of metamaterials requires a collaborative approach, with expertise spanning electrical engineering, mechanical engineering, manufacturing, physics, chemistry, materials science, semiconductor engineering, nanoscience, optics, and antennae engineering, among others. Across these distinct disciplines and applications of metamaterials, manufacturers and researchers could better share similar manufacturing opportunities and challenges. In many cases, some of the most important translational research and development topics fall between the basic scientific research performed at universities and the applied product-specific research performed at companies. The center will perform and lead these translational research efforts, which are enablers for scaled metamaterials production. The research will focus on, and be guided by, the needs of manufacturers, with ample academia-industry collaborative projects. Key research topics for the center should begin with those detailed throughout this report.

Shared Manufacturing Equipment and Computational Resources

A key attribute of the center is an infrastructure of large capital cost manufacturing equipment and experts able to operate the equipment and provide guidance. This equipment, which would otherwise be prohibitively costly to obtain for independent research teams, will be oriented toward translational research efforts for scalable metamaterials manufacturing processes. The specific equipment for inclusion in the center will be guided by member organizations and provided as open access (membership fee and/or fee for use) for internal and external projects by U.S. researchers and companies. Example equipment includes tools for nanoimprint lithography, 3D laser writing, roll-to-roll manufacturing, and high-speed metrology. Beyond commercial capital equipment, the center will also serve as an incubator to accelerate the development of novel manufacturing processes that show promise for mass production of metamaterials. This incubation would apply to both processes developed at the center and processes developed by outside researchers.

Software, models, data, and simulations serve a key role in refining metamaterials manufacturing processes and in relating designs from process parameters to performance (i.e., Integrated Computational Materials Engineering). The center will serve as an aggregator of these models and data generated by the community and from the center's manufacturing equipment. The center will further facilitate access to high performance computing resources to drive contributions such as data-driven manufacturing best practices, scaling metrics associated with manufacturing process and metamaterial physics, and decision-making tools for design and manufacturing trade-offs.

Shared Intellectual Property Generation and Use

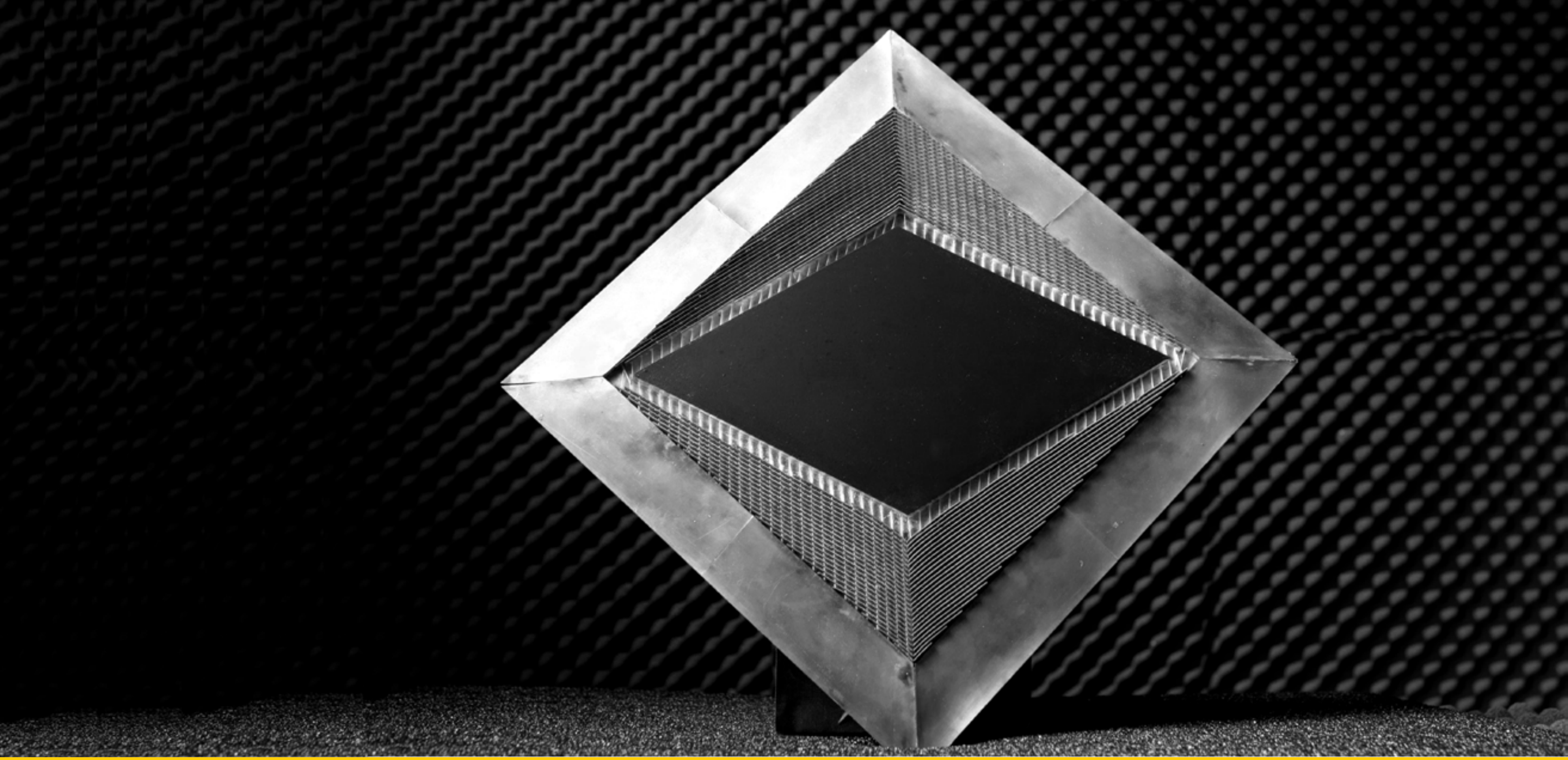
To facilitate and accelerate technology transfer of the precompetitive translational research, intellectual property (e.g., patents) resulting from the research will be provided as nonexclusive licenses to member organizations. This collaborative intellectual property portfolio arrangement enables member companies to avoid patent thickets and the associated challenges with freedom to operate. This also reduces the burden of intellectual property generation and protection on each individual company for cross-cutting technologies. Further, this arrangement ensures that member companies protect their joint intellectual property on these platform technologies, while still enabling each company to individually pursue application- or product-specific patents as they see fit.

Workforce Training Development and Deployment

Adopting existing manufacturing methods and realizing the next generation of novel manufacturing processes will require a unique set of skills in the workplace. The multi-disciplinary nature of metamaterials manufacturing further drives the need to provide workforce training. The center will be tasked to identify key competencies and to develop a robust talent pipeline for the emerging metamaterials manufacturing sector by coordinating industry workforce needs, developing workforce training programs and curriculum, and disseminating the curriculum through on-site and off-site training. Further the center will inherently create a skilled workforce on the projects and equipment of interest to manufacturers through continued research at the center. A domestic pipeline of expertise will greatly improve the anchoring of metamaterials manufacturers in the United States.

Recommendation 5: Create a National Center of Excellence. Funded through a public-private partnership, the Metamaterials Manufacturing Center of Excellence will play the essential role of coordinating efforts to secure American technological leadership and enhanced U.S. manufacturing competitiveness in metamaterials manufacturing. The center will support the national effort through the following actions:

- Coordinate industry participation and needs.
- Support and accelerate collaborative research.
- Provide shared manufacturing equipment and computational resources.
- Generate shared intellectual property for precompetitive technologies.
- Create and facilitate workforce training programs.



A Call to Action

Metamaterials are a rapidly expanding opportunity with cross-cutting applicability, serving as both a platform for economic growth and an essential technology to realize key national priorities from national security to health to energy independence. The United States has made significant investments in metamaterials research through a wide range of federal agencies and has developed world-class expertise, research facilities, and intellectual property. Widespread utilization of metamaterial technologies, and return on these investments, critically relies on advancing metamaterials from lab-scale prototypes to products produced at scale by U.S. manufacturers.

The United States is well positioned to be the sustained global leader in metamaterials manufacturing, but targeted action must be taken quickly to sustain this position. Acute challenges are restraining metamaterials from reaching their commercial potential and need to be addressed. These relate to manufacturing process knowledge, availability of feedstocks, access to necessary equipment, and a lack of cohesion across the metamaterials community. Through coordinated action by stakeholders in academia, industry, and the federal government, these barriers are not insurmountable. From translational research efforts to collaborations with federal facilities to public-private partnerships, the federal government has a critical role to play.

**Top image Image courtesy of David Smith (Duke University). A cloak for microwave frequencies.*

Appendix 1: Methodologies

Publication and Citation Analysis

Publication and citation data were gathered from the Scopus[l] database through a search for article titles, abstracts, and keywords containing the word "metamaterial." Only articles and conference papers for the date range of January 1, 2001, to December 31, 2017, were considered for analysis. The country of affiliation of the last author was extracted from Scopus data, or manually determined when affiliation data were lacking, and was used to determine the number of publications and cumulative citations received for each combination of year and country. The countries with the highest count were reported, and the remaining countries were grouped geographically (European Union, Asia Pacific, and rest of the world). European Union was determined by membership in the European Union, and Asia Pacific was determined by the Daniel K Inouye Asia-Pacific Center for Security Studies[m] definition.

Intellectual Property Analysis

InnovationQ Plus[n] was used to search for patents metadata (including title and abstract) in the database containing the word "metamaterial." A relevancy of 0.600 or higher (on a 0 to 1.000 scale) on InnovationQ's semantic search algorithm was imposed on the results. Patents in the date range of January 1, 2006, to December 31, 2017, were analyzed for this report. The patent data were de-duplicated (such that a single patent filed in multiple countries only counts once). This was done using the Simple Family Number, and only including the earliest patent in the family. For Australian entries, where patent and patent application data were not readily separated in the database, patent applications were removed by eliminating entries with numbers ending in "A1."[o] The country of origin was manually determined for all patents lacking origin data by determining assignee, or inventor for patents without an assignee. The number of patents published was determined for each combination of year and country. Patents with the inventor listed as "LIU RUOPENG," "RUOPENG LIU," or similar relevant inventors were flagged as coming from inventor Liu Ruopeng in the analysis.

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[l] scopus.com

[m] apcss.org/about-2/ap-countries/

[n] iq.ip.com/discover

[o] bios.net/daisy/patentlens/3493.html

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Appendix 3: Workshop Agenda

Metamaterials Manufacturing

8:00	Welcome and Introductions
8:30	Meeting Focus and Scope
8:45	Keynote: Dr. Bill Carter, HRL Laboratories, LLC
9:15	Break – proceed to Breakout Session 1

Identify Key Challenges to Scalable Metamaterials Manufacturing

9:30	Session 1: By Function Optical and X-ray Terahertz and Microwave Mechanical and Acoustic Metasurfaces
10:30	Break – proceed to Breakout Session 2
10:45	Session 2: By Manufacturing Method Printing Lithography Bottom-up Emerging Areas
11:45	Lunch
1:00	Report Outs and Group Discussion

Develop and Prioritize Actionable Recommendations

1:45	Overview of Actionable Recommendations
2:00	Sessions 3A-3D: Solutions and Recommendations Breakout Sessions: Address the Eight Key Challenges Identified in Sessions 1 and 2
4:00	Break
4:15	Group Discussion of Key Actionable Items

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