Research Opportunities
in
High Energy and High Average Power Lasers

Study for the Air Force Office of Scientific Research
September 20, 2009
Research Opportunities in High Energy and High Average Power Lasers

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July 4September 20, 2009
Executive Summary

Progress in advanced solid state and fiber lasers in energy and power scaling has been exponential since the first demonstration of the laser nearly 50 years ago. The year 2009 saw the demonstration of a 105kW diode pumped slab laser system, and the completion of the National Ignition Laser system with over 4MJ of output energy at 1 micron and greater than 1MJ of energy at the third harmonic from 192 beams. Progress in fiber lasers has continued with increased power output, demonstration of operation in the eyesafer regions of 1.5 and 2.0 microns and demonstration of phased arrays of fibers.

However, future progress in scaling energy and power is not assured. The Air Force Office of Scientific Research convened a Panel of laser experts to consider energy and power scaling of lasers and to “assess research opportunities in high energy and high average power lasers.” The Panel consisting of 15 members from the United States and two members from abroad, held a series of meetings from February to June, 2009. The Panel undertook to identify key research opportunities of the kind normally conducted in the university environment. The Panel also met with the director of the Joint Technology Office to assure that research under JTO support was taken into consideration and that research opportunities were identified where AFOSR could make substantial contributions.

The Panel identified research opportunities in optical materials as critical to future energy and power scaling. The Panel noted that the infrastructure supporting research in the United States is particularly weak in fundamental materials science, characterization of materials, preparation of advanced materials including advanced ceramic and fiber laser gain media. The Panel also noted that infrastructure is lacking in optical coating research and in the evaluation and understanding of optical damage of materials and coatings.

The Panel identified opportunities for research in ceramic laser gain media, laser fibers, optical coatings, wavefront control, and the operation of lasers at cryogenic temperatures. Ultrafast lasers offer a wide range of capabilities in the future. Energy and power scaling of ultrafast lasers depends critically on advances in broad band gain media, broad band coatings, coatings for dispersion control, and on improved damage resistance of optical materials.

The Panel noted that there remain areas of research in research opportunities for improving the efficiency and power of laser diodes especially operation at near IR wavelengths and at increased junction temperature.

The Panel encouraged coordination between noted that the Joint Technology Office, JTO, and the AFOSR should coordinate research programs such that key opportunities are not missed overlooked and research investments for energy and power scaling of lasers is optimized.

The Panel provided descriptions of Research Program Opportunities at the MURI Scale as examples of specifically defined research programs that would enable energy and power scaling of advanced lasers.
Charge to the Panel

The Air Force Office of Scientific Research would like to have an outside expert panel to assess research opportunities in high energy and high average power lasers.

The study would be used solely for research planning by AFOSR. Its scope would be limited to the lasers themselves, and not to other aspects of an ultimate Air Force system. Further the scope would be limited to innovative research of the kind that is normally – though not exclusively - the strength of universities, and is also the mission of AFOSR to fund.

As you know, there is much ongoing research in high energy/average power lasers, sponsored by the Joint Technology Office and others. The interest of AFOSR is in assessing whether the field is being well covered, or if there are promising opportunities being neglected where AFOSR funding could make substantial contributions.

We would hope the study could be completed in about six months, and result in a short report explaining what, if any, opportunities AFOSR is currently missing.

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Findings and Conclusions

**Optical Materials Research**

Finding
The infrastructure for supporting basic research in advanced high energy and high power lasers is lacking in the United States. The infrastructure is particularly weak in fundamental materials science, characterization of materials, preparation of advanced materials, preparation of fiber preforms and pulling of fibers, characterization of coatings, improvements in coating design and damage properties.

Conclusion
The multifaceted areas of materials preparation and characterization with an emphasis on energy and power scaling of lasers would benefit from investment in underlying infrastructure. This investment could be accomplished through joint research programs that bridge across funding agencies and could be accomplished by creating virtual research institutes that share key capabilities across separate locations.

Finding
Future energy and power scaling of advanced lasers depends critically upon advances in optical materials, laser gain media, laser fibers, optical coatings and beam control. Progress in the fundamental understanding of materials properties, including optical damage, will enable future progress in high energy and power lasers.

Conclusion
Research in optical materials, laser gain media including ceramics and fibers, optical coatings, absorption loss and damage mechanisms, is critical for progress in the energy and power scaling of lasers.

Finding
Optical loss and optical damage of optical components, optical coatings, and especially electro-optic and nonlinear optical materials, severely limit energy and power scaling of advanced lasers.

Conclusion
Future energy and power scaling of lasers depends on fundamental advances in laser gain media, optical window materials, nonlinear and electro-optic materials and mirror coatings and materials. Future energy and power scaling of lasers requires reduction in optical absorption and scatter loss and development of high damage threshold optical components and mirrors.

**Ceramic Gain Media**

Finding
Ceramic gain media offer new approaches to engineering the gain medium for energy and power scaling of solid state lasers. The ability to engineering ceramic gain media, to spatially modulate the gain profile, to broaden bandwidth by preparing mixed oxide ceramics, to explore new dopant-host combinations not possible to prepare by crystal growth, to suppress ASE by edge cladding, and to scale gain media to larger dimensions to arbitrary size depending on limited only by oven size, offers unprecedented opportunity for energy and power scaling of solid state lasers.
Conclusion
Basic research in advanced ceramics for lasers offers a high probability of success in enabling energy and power scaling of the next generation of lasers at operating efficiencies greater than 30%.

**Fiber Lasers**
Finding
Fiber lasers and arrays of fiber lasers offer new avenues for power scaling to greater than 100kW. Infrastructure in the United States for supporting research in fiber lasers is insufficient. The lack of infrastructure for preparing pre-forms, for pulling fibers, especially photonic crystal fibers, is slowing the progress of research and development in power scaling of fiber lasers.

Conclusion
Research programs in advanced fiber lasers, new fiber-dopant combinations, lower loss fibers with suppressed photo-darkening, coherent and incoherent combining of arrays of fiber lasers, and efficient high brightness diode pump sources for pumping fiber lasers, offer the possibility of significant advances in fiber laser power scaling at high efficiency.

**Wavefront Control**
Finding
Wavefront control is an essential element for the effective use of advanced solid state lasers. There are research opportunities for research in wavefront sensing, optical elements for wavefront control, and in optical coatings that enables the operation of adaptive optical systems for wavefront control at high average power.

Conclusion
Operation of a laser near the diffraction limit is critical to many applications of energy and power scaled lasers. Adaptive optics is an essential element for beam control in the laser architecture and in the optical systems that operate at high average power. Research in adaptive optics for beam control, beam monitoring, and beam propagation is a critical element in the successful application of high power lasers.

**Cryo-Operation of Lasers**
Finding
Operation of lasers at cryogenic temperatures offers more than one order of magnitude improvement in key laser material properties that enable energy and power scaling. Operation at cryogenic temperatures leads to simpler laser architectures and significantly improved optical quality of the output.

Conclusion
There are significant advances to be made in laser performance by operating at cryogenic temperatures. Research in laser materials properties, optical coatings, and windows at cryogenic temperatures will enable rapid progress in this approach to scaling lasers to high energy and high average power levels.
**Ultrafast Lasers**

Finding
Solid state lasers have led to a revolution in ultrafast lasers with pulse durations reduced to a single cycle, bandwidths broadened to greater than an octave, and energy and power scaling for high field physics and applications to x-ray generation and laser particle acceleration. Power scaling of ultrafast lasers and operation at high efficiency is a cornerstone for future advances in science and commercial applications.

Conclusion
Ultrafast lasers directly pumped by laser diodes offer the potential for power scaling with high efficiency. Ultrafast laser applications in basic research are an extension of the research in energy and power scaling of ultrafast laser sources with a high probability for significant advances. Future advances in Ultrafast lasers depends on advances in special broad band gain media and broad band coatings with dispersion control.

**Laser Diodes**

Finding
Laser diodes have improved in power and efficiency over the past twenty years. The demonstration of laser diodes with 72% electrical operating at efficiencies opens the possibility for significantly improved efficiency of laser diode pumped solid state and fiber lasers. The demonstrated laser diode efficiency has yet to be transitioned to commercial products. High brightness, high power laser diodes are essential for efficient pumping of fiber lasers. Laser diodes for pumping Mid-IR lasers are not yet available. Laser diodes that operate at greater than 50C heat sink temperature may avoid the need for water cooling and reduce the cost and complexity of high power laser systems for field applications.

Conclusion
There remain areas in laser diode science and technology where basic research investment has high leverage. Longer wavelength operation, high junction temperature operation, and the transition to high electrical efficiency into commercial laser diode products are examples.

**JTO – AFOSR Research**

Finding
JTO is sponsoring research in advanced solid state lasers, fiber lasers, ceramics, and adaptive optics for beam control. JTO is sponsoring exchange of scientists with AFRL that, over the longer term, brings talent to AFRL.

Conclusion
The AFOSR and JTO need to coordinate research programs in energy and power scaling of solid state and fiber lasers to optimize the basic research investments made in this area.
Report

Introduction
In 2010 the solid state laser will we will celebrate 50 years since the operation demonstration of the Ruby Laser in 1960. Over the past fifty years the energy and power and efficiency of solid state lasers has increased exponentially. This year, 2009, saw the demonstration of greater than 105kW of cw output from a solid state laser at near 20% electrical efficiency. This year also witnessed the completion of the National Ignition Facility, NIF, with more than 4 MJ of energy at 1micron and 1MJ at the third harmonic. This is the largest laser in the world with 192 beams on target for laser inertial fusion studies.

The solid state laser has led in to a revolution of in ultrafast lasers, initially based on the wide gain bandwidth medium titanium doped sapphire, but now extended to fiber laser gain media and to ceramic based lasers. Output pulses are a few femtoseconds or one optical cycle in duration. The modelockedUltrafast laser technology, coupled with nonlinear frequency conversion, has led to a white light “comb of modes” source that when properly phased and locked to an atomic resonance is the most precise clock ever demonstrated by mankind.

The high peak and average power generated by solid state lasers has enabled efficient frequency conversion by nonlinear optics to the ultraviolet and now across the infrared and far infrared to the terra-hertz frequency region. Nonlinear frequency conversion in parametric devices has led to tunable outputs that are critical for sensing applications. The high pulse energy generated by solid state laser has open applications to laser radar and to laser remote sensing of atmospheric constituents and parameters including wind, humidity and temperature.

After 50 years of research, the expectation is that the progress in solid state laser development would slow as the field matures. For solid state lasers this is decidedly not the case. New solid state lasers based on photonic crystal fibers, and on large mode area fibers have extended the output power of fiber lasers to multiple kilowatts. The fiber sources are efficient and offer the possibility of coherent combining for power scaling to tens of kilowatts. The thin disk lasers, a version of one dimensionally cooled slab lasers, have been improved in power and efficiency and are now making the transition to the commercial market at greater than the 5kW average power level. The demonstration of low loss transparent ceramic gain media such as ceramic Nd:YAG, has led to increased average power levels as the ceramic gain media can be fabricated at higher optical quality than single crystals and can be scaled in size to the meter scaledimensions, limited only by the dimensions of the oven. Virtually every multiple kilowatt power solid state laser today utilizes ceramic gain media in place of single crystal gain media because of the improved optical quality of the ceramic vs relative to the single crystal. The progress in average power scaling has been exponential over the past twenty five years since the demonstration of the modern diode pumped Nd:YAG solid state laser in 1984. that was The early laser was pumped by 8mW of laser diode power and providing 1.5 2mW of output power.

Today it is possible to envision solid state lasers with more than 1MW of average output power and with an operating efficiency approaching 40% in perhaps one decade. To reach such power levels, however, requires exceptional quality of all optical materials that transmit or reflect light. The laser gain media must have extremely low loss, of the order of part per million per centimeter, and must be free of scatter sites that may lead to optical damage. The laser mirrors and coated surfaces must withstand MW/cm² of average power without damage or optically induced wavefront distortion. The high average power laser beams must be switched, modulated, and frequency converted to be useful in many applications. Therefore, before MW average power
lasers find widespread applications, the optical elements used to control the light must be improved and shown to be robust.

The panel is charged to assess research opportunities in high energy and high average power lasers. The research opportunities are to be focused on lasers and are to be of the type that normally is found in university research programs. The panel is charged to find promising areas of research, not now supported by other sponsoring entities, where AFOSR funding could make substantial contributions to advances in energy and power scaling of lasers.

**Summary of Panel Meetings**

**Panel Meeting at the ASSP Conference: February 3, 2009, Denver, Colorado**
The charge to the panel was presented and discussed. The duration of the study, to be completed in six months, was also discussed.

Each member of the panel in attendance was asked to present a few minute summary overview of the promising areas of research from his/her perspective. Following the presentations, the panel addressed research opportunities that surfaced from the general discussion.

On a five year scale, appropriate for innovative research programs in the university context, two broad themes emerged from the discussion:

1. rebuilding the infrastructure required to support research in all aspects of optical materials and high power lasers, and
2. strategic materials research into new laser materials and improved optical components and coatings.

An example of a new initiative in infrastructure is fiber development and fabrication. The United States has lost the capability to prepare special fiber preforms and to pull special fibers for research such as a photonic crystal fibers or thulium doped fibers for two micron wavelength operation. Investment in this capability a decade ago at the Optical Research Center in Southampton, UK lead to rapid improvements in fiber laser performance as novel ideas could be tried at a rapid pace because of with the fiber infrastructure in place. A modern facility for preparing photonic crystal fibers has recently been created at the Max Planck Institute for the for the Study of the Science of Light located in Erlangen, Germany. In the United States today, specialty fibers must be purchased from commercial vendors at significant cost and with very slow turnaround times. Often, the special fibers are not available due to the lack of support for preparation and pull.

**Advanced Materials and Coatings**
Advanced materials essential for high average power laser operation include new host-dopant combinations, novel nonlinear crystals that perhaps could be scaled in dimensions required to accommodate high average power laser input, and ceramic materials that offer the promise of engineered properties to control optical beam quality, suppress Amplified Spontaneous Emission (ASE), operate at an eyesafe wavelength, and at higher efficiency by diode pumping directly into the laser band. Improved optical coatings are a second material issue. Coatings today have been developed with absorption losses as low as 1 part per million (ppm). However, when illuminated with UV light, the same coatings show color center formation with photo-darkening that leads to significantly higher absorption loss.
Dispersion controlled mirror coatings
The use of ultrafast lasers demands that coatings be designed with dispersion control so that the femto-second duration pulses are maintained upon reflection from mirrors. Dispersion control of the optical coating is an essential design feature of the coating for ultrafast laser beams. Unfortunately, dispersion control of mirror coatings is an evolving science and dispersion controlled coatings are not yet available in the Infrared spectral region.

Cryogenic temperature operation for power scaling
The thermal mechanical properties of materials improve by more than one order of magnitude for crystalline materials at cryogenic temperatures. An extensive study of physical and optical properties of materials at cryo-temperatures has recently been undertaken at Lincoln Laboratory. The measured materials properties include thermal conductivity (significantly improved at cryogenic temperatures) and change of index of refraction with temperature (significantly reduced at cryogenic temperatures). The improvement in material properties at cryogenic temperatures has been noted published and high average power laser operation of cryogenic cooled Yb:YAG has now been demonstrated near liquid nitrogen temperatures.

Optical Damage
Optical damage of materials is now a limiting factor in energy scaling, and in some cases, average power scaling of lasers. The traditional limits to power scaling by optical damage of the laser host material or the mirror coatings may be improved by laser treatment of potential damage sites prior to installation. In addition, damage sites may be pre-identified in key optical elements and pre-annealed by a laser to mitigate the onset of damage. These techniques have the potential to lead to significant improvements in low repetition rate high pulse energy lasers that operate near or even above the damage limit. The work at the Lawrence Livermore National Laboratory, LLNL, has shown that growth in the damage sites detected in the laser beam path can be detected and avoided by using two-dimensional phase masks in the low power pre-amplifier stage of the relayed imaged laser system to project a dark spot onto the damage site that resides in the high power amplifier beam. This allows the laser system to continue to operate until it is convenient to remove and replace the damaged optic component. The overall cost of operation of the laser systems is reduced and the available operational time for application increased by the damage mitigation approach.

For high average power lasers damage mitigation by inspection followed by projection of dark zones to protect the optic is not available. Other methods to avoid damage, especially from dust or dirt, may benefit from research programs targeted toward finding novel solutions to the damage limitations of optical components. An example of thinking outside of the box is the recent adoption of piezoelectric shakers on digital cameras to shake off the dust from the protective window that encases the sensor chip, for example, may be.

Mid-Infrared Lasers an approach to reduce dust on laser optics in the future.
The mid-IR region of the spectrum is significantly less well developed for high power laser operation than the visible spectral region. However, there are significant applications of high power IR lasers to laser radar, remote sensing of molecular species, and to Higher Harmonic Generation (HHG) for X-ray generation. Thus there is a recognized need to improved optical materials and coatings in the mid-IR region.
Recently there has been significant progress in mid-IR laser sources. Examples include quantum well and dot semiconductor diode lasers, quantum cascade lasers that now operate at watt power levels at room temperature, and optically pumped semiconductor Lasers (OPSLs) followed by nonlinear frequency conversion. In addition, the semiconductor saturable absorbing mirrors (SESAMS) have also been extended to the IR to enable ultrafast modelocked laser operation. For this region of the spectrum, it is essential that materials for the laser source, the control of laser beams, and the modulation and control of mid-IR laser beams be significantly improved in the power handling characteristics.

Progress in heat removal
The removal of heat without degrading the beam quality or fracturing the material is also critical to power scaling. Heat removal is often accomplished by conduction and not by direct fluid cooling to preserve the optical quality of the laser beam. There remain opportunities for progress in heat removal using heat spreaders of diamond or SiC, using high velocity flowing liquids against surfaces to which the laser gain medium is bonded, and using special solders such as gold-tin, to maximize heat flow while minimizing residual strain. These are engineering issues, but breakthroughs in heat removal lead directly to power enhancement of the laser system.

Improved Laser Diode Pump Sources
Over the past twenty years the laser diode sources have improved in power and in brightness by orders of magnitude. Recently demonstrations of operation of laser diodes have operated in excess of 70% electrical efficiency. Illustrate that more progress lies ahead for both power and efficiency. In this area, there now appears to be adequate investment in the commercial sector to drive the laser diode technology forward. The reduction in costs is now largely market driven by the increase in the volume of production of laser diodes to meet the increasing market demand. Further, the efficient coupling of single diodes or diode bars to fibers is also improving rapidly.

However, there remains an area where research investment in laser diode technology may pay dividends. For example, the automated assembly of large arrays of laser diode bars at low cost is critical for energy scaling of lasers. To achieve MJ pulse energy operation at 10Hz repetition rate or 10MW of average power, diode arrays approximately 50 x 50cm in area are needed to be developed at a cost of approximately $0.01 per watt of average power. Innovative new assembly and testing approaches are needed to meet this aggressive goal.

Virtual Institute for Laser Research
The panel discussed ideas of how best to approach innovative research that is needed to promote energy and power scaling in solid state lasers. One idea discussed at length is to create a National Institute for Laser Research that is a network of Centers for Optics that are located at multiple sites. The virtual Institute has the advantage of building on existing strengths and infrastructure and obtaining new infrastructure only when it is clearly indentified and necessary. The research in advanced solid state lasers is international in scope. Major research programs are underway in both Europe and in Japan and the rest of Asia. A series of National Institutes for Laser Research could reach across boarders and undertake long range studies critical to the future energy and power scaling of advanced lasers.

High energy lasers and average power lasers are now being considered seriously as drivers for laser fusion and for energy generation by inertial confinement fusion energy generation. A timeline suggests a single beam line of the future diode pumped fusion laser could be demonstrated within five years. and an engineering design in fifteen years. The outcome of this laser fusion research has international impact consequences and is of the scope to merit international collaboration in the research and exploratory engineering phases.
High average power lasers have applications in basic science. For example, laser driven accelerators demand greater than 10MW of laser average power per kilometer to drive a kilometer length accelerator to explore physics for particle physics studies at the TeV energy frontier. High average power lasers of the less than 1MW of average power scale also have defense applications for the protection of regions from incoming threats.

Research Infrastructure
The panel discussed briefly the scale the type of the research that could best be sponsored by AFOSR at the level of basic research in support of energy and average power scaling of solid state lasers. Unlike demonstrations of high power lasers, as now supported by Joint Technology Office (JTO), innovative research can make significant contributions with studies that do not require operating high power lasers scaling and with its associated costs. However, adequate infrastructure must be provided to enable progress especially in the fabrication and characterization of new materials that are essential for power scaling.

Virtual Institute for Laser Research
One idea discussed at length is to create a Virtual Institute for Laser Research that is a network of Centers for Optics that are located at multiple sites. The “virtual” Institute has the advantage of building on existing strengths and infrastructure and obtaining new infrastructure only when it is clearly identified and necessary. The research in advanced solid state lasers is international in scope. Major research programs are underway in Europe and in Japan and the rest of Asia. A series of Institutes for Laser Research could reach across borders and undertake long range studies critical to the future energy and power scaling of advanced lasers.

Research Opportunities Statements – Appendix A
Panel members were invited to prepare one page descriptions of Research Opportunities at the scale appropriate for future MURI programs. These one page Research Opportunities are found in Appendix A.

Panel Teleconference February 27, 2009
The teleconference held on Friday, February 27, 2009 was aimed at broadening the input from panel members who were unable to attend the meeting at Advanced Solid State Photonics meeting held in Denver. Further, the teleconference allowed the introduction of new ideas and concepts that had yet to be identified and discussed by the panel.

The idea of a Center of Excellence in high energy and high power laser technology was raised and discussed. The Center, which could be a virtual Center, could take advantage of key facilities located around the country to pursue research on materials, coatings, ceramics, and fibers. It was agreed that the infrastructure in the US for supporting materials research was very limited.

Examples of lack of infrastructure include the lack of facilities for pulling special fibers, preparing special low loss and high damage resistant coatings, capabilities for testing damage of optical components, and capabilities for ultrafast pulse generation and facilities for preparing and testing nonlinear materials.

Nonlinear materials were identified by the Panel as an area for special concern especially for frequency conversion of high energy and average power lasers. Three panel members volunteered to prepare a statement on nonlinear materials research opportunities. The statement is included in Appendix A.
High thermal conducting and high damage resistant coatings were also identified as an area that deserved special attention. The next generation coatings must not only be low loss, that is less than ppm absorption loss, but must also be strain free on the substrate material. Coatings are recognized as a key factor road block on the path to preventing the operation of high average power scaling of lasers.

The measurement of the thermal-physical properties of laser-host materials is also of concern. As power levels increase, the residual heat must be removed from the gain medium by controlled means to avoid by means that avoid excessive optical distortion of the medium. Recent work at cryogenic -temperatures at Lincoln Laboratorys has shown that at 77K many crystalline materials have increased thermal conductivity and lower index of refraction change with temperature leading to more than an order of magnitude improvement in laser performance. There is, in general, a lack of data on the physical and optical properties of laser host materials at cryogenic temperatures. This issue is being rectified needs to be addressed for crystals and for the new ceramic laser host materials as samples provided by the suppliers are being tested and measured. However, eventually standards for key material properties will have to be established and materials qualified relative to the standards as part of acceptance tests prior to integration into high energy and high power laser systems. The optical industry still operates much like a cottage industry and has much to learn from the semiconductor industry in setting standards and acceptance tests for critical elements of high power laser systems.

The telecom teleconference call concluded with commitments of panel members to provide additional one page summaries of Research Opportunities in eye-safe lasers, fiber and ceramic lasers, nonlinear optical materials and advanced coatings, chirped mirror coatings and power scaling of fiber lasers. These one page Research Opportunity statements are to be found in Appendix A.

Panel Meeting at the HEL-JTO Conference: May 6, 2009, Albuquerque, NM
The meeting at the HEL-JTO Conference allowed the Panel to meet with the Director of JTO, Dr. Mark Neice to hear a briefing on the JTO research plans in support of power scaling of lasers. One goal was to identify areas of research that were appropriate to AFOSR and not covered by the JTO portfolio of research projects. A second objective of the meeting was to discuss further the concept of the Virtual Center as an approach to meeting the infrastructure needs for progress in high energy and power lasers. A third goal of the meeting was to review the Research Opportunities one page statements to confirm that no important topics had not been omitted. Topics were identified and three additional Research Opportunities statements were prepared by panel members.

The presentation and discussion byof Mark Neice was appreciated by the Panel. In addition, it should be noted that Dr. Thomas W. Hussey, Chief Scientist of AFOSR, and Dr. Howie Schlossberg of AFOSR attended the briefing and discussion by the Panel.

Presentation by Mark Neice, Director JTO
Mark Neice presented an overview of the JTO research portfolio. The basic research element is supported at $12.5 million per year with projects that started in 2002 completed in 2007 and a new call for proposals. The funding not only has supported research in support of JHPSSL, but also Education and Internships. The JHPSSL support led to the recent successful demonstration of 105kW of output power from the diode pumped slab laser MOPA system developed by Northrop Grumman. The laser architecture and performance was were reported at the HEL-JTO meeting. Of note was the use of Adaptive Optics in the double pass slab amplifier beam lines and
the phased tiling of the seven beams to form the final beam. The output beam quality was near $M^2$ of two, slightly lower beam quality than expected. The laser did operate in a continuous mode continuously for tens of minutes and did meet the less than one second turn-on time.

Of interest to the panel was JTO basic research support in fiber lasers, and laser diode reliability. Ceramics were supported at the 6.2 level indicating a more mature materials research effort. Research in adaptive optics and high damage threshold coatings research was also supported.

The next phase in the JTO high power laser effort is to test a 25kW laser at the THEL site. The goal will be to learn about systems issues and about atmospheric propagation issues for the 1064nm wavelength laser wavelength. One member of the panel raised concern about the atmospheric propagation issue and whether the AO requirements have been adequately addressed by the JTO support.

The discussion included consideration of power scaling of fiber laser based high power systems and, limits in power scaling due to the onset of nonlinear effects. New fiber architectures for coherent adding of fiber lasers, and operation of fiber lasers at eye-safer laser wavelengths, and using electrical power requirements for the laser systems including the power to achieve adequate cooling of the laser system.

The lasing ions, Er, Tm and Ho were discussed as options for eyesafer operation at 1500nm, 2010nm. Fiber laser components including polarizers, couplers, and isolators were identified as weak links in power scaling of fibers.

The exchange of scientists between the AFRL Laboratories and Universities was presented as a positive step in building long term collaborations and in helping to bring young scientist and engineers into the field.

JTO Call of Proposals - November 2009
The next call for proposals at the 6.1 basic research level will be in late Fall, 2009 with proposals due in early 2010. The call for proposals will be for a 3 year plus 2 year option research program option.

A digital summary of the presentation by Dr. Mark Neice was provided to the AFOSR. A written summary of the JTO annual report is available as a presentation presented at the HEL-JTO technical meeting. For example, see paper CTuHH1.pdf, “Progress in the Development of High-Power Solid-State Laser for Directed Energy Applications” by Mark Neice, Jack Slater, Siva Mani, at the High Energy Laser Joint Technology Office, 901 University Boulevard, SE, Suite 100, Albuquerque, NM 87106.

Virtual Institute as means to address Infrastructure issues
Following the presentation by Mark Neice, the panel opened further discussion regarding the concept of the Virtual Institute to support basic research opportunities in materials and optical components critical to power scaling of lasers. It was noted that AFOSR has been well invested in laser research but not well invested in energy or power scaling of lasers. The materials and It was noted that special facilities in the US are not adequate to conduct research in lasers and key materials and optical components required for power scaling. One approach to address this lack of infrastructure, is to create a collaboration across key institutes. With technical
capabilities, that is create a Virtual Institute to focus on the key issues for energy and power scaling. Models of Centers include the STC and ERC of the NSF, and MRIs in the Defense funding researchDoD. The discussion did not reach a conclusion due to lack of time.

In addition to Panel members, the meeting was attended by guests Pete Latham of AFRL, Ian McKinnie of KML Labs and Eric Johnson of UNCC.

**Panel Meeting at CLEO**  – June 3, 2009 CLEO, Baltimore, MD
The final meeting of the Panel was held on Wednesday, June 3 at the CLEO Conference in Baltimore. The goal was to provide a rank order of key of 6.1 basic research areas that are of importance to the energy and power scaling of lasers. The panel discussion is summarized below. The Panel then met and discussed its findings with Dr. Thomas Hussey, Chief Scientist, Air Force Office of Scientific Research.

The discussion opened with the identification of areas of research that fit into the university research environment supported by AFOSR. Again progress in materials was identified as the key to making future progress in high energy and high power lasers. Materials research that held the most promise were ceramic gain media and fiber gain media, and optical coatings. Additional areas identified as important were highly efficient laser diodes for pumping solid state lasers, direct diode-pumped ultrafast lasers for high efficiency and high power operation, wavefront control of high power lasers, and progress in Mid-IR Lasers for applications to spectroscopy, remote sensing, and laser radar.

**Basic Research in key Materials**
The panel again returned to a theme that has been identified in previous meetings. The key to future scaling of energy and power is research in advanced materials. Of critical important is lower optical loss, higher damage threshold, and controlled heat removal.

**Ceramic Laser Gain Media**
Ceramics offer, for the first time, scaling of gain media to the meter scale dimensions at high optical quality. In addition, ceramic gain media can be engineered to optimize the performance of solid state lasers. In the past many materials potential laser crystals were not possible to prepare by the traditional melt and growth process because of the high melting point or the instability of crystal growth of the crystals. Ceramics open the door to many new laser materials because sintering temperature is well below the melting temperature. Further, in ceramics the dopant and index of refraction spatial distribution distribution of the dopant can be controlled to allow improved pumping laser efficiency and the control of the spatial mode. Cladding can be added to, control of Amplified Spontaneous Emission (ASE) and efficient pumpingand parasitic oscillation. The rRecent demonstrations of the preparation of ceramic laser gain media a from low- birefringent ceramic laser gain mediamaterials openss the door to the study of interesting gain media such as Yb doped S-FAP that hawiths a gain cross section that is nearly ideal for high energy storage lasers for fusion energy applications.

There are in place a number of research programs in the US, Europe and in Japan in laser ceramics. However, the surface has only been scratched by research to date and much remains to be done to the optimization of laser performance by ceramic engineering. The key areas of future progress lie is reducing the absorption and scatter loss, controlling the dopant distribution for efficient pumping and power extraction, engineering the gain media using mixed oxides to
broaden the gain bandwidth and reduce operating pulse widths to sub 50 fsec, for ultrafast operation, and removing defects and improving damage threshold by processing improvements.

Ceramics open the door to the exploration of new laser host and ion dopants. Examples include the sesquioxide host materials with their high thermal conductivity, the fluoride and mixed fluoride host materials for with millisecond energy storage times, and mixed oxide materials for broadening the gain bandwidth. At this time ceramic gain elements are fabricated in 10 x 10cm size. Progress in scaling to 100 x 100 cm is also important as is improving the optical quality and reducing the scatter and absorption loss.

The demonstration of the preparation of birefringent ceramic gain media and orientation of the ceramic via external magnetic field during sintering, open the door to the study of the preparation of electro-optic and nonlinear optical material that could eventually be scaled to the meter size. This area of research has very high payoff potential as it is very difficult to conceive of other approaches to prepare electro-optic and nonlinear materials at the size required to support energy and power scaling.

In addition to laser host materials, ceramics offer the opportunity to prepare highly transparent window materials with with improved power handling capability, and resistance to optical damage caused by external environmental factors, for example, dust, water, and flying objects. Ceramics can be formed into special conformal shapes to conform to the vehicle. This area of research is an extension of that of direct applicability to the laser sources, but they that enable the operation of the laser in unusual environments outside of the laboratory.

Fiber Lasers
The progress in fiber lasers has been enabled by the early investment in fiber preperform and fiber pulling technology by the telecommunications industry. Recent advances in photonic crystal fibers and in large mode area fibers for power scaling, and in high brightness laser diodes for pumping double clad fiber amplifiers have come about through research in both the university and industrial environments. Future progress in fiber lasers depends upon continued research investigations in multiple areas. However, in the United States the lack of fiber perform fabrication facilities and fiber pulling facilities suitable to support research studies has slowed progress.

Research in the design of the fiber oscillators and amplifiers is necessary to promote power scaling at high efficiency while limiting the onset of nonlinear effects such as Stimulated Brillouin Scattering (SBS), and Stimulated Raman Scattering (SRS), and Self-focusing. Significant progress has been made in power scaling of a single fiber by doubled clad pumping and large mode area fibers with means for spatial mode control. In addition, methods of temperature and strain modulation have been used to suppress the onset of nonlinear effects. Future progress will undoubtedly explore new fiber designs, novel new fiber materials such as phosphate glass with its resistance to photodarkening, and new dopant materials such as Tm for 2 micron wavelength operation. These areas of exploration are suitable for research programs in universities as they explore both laser design and material issues for innovative approaches to power scaling.

The limits of output power from a single fiber can be extended by adding fibers either incoherently or coherently. Fiber arrays are now being studied and approaches to coherent addition and phase control of multiple fiber systems is a topic of investigation. There remains
considerable room for innovation and improvement in both fibers and fiber arrays to enable power scaling to beyond the 100kW level.

Fibers are not perfect and suffer from optical damage and from the onset of photodarkening or color center formation. The underlying reasons for the photodarkening need to be investigated so that the issue can be resolved. Further, point failures of fiber systems by optical breakdown and damage remain an issue for power scaling and reliability.

Fibers that operate in the ultrafast regime are now commercially available for the generation of ultrafast light in a small, reliable system. There remains room for improvement through fiber design and dispersion control such that ultrafast fiber amplifiers can be improved in performance and reliability.

Optical Coatings
Optical coatings are critical for the control of light from high power and ultrafast lasers. Again, in the past the United States had research programs and Centers with capabilities for research in special optical coatings. This capability has eroded and research on special coatings is often led by teams outside of the United States. However, there remains a strong need for continued research on optical coatings to improve resistance to optical damage, to enable dispersion control of mirrors for reflecting ultrafast light. In addition, for special coatings at unique wavelengths and spectral regions such as the deep UV and the mid-Infrared are areas that would benefit from research.

Optical coatings in the past have been developed for laboratory environments with a clean, low-dust level, laboratory environment. In the real world, lasers and optical coatings will be used in the atmosphere with dust, high humidity and liquid water present. There is a clear strong case need for research to explore coating designs that can be easily and quickly cleaned, that have high damage threshold even with dust and dirt on the surfaces, and can withstand high average power from future lasers without significant thermal distortion.

Laser Wavefront Control
Wavefront control of laser radiation is often critical to the application. Wavefront control is especially important for the propagating propagation of laser beams through the atmosphere where thermal distortion of the air path leads to rapid deterioration of the laser beam quality.

There is a significant advantage to power scaling of lasers if beam control can be designed into the laser at the outset. This is often done through one dimensional cooling of the laser media (zigzag slab laser, thin disk laser, and fiber lasers are examples) to enable laser operation with minimum wavefront distortion. However, some wavefront distortion does occur, and modern lasers have been designed with adaptive optics integral to the design of the laser. This in turn leads to a natural hand-off of the laser beam to the optical delivery systems such as a transmitting telescope that may also include adaptive optics to correct for the distortion of propagation induced by propagation through optical path or through the atmosphere.

There are research opportunities for beam control and novel approaches for adaptive optics mirror design that should be explored to enable power scaling of lasers at high beam quality. The beam quality control extends to precise beam quality measurement and to means of confirming beam quality across the spectrum from the UV to the mid IR.

Ultrafast Lasers
There are a growing number of applications for ultrafast lasers that require pulse durations that approach a single cycle and also demand power scaling. Examples include optical clocks, precise physics measurements, high field physics, and the generation of coherent X-rays or X-ray lasers. The recent progress in ultrafast lasers has revolutionized the use of the laser as a precise tool for spectroscopy and for nonlinear imaging such as two-photon and Coherent Anti-stokes Raman Spectroscopy (CARS) microscopy.

The panel observed that the need for higher power ultrafast lasers places a demand on direct diode pumped ultrafast laser systems. Examples include diode pumped fiber ultrafast lasers and diode pumped mixed oxide ceramic lasers. Ultrafast lasers also place conditions on optical elements such as dispersion controlled mirrors, high reflectance dielectric gratings, and nonlinear frequency extension via Optical Parametric Oscillators (OPO) and Optical Parametric Chirped Pumped Amplifiers (OPCPA) for pulse compression and frequency conversion. There is clearly a need for research to extend ultrafast lasers to the Mid-IR for precision spectroscopy of molecular species.

Power scaling of Ultrafast lasers will enable new experiments on the interaction of light with matter at the ultra high field regime. Modern High Field Physics laser systems allow science to explore the interaction of high fields with matter and even explore the ionization of the vacuum. Further, high power ultrafast lasers in the Mid-IR enable the generation of soft X-ray by Higher Harmonic Generation (HHG). These coherent X-ray sources could be used to seed X-ray Free Electron Lasers (FEL) to improve the coherence. In the future, laser driven accelerators will enable scientists to probe physics at the TeV energy scale. A TeV scale laser accelerator will require 10kW of average power per meter from an ultrafast laser or 10MW of average power per kilometer for a 1TeV, 1km long laser electron accelerator.

On the lighter side, only a few milliwatts of ultrafast light is necessary to generate a white light comb of frequency comb across a modes spectrum that is more than one octave in bandwidth. This frequency comb enables the comparison of optical frequencies of two separate lasers and also enables the demonstration of an optical clock by locking one mode of the comb to an atomic reference transition. There are significant opportunities for research in atomic and molecular physics using precise optical clocks and frequency comparisons with a comb of modes. Precise clocks leads naturally to precise position and navigation. Today optical clocks are so precise that to tell time properly, the clock position must be known in the gravitational potential as raising or lower a clock relative to the center of the earth by a meter changes the clock rate.

Laser Diodes
The Panel discussed the importance of laser diodes to energy and power scaling of lasers. There are a number of fundamental physics and materials issues in the power scaling and efficiency improvement of diode lasers. The DARPA led SHEDS program was useful in leading to demonstrations of high efficiency diode lasers for pumping solid state lasers. However, the demonstrated 72% operating efficiency has yet to be transferred to commercial products. There is a clear need for research in diode lasers in both power scaling at higher efficiency and in extending the wavelength to the near IR for pumping novel Mid-IR lasers such as Tm:Ho:YAG. There is also a need for research to explore the fundamental limits of laser diode operation especially at higher temperatures. The two factors that will enable energy and power scaling of lasers are improved efficiency of the pump diodes and operation of the diode bars at higher temperatures. From a cooling perspective, higher temperature operation is a key to enabling operation in the field without water cooling.

Summary
The Panel held an open discussion with Dr. Thomas Hussy of the AFOSR. The key research topics for enabling for energy and power scaling of lasers were discussed at length. The dialog led to give and take discussion and clarification of opinions and assertions, and for testing the understanding of the concepts proposed for research exploration through future research. The discussion confirmed that the proposed research topics are at the 6.1 basic research level that is the strength at the core of AFOSR sponsored research programs.

**Findings and Conclusions**

The Panel meetings and teleconference were summarized into Findings and Conclusions. The key areas are:
- Optical Materials Research,
- Ceramic Gain Media,
- Fiber Lasers
- Wavefront Control
- Cryo-Operation of Lasers
- Ultrafast Lasers
- Diode Lasers
- JTO – AFOSR Research.

The Findings and Conclusions, organized as listed above, are listed separately at the front of the report.

**Research Program Opportunities at the MURI Scale**

In addition, the Panel prepared a series of Research Program Opportunities at the MURI Scale. These statements are concise summaries of the research area, the motivation for the research, the proposed research program, cost and duration, and the long range vision of the outcome of the research program. The Research Program Opportunities are listed in Appendix A.

The key areas include:
- Optical Materials Research for Energy and Power Scaling of Lasers
- Ceramic Gain Media
- Fiber Lasers
- Wavefront Control
- Ultrafast Lasers and Applications
Appendix A  Research Program Opportunities at the MURI Scale

Optical Materials Research for Energy and Power Scaling of Lasers

Title: Characterization of Optical Materials and Components for Advanced High-Power Solid State Lasers

Author: T.Y. Fan, Lincoln Laboratorys.

Abstract: Improved optical materials, including laser gain media and nonlinear optical crystals, and optical components are necessary for supporting the development of the next generation of high-power lasers. Characterization of these materials and components is key to making assessments of utility, to providing laser design inputs, and to providing feedback to materials and component developers.

Motivation for Research: Improvements in the quality and properties of laser materials and optical components have the potential to lead the next generation of solid-state lasers to higher power, higher efficiency, and smaller size, while maintaining diffraction-limited beam quality. For example, improvements in gain media characteristics such as thermal conductivity, thermal expansion, and thermal coefficient of refractive index enable higher power lasers with reduced thermal distortion. Higher efficiency lasers require lower loss optical materials and optical coatings that handle higher power densities. Characterization of advanced materials and components is required to quantify improvements and make assessments of progress. Measurements are also critical as feedback to materials and component developers as part of the research and development process. Much of the effort on characterization of advanced optical materials and components is performed on an ad hoc basis, often leading to unknown systematic measurement errors. Development of accurate measurement capabilities, along with advances in new measurement methodologies would enable more rapid and efficient progress.

Proposed Research Program, Cost and Duration: Accurate characterization is essential for progress in advanced optical materials and components. For laser gain media the important characteristics include, but are not limited to, thermal conductivity, thermal expansion, refractive index, parasitic optical absorption, optical scattering, and spectral characteristics (pump absorption spectrum, metastable level lifetime, gain spectrum). For nonlinear optical materials, these characteristics are similar except that the spectral characteristics are replaced by optical nonlinearities. A wide variety of optical components, such as dielectric reflectors, gratings, and modulators are used in high-power lasers. Damage or distortion of these components often limits the optical power density in laser systems, and consequently, absorption loss, scattering, and reflectivity are key characteristics. This area requires an investment on the scale of $2 M/year for the initial two years to stand up and validate measurement capabilities. An additional $1.5 M/year will be required for an additional 3 years to provide these capabilities to the community. It is envisioned that this effort be carried out across multiple institutions, each specializing in a subset of the measurement set.

Long Range Vision: The long range vision is a capability for accurate and rapid measurements and assessments of advanced materials and components to provide an integrated development environment open to the wider research community, in contrast to the fractured environment that currently exists. This will provide the basis for more rapid development and maturation of high-power solid-state lasers.
Title: **Eye-safe high-power lasers**

Author: Adolph. Giesen, Director, Institute for Technical Physics, DLR

Abstract: High-power eye-safe lasers can be operated with fewer hazards to people and to the environment since they are much safer concerning scattered radiation. This may offer complete new applications in many fields (materials processing, operation in open environment) and especially in DoD applications.

Motivation for Research: Today’s high power lasers operate in the 1 µm wavelength range with high efficiency and good beam quality, but these lasers are not eye-safe against scattered radiation. Therefore, a laser operating wavelength beyond 1.5 µm is desirable for avoiding hazard to people for all fields of application (e.g. materials processing, defense application, etc.). This will allow using high power lasers also in environments which can not be shielded against scattered laser radiation.

Proposed Research Program, Cost and Duration: Basic research will be necessary for the development of high-power, eye-safe solid state lasers. This research includes the laser materials (laser ions and host materials, as well), the laser diodes for pumping, and the complete design of the laser system. It includes also research on bulk designs (slab and disk lasers) and fiber lasers. For fiber lasers Tm and Er doped fibers seem to be an excellent choice for such a research whereas for bulk lasers, Ho-doped materials may also play an important role. Laser ceramics for this wavelength range should be included as well in this research. For such a research program, funding at the level of $2-4M/year will be necessary for a period of 5 years.

Long Range Vision: If high-power eye-safe lasers are available at the same power level as lasers in the 1 µm range, many more applications of high power lasers can be envisioned for all applications with far fewer laser safety precautions and without hazard to people and to the environment.
Title: New Nonlinear Optical Material Architectures

Author: Christopher Ebbers, Lawrence Livermore National Laboratory, Livermore, CA

Abstract: Tremendous advances in nearly all areas of laser architecture (i.e. ceramic gain materials, novel resonator architectures, low loss coatings) have occurred due to advances in materials research. However, nonlinear optical devices (electro-optic switches and nonlinear frequency conversion devices) still rely upon traditionally grown crystalline substrates. As an example of a recent disruptive technology, Japanese researchers have potentially revolutionized the field of ceramic laser gain media (again) through the use of anisotropic precursors for ceramic laser hosts. A concentrated effort in novel nonlinear optical devices, methods, and techniques will also enable high pulse energy, high average power, wavelength, and pulse length agility of the next generation of laser sources.

Motivation for Research: Ceramic laser media remove many of the constraints imposed by conventional crystal growth for high power nonlinear optics. These concepts include:

- Large aperture, high power nonlinear optical switches and frequency converters (> 10 cm aperture) for high energy and high repetition rate fusion lasers.
- High average power frequency, high efficiency, up/down converters for blue-green wavelengths and “eye-safe” wavelengths.
- Ceramic fiber frequency converters for fiber coupled laser sources.
- Graded nonlinear optical conversion profiles that enable optimum conversion of Gaussian and other non-flat-top pulse profiles.
- High power, lower voltage electro-optic switches from materials developed for high efficiency sonar (such as transparent PLZT).

Proposed Research Program, Cost and Duration: To achieve these goals, a coordinated nationwide program is needed to address both the materials science of transparent nonlinear optical ceramics and the laser technologies they enable. This program will not only underpin the fundamental science for sustained industrial development, but will also provide the next generation of scientists and engineers to attain technical leadership in this field.

Despite the initial Japanese lead [1-2], their principal achievement being the initial demonstration of an non-cubic laser ceramic, there are many unsolved questions before the full impact of this novel technology can be realized with other materials. Magnetically (or electrically) oriented nonlinear optical ceramics is currently only a concept. With the advent of the demonstration of oriented anisotropic ceramic laser hosts [1-2], a significant return on investment for both the commercial and government sectors is possible in terms of new laser technologies, new architectures, and new capabilities. A substantial (several $M/year program spread over 5 years) should be sufficient to accomplish this objective.

Long range vision: It is anticipated that most solid-state lasers of the future may be built with ceramic materials. Small high power lasers, fiber lasers, or “free-energy scavenger” lasers will exist at new wavelengths with compact monolithic pumping architectures at low cost. Even laser fusion energy generation may be possible with high-repetition-rate Mega Joule class laser systems. Each facet of development in laser technology has relied extensively upon materials development. An investment in the area of ceramic nonlinear optics and novel nonlinear conversion techniques and devices will pave the way, reducing the need of limited aperture conventional growth crystals, enabling the pulse and wavelength agility needed for tomorrow’s missions.

Ceramic Gain Media

Title: New Laser Architectures with Ceramic Laser Materials

Authors: Martin Richardson, Townes Laser Institute, College of Optics & Photonics, UCF
         Gary Messing, Dept. Material Science, Penn State University, PA.

Abstract: Japanese laboratories have established a commanding lead in the development of low-loss transparent ceramic laser gain media using high-pressure sintering of nano-particles. This disruptive technology promises to revolutionize the architecture and options of solid-state lasers as fundamentally as diode-pumping did a decade ago. The Townes Institute is investing > $2M in major facilities and new faculty to help the nation gain leadership in this pivotal technology.

Motivation for Research: Ceramic laser media remove many of the constraints imposed by conventional crystal growth for high power solid state lasers. These include:

- Large aperture gain media (> 10 cm) for HEL and HRR fusion lasers.
- High dopant concentrations enabling simpler, less costly waveguide and disc lasers.
- Ceramic fiber lasers.
- Graded dopant profiles that can be matched to new optical pump architectures.
- New dopants enabling high power lasers at new wavelengths and pumping architectures.

We need a coordinated university-based program to address both the materials science of transparent ceramics and the laser technologies they enable. This will not underpin the fundamental science for sustained industrial development, but will also provide the next generation of scientists and engineers to attain technical leadership in this field.

Proposed Research Program, Cost and Duration: To leverage the US into leadership in this area we must marshal the available academic expertise and interest in the country into a coordinated national effort. We propose a collaboration between the groups at UCF, Penn State and Stanford, including perhaps other universities, and possible industrial (VLOC, Raytheon, etc) and national lab partners to address the fundamental materials science, laser science and engineering to bring this technology to the ‘take-off point’ for industrial development. Despite the Japanese lead, their principal achievement being the development of high quality Nd:YAG ceramic, there are many unsolved questions before the full impact of this novel technology can be realized with other materials. Tm-doped ceramics for 2 m lasers and co-doped Cr:Nd ceramics for solar-pumped lasers are but two of these. A $2-4M/year program spread over 5 years should be sufficient to accomplish this objective.

Long range vision: In 10 years, we believe most solid-state lasers may be built with ceramic materials. They will be super-efficient (approaching 80% wall-plug, versus today’s 30% values) compact rugged light engines. Small high power lasers will exist at many new wavelengths with compact monolithic pumping architectures at low cost. These will enable eye-safe and multi-purpose sensing and interdiction lasers. Solar-pumped lasers will be employed in satellite beam powering, imaging and sensing. A new generation of crystal (ceramic) fiber lasers will exist. High-energy and high power lasers will revolutionize laser weapons, producing powers in the MW range, and lower-cost industrial light engines for welding and cutting than today’s lasers. Dual use lasers for defense and medical applications with wavelengths in the Mid-IR will revolutionize the sensing of organics for CBND and motivate new developments in non-invasive, medical and cancer diagnostics and therapy.

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1 Un-doped transparent ceramics will offer many advantages for windows, domes, and mid-IR optics
Title: Next Generation of Laser Ceramics

Author: Takunori Taira, Laser Research Center, Institute for Molecular Science, Japan

Abstract: Newly developed rare-earth doped transparent ceramics offer the possibility of larger size, lower loss, and higher optical quality than traditional single crystal laser media. Laser ceramics also offer the potential of new host, ion combinations, doping profile to optimize beam quality and laser performance. However, they were limited only to the cubic materials. If the polycrystalline anisotropic ceramics are available by the sintering method, a tremendous breakthrough should be expected in the cutting edge of photonics.

Motivation for Research: Two typical Yb-lasers are prime candidates for a laser fusion driver; one is the Yb:SFAP and the other cryogenic cooled ceramic Yb:YAG ceramics. Both systems are attractive for the extreme high-energy high-power lasers from a gain and efficiency point of view. Well known Yb:YAG has a small quantum defect, enough high but excellent thermo-mechanical properties and scalability by as a ceramics nature., however, its small emission cross-section is too small at room temperature. That is why, we have to require operation below room temperature. cool down the material to increase the emission cross-section (laser gain). On the other hand, the gain of cross-section of Yb:SFAP is is enough high near optimum at room temperature. However, it was in the past it was not impossible to fabricate Yb:SFAP it as a ceramic due to its anisotropic nature and therefore, . (There was is no way for to scalability scale in Yb:FAP to the large dimensions needed for energy scaling. If we can find the way for to prepare optically transparent anisotropic ceramics (include RE:FAP, YVO₄ etc.), the new window when a new era of extreme high-power energy laser systems is possible.(the future application for ~MW solid state lasers, Energy storage in ceramic gain media would open the possibility to the generation of energy via laser fusion/fission reactions., Other applications include and laser driven advanced particle accelerators for exploring nature at the TeV energy scale, and for the generation of coherent X-ray radiation .) could be expected.by accelerator driven FEL lasers.

Proposed Research Program, Cost and Duration: Basic research in ceramic processing technology will be is essential for progress to occur in advanced solid state ceramic lasers. To open the possibility for the given up exotic materials such as anisotropic ceramics, we’d like propose to apply explore the use of the magnetic fields under during the sintering process. Because we have recently found that the spin-orbital magnetic moment of the doping rare earth ion strongly enhances the net magnetic anisotropy of laser ceramics, recently. By using this magnetic alignment, it is possible to achieve crystal orientation controlling of the polycrystalline ceramics easily. Also, this method could be extended many of the rare-earth ions such as Yb, Nd, Ce, Tm, Ho, and Er, and so on for and to the new laser hosts, nonlinear materials, and electro-optics materials. This kind new ceramic should be compensated the drawback of current single crystal and ceramics lasers. We can expect the extremely high power and/or high-field lasers, the wavelength from THz-wave to hard X-ray region compact light sources to accelerate the cutting edge of laser science. These research opportunities are of the scale of 2 – 4 million dollars per year for five years.

Long Range Vision: The long range vision is the confirming of the advantages of Yb:SFAP ceramics as a next generation of fusion drivers, not only for the thermo-mechanical improvement, but also the engineered structure and spectrum profiles for the sophisticated extreme high-power lasers and/or ultrafast short pulse lasers. On the other hand, RE-doped vanadate lasers are opening the laser applications, such as the
machining, printing, and laser TV., and measurement systems. If vanadate ceramics can be realized, then new applications would open for ceramic lasers. field could be expected. The next generation of laser ceramics, The development of the fabrication principle for the anisotropic laser ceramics, will involve the giant micro-photonics in the laser science and industrial applications. will enable energy and power scaling of solid state lasers to MegaJoule and MegaWatt levels at optimum efficiency and performance.

Title: Research in Laser Ceramics for Advanced High Power Solid State Lasers

Author: R. L. Byer, Ginzton Lab, Stanford University

Abstract: Ceramic gain media offer the possibility of larger size, lower loss, and higher optical quality than traditional single crystal laser media. Virtually all highall multi-kilowatt average power lasers today are based on transparent, low loss, laser ceramics. Ceramics also offer the potential of new host, ion combinations, and control of the doping profile to optimize beam quality and laser performance.

Motivation for Research: The application of high average power lasers depends upon the efficiency and reliability of the laser system. Today diode pumped solid state lasers operate at 20% electrical efficiency with the potential of reaching 40% efficiency in the future. Today, advanced solid state lasers operate at 100kW of average power with the potential for scaling to beyond MW of average power. Today, solid state lasers operate at near diffraction limited beam quality by use of adaptive optics within the laser. Future applications demand high beam quality, high efficiency, and high reliability for the laser system. The application for ½ 1 to 10 MW solid state lasers include RAM defense, generation of energy via laser fusion/fission reactions, and laser driven advanced particle accelerators for exploring nature at the TeV scale and for the generation of coherent X-ray radiation.

Proposed Research Program, Cost and Duration: Basic research is essential for progress in advanced, ceramic-based, solid state lasers. To increase efficiency the laser gain medium must have reduced absorption and scattering loss. To increase beam quality, the laser gain medium must be ‘engineered’ to allow heat removal with minor disturbance of beam quality. There exists opportunities for new discoveries in ceramic gain media due to the wide range of new host materials that can be prepared by ceramic processes but not by single crystal growth. One example is Tm doped ceramics for operation at two microns in the eye safe spectral region. Another example is the engineering of wide gain bandwidth laser transitions for ultrafast operation of the laser to enable Higher Harmonic Generation and frequency combs spanning the Infrared section region. These research opportunities are of the scale of 2 – 4 million dollars per year for five years.

Long Range Vision: The long range vision is the era of 40% efficient electrically driven solid state lasers with power levels that extend to multi-megawatts of average power. A modular all solid state laser system with built-in adaptive optics beam control will enable key advanced energy, basic research and DoD applications.
Fiber Lasers

Title: Scaling of fiber laser output power and pulse energies

Authors: Chris Barty, Ray Beach, Mike Messerly and Jay Dawson, Lawrence Livermore National Laboratory

Abstract: Fiber lasers have scaled rapidly in recent years in both output power and pulse energy. It is now possible to make efficient robust fiber lasers with output powers on the order of 10kW or pulse energies on the order of 10mJ. Optical fiber laser architectures are compact and do not require alignment after manufacture as the system is a continuous waveguide that can be designed to support only one spatial mode. These qualities make this technology of high interest for military applications particularly in the area of pointing, tracking and illumination lasers. This topic area proposes R&D in support laser systems that scale, at eye safe wavelengths, to militarily relevant output powers and pulse energies.

Motivation for Research: Advances in compact, efficient, robust fiber laser technology with the potential to scale beyond the current limitations of 10-20kW average output powers\(^1\) and 4MW peak pulse powers\(^2\) would be enabling for both illuminators and for directed energy weapons. Further scaling of both pulse energy and average power of fiber lasers requires scaling of the effective area or aperture of the fiber waveguide. This must be done without sacrificing the desirable attributes of the fiber waveguide such as the ability to bend it for packaging in a compact form factor without degrading the performance.

Currently the highest output powers and pulse energies are only obtainable with good efficiency at 1µm laser wavelengths. At this wavelength eye safety is concern, particularly for use in uncontrolled settings. At eye safer wavelengths such as 1.5µm or 2µm, optical to optical efficiencies for fiber lasers is much lower. R&D is needed that supports development of fiber laser systems with >80% optical to optical efficiencies at wavelengths longer than 1.3µm.

Finally, for these systems to produced the powers and pulse energies desired for military applications, peripheral components such as all fiber optical isolators, fiber pump signal combiners, fiber couplers and fiber amplitude and phase modulators capable of handling the power and energy levels under consideration need to be developed. Technology in this area is very embryonic, but essential to fielding a useful system.

Proposed Research Program, Cost and Duration: There is a need to invest in research in:
- Concepts for waveguides that enable scaling of fiber laser average power and pulse energy in a form factor that retains the ability to be packaged.
- Improving efficiencies of fiber laser systems that operate at wavelengths longer than 1.3µm.
- All fiber components such as optical isolators, pump signal combiners, couplers and amplitude and phase modulators that are compatible with the wavelengths, powers and pulse energies needed for military applications

To make significant progress in developing new concepts in these areas an investment of $2M/bullet point/year over a 3-5 year timeframe would be required.

Long Range Vision: At the completion of this R&D new concepts will have been developed for scaling the average powers and pulse energies of fiber lasers to levels needed for military applications such as LADAR and directed energy weapons at eye safe wavelengths and be ready for development into commercial systems that can be fielded in a military environment.

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Title: Fiber Beam Combination

Author: Joshua Rothenberg, Northrop Grumman Aerospace Systems

Abstract: Fiber lasers have recently been demonstrated at both high efficiency and power, and also have an excellent path for ruggedized and compact packaging, making them a very attractive option for directed energy (DE) applications. The rapid progress in development of high power fiber lasers has resulted in single-mode fibers emitting average power over 5 kW. Further progress is to be expected, however, for DoD applications requiring 100 kW or higher with excellent beam quality, combination of many individual fiber beams will undoubtedly be required. Beyond power scaling, fiber beam combination architectures can also enable smaller and lighter payloads via electronic beam steering, atmospheric compensation, and elimination of large aperture beam directors.

Motivation for Research: Significant progress has been made in recent beam combination research, resulting in a number of architectures that appear well positioned to address the goal of 100+ kW scaling. These architectures include active and passive coherent, and wavelength beam combination methods, and have varying degrees of scalability and efficiency. Although initial work has shown promise for these techniques, the realization of much higher power scaling requires more research to show that hundreds of beams, or more, can be efficiently combined well beyond 100 kW. These approaches also often require precisely aligned free space optics, which can be undesirable in harsh environments. Further research in this area offers the promise of much more compact, rugged, and all-fiber architectures with greatly reduced laser, as well as beam-director, size and weight.

Proposed Research Program, Cost and Duration: Beam combination topics of interest include
- Highly scalable, compact architectures with a maximum efficiency and beam quality
- All-fiber architectures or those with a minimum of free-space optics
- Simplified, yet scalable active and passive phasing or other combination architectures
- Electronically steered systems with robust tracking and atmospheric compensation

Long Range Vision: Fibers have the clear potential to be the ideal technology for DE on mobile platforms, where size, weight, and rugged and flexible packaging are paramount. In the long term, this research can lead to the development of a highly efficient, compact, and rugged laser system, with a minimum of free space optics; perhaps completely all-fiber. In addition, some approaches allow for a conformal array of small apertures and electronic beam steering, potentially eliminating the need for a large and heavy beam director. With such advances, the deployment of significant DE power on platforms with very limited payload capacity (such as UAVs) may become within reach, enabling a revolutionary military capability. In addition, a compact system with the demonstrated reliability of fiber laser technology may become a practical alternative to chemical laser sources for MW-class scaling.
**Title:** Next-Generation Fiber Laser Technologies

**Authors:** Martin Richardson and Ayman Abouraddy, Townes Laser Institute
CREOL, College of Optics & Photonics, UCF

**Abstract:** Fiber laser development is on a strong upward trend, with world-wide industrial growth advancing at ~25%/yr. Their efficiency, compactness, ruggedness and low cost are attractive for weapons and sensor systems. The US has long suffered from not having an academic center of excellence in fiber lasers that is comprehensive enough to encompass fiber fabrication and design through to fiber laser development. Consequently, the DoD resorts to expending We note significant funds at research breakthroughs at Southampton University for present-day fiber development. Furthermore, we see strong fiber laser groups evolving at Erlangen and Jena, Germany and a significant investment in portion of all photonic crystal fiber work located in Denmark. The next generation of these fiber laser researchs will involve multi-structured, multi-material fibers that feature photonic band gap structures, extending high-power lasers to new wavelengths, particularly in the eye-safe IR and mid-IR regions, and to broad-band and high-power ultra-short pulse regimes. The Townes Laser Institute at the University of Central Florida, a new $10M center of excellence in advanced laser technology in Florida, is investing ~ $5M in new facilities and several new faculty positions to regain the US initiative in fiber laser technology, not only by matching capabilities abroad, but also introducing new modalities not yet achieved elsewhere.

**Motivation for Research:** New fiber designs relevant to fulfilling the DoD mission necessitate the incorporation of new materials and the development of new fiber-fabrication strategies. The new designs will produce fiber laser sources in the eye-safe IR and mid-IR, ultra-high power continuous wave lasers, ultra-short high-intensity lasers, and ultra-broad bandwidth sources. Some of these new designs will incorporate oxide and non-oxide materials in single multi-material fiber structures, an approach that has not yet been attempted abroad. They will take advantage of emerging preform and fiber fabrication techniques that will to reset the landscape in fiber laser technology. Not only will these combined developments lead to higher-power lasers and devices, they will further introduce innovative modalities for fiber lasers open up new avenues for their associated applications.

**Proposed Research Program, Cost and Duration:** We need to invest in research in:

- Next-generation photonic crystal fibers for high power lasers (eye-safe and mid-IR).
- Large-mode area (LMA) fiber design and fabrication for high-energy pulsed fiber lasers
- New glass science and preform fabrication technology that enable new laser modalities.
- New fiber-device development both for pumping and fiber-beam-combining.
- Ultra-short (femtosecond) and wide-bandwidth or tunable fiber laser technologies at new wavelengths, including THz, for sensors, interdiction and countermeasure techniques.

A sustained investment (~5 years) at the $2-4M/yr level, drawing on expertise in other universities, national laboratories, and industry will help pull the US into prominence in this critically strategic technology.

**Long-range vision:** Fiber lasers are already heading towards powers in excess of 100 kW, the threshold for many weapons applications, and appear capable of providing powers approaching the MW range. Investing in the next generation of fiber laser technology will help the US attain leadership in many DoD arenas. Moreover spinoffs in medical and manufacturing technologies will give a competitive edge to US industry, and a university-based program will ensure the training and education of the next generation of scientists and engineers in this field.
Wavefront Control

Title: Wavefront Control

Author: Hagop Injeyan, Northrup Grumman Advanced Systems (retired)

Abstract: Wavefront control is a fundamental issue for scaling of solid state lasers. Novel gain media architectures that intrinsically provide good beam quality can provide a quantum leap in power and brightness.

Motivation for Research: Power scaling of solid state lasers with near-diffraction limited beam quality continues to be an essential goal for future military and industrial applications. Wavefront control is a critical part of the scaling process as existing approaches become less effective and more cumbersome at increasing power levels. A look back at the rapid increase in solid state laser brightness points to approaches that have enabled quantum leaps in solid state laser brightness. The first was the implementation of the zig zag slab architecture which enabled power scaling from 10s of watts to multikilowatt level, the second was the development and power scaling of the fiber laser which has results in similar breakthrough in brightness. The zig-zag slab architecture was design to substantially average over the aberrations in a gain medium and now relies on complementary technology such as nonlinear phase conjugation or deformable mirrors for near diffraction limited beam quality. The fiber laser approach, on the other hand, consisted of an architecture that is inherently immune to wavefront aberrations and this approach has now enabled scaling the power level of a single aperture to > 5 kW with no external wavefront control. However, fiber lasers are now approaching the intrinsic damage limit of fiber and are not well suited for pulsed applications. Thus innovative approaches that can potentially produce bulk gain media that are inherently only supportive of flat wavefront propagation could represent another quantum leap in solid state laser brightness.

Proposed Research Program: The proposed research would be directed in developing scalable laser gain media architectures that are inherently supportive of only flat wavefront propagation. An example of such an approach might be to engineer gain media that have no index variation with temperature using transparent mixed ceramic materials. Another approach would be to incorporate photonic band-gap structures in bulk laser media. Recent studies in materials with photonic band-gap structures have shown that the propagation vector of beams in such materials can be controlled and manipulated. The proposed research may be structures in multiple phases. The first phase would consist of modeling to simulate wave propagation through such media and demonstrate analytically that it robustly maintains wavefront uniformity in the presence of temperature variations. This phase would also include evaluation of various methods to fabricate such media. The second phase would be the fabrication and testing of small samples of the proposed materials to validate the analysis. Determining the power scaling limits of the material should also be an important goal of the research.

Long Range Vision: The long range vision of this research is to lay the ground works for fabricating and testing large pieces of gain media that are inherently resistant to wavefront distortions in high power lasers. The material can then be used to assemble high power solid state lasers that are well beyond the current SOA.state of the art.
Title: Enhanced Laser Beam Quality with Advanced Gain Media - Infrastructure

Author: L. A. (Vern) Schlie, Integral Laser Solutions, LLC, Albuquerque, NM

Abstract: Thermal management of laser gain media is intimately coupled to the resultant laser Beam Quality (BQ). For future Air Force High Energy Laser (HEL) airborne applications, excellent BQ values less than 1.1 x Diffraction Limited (DL) performance is essential along with high efficiency and compact size. Any excess pumping energy not extracted as laser energy and deposited in the gain medium creates significant effects on the ultimate laser BQ. Today, typical Solid State Lasers (SSL) lasers have thermal conductivity values in 2 – 10 W/m K° range. Significantly higher values of 100 – 200 W/m K° for the laser gain mediums and conductive heat removal infrastructures like heat spreaders would result in a paradigm shift toward achieving excellent BQ in SSL system. Therefore, it is recommended that materials like a “doped SiC or BN gain medium” be investigated using nanotechnology or “other to be conceived / developed approaches” to create these desired, very specialized materials.

Motivation for Research: Advanced laser gain media and supporting high thermally conductive infrastructure materials should be explored to minimize thermally induced stress birefringence and polarization dynamics under high power volumetric excitation. Although ceramic laser media remove many of the constraints imposed by conventional crystal growth as described in the “New Laser Architectures with Ceramic Laser Materials” short paper, ceramics still have K values in the 2 – 10 W/m K° range which can resultant in large aberrations in the gain medium. Greatly improved laser gain / infrastructure materials with much higher thermal conductivity values offer significant features including

- Potential isothermal temperature profiles across gain medium and along gain axis
- More efficient laser operation due to lower quenching kinetic rates
- Large aperture gain media values for HEL with increased “thin” disk thicknesses.
- High dopant concentrations enhancing gain with minimal temperature increases
- Reduced crystal failures for bonded gain media due to” non-matched “ CTE effects
- Higher volumetric power excitations for laser gain media without crystal failure and reduced efficiency

To acquire these materials, AFOSR should attempt to utilize the US national programs on nanotechnology plus have a coordinated university-based program emphasizing thermal properties of laser gain / infrastructure materials that minimize deposited energy effects in the laser gain medium. Monolithic laser gain media and thermal removal systems should be investigated. In addition, the US should attempt to be very selective to acquire US students and/or foreign students desiring to remain in the US after they acquire their degrees in order to enhance the United States’ HEL manpower for future years.

Proposed Research Program, Cost and Duration: research should capitalize on the large US and international nanotechnology efforts to “engineer” high thermal conductivity materials in both (1) SSL gain media with high quantum efficiency and operation in the 1-2 micron region and (2) supporting infrastructure. Specifically, AFOSR has a very large effort in nanotechnology; they should interact with the DOE national labs; and they should incorporate international activities into their efforts via the EOARD and AOARD interactions. These activities should address room temperature and lower including operation at liquid nitrogen temperature if appropriate for the specific new laser systems developed. A $1.5 - 3M/year program spread over 10 years should be advocated to explore and demonstrate approaches toward making available much higher thermally conductive SSL materials. These materials, if they become available, would enable the demonstration of excellent BQ SSL in the 10 – 25 kW (cw) range and be traceable to average powers greater than 100 kW’s.

Long range vision: In the next 5 - 10 years, it appears reasonable that the use of the nanotechnology field would enable the “engineering” of very highly thermal conductivity SSL gain / infrastructure materials which could result in excellent BQ performance. Such materials should allow SSL systems to be much more compact along with high efficiency at much higher volumetric power loading (>> 100’s kW’cm³). The AF’s use of such SSL would be extensive for various airborne platforms. A paradigm shift in the advances of HEL technology could occur for cw, pulsed (> nsec) and ultrashort laser system at high average powers.
Ultrafast Lasers and Technology

Title:  Research in Coherent High Energy Laser Pulse Synthesis

Author:  F. X. Kaertner,  MIT

Abstract: The advent of carrier-envelope phase stabilized ultrafast lasers has revolutionized frequency metrology providing a set of equally spaced optical lines. There is an enormous opportunity to turn these new laser stabilization techniques around and exploiting them for the construction of novel high energy and high intensity laser systems using pulse synthesis in the frequency domain or coherent pulse addition in picosecond and femtosecond enhancement cavities. Here, we consider the former approach.

Motivation for Research: The generation of ultrashort (single-cycle) and high energy laser pulses is limited by the bandwidth of available laser materials and the capability of matched stretching and recompression of pulses in chirped pulse amplifiers. The first limitation can be overcome by using multiple parametric amplifier stages with moderated bandwidth but different center wavelength pumped by individual high energy pump lasers. Such a system can in principle cover the full visible and infrared wavelength range. The individual optical parametric chirped pulse amplifiers (OPCPA) can deliver 100-200 TW pulses at different center wavelength. Wavelength multiplexing of these high energy pulses via gratings and large scale dichroic mirrors enables the synthesis of Petawatt class single-cycle waveforms overcoming both bandwidth limitations and the power limitations due to the limited stretching/compression ratios achievable in each individual stage. Key to this technology is the coherent pulse synthesis at both high repetition rates (100 MHz) as well as on single shot systems with attosecond precision, roughly to a precision of a tenth of an optical cycle.

Proposed Research Program, Cost and Duration: Basic research in attosecond precision laser synchronization and pulse synthesis is essential for exploiting these new degree of freedom for engineering both the wavelength coverage, i.e. pulse duration, and pulse energy of future high peak power laser systems. For high energy laser systems this has to happen at low repetition rates, which is only possible if underlying to the high energy pulse a pulse train at high repetition rates is present, which is possible to achieve. Our group made major progress towards this goal over the last few years. Next, is the development of 100 TW class OPCPAs covering the wavelength range from 600 nm to 2 m. Large area multiplexers based on the combination of gratings and dichroic mirrors need to be developed to achieve the coherent beam combining of the partially compressed output from the OPCPAs. Characterization of the generated high energy pulses and feedback to the individual OPCPAs needs to be accomplished to maintain compressed pulses over arbitrary operating times. This research would require funding at a level of $500k per year for five years to demonstrate feasibility of this concept

Long Range Vision: The long range vision is the construction of a modular Petawatt class single-cycle laser technology, with full control over the electric field waveform, for high intensity laser physics studies, such as laser acceleration and attosecond pulse generation from solids. As an example this technology should enable the generation of 3-Petawatt, 3-fs laser pulses at 10-100 Hz repetition rate using a chain of 5-10 OPCPAs pumped by individual cryogenically cooled Yb:YAG lasers.
Title: Research in Dispersion Compensating Laser Mirrors

Authors: L. Kolodziejski and F. X. Kaertner, MIT

Abstract: Active and passive ultrafast laser systems are revolutionizing many areas central to DOD missions and capabilities, such as directed laser energy systems, precision optical metrology to enhance inertial navigation systems, and hyper-spectral radiography sources. Many, if not all, of these applications either benefit considerably or are only possible due to exquisitely precise dispersion control enabled by novel Dispersion Compensating Mirror Systems (DCMS).

Motivation for Research: The difficulty in the use of DCMS is in its design and fabrication matched to the demands in a given application. Typical layer thicknesses of dielectric mirrors in the visible to infrared are on the order of 100 nm. In lasers generating octave spanning spectra or close to single-cycle pulses (3 fs duration at 800 nm wavelength), the control of the optical thickness of these layers must be accurate to about 0.25% of the layer thickness (i.e. a few Angstroms) to achieve dispersion control good enough to not impact the pulse formation in the laser cavity. An acute need for more challenging dispersion control of DCMS exists to enable completely new applications, such as passive high power femtosecond enhancement cavities to enable the build-up, storage and use of high energy femtosecond laser pulses with bandwidth greater than 40 nm, which are needed for efficient EUV generation or EUV laser frequency combs or passive filtering of femtosecond laser frequency combs to achieve higher mode spacing over extended wavelength ranges approaching one octave.

Proposed Research Program Cost and Duration: Basic research in the design and fabrication of high damage threshold chirped mirrors is needed to enable DCMS for wideband dispersion compensation of both few cycle pulse oscillators and amplifiers. We propose to work both on novel design and fabrication methods and especially control of layer thickness during growth. The Kolodziejski group has a dedicated state of the art VEECO ion beam sputter deposition system for high precision growth of high damage threshold dispersion compensating laser mirrors. This research will require funding at a level of $250k per year for five years to further develop both the necessary design, fabrication and characterization tools enabling a reliable fabrication of DCMS.

Long Range Vision: The long range vision is to develop reliable design and fabrication processes for DCMS pushing the effective fabrication tolerance of layers to the 0.1% range. This will enable the fabrication of ultra wideband DCMS for octave spanning laser and amplifier systems and for high power (multi-MW) femtosecond enhancement cavities. Such cavities are the equivalent of microwave cavities and will enable a host of novel laser driven radiation and particle sources.
Title: Research in Saturable Bragg Reflectors for Modelocking Short Pulse Lasers

Author: Leslie Kolodziejski, MIT

Abstract: Saturable Bragg Reflectors (SBRs) are necessary components in short pulse lasers by providing an intensity-dependent reflection that establishes and sustains modelocking conditions for the laser cavity. A SBR consists of an absorbing layer integrated with a high-reflectivity mirror; designs can also incorporate dielectric coatings to affect the intensity and position of the peak of the electric field within the SBR. Of critical importance for modelocking are the mirror reflectivity and bandwidth, the absorption wavelength and bandwidth, the saturation fluence, the carrier lifetime, and the semiconductor material stability within high power laser cavities.

Motivation for Research: Specifically designed saturable Bragg reflectors are necessary for short pulse generation with a particular laser medium and laser cavity. Improved SBRs provide the opportunity to create new femtosecond (fsec) lasers with an increased bandwidth coverage than is available today at different repetition rates and output powers. Semiconductor-based SBRs enable the absorption wavelength to be varied from visible wavelengths to infrared (~3 µm) wavelengths. Similarly, the use of integrated semiconductor/oxide dielectric stacks allow the mirror bandwidth to be appropriately broad and centered accordingly to create femtosecond pulses.

Proposed Research Program, Cost and Duration: Thus far, SBRs, operating at telecom wavelengths (1550 nm) and at shorter wavelengths (~800 nm), have been developed with broad bandwidth (~100 nm) and have created short fsec pulses in a variety of laser cavities and laser materials (Ti:sapphire, CrLiCaF, CrLiSAF, Cr:LiSGAF, Cr:YAG). The broad bandwidth coverage is achieved by initially integrating the desired absorber with a low dielectric contrast mirror stack that is composed of AlAs and AlGaAs; subsequent exposure of the AlAs to a high temperature steam environment transforms the AlAs into AlxOy creating the necessary high dielectric contrast mirror. Issues related to strain, when the high Al-content AlGaAs is transformed into an oxide layer, has restricted the SBR size (~500 µm) and affected the SBR stability when the pulse energies are increased. Furthermore, integrated absorbers onto such broad bandwidth mirrors have been limited to InGaAs or GaAs-based absorbers due to lattice-mismatch considerations. However, the III-V materials including arsenides, phosphides, nitriles and antimonides offer a very wide range of material combinations for designing SBRs to function as modelocking elements in fsec pulse lasers. The research that is needed involves SBR design, III-V layer growth, further refinement of oxidation conditions, and application of necessary coatings for additional control of the electric field. This research would require funding at a level of $250k per year for five years to develop and provide a stable supply for SBRs covering the visible to 3000 nm wavelength range.

Long Range Vision: The long range vision offers a greatly expanded wavelength coverage for pico and femtosecond pulse lasers from the visible to the infrared and with high output powers.
Solid State Laser Drivers for X-ray Generation

Title: Development of High Power Infrared Lasers (1 – 10 μm) for Applications in Coherent X-RAY Generation and Nanoimaging

Authors: Margaret Murnane and Henry Kapteyn, University of Colorado at Boulder Boulder, CO 80309-0440

Motivation: New scientific opportunities have become apparent that rely on the development of high-power ultrafast lasers in the infrared between 1.5 and 10 μm. Our work to-date used ultrafast Ti:sapphire-based lasers to generate coherent beams of short-wavelength light in the soft x-ray regions of the spectrum. This approach uses extreme nonlinear optics to coherently up-convert laser light from the visible region of the spectrum,[1, 3] resulting in tabletop coherent beams of soft x-rays. Moreover, this source has proven to be a powerful tool for science and nanotechnology, making possible new applications in high-resolution imaging, understanding heat transport on nanoscale dimensions, and monitoring chemical reactions in real time.[4-7] Recently, we made two breakthroughs by demonstrating through fundamental scaling that this process can be phase matched even into the multi-keV region of the spectrum,[2, 3] making it feasible to generate bright and fully coherent hard x-rays. We have experimentally verified these ideas up to photon energies of ≈ 0.4 keV. The ability to produce coherent hard x-ray beams would allow for a revolutionary advance in spatial resolution for x-ray imaging techniques. Moreover, the development of a coherent hard x-ray light source on a tabletop would be among the most significant advances in optical technology since the invention of the laser itself.

Proposal: To produce bright beams of coherent hard x-rays in the lab, cryo-cooled, high average-power (tens to thousands of watts) ultrafast lasers in the mid-infrared region of the spectrum between 1 and 10 μm will be required to drive this process. This laser technology alone has many applications of interest to DoD, including the generation of hyperspectral sources, directed energy beams of particles and photons, nanoscale imaging, and remote sensing. This region of the spectrum also corresponds to the eye-safe region of the spectrum, making potential field applications of ultrafast lasers much more feasible compared with current lasers operating at ~800 nm region. To accomplish this, a number of mid-IR laser materials that have been developed for LIDAR (laser radar) applications would also be suitable for ultrashort pulses. The other approach is to use nonlinear optical techniques – specifically optical parametric amplification– to convert near-IR to longer wavelengths.

References:
Title: Research in Laser Driven Table-Top Collimated X-Ray Sources

Author: H. Injeyan, Northrup Grumman Advanced Systems (retired), Redondo Beach, CA

Abstract: Coherent or highly collimated table-top x-ray sources have the potential to create a new paradigm shift in laser weapon systems by penetrating through the shell and disabling the target at modest powers instead of using high powers to burn through the target shell.

Motivation for Research: High power lasers have been slow to deploy as weapon systems either because of the undesirable logistics of handling unsafe chemicals or because of difficulties in scaling electrical lasers. In addition, deploying optical frequency lasers over long ranges requires large mirrors; a problem which was in part responsible for the termination of the space-based laser program. Energetic x-rays have the capability to penetrate through materials, destroy the electronics and disable the target without the thermal kill that is the current paradigm. In addition, because of the short wavelength, their natural divergence is 5 to 6 orders of magnitude lower than optical wavelength lasers. Thus, an objective that currently requires 100s of kWs or MWs and multimeter diameter mirrors can be achieved with a few watts and no mirrors.

Proposed Research Program, Cost and Duration: Recent demonstrations of laser driven acceleration of electrons promise to reduce the scale size of highly relativistic electron accelerators by four orders of magnitude. In addition, novel concepts for cm-scale laser driven dielectric wigglers or plasma betatron wigglers provide the capability to generate energetic x-rays from these relativistic electrons. Significant basic research remains to be done in both acceleration and x-ray generation to achieve multiwatt x-ray sources with good efficiency. The research effort to bring this technology to a TRL 4 or 5 level is a 5 – 7 year effort on the scale of 3 - 4 million dollars per year for the initial 2 to 3 years increasing to 5 – 7 years the last couple of years.

Long Range Vision: The long range vision is a new generation of laser weapon systems where energetic x-rays are used to interrogate and if appropriate disable a wide range hostile targets