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UPON THIS ROCK… A FOUNDATIONAL SPACE SITUATIONAL AWARENESS TECHNOLOGY FOR 2030

by

Todd E. Wiest, Maj, USAF

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Advisor: Lt Col Christopher Shannon

Maxwell Air Force Base, Alabama

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Abstract

The use of space permeates all aspects of the American way of life. If the U.S. is to protect its space capabilities, it must increase its space situational awareness (SSA) to provide the foundation for activities in space. In the year 2030, congestion will describe the space environment. Space debris will be abundant, and satellite size will diminish through technology proliferation. The Air Force, as the Executive Agent for Space, will need to diagnose and attribute space events to meet this threat; however, current radar and optical telescopes cannot resolve these small objects. Using fluoride fiber lasers will address the threat and technological imperatives because this technology can enable intelligence, surveillance, and reconnaissance collection capabilities from space. This paper postulates a conceptual SSA system using a fluoride fiber laser payload to investigate system performance in three 2030 space scenarios. This conceptual SSA system provides benefits to the U.S. in all three scenarios; however, the system still has impediments to overcome. This paper discusses the political, economic, and legal impediments to system development and recommends developments in pulsed fluoride fiber laser output power, fluoride fiber devices, and small pump lasers to overcome the technical challenges. In addition, the paper recommends follow-on SSA system concept exploration.

Preface

This document is just one paper in the Blue Horizons Space research seminar, a CSAF-commissioned research project devoted to providing a 20-30 year estimate of strategic and technology trends. The Blue Horizons Space research seminar looked at different potential technological advances that could influence space policy, operations, and support. The results of the Blue Horizon Space research are an executive summary, underpinned by student-prepared white papers, targeted at key decision makers and planners. This research provides a framework for Air Force strategic planning, investment, and capability decisions.

While I have not been able to lead any laser projects for the Air Force recently, it was nice to return to my technological home, albeit for a short time. It was also nice to use my scientific background to support Air Force future planning. However, completing this paper required more than my background, so a few thanks are in order. First, my thesis advisor, Lt Col Christopher Shannon; thanks for helping me clear the fog quickly so I could focus on research. In addition, I owe thanks to Lt Col (Ret) Moscarelli for directing the Blue Horizons project. I'd also like to thank my fellow Blue Horizons Space seminar mates. It has been a fun and challenging journey with all of you. To Majors Bell, Galbreath, Keyser, and Ziegler, thanks for taking your precious time to read and comment on my early draft. To my son, Andrew, thanks for keeping me in touch with reality. To my daughter, Claire, thanks for helping me re-discover the wonders of the world, and to my wife, Corinne, thanks for all your love, support, and letting me use the dining room table as my "paper creation space."

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Section 1: The Importance of Space Situational Awareness

"The U.S. will not remain the world's leading space-fairing nation by relying on yesterday's technology to meet today's requirements at tomorrow's prices"—*Space Commission*

In March 2003, the 3rd Infantry Division (3d ID) pushed toward Baghdad. During this push, the 3d ID suddenly lost communications.[1] Since Milstar provided their connectivity, the call went out to the 4th Space Operations Squadron (4 SOPS) to fix the problem.[2] Air Force (AF) space personnel at 4 SOPS controlling the Milstar constellation quickly identified the problem; for some reason the Milstar spot beam moved.[3] After only 15 minutes, 3d ID regained connectivity.[4] The knowledge of the situation in space allowed a quick diagnosis and remedy to this communication problem. This support was possible because the AF had space situational awareness (SSA) of the Milstar system configuration. Rudimentary SSA allowed 4 SOPS personnel to diagnose and quickly remedy the problem maintaining the ground forces momentum as they pushed toward Baghdad.

This example shows the importance of SSA to the military instrument of power (IOP), but the United States (U.S.) relies on SSA to support all IOPs. According to the current U.S. National Space Policy, countries that "effectively utilize space will enjoy added prosperity and security and will hold a substantial advantage to those who do not."[5] Space-based communications allow one country to affect another country's economy because of information passed through space. This same communication path allows a country to influence how another country's populace view their own government. These space-dependent communications link the space domain to both the Economic and Information IOPs. The U.S. derives its Diplomatic power from the other IOPs. Consequently, space, and therefore SSA, is fundamental to the U.S. IOPs. President George W. Bush entrusts the DOD with maintaining SSA for the U.S. Government.[6] While maintaining the joint aspect of SSA, the Department of Defense identified the AF "as Executive Agent for Space."[7] Based on this policy, the entire U.S. Government depends on the AF to provide SSA to support all of the U.S. IOPs.

The AF has some SSA capabilities, but complete SSA is difficult to obtain. The Milstar example highlights AF SSA on its own systems, but complete SSA requires considerably more information. To achieve complete SSA, the AF needs knowledge of much more than its own systems or even that of the sister services. Beyond the status of U.S. space systems, SSA includes space intelligence, surveillance, and reconnaissance (ISR) data as well as analysis of the space environment.[8] Given today's strategic environment, SSA must help diagnose problems when surprise is the norm and the threats are less predictable.[9] In this reality, the AF requires additional SSA capabilities to gain knowledge of adversary systems and intent as well as the space environment to diagnose future problems. From a resource and capability perspective, obtaining adequate SSA of all space objects is difficult. For example, the increasingly diminutive nature of future satellites complicates the space ISR problem. Taken in total, obtaining SSA for the U.S. Government is a daunting task for the AF.

Additional SSA capabilities are also necessary to remedy future space events because not all of them will be easy to diagnose or remedy. In the Milstar example, the diagnosis was a misaligned spot beam; the solution was to move the spot beam back in place.[10] This was relatively simple problem to diagnose and remedy; unfortunately, harder problems exist. Consider the recent Chinese test of an Anti-satellite (ASAT) system.[11] For the ASAT test, U.S. detected a missile launch from China and found a debris cloud in the location of a satellite.[12] Since China's ASAT weapon was ground launched, the diagnosis attributes China as the originator of the test. This problem has two solutions. First, preventing future ASAT tests, and second, avoiding the resulting debris cloud. The first solution for future Chinese ASAT tests is much more difficult; it will require all of the U.S. IOPs. For the second solution, the U.S. will rely on SSA to characterize the debris cloud to minimize space object collisions with this cloud. This ASAT event would have been even more difficult to diagnose and remedy if it originated from another satellite. In the 2030 timeframe, satellites may attack other satellites.[13]

How will the AF diagnose and attribute future space events so the U.S. can remedy the situation? What if the diagnosis shows the attack occurred from a region in space? How will the U.S. be able to attribute the attack to facilitate the use of its IOPs against the perpetrator? The U.S. can only answer these questions with complete SSA. In particular, the U.S. needs knowledge of small objects and the ability to enhance satellite intelligence collection. This leads to a capability question. How will the U.S. increase small object awareness and enhance object satellite intelligence collection to improve SSA in the 2030 timeframe to support all U.S. IOPs?

One way the AF can increase space debris and satellite awareness to diagnose and attribute a satellite-to-satellite attack is placing a fleet of active sensor systems into orbit. Using lasers as the active source, these systems can locate smaller objects and enhance SSA. Developing fluoride fiber lasers as the active source for these systems will significantly reduce the size and the weight of the laser while allowing multi-spectral imagery of the space object. This paper recommends the AF investigate infrared and visible fluoride fiber lasers as the active source for a fleet of small satellites to increase SSA by tracking and imaging objects as small as 0.1 centimeter (cm).

Because this paper recommends changing funding priorities, it seeks to modify the AF organizational culture.[14] As a result, the paper will discuss the threat, technological, and strategic imperatives for a cultural change. Section 2 will discuss the 2030 threat imperative of space objects as small as 0.1 cm. Through a discussion of the current space surveillance and reconnaissance capabilities, Section 3 will identify a technical imperative for a funding change. Section 4 will present how laser technology in space can overcome current technology challenges and identify the fluoride fiber laser as the best laser solution. Expanding from the laser source, Section 5 will postulate a conceptual SSA system followed by limitations of fluoride fiber lasers. Identifying the utility of the conceptual SSA system through potential 2030 scenarios in Section 6 establishes a strategic imperative to modify AF funding priorities. Since many factors influence the development of a new system, Section 7 discusses some external factors that could impede the use of fiber lasers for SSA in an attempt to tackle them directly. By establishing the imperatives, a conceptual SSA system, and external limitations, the paper concludes with recommendations to achieve enhanced SSA from a satellite constellation using fluoride fiber lasers.

Section 2: Threat Imperative – The Orbital Environment Today and in 2030

"Space has become a place that is increasingly used by a host of nations, consortia, businesses, and entrepreneurs." – *U.S. National Space Policy*

There are many components of SSA; however, this paper will focus on the collection of space ISR data. Space ISR capabilities have similar technical requirements and therefore create a logical grouping. Focusing on the ISR portions of SSA, this section discusses the space object threat from natural or man-made objects as small as 0.1 cm and the projected increase of these objects in the 2030 timeframe. While the number of these objects increases, satellite sizes are simultaneously decreasing posing an additional threat. While both of these trends occur, nations are becoming more active in space, which compounds the criticality of effective SSA.

Complete SSA requires knowledge of the location of all objects, regardless of the object's size. Collecting data on small objects provides protection from orbital collisions. For this paper, small space objects, whether natural or man-made and not performing a mission, are referred to as space debris.[15] Knowledge of space debris is necessary because it can have disastrous effects on spacecraft. Figure 1 illustrates the effect of a 0.1 cm piece of space debris on the window of the space shuttle.[16] Consider this same impact on a solar array used to power a U.S. imagery satellite. Impact on the solar panel could degrade the ability to recharge the satellite's batteries. Without charged batteries, the satellite may lose some of its imaging ability, potentially resulting in degraded intelligence preparation of the operational environment for the Military IOP. To reduce the possibility of a disastrous collision, the AF needs to know the location and orbit of space debris.

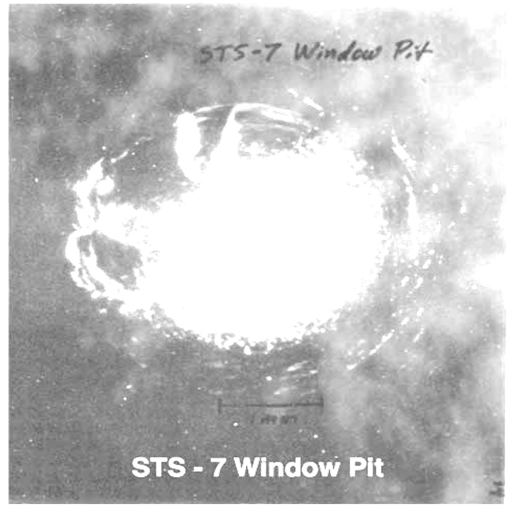

Figure 1. Space Shuttle window pit after collision with a small (0.1 cm) piece of debris. (Reprinted from D. J. Heimerdinger, "Orbital Debris and Associated Space Flight Risks," ***Reliability and Maintainability Symposium Proceedings*** [2005]: 508.)

Because man-made items are part of space debris, the space debris problem will only be worse by 2030. Today, 32 nations, commercial companies, and private consortia have satellites in space.[17] According to a United Nations (UN) study, a satellite in Low Earth Orbit (LEO) measuring 10 meters by 10 meters today will impact 0.1 cm space debris every three to ten years.[18] Because more space activity will occur, the UN predicts that each satellite can expect to experience five to ten impacts by 2030.[19] This data did not include the millions of pieces of space debris resulting from the Chinese ASAT test, so the frequency of collisions will increase between now and 2030.[20]

Space debris will not be the only small objects in space in 2030; the size of satellites is decreasing as the use of space is increasing. The technology to create smaller devices influences more than the computer and cellular telephone industry; it enables smaller satellites as well.

Today, there are companies teaching customers how to develop and operate satellites as small as compact disc players; 17 different countries have access to these technologies.[21] Clearly, there is a market for this technology since companies are seeking to profit from training. This proliferation is occurring while a number of countries seek to increase their activity in space to improve their economic prosperity and security.[22] Consequently, there will be numerous small satellites by 2030 as countries expand their use of space. These small satellites pose the dual threat of collision and satellite missions to deny U.S. space capabilities.[23]

The threat posed by small space objects will increase by 2030, and this threat is two-fold. First, the threat of orbital collisions will increase because more space debris and small satellites will exist. Any collision could affect a future military operation if it disables a satellite critical to the prosecution of war. Small satellites pose an additional threat; they could limit U.S space capabilities. To enhance SSA, the AF needs to know the satellite's mission, and this need will only increase as many nations, commercial firms, and private consortia venture into space. With a congested space environment and an atmosphere where surprise is the norm, the small object threat to satellites will increase in 2030.

Section 3: Technological Imperative – Surveillance and Reconnaissance

"Counterspace operations, both defensive and offensive, supported by situational awareness, will ensure we maintain our superiority in space." – *General Jumper*

For success in the 2030 space environment, the AF needs to be able to provide SSA of small objects. This section looks at the current and near-term planned AF capabilities to perform SSA and identifies the shortcomings of using these capabilities with regard to small objects. The inability to meet the 2030 threat creates a technological imperative to change funding priorities.

Current and planned AF SSA capabilities cannot track small objects. The Space Surveillance Network (SSN) operated by AF Space Command (AFSPC) consists of "dozens of ground telescopes and radars distributed over the globe" and a single optical sensor in orbit.[24] However, the SSN is ineffective in tracking objects smaller than 10 cm, i.e., about 4 inches.[25] These shortcomings result from technological and environmental constraints. Since the 2030 threat consists of increased space debris and satellites smaller than 10 cm, the sensitivity of the SSN must increase to track these small objects.

The shortcomings of radar have to do with the technology itself. Even though radar has excellent capabilities to track objects in space regardless of atmospheric weather and the time of day, the amount of power used and the wavelength of radar limit its ability to see small objects in space.[26] This limit occurs because objects smaller than the wavelength do not affect the returned signal. As a result, radar can only see objects about 0.75 cm or larger.[27] This technological shortcoming holds regardless of whether the radar is looking for space objects from the ground, from the air, or from space.

Optical telescopes provide another SSA capability, but there are environmental shortcomings of optical telescopes. Ground- or air-based telescopes can detect objects when they are sunlit against a dark background.[28] In low earth orbit, only one to two hours of detection are possible during dawn and dusk each day while at higher earth orbits, detection is possible throughout the night.[29] Another environmental limitation of ground and air-based telescopes is the atmospheric weather over the telescope; cloud cover inhibits the telescope effectiveness.

Another possible location to deploy a telescope is in space; this basing location eliminates most of the shortcomings of ground- and air-based telescopes, but the 2030 environment is still out of reach. In April 1996, the Ballistic Missile Defense Organization launched the Midcourse Space Experiment (MSX); one of the payloads on this satellite was a telescope capable of sensing the visible spectrum of electromagnetic radiation.[30] MSX provided a pathfinder for space-based telescopes. It showed space-based telescopes could detect objects almost continuously by removing the environmental shortcomings. Consequently, the AF plans to field a number of satellites under the Space Based Space Surveillance (SBSS) program.[31] The SBSS telescope allows detection of smaller objects; the goal for the first satellite is objects smaller than 60 cm.[32] However, these systems cannot resolve the small objects of the 2030 space environment.

Today's SSN cannot meet the 2030 threat posed by small space objects. Technology limits radar, and ground or air-based telescopes have environmental limitations. While space-based telescopes do not have environmental limitations, current AF development plans will not resolve objects as small as 0.1 cm. These limitations create a technological imperative for change.

Section 4: Technological Solution – Fluoride Fiber Lasers

"The compelling motive for the development of space technology is the requirement for national defense." – *Gen Bernard Schriever*

Given the technological imperative, the AF needs to address the 2030 threat with a different technology; that technology is the laser. While a discussion of how lasers operate is in the Appendix, this section enumerates the advantages of applying lasers to solve the problem of small object SSA; it will also address where to employ the lasers. By investigating the limitations of laser systems previously in space, this section will identify the fluoride fiber laser as the solution to these limitations because of its ability to produce multiple laser wavelengths simultaneously from a single fiber.

The advantage of using lasers is inherent in their wavelength. While radar wavelengths can reach 0.75 cm, near-infrared laser wavelengths are about 1 micrometer or 1/1,000th of a centimeter.[33] Since the wavelength is so small, detection of small objects and small details is possible. The inherent sensitivity of a laser enables tracking of objects down to 0.1 cm as well as provide detailed information about the illuminated object.

Since a laser can resolve small space objects, the question boils down to the laser employment location. Previous studies looked at using laser technology for space surveillance and space object imaging (SOI); however, these studies identified significant limitations for lasers based on the ground or in the air. Like ground or air-based telescopes, this employment location suffers from atmospheric conditions. These conditions are the most difficult to overcome.[34] Since atmospheric contents absorb certain wavelengths of light, the laser wavelength must be different from the wavelengths absorbed.[35] Unfortunately, nature specifies the wavelength the laser produces as described in the Appendix. The atmosphere also causes wavelength independent problems. Regardless of the absorption of the laser light, the particles in the atmosphere will scatter the light in many different directions.[36] More laser power will overcome this scattering, but increased laser power comes with a large increase in development cost. It is possible to develop a higher power laser in a minimal atmospheric absorption region; however, the costs of development and operations of a sub-optimal laser system is not worth the safety concerns created from using hazardous materials to generate the laser light.

Just as space basing helped telescopes overcome natural limitations, placing a laser in space achieves the same benefits with one major technological drawback. Since the atmosphere is no longer between the laser source and the object, absorption no longer affects the laser wavelength chosen; only the characteristics of the mission drive wavelength selection. Similarly, there are very few particles in space to scatter the laser light. However, lasers beams do not spread out very quickly.[37] This lack of dispersion limits how much volume the laser interacts with, i.e., the laser has a limited field of view. This limited field of view is a drawback for the large volume searching required to locate objects in space.

Even with the field of view limitations, laser systems have orbited in space, but these systems had additional limitations. It would appear the biggest limitation of a laser remotely investigating an object would be the strength of the return signal. However, hard objects, e.g., satellites, produce relatively strong returns.[38] The limitations of early space laser systems were "laser design and operation in space, thermal management, alignment and control, and autonomous system operation."[39] Of these limitations, all but autonomous system operation are problems of the laser source.

The problematic laser source for these previous space-based laser systems was a bulk solid-state laser; a different laser source is necessary to address these obstacles.[40] For a bulk solid-state laser, the biggest drawback is extracting heat from the crystal used as the gain material.[41] By using bulk solid-state lasers, previous space-based systems had to account for thermal management to keep the crystal cool and allow laser operation. Because bulk solid-state lasers require external mirrors and optics to generate and condition the laser beam, alignment control is necessary to maintain operations of the laser. Even with these limitations, early space-based laser experiments were successful.[42] However, a future SSA system needs an alternative to bulk solid-state laser technology. This alternative should minimize size, weight, and laser design difficulties and reduce the thermal management needs as well as address laser alignment control.

The fiber laser has advantages for a space-based system; it is small, lightweight, and has a simple design. While a fiber laser may require a long piece of optically active fiber to generate the laser light, coiling the fiber into loops does not affect the creation of laser light.[43] A coiled fiber laser appears in Figure 2.[44] The ability to bend and coil the fiber simplifies the laser design. Because these fibers are small, a fiber laser device requires less volume. A typical bulk solid-state laser has a footprint of 118 square feet while a similarly powered fiber laser requires only 5.4 square feet.[45] As for weight, fiber lasers are about half the weight of a comparably powered bulk solid-state laser.[46]

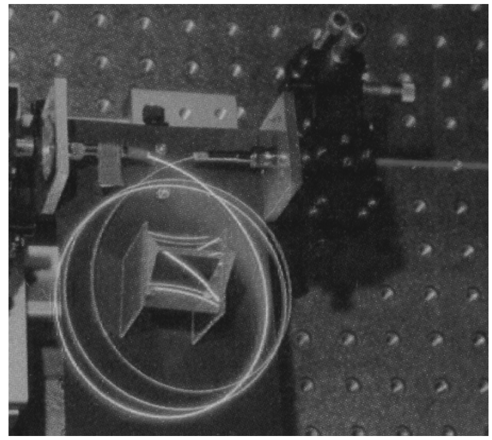

Figure 2. 440 milliwatt fiber laser. Fiber coil diameter is about 5 inches. **(Reprinted from Uwe Brinkman, "1.3-kW Fiber Laser Can Be Further Scaled,"** ***Laser Focus World*** **40, no. 8 [2004]: 2.)**

The fiber laser advantages reduce overall cost compared to a comparably designed bulk solid-state laser SSA system. With a fiber laser payload, the satellite weighs less and may be smaller than a satellite for a bulk solid-state laser system. Since the satellite weighs less, launch is possible with a smaller, less expensive vehicle.[47] By using a fiber laser instead of a bulk solid-state laser as the payload, the overall SSA system cost is less.

The fiber laser also surpasses the bulk solid-state laser with regard to thermal management and alignment problems. For a bulk solid-state laser, the small surface to volume ratio limits the laser crystal from dissipating heat. The bulk solid-state laser requires additional water-cooling for thermal management.[48] This water-cooling complicates the laser design and adds weight and volume. On the other hand, the optically active fiber in a fiber laser is typically long, e.g., up to two meters, but the fiber has a small diameter.[49] Because of the long length and small diameter, the surface to volume ratio of a fiber laser allows it to dissipate heat very effectively, even when coiled, without the need for water-cooling.[50] In addition, a fiber laser is much less sensitive to alignment. As described in the Appendix, bulk solid-state lasers require external mirrors to create the laser cavity; in contrast, fiber lasers can have a laser cavity wholly contained in fiber. Since light will stay within fiber and this fiber contains the entire laser cavity, laser alignment is not an issue after assembling the laser.

Fiber lasers also have more military utility than other laser types making them a perfect selection for space applications. Fiber laser operation does not require flowing chemicals.[51] In addition, fiber lasers have an unlimited fuel supply unlike chemical lasers.[52] While fiber lasers rely on a pump laser for excitation as shown in the Appendix, these pump lasers rely on electricity. This makes the fiber laser highly compatible with spacecraft design. Fiber lasers can operate as long as the spacecraft has electrical power and the pump laser operates. With improved military utility, the fiber laser is an ideal source for space-based applications.

A fluoride fiber laser has an additional benefit; it can produce multiple wavelengths from the same fiber. As discussed in the Appendix, a single fluoride fiber laser can generate multiple laser wavelengths. This allows multi-spectral data collection each time the laser illuminates an objects without increasing the laser size and weight. Using a fluoride fiber laser provides multiple data collection opportunities without adding additional size and weight.

Laser technology does not have the limitation radar has; the laser can find, track, and collect information about objects smaller than 0.75 cm. A laser placed in space eliminates the shortcomings imposed by the atmosphere. Most of the problems associated with previous space-based laser systems resulted from the bulk solid-state laser source. To make a future space-based laser system viable, a different source is necessary; this source is a fluoride fiber laser. With a fluoride fiber laser, laser design and alignment are simpler in a smaller, more lightweight package. Because fluoride fiber lasers are small, lightweight, and can produce multiple wavelengths, this is the best laser source to enhance SSA capability in 2030.

Section 5: Conceptual SSA System and Fluoride Fiber Laser Limitations

"You mean I finally have frickin' sharks with frickin' laser beams attached to their frickin' heads?" – *Doctor Evil*

Conceptualizing an SSA system with a fluoride fiber laser payload can identify if a strategic imperative for change exists by 2030. The orbit selected for this system is a medium earth orbit (MEO). MEO is appropriate for three reasons. First, MEO is approximately midway between satellites operating in low earth orbit (LEO) and high earth orbit (HEO). In addition, one can assume earth-sensing satellites have first priority for LEO positions if LEO is not already full by 2030. Finally, this orbit reduces the opportunity for laser light to affect LEO satellite imaging payloads of because the conceptual SSA satellite is above and behind the LEO satellite. For these reasons, the conceptual system is in MEO. This section describes important sensor and command and control portions of the conceptual SSA system and outlines the fluoride fiber developments necessary to realize the system.

Lasers can provide a source to illuminate small objects, but a complete system must detect laser illumination returned from objects. The first sensor required for the system is a passive optical sensor. This sensor provides multi-spectral data of the imaged object increasing the SOI and intelligence data collected. To take advantage of the multiple laser wavelengths generated by a fluoride fiber laser, the passive optical sensor consists of a telescope to capture the light and a dispersive medium, e.g, a prism, which separates the returned laser light allowing single and multi-spectral images of the object. By providing SOI and intelligence, this sensor can help attribute an action to that satellite.

The second sensor necessary for the collection of space ISR data relies on Light Detection and Ranging (LIDAR). This sensor provides reconnaissance and surveillance data. Using a LIDAR concept allows measurements of the distance, speed, rotation, and chemical composition of an illuminated object.[53] For example, the distance from the SSA satellite to a space object provides the object's current position. Using LIDAR also provides considerable information about an object in space, especially if the laser wavelength is in the visible region of the electromagnetic spectrum. This part of the spectrum allows for the direct measurement of optical characteristics of the object.[54] This sensor combination captures data for space ISR.

The data provided by the conceptual SSA system supports the diagnosis and attribution of space events. The passive optical sensor records the object's orientation, which provides clues to a satellite's current mission. Similarly, the satellite's rotation and chemical composition, provided by the LIDAR sensor, provides space ISR. The rotation information could indicate either the satellite's mission or its current tasking, and the chemical composition of the object may provide indications of the satellite's mission or, if the object is space debris, could help identify a way to eliminate it. This information could diagnose and attribute a space event to a space debris collision or a satellite action taken by its owner.

Control of the space segment will be vital for the conceptual SSA system because near real-time tasking is necessary for diagnosing and attributing anomalies in space. Control enables the satellite to look at a particular object to collect additional SSA information. This tasking must be available in near real-time to respond to the potentially dynamic threats of 2030. If a U.S. satellite experiences an anomaly, this constellation must rapidly collect data on space objects to diagnose the situation. Based on this data, the AF can attribute the anomaly to the appropriate cause; if caused by another satellite, the U.S. can then use the appropriate IOPs to remedy the situation. The ability to make this diagnosis and attribution relies on control. The ground station's command and control must be responsive to the changing space situation and be able to attribute the cause of an anomaly.

For the conceptual SSA system to attribute space actions, the AF must allocate funding to develop technology supporting the fiber laser payload. The first area for development is sufficient laser pulse power from fluoride fiber lasers. While Motes predicts an exponential growth in continuous power, the power prediction is for a fiber laser with silica as a glass host.[55] Fiber lasers with a fluoride host can produce high powers, but the fluoride fiber laser power lags behind silica-based fiber lasers because of a smaller economic market.[56] Looking at the growth trend in pulsed laser output, Geis found an exponential increase.[57] Additional research to increase fluoride fiber laser pulsed output power should follow these exponential trends. By funding fluoride fiber laser research, the pulsed output power of these lasers would experience a similar exponential growth by 2030 making them a viable source.

While increasing the pulsed output power of fluoride fiber lasers is necessary for the system, the system also requires the development of fluoride fiber devices. A fiber coupler is an example of a fiber device. A fiber coupler brings the pump laser light into the fiber gain material to provide the excitation source. Fiber-coupling devices exist for silica fiber used in the telecommunications industry, and these devices introduce limited losses.[58] Another important device is a fiber reflective device because these devices provide the optical feedback necessary to create a laser as described in the Appendix. Once again, silica fiber reflective devices exist. When attached to silica fiber gain material, these devices create an all fiber laser cavity for silica fiber lasers. For fluoride fiber, neither fiber couplers nor fiber reflective devices exist today. Without these devices, fluoride fiber laser design complications arise, and the alignment advantage of fiber lasers is lost.

The pump lasers used to generate the fluoride fiber laser light must be small and lightweight as well. The fiber laser shown in Figure 2 used a large bulk solid-state laser as the pump laser.[59] As mentioned in Section 4, a bulk solid-state laser has considerable size, weight, and alignment difficulties. Consequently, using one of these lasers as the pump laser for the conceptual SSA system would be a significant drawback. Developing small, efficient semiconductor pump lasers, similar to the ones used in laser pointers, would eliminate this problem just as it has for the silica fiber lasers used by the telecommunications industry. These lasers, which are the size of a penny today, would allow the fluoride fiber laser payload to achieve the promised advantages.

A conceptual SSA system using a fluoride fiber laser would provide near real-time ISR data about small space objects. By using a passive optical sensor and a LIDAR sensor, this system provides data to diagnose and attribute situations in space. However, effective use of this system requires near real-time control for immediate tasking. To make the fluoride fiber laser of this conceptual SSA system viable, the AF should fund the development of fluoride fiber lasers with pulsed power high enough to provide the data. The development of fluoride fiber devices similar to those already available for silica fiber must occur as well. Finally, the last laser development hurdle is the creation of small, lightweight pump lasers.

Section 6: Strategic Imperative – Conceptual SSA System Impact in 2030

"The U.S. is more dependent on space than any other nation." – *Space Commission*

While there is a threat imperative and a technological gap, investigating the strategic environment of 2030 is necessary to establish the benefit of overcoming the system development hurdles. To establish this benefit, this section looks at system utility in a number of potential 2030 strategic scenarios. These scenarios, developed by the Organisation for Economic Co-operation and Development (OECD), resulted from participation of individuals from 30 different countries.[60] As a result, the developed scenarios have little bias from a particular country or viewpoint of the future world situation and its affect on the uses of space. The OECD titled the scenarios "Smooth Sailing," "Back to the Future," and "Stormy Weather" to generically identify the world situation.[61] These scenarios have political, economic, social, energy, environmental, and technological features that have consequences across the military, civilian, and commercial space sectors.[62] This section will discuss an assumed future approach taken by other countries to limit the U.S. space advantage before looking at the conceptual SSA system utility in the different scenarios. Each scenario starts with the strategic context of the scenario followed by the affect this strategic context has on the space sector, and the section concludes with the conceptual SSA system utility for the scenario.

U.S. military success since Operation DESERT STORM relies on space to support rapid, precise engagements. Through satellite communications and navigation, to name a few examples, space systems enable our asymmetric advantage. Any potential U.S. adversary has two approaches to address this advantage. Either the adversary can try to catch up to the U.S. over the next few decades, or the adversary can attempt to nullify the U.S. advantages derived from space capabilities. Because the frailty of space systems leaves them vulnerable to attack, many nations, like China, view U.S. space systems as "a potential Achilles heel."[63] Because nullifying the capabilities is more readily available and less expensive, adversaries plan to reduce U.S. military dominance by attacking the space capabilities that enable it. For the following scenarios, the analysis assumes any U.S. adversary will target our space assets to eliminate our asymmetric advantage.

Section 6.1: Smooth Sailing

The first scenario resembles the world order at the beginning of the 21st century. While this scenario may become the future, it seems least likely in light of the Chinese ASAT test. This scenario has the global world order under the guidance of international organizations where free market economies and democracies are the norm.[64] This results in an interest in global issues, and the international co-operation created effectively contributes to solving world problems.[65] However, while the world works on these problems, certain groups with differing ideologies feel left out causing continued terrorist actions.[66] These terrorists may use "states of concern" as locations for bases and recruitment, and the terrorist groups have access to weapons of mass effect (WME) that they use to blackmail vulnerable governments.[67]

Because of this strategic environment and 30 more years of technology development, the space sector takes a commercial feel. Despite a decline in military space expenditures in this scenario, military systems experience a modest growth in usage; meanwhile commercial space expands significantly.[68] While the U.S. devotes less funding to military space, other countries increase their infrastructure focusing on telecommunications, navigation, and earth observation.[69] With the more open environment of commercial space, space-based services, such as space tourism, become affordable and global with the relaxation of space technology export controls.[70]

With the largest space sector growth in commercial applications, the need for SSA transcends the military, but the AF-developed conceptual SSA system provides considerable benefits. As space tourism increases, the amount of space debris increases as well. Monitoring the space debris minimizes the possibility of an orbital collision that could result in the loss of an operational satellite or an entire orbiter full of space tourists. Monitoring small satellites minimizes that threat as well. Even though countries are working together, terrorists are a threat to U.S. space systems. They could blackmail a vulnerable government and force that government to fly a small satellite into a U.S. satellite to execute an attack. For the safety of future space tourists and knowledge of the location and capabilities of small satellites, the conceptual SSA system provides adequate and effective SSA in this scenario.

Section 6.2: Back to the Future

In light of recent events, this scenario appears most likely. This scenario starts with three economic powers: U.S., Europe, and China.[71] After some time, the U.S. leadership position erodes, and China becomes the main challenger of U.S. leadership.[72] While Russia throws its support behind China, the U.S. increases its ties with Europe, and a bipolar world gradually re-emerges.[73] With the increased tensions, economic sanctions abound between the two blocs.[74] This scenario seems most likely because difficulties in Iraq may erode U.S. international leadership position and the Chinese ASAT test may be a confrontational move.[75]

Similar to the response in the Cold War, the U.S. and China in this scenario build up their military capabilities to address their security dilemma; the military space sector grows in this scenario. The space sector benefits from increased military space spending, but the restrictive trade blocs limit the commercial sector.[76] A new "space race" results in the "weaponization" of space with the development of advanced surveillance and warning systems, ASAT systems including parasitic satellites, and space-based lasers capable of attacking satellites.[77] The existence of ASAT systems limits the reliance on commercial space systems because of their vulnerability, and the "space race" prompts other countries, including India, to increase the development of communications and imaging capabilities relying on small satellite technology.[78]

With small satellite technology available and a security dilemma resulting in a "space race," the conceptual SSA system has merit. As tensions run high, knowledge of the situation in space is necessary to leverage all IOPs. The conceptual SSA system provides knowledge of small satellite locations and SOI. While providing the same capabilities identified for the "Smooth Sailing" scenario, the system provides early warning as well. By helping classify satellites owned and operated by other countries, this system facilitates the development of the other countries' space order of battle. Based on that order of battle, this system increases collection efforts on satellites of interest and provides early warning to diagnose and attribute an adversarial action taken in space. Being able to attribute an action to another country allows the U.S. to use all of the IOPs against that county in response. Along with the system's capabilities to catalogue, image, and provide intelligence information on small objects in space, the conceptual SSA system also has merit by frequently doing reconnaissance on other countries' potentially threatening satellites.

Section 6.3: Stormy Weather

One indication of this scenario is U.S. unilateral action. While regime change in Iraq was a unilateral U.S. decision in 2003, this is the only indicator of this scenario thus far making it less likely than "Back to the Future." An additional scenario precondition is the use of the U.S. military only when America's vital interests are at stake.[79] With an isolationist U.S., ethnic conflicts spawn migrations and increased terrorism throughout the globe, and many states develop nuclear capabilities to protect themselves.[80] Here again, the security dilemma drives spending and political decisions.[81]

The space sector experiences an increase in military expenditures across the globe to address the security dilemma. In a divided world without clear alliances, each country develops their own space capabilities and, once again, space is militarized.[82] In this scenario, the U.S. and other countries develop a number of anti-satellite capabilities similar to the previous scenario.[83] The focus on state security limits international institutions and strategic space co-operative efforts to mitigate world problems.[84] In addition, many other states, inspired by India, begin their own space programs.[85]

In this scenario, the conceptual SSA system aids the U.S. again. Not only does this scenario have the same "weaponization" of space, but also many countries enter the space sector alone because alliances are weak. This increased number of space-fairing states results in even more satellites in orbit as each country establishes its own space infrastructure. This increases the amount of space debris because most space debris results from man-made space activities.[86] Along with the need to track debris to protect U.S. satellites, monitoring other country's satellites for malicious actions remains important in this scenario. In fact, monitoring becomes a larger problem in this scenario. Instead of a single direct competitor in the "Back to the Future" scenario, the U.S. faces an array of non-aligned actors in this scenario. An increased number of space-fairing states results in multiple orders of battle to monitor. This requires more satellites in the conceptual SSA system. An additional benefit of the conceptual SSA system in this scenario is its support to other space actions. Because the U.S. has offensive capabilities in space, the conceptual SSA system provides near real-time location and speed of an adversary satellite to trigger defensive or offensive capabilities. In this scenario, the conceptual SSA system provides cataloging, imaging, and intelligence as well as triggering to defensive or offensive systems.

The conceptual SSA system has merits in all three future scenarios. These three scenarios, generated by a multi-national organization, identify the space sector consequences on space activities resulting from political actions taken by states. All scenarios require the ability to locate and track small objects to reduce collisions with space debris and small satellites, only the motivation for and use of small satellites changes in the scenarios. The conceptual SSA system enables detailed SOI and near real-time intelligence collection in all scenarios; the last two scenarios highlight the military significance of the data collected by this system. These capabilities support the creation of another county's space order of battle, and set the stage for the system to accomplish increased reconnaissance on high priority satellites. The data collected by the system enables the U.S. to diagnose, defend, and attribute a space event to another country's satellite. With attribution, the U.S. can then apply any or all of the IOPs against that country to influence their will including, as identified in the last scenario, offensive military space capabilities.

Section 7: External Limitations to System Development

"For a successful technology, reality must take precedence over public relations, for Nature cannot be fooled" – *Richard P. Feynman*

The technology necessary to develop the conceptual SSA system should be in reach by 2030 if the AF concurs with the threat, technological, and strategic imperatives and funds development of fluoride fiber laser technology. This section will look at the impacts of non-technical aspects of system development. As with any new technology, the benefits afforded for national defense must overcome the non-technical impediments for development. Of the numerous possible non-technical impediments to the conceptual SSA system, this section will look at political, legal, and economic limitations.

Politically, two possible limitations are a U.S. lackadaisical attitude toward space situational awareness and an international disbelief of the conceptual SSA system mission. Currently, the U.S. desires space situational awareness enhancements; this is a positive environment for development of the conceptual SSA system. The latest U.S. National Space Policy specifically addresses the need for space situational awareness for the entire U.S. government as well as commercial and foreign entities.[87] The policy also specifically mentions the threat posed by space debris.[88] In 2007, U.S. space policy is seeking to improve space situational awareness; however, a future U.S. administration may not share this view. Future administrations may focus on entitling American citizens with increased social programs at the cost of the defense budget and space programs.[89] With a shrinking budget and no administration support for space technology development, the DOD could severely limit or terminate funding for the conceptual SSA system. If the U.S. moves from an attitude of improving space capabilities to a lackadaisical attitude toward space, it would be impossible to have the conceptual SSA system capabilities in the 2030 timeframe.

The other political limitation is the international perception of the use of a fluoride fiber laser as an active source for collecting space ISR data. Since collecting this type of data from a MEO system is non-intrusive, fielding a system to collect this data falls in line with the first principle of the U.S. National Space Policy.[90] However, each state's perception will be that state's reality. Consider the international reaction to the U.S. desire to achieve space superiority through offensive means. In response to the U.S. position, China specifically denounced the use of space weapons in their defense white papers released in 2002 and 2004.[91] Accordingly, some states will perceive the laser payload of the conceptual SSA satellites as a weapon. This perception could be a problem if the "Smooth Sailing" scenario materializes. While the other two scenarios have the gradual "weaponization" of space, the strong international bodies in the "Smooth Sailing" scenario could produce a negative international response. For this political reason, the conceptual SSA system may never make a single orbit.

The legal limitation closely resembles the last political limitation. While no treaty currently bans lasers from space, interpretation of an existing treaty or the creation of a new one could have that result. The treaty currently governing the activities in space is the Outer Space Treaty of 1967; this is the only treaty dealing exclusively with activities in space.[92] This treaty is open for interpretation, and the ability to field the conceptual SSA system depends on the interpretation of "peaceful purposes."[93] With a strict interpretation, the Outer Space Treaty bans the military use of space including self-defense or non-aggressive activities like communications.[94] The U.S. does not follow this strict interpretation; instead, the U.S. and the consensus of the UN agree the military can lawfully use space in a "non-aggressive" way.[95] The development of the conceptual SSA system meets the Outer Space Treaty today because the intent is "non-aggressive," but a new treaty could ban all lasers in space. The prospect of a new treaty regarding space is possible; China requested one in their 2002 and 2004 defense white papers.[96] The U.S. needs to guard against the regulations of new treaties since these treaties may restrict our ability to develop non-aggressive systems similar to the concept presented here.[97] The use of the conceptual SSA system meets the U.S. and UN interpretation of "peaceful purposes;" however, any future space treaties could eliminate the ability to develop this system.

Even with political will and an unchanging legal environment, the cost of fielding this system may be prohibitive because many satellites will be necessary to perform the activities identified in Section 6, especially in the "Stormy Weather" scenario. Because lasers have a limited field of view, the volume of space a single satellite can cover is small. In addition, the distance the light must travel to an object and back is significant.[98] This distance limits how far away the space object can be from the conceptual SSA satellite. In addition, larger distances between the space object and the conceptual SSA satellite require larger optics for the passive sensor to obtain a detailed image of the space object.[99] To sufficiently cover space and frequently reconnoiter other countries' space order of battle, the U.S. requires many conceptual SSA satellites. Further, while small satellites are the basis of this system to reduce the cost, physical and design realities may increase satellite size and total development cost. Even though the capabilities of the system may allow it to provide SSA data to help diagnose and attribute space activities to a specific satellite, the size or number of conceptual SSA satellites may make development cost-prohibitive.

Not only must the conceptual system overcome technological hurdles, but the program must also overcome non-technical impediments as well. Politically, the U.S. must continue to aspire to international space community leadership and fund programs that maintain that advantage. In addition, international politics can cause problems for system development if the international community believes this system is "weaponizing" space even though this system falls in line with the UN recognized "peaceful purpose" intention. Accordingly, this system is not a violation of the Outer Space Treaty of 1967, but the U.S. must ensure no future treaty blocks the technology used by this system. Because lasers have a limited field of view, data collection occurs over large distances, and the U.S. may need to monitor many satellites, the conceptual SSA system may require too many satellites to be economically feasible.

Section 8: Conclusions and Recommendation

"Space is the ultimate high ground. Our military advantage there must remain ahead of our adversaries' capabilities. And our own doctrine and capabilities must keep pace to meet that challenge." — *Honorable Peter B. Teets*

To the U.S., the space domain is the key for the prosperity and security of the nation.[100] Space allows economic and information transactions instantaneously across the globe as well as supports U.S. military actions all of which enhance U.S. diplomatic power. Consequently, SSA supports all of the U.S. IOPs. If the U.S. is to maintain its prosperity and security, it must increase its SSA. By the year 2030, the threat posed by small space objects will increase. Not only is there an increased threat of orbital collisions with space debris because of a larger debris volume, but there is also an increased threat from small satellites. While these small satellites pose a collision threat, their mission may be the denial of U.S. access to space capabilities. With a congested space environment and an atmosphere where surprise is the norm, there is a threat imperative to enhance SSA by 2030.

Current and near-term SSA capability is not effective for the small space object threat in 2030. The SSN, comprised of radar and telescopes, cannot detect space objects as small as

0.1 cm. Basing a telescope in space, like MSX or SBSS, can overcome environmental limitations, but these systems do not meet the 2030 technological requirements. While radar does not have any environmental limitations, the technology of radar limits small object detection. These limitations create a technological imperative for change.

Laser technology does not have the limitation of radar; lasers can track and collect information about objects smaller than 0.75 cm. A laser placed in space eliminates the shortcomings imposed by the atmosphere. With a fluoride fiber laser, laser design and alignment are simpler in a smaller, more lightweight package. Having more military utility than chemical or bulk solid-state lasers, fluoride fiber lasers are also capable of producing multiple wavelengths from a single device making them the best laser source to enhance SSA capability.

A conceptual SSA system using a fluoride fiber laser would provide near real-time ISR data about small space objects. By using a passive optical sensor and a LIDAR sensor, the conceptual SSA system provides data to diagnose and attribute situations in space. However, effective use of this system requires near real-time control for immediate tasking. This system has merits in all three future scenarios generated by a multi-national organization. All scenarios require the ability to locate and track small objects to reduce collisions with space debris and small satellites, only the motivation for and use of small satellites changes in the scenarios. By enabling detailed SOI and near real-time ISR collection, the conceptual SSA system supports the creation of another county's space order of battle. The system enables the U.S. to diagnose, defend, and attribute a space event to another country's satellite and triggers either an offensive counterspace response or the application of other IOPs to remedy the situation.

To make its first orbit, the conceptual SSA system must overcome non-technical impediments. Politically, the U.S. must continue to aspire to international space community leadership and fund programs that maintain that advantage. In addition, international politics can cause problems for system development if the international community believes this system is “weaponizing” space. The technology itself drives a possible economic impediment. With the laser’s limited field of view, the potential distances between the satellites and space objects, and a desire to monitor many other countries’ space order of battle, the cost of a fully capable SSA system may be high.

If the AF, the DOD, and the U.S. want to maintain an advantage in space, the AF needs to fund academia and commercial laboratories to focus fluoride fiber laser development. In particular, the AF should fund both entities to increase pulsed laser output power from fluoride fiber lasers. Simultaneously, the AF should fund fluoride fiber device development in commercial laboratories to create all fiber devices. Finally, the AF should fund commercial laboratories to develop small, lightweight pump lasers operating at the appropriate wavelengths. To make this funding available, the AF should re-aligning AF Science and Technology priorities. Without these developments, the AF cannot recognize the size, weight, and military utility advantages of fluoride fiber lasers and gain complete SSA by 2030.

In addition to these recommendations, the AF should lead additional studies and recommendations prior to initiating a system development. The AF should lead studies into the sensors identified in the conceptual SSA system. These studies should establish parameters for laser power requirements and imagery resolution. Following the sensor study, the AF should lead a concept exploration study refining the necessary parameters for conceptual SSA system development. Variables for this study include the satellite orbit, number of satellites necessary, pulsed laser output power, imagery resolution, and methods to command and control the satellites in near real-time. Even though these studies are important for the system, the long lead-time efforts are the fluoride fiber laser recommendations; the AF should fund developments in these areas immediately so the conceptual SSA system has a chance to meet the 2030 imperatives.

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Appendix: Lasers, Fiber Optics, and Fiber Lasers

Lasers

Laser is really an acronym for Light Amplification by Stimulated Emission of Radiation.[101] This definition hints at the components necessary to create a laser; something needs to stimulate something else to emit radiation (light), and somehow this light is amplified. Using these hints identifies the components necessary for a laser: an excitation source, the something, provides energy to stimulate a gain material, the something else, to emit light and feedback amplifies it. This section of the Appendix will briefly discuss how these components come together to create a laser, and it uses a bulk solid-state laser as an example.

The most important piece of the laser is the gain material. For a bulk solid-state laser, this material is a crystal grown with impurity ions added into the structure. Ions normally added when growing the crystal are rare-earth ions because these ions are optically active, i.e., they absorb and create photons of light in the visible and infrared portions of the electromagnetic spectrum.[102] A typical bulk solid-state gain material is the neodymium: yttrium-aluminum garnet (Nd:YAG).[103] In this gain material, the Nd ions are the impurity ions, and these ions can produce light at a wavelength of 1.06 micrometers (μm).

Since nature is inherently lazy, all the electrons associated with the Nd ions remain in their ground state in the crystal until an excitation source adds energy. In the case of the Nd:YAG system, a high-intensity lamp provides enough photons to excite the Nd electrons to an excited state. Because the ground state is equilibrium, these excited electrons seek to return to the ground state. By returning to the ground state, the electron spontaneously generates a photon of light containing the exact amount of energy lost by the electron. As this photon passes by other excited electrons, the photon stimulates the excited electrons to return to the ground state by creating another photon matching the original. This produces a cascading effect as a photon creates two photons, which create four photons, which create 16 photons, etc. The result is a large number of matching photons. That first photon stimulated the production of many exact replicas.

Since spontaneously generated photons can occur in any direction, their direction limits the number of photons produced; there is no control over the spontaneous emission of photons. The way to gain control of this cascading effect is adding some manner of optical feedback. For the case of the Nd:YAG bulk solid-state laser, that feedback is in the form two separate mirrors. By placing mirrors that reflect 1.06 μm light at either ends of the crystal to create a laser cavity, the initial cascade of photons reflects back into the crystal again. Providing the excitation source excited the electrons again, these reflected photons create another cascade of photons. This cycle repeats itself every time the photons pass through the crystal containing excited Nd ions. By making one of the mirrors partially transmissive at 1.06 μm, some of these photons escape the laser cavity for use as laser light. Providing optical feedback controls the cascading effect of the photons and allows some laser light to exit the cavity.

This discussion addresses how to create steady state, continuous laser output power; producing pulses of laser light provides additional advantages. Producing laser pulses is similar to blocking a water line. Pressure builds while the water line is blocked, and the pressure at the output is initially higher after removing the blockage. By blocking the laser cavity while the excitation source excites the gain material, additional photons build up. When the blockage leaves the laser cavity, a larger number of photons exit the cavity than the steady state output just as more water left the line after removing the blockage. Rapidly switching the laser cavity between “blocked” and “unblocked” produces a chain of pulsed laser light where each pulse interacts with the environment outside the laser cavity independent of other laser pulses. This allows time-dependent measurement of changes outside the laser cavity providing additional advantages for using laser light as a measurement device.

Fiber Optics

Fiber optics is something many people have heard of but do not really know how they work. Imagine a garden hose. The inside of the hose is the core; to transport water, the core is hollow. Bounding the core is a waterproof material; refer to this as the cladding. A fiber optic cable is similar to the water hose, but the core is one material with a particular index and the cladding is a similar material with a slightly different index. Just as the water cannot get through the garden hose cladding, an appreciable amount of light cannot get out through the fiber optic cladding. Simply stated, a fiber optic cable directs light similar to the way a water hose directs water.

With the wavelength of light being small, a fiber optic cable can be small. In fact, the cable is only 1/10,000th of a meter, or 10 μm, in diameter.[104] Even though the fiber is so small, the fiber optic cable has very little loss as the light guides down the fiber. Light correctly launched into the fiber will even propagate with minimal loss in coiled fiber; the light propagates down the fiber just like water flows through a coiled garden hose. Because coils do not affect the fiber and it is small, a small package can hold considerable lengths of fiber.

Fiber Lasers

Just as Nd is optically active in the YAG glass host to form a bulk solid-state laser, fiber can be optically active by adding rare-earth ions allowing all-fiber lasers. Because fiber starts as a crystalline structure, rare-earth ion additives can change the fiber. By introducing these ions, like Nd or Erbium (Er), the modified fiber becomes optically active. This creates a gain material in fiber. Because the diameter of the fiber is so small, only other lasers provide the appropriate means for exciting the rare-earth ions. These lasers, referred to as pump lasers, excite the rare-earth ions, and the spontaneously created photons propagate down the fiber stimulating the creation of more photons. While the fiber directs the photon cascade, optical feedback is still necessary to form a laser. A fiber reflective device can provide the optical feedback to produce an all-fiber laser. The telecommunications industry uses fiber lasers. These fiber lasers consist of Er-doped silica host (Er:silica) fiber because silica is the standard telecommunications fiber host. A small 0.98 μm laser provides excitation for the Er:silica fiber, and fiber reflective devices provide optical feedback. Rare-earth ion dopants, another laser as the excitation source, and fiber reflective devices make an all-fiber laser possible.

Just as the rare-earth ions can change the optical properties of the fiber, changing the fiber glass host creates different optical phenomenon as well. While silica is the most common host glass, another fiber host glass is fluoride.[105] It is possible to introduce rare-earth ions into this glass host to create optically active gain material. In a fluoride fiber, the rare-earth ion's electrons stay in their excited state longer than in silica fiber. This allows the electron to receive additional energy from the excitation source and move into a highly excited state before relaxing back to the ground state. The photon produced by this highly excited electron relaxation has a higher energy than the photon from the excitation source. This is an upconversion process.[106] For example, a 1.12 μm excitation laser providing low-energy, infrared photons can produce higher energy, visible photons at 0.48 μm because rare-earth ions in fluoride fiber reach a highly excited energy state before relaxing back to the ground state. This process produces visible and infrared photon emission within a single fiber.[107] Through the selection of appropriate optical feedback, it is possible to create a multi-wavelength fiber laser from a single, easily packaged fiber.

While many rare-earth ions in fluoride fiber can produce multi-wavelength laser emission, thulium-doped fluoride (Tm:fluoride) fiber provides a representative example. Using Tm:fluoride fiber, spontaneous emission can occur at across the infrared and visible spectrum with infrared excitation lasers.[108] By adding optical feedback in the form of external mirrors, Tm:fluoride fiber produces laser emission at 0.480 μm.[109] Using fluoride fiber reflective devices instead of the external mirrors would create an all-fiber laser. By tuning these fiber reflective devices for the other spontaneous emission wavelengths, laser emission from Tm:fluoride gain material occurs at multiple wavelengths in a single fiber.

Pulsed fiber laser output is also possible to record time-dependent phenomenon. To have all the advantages of a continuous output fiber laser, the pulsed fiber laser needs components built in fiber as well. The Laser section of this Appendix described pulsed laser output occurring by using a "block" in the laser cavity. This does not need to be a physical "block," rather, this "blocking" can be any phenomenon that keeps the stimulated emission from occurring. There are many ways to "block" a fiber laser; one of these is designing the fiber laser cavity in the shape of a ring. By twisting a part of this ring to change the fiber properties, stimulated emission occurs for only a short period of time. This produces a stream of laser pulses, and these pulses escape through a fiber coupling device for use outside the laser ring cavity. This allows the time-dependent measuring capabilities of pulsed lasers from an all-fiber laser system.

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[101] LLC Mountain Data Systems, "Acronyms and Abbreviations," http://www.acronymfinder.com/af-query.asp?acronym=LASER.
[102] Wiest, "Blue Emitting Fiber Laser," 2.
[103] B.E.A. and M.C. Teich Saleh, *Fundamentals of Photonics* (New York: John Wiley & Sons, Inc., 1991), 478.
[104] Beason, *The E-Bomb: How America's New Directed Energy Weapons Will Change the Way Future Wars Will Be Fought*, 200.

[105] Wiest, "Blue Emitting Fiber Laser," 1.
[106] Ibid.
[107] Ibid., 19.
[108] Ibid.
[109] Ibid., 4.