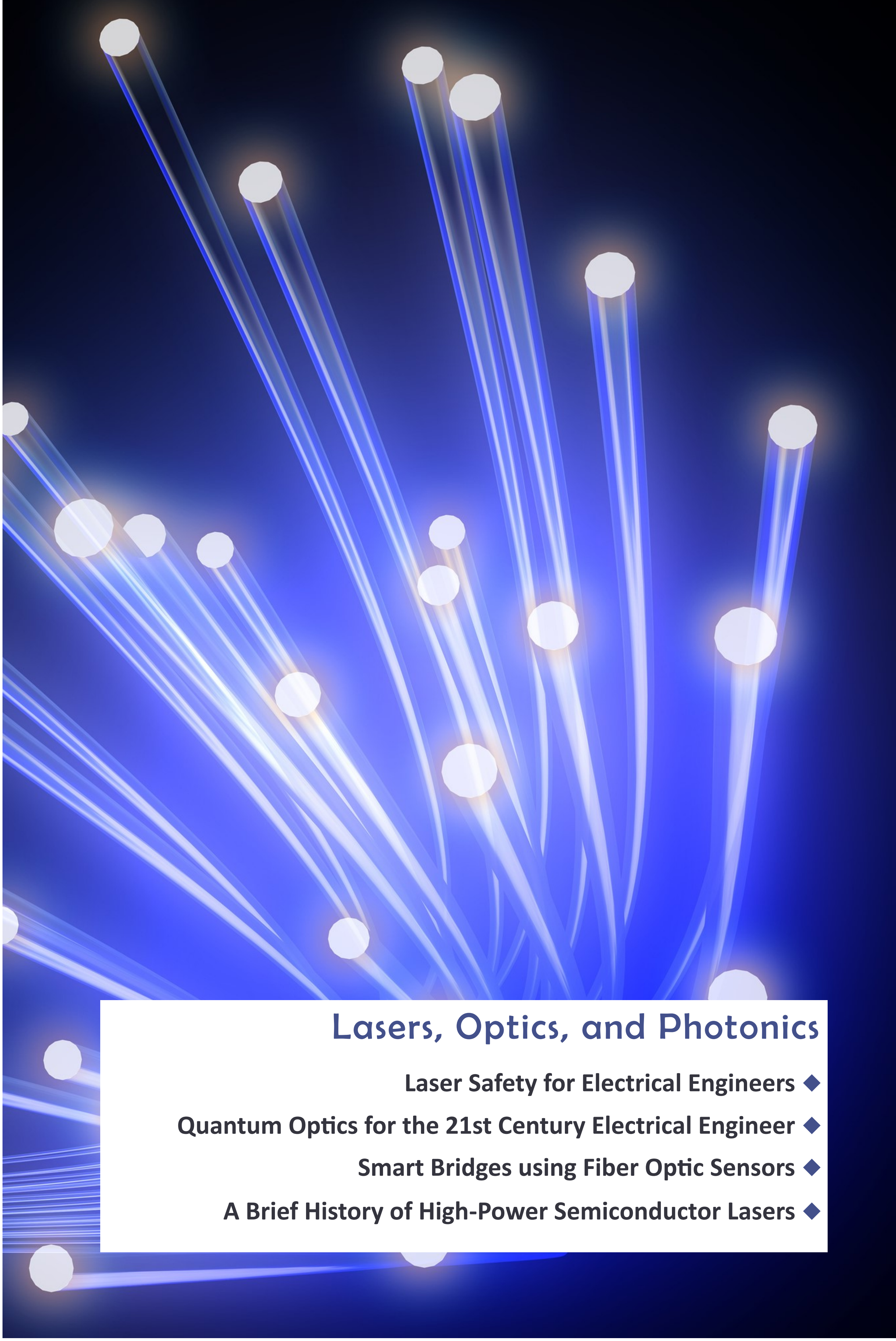
THE ◆ BRIDGE

The Magazine of IEEE-Eta Kappa Nu



Lasers, Optics, and Photonics

March 2014 Vol. 110 / No. 1

HKN IEEE

IEEE-HKN AWARD NOMINATIONS

As an honor society, IEEE-Eta Kappa Nu has plenty of opportunities designed to promote and encourage outstanding students, educators and members.

Visit www.hkn.org/awards to view the awards programs, awards committees, list of past winners, nomination criteria and deadlines.

Outstanding Young Professional Award

Presented annually to an exceptional young professional who has demonstrated significant contributions early in his or her professional career. (Deadline: 30 April)

Vladimir Karapetoff Outstanding Technical Achievement Award

Recognizes an individual who has distinguished him or herself through an invention, development, or discovery in the field of electrical or computer technology. (Deadline: 30 April)

Outstanding Student Award

Annually identifies a senior who has proven outstanding scholastic excellence, high moral character, and exemplary service to classmates, university, community and country. (Deadline: 30 June)

Outstanding Chapter Award

Singles out chapters that have shown excellence in their activities and service at the department, university and community levels. Winners are determined by their required Annual Chapter Reports for the preceding academic year. (Deadline: 15 October)

C. Holmes MacDonald Outstanding Teaching Award

Presented annually to a dedicated young professor who has proven exceptional dedication to education and has found the balance between pressure for research and publications and enthusiasm and classroom enthusiasm and creativity. (Deadline: 30 April)

Distinguished Service Award

Presented annually to recognize those members who have devoted years of service to the society, resulting in significant benefits to all of the society's members.
(Nominations accepted ongoing)

IEEE-Eta Kappa Nu (IEEE-HKN) was founded by Maurice L. Carr at the University of Illinois at Urbana-Champaign on 28 October 1904, to encourage excellence in education for the benefit of the public. IEEE-HKN fosters excellence by recognizing those students and professionals who have conferred honor upon engineering education through distinguished scholarship, activities, leadership, and exemplary character as students in electrical or computer engineering, or by their professional attainments. THE BRIDGE is the official publication of IEEE-HKN. Ideas and opinions expressed in THE BRIDGE are those of the individuals and do not necessarily represent the views of IEEE-HKN, the Board of Governors, or the magazine staff.

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THE BRIDGE
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March 2014 Features

Departments

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LETTER FROM THE PRESIDENT

JOHN A. ORR
Alpha Chapter

Dear IEEE-Eta Kappa Nu Members and Friends:

Nothing exemplifies the culmination of the mission of IEEE-HKN more than our induction of Eminent Members. Our activities begin with recognizing and supporting academic excellence in college, and then in fostering professional development throughout our members' professional lives. It is humbling and inspiring to see the lasting impact on both technology and society that members of our profession have had during their careers.

In October, we had the honor of adding Faqir Chand Kohli to our roster of Eminent Members at a ceremony held at MIT, one of Dr. Kohli's alma maters. F. C. Kohli's vision and leadership of Tata Consulting helped drive India's IT industry from a handful of computer professionals to a multibillion dollar industry with over two million highly trained professionals.

In November, as part of the IEEE Educational Activities Board (EAB) Award Ceremony in New Jersey, our roster of awardees grew with the addition of three more extremely distinguished members – N. R. Narayana Murthy, Susan Graham, and Martin Cooper. Learn more about these winners in our recap of the awards ceremony on page 16.

Our other awardees at the EA ceremony exemplify two other key aspects of IEEE-HKN's role: recognition of early career success, and of the teaching excellence that is essential to launching our members' careers.

Sampathkumar Veeraraghavan, our Outstanding Young Professional, has made pioneering contributions to creating computing solutions to assist millions of disabled individuals in developing nations.

The recipient of the C. Holmes MacDonald Outstanding Teacher Award is Prof. Sayan Mitra at the University of Illinois at Urbana-Champaign. His success in teaching comes from an innate ability to convey complex material to his students.

Having had the opportunity to chat with these extremely accomplished people, I am always struck by what truly "nice" people they are, and their widespread range of interests.

The time for nominating terrific colleagues, mentors, and professors for these achievements is quickly approaching. Visit the IEEE-HKN website to learn more about these prestigious honors and the nomination process.

My very best wishes,

Phone + 1 508-831-5273
Email: j.orr@ieee.org

DR. STEVE E. WATKINS

Gamma Theta Chapter

Dear IEEE-Eta Kappa Nu Members and Friends:

This issue of THE BRIDGE magazine has a theme of “Lasers, Optics, and Photonics.” We have features that encompass laser safety in laboratory, developments in quantum optics, applications of fiber optic sensors, and a history of high power semiconductor lasers.

Such technologies are increasingly important and are interdisciplinary. In 1999, the U.S. National Academy of Engineering sponsored a project to select the Greatest Engineering Achievements of the Twentieth Century (www.greatachievements.org). Lasers and fiber optics were among these greatest achievements. Additional categories of imaging and health technologies were selected for which optical elements were an important part. The recent approval of formal program criteria for optical engineering undergraduate degrees by ABET reflects the importance of this broad field in the twenty-first century. Divisions of optics are optical imaging, quantum optics, lasers, photonics, electro-optics, fiber optics, biomedical optics and more.

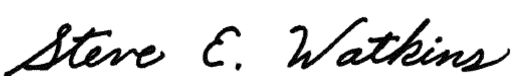
In addition, I refer you to the IEEE Global History Network (www.ieeeghn.org) for related IEEE Milestones. The invention of holography (1947) is commemorated with a Milestone plaque at Imperial College, London, England. The first working laser (1960) is commemorated at Hughes Research Laboratory, Malibu, California. The first low-loss optical fiber for telecommunications (1970) is commemorated at Corning Sullivan Park Research Center near Corning, New York.

The next issues of THE BRIDGE magazine will have the following themes:

- June 2014 “Engineers’ Involvement in Society” and
- November 2014 “Spotlight on Student Undergraduate Research”

For undergraduate readers, consider submitting content for this November issue. The deadline is 15 April. See page 15 of this issue for more information.

Best regards,



Phone + 1 573-341-6321

Email: steve.e.watkins@ieee.org

The first successful working laser, constructed by Dr. Ted Maiman in 1960. Courtesy: HRL Laboratories, LLC.

NANCY M. OSTIN, CAE

Dear IEEE-Eta Kappa Nu Members and Friends,

2014 is a year of opportunities, growth and vitality for IEEE-HKN. We are represented by 157 active Chapters – these include new Chapters, revitalized Chapters, international Chapters and growing Chapters.

IEEE-HKN students and professionals are making a difference. Chapters are having a positive impact on their fellow students, within their universities, in their communities and to each other. In the last academic year, IEEE-HKN Chapters reported more than 56,000 hours of service overall.

Service to others is a defining quality of an IEEE-HKN student and Chapter. It directly relates to the organization's principle of CHARACTER. The scholastic achievement requirement to qualify for an invitation to join IEEE-HKN is rigorous. However, beyond achievement in the classroom, our members display that very desirable trait of CHARACTER.

Remember the quote: “At the end of your lives you will not be judged by academic successes, the degrees or diplomas earned, the positions held, the material wealth acquired, or power and prestige, but rather on the basis of what you have become as persons and what you are in conduct and character.” — Howard W. Hunter

Since 1904, Eta Kappa Nu has recognized more than just academic achievement and focused on the development of the character of our members. Our big, audacious goal is to “be recognized as the premier global honor society that helps to develop well-rounded students through excellence in scholarship, technical achievement, leadership and service, and transitioning to professional practice, benefitting society over the span of their careers in the IEEE’s technical fields of interest.“

In short, our goal is to provide opportunities from which an individual can become “the complete engineer or professional.” The vision of our founders was that scholarship plus character and attitude would determine success in the engineering field.

At the Student Leadership Conference held 14-15 March, many of our student leaders, Faculty Advisors, members of the Board and professional staff met to exchange ideas about the challenges facing our organization and brainstorm on future programs, services, needs and direction of IEEE-HKN.

Join the conversation and share with us your thoughts, offer suggestions, and consider becoming involved. Once Eta Kappa Nu – always Eta Kappa Nu. We hope to hear from you soon.

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Mark your Calendar!

IEEE-HKN 2015 Student Leadership Conference in Berkeley, California

Join the Mu Chapter at the IEEE-HKN 2015 Student Leadership Conference in Berkeley, California.

Are you and your Chapter members seeking opportunities for professional development, leadership training and networking with outstanding leaders of industry and academia as well as members of IEEE-HKN from around the globe? Then start planning now to attend the IEEE-HKN 2015 Student Leadership Conference, to be held in spring 2015 by the Mu Chapter at the University of California, Berkeley. At the same time, the Mu Chapter will also celebrate its 100th anniversary. As always, registration for this exclusive event is free for IEEE-HKN members. More information about this event will be available in the upcoming months on the IEEE-HKN website and social media platforms.

IEEE-HKN Virtual Campus

The new IEEE-HKN Virtual Campus is a platform for all HKN and IEEE-HKN to meet, share, learn and stay in touch. The platform (http://bit.ly/15LTalC) includes:

- **Chapter Officers Forum**
- **General IEEE-HKN Forum**
- **Conferences (permanent and new content on demand)**
- **Resource Library (to share and find resources)**
- **Alumni Reconnection Center**
- **Chapter Websites**
- **Shared Google Calendar**

The IEEE-HKN Virtual Campus was created to make it easier for Chapters, members and Headquarters to share resources with each other. Under this Virtual Campus exists a place to participate in workshops, share best practices and ask questions about IEEE-HKN. With the IEEE-HKN Virtual Campus, we can all work better together.

Laser Safety for Electrical Engineers

Minimum Safety and Performance Pointers

By David Brown Iota Chapter

Introduction

Electrical engineers are often called on to help with problems that involve more than just electricity. One of these areas is often lasers. Unfortunately, most companies are not large enough to have a dedicated optics engineering staff. Many health and safety departments have not had to set up procedures to keep you and other employees safe around laser work.

If you are a young engineer just beginning your career or an experienced engineer that is being asked to work with lasers the first time, you should be able to use this article to help you get started in a safe manner. Just as important, references are provided to help you find additional rules and safety considerations that will save you time and prevent injury.

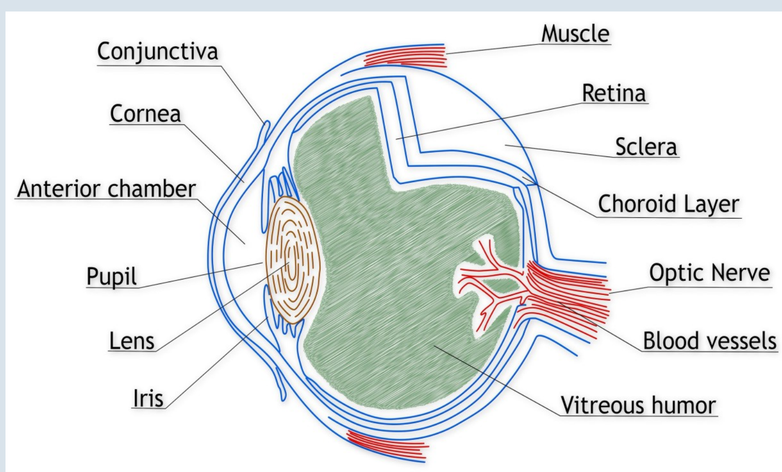


Figure 1. Parts of the Eye.

Classification of Laser Types

Each laser has its own wavelength and power or energy specifications. Some lasers are inside other systems with magnification or other optics that can alleviate or enhance risks to the operator or maintenance engineer. When building up your own laser application, you have to be aware of all these factors and maintain safe practices.

Proper precautions must be taken for both eye and skin hazards. The eye is particularly sensitive and damage can be done to the various parts as shown in Figure 1. For instance, the cornea and lens act as a magnifier to concentrate light into a small patch at the back of the eye for visible and near infrared ranges.

Special consideration of the impact of different wavelengths requires an understanding of where each wavelength is absorbed by the parts of the eye. Different spectral ranges are shown in Figure 2.

When using a laser that was purchased there is always an evaluation of what level of safety is required. These are communicated by the classification markings. Each of the laser type designations has been developed to provide appropriate protection for the risks associated with each laser type. These classifications are usually marked on the outer housing to indicate the risk of the laser as it was intended to be used. If covers, filters, lenses or other components of the system are removed, the marking may be inadequate to describe the real threat posed by the laser inside. Table 1 below describes the laser markings and hazards for current commercial laser systems.

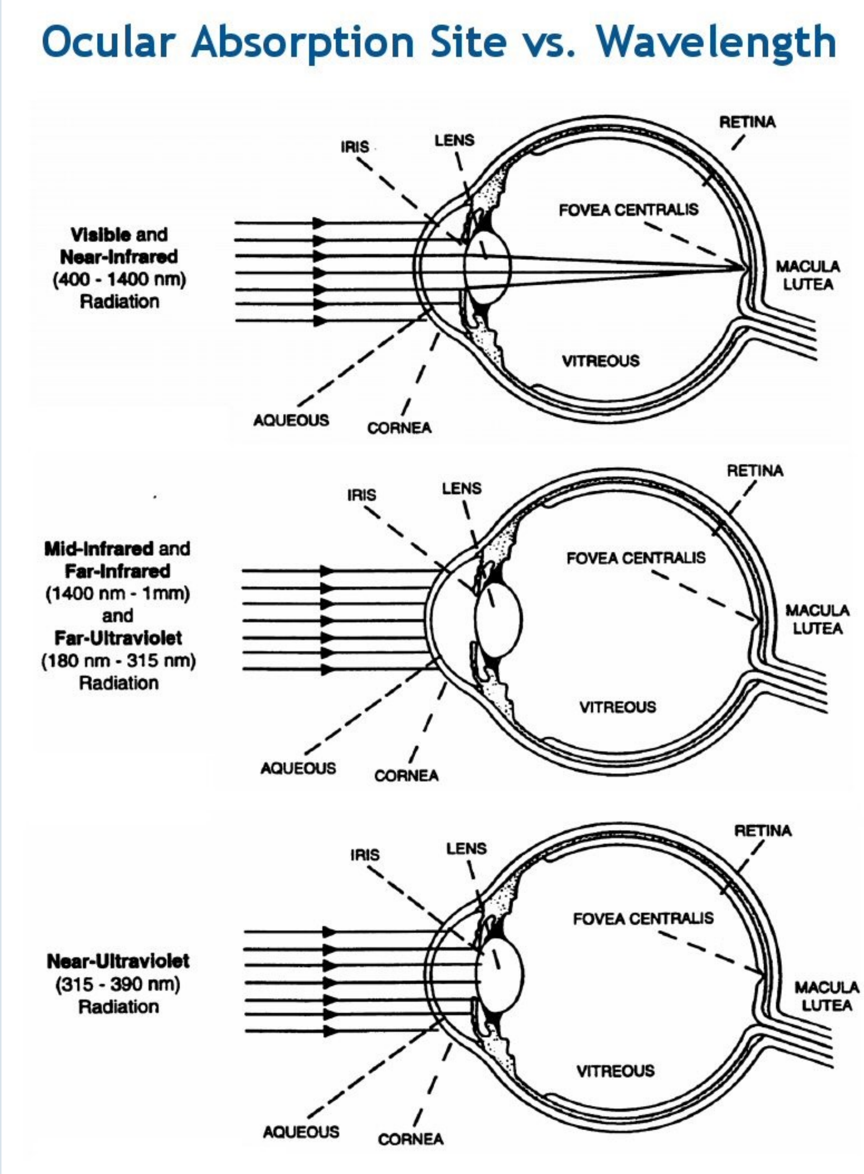


Figure 2. Ocular Absorption Site vs. Wavelength.

Class	Hazard	Description
1	None	Emissions are below the minimum damage thresholds even with magnification. (i.e. the lenses of the eye)
1M	Eye Hazard when viewed with magnification	Emissions are only dangerous if viewed through magnification such as a microscope, binoculars, magnifying glass and eye glasses.
2	Eye Hazard when stared into.	Short duration safe due to speed of blink reflex. Staring or exposure through magnification can be dangerous to eyes.
2M	Eye Hazard when stared into or with magnification.	No exposure is safe with these lasers through any kind of magnification. Exposure exceeds minimum damage threshold for the eyes.
3R	Restricted Viewing	Eye safe for short duration or expanded viewing. Low risk of immediate damage. Magnification or long duration without expansion can be dangerous to the eyes.
3B	Eye Damage	No direct viewing of the beam or damage may occur.
4	Eye and Skin Damage	Exposure to minor reflections may damage skin and eyes. Direct emissions are extremely damaging to skin and eyes.

Table 1. Current Laser Hazard Classifications.

Before 2000, the laser hazard classifications were different. As shown in Table 2 below, these markings will be encountered and should be understood before working with older lasers.

I – Eye safe due to enclosures or emissions are below safety standards. Now in the revised Category I.

II – Eye safe due to blink reflex. Always visible wavelengths. Do not stare into beam. Now in revised Category 2.

IIa – Eye safe if not stared into over 1000 seconds. Now in revised Category 2M for most lasers.

IIb – Not eye safe if beam incident on the eye directly. Now in revised Category 3R.

III – Not eye safe. Direct incident beam on skin or eyes will cause permanent damage. Now in Category 3B or even 4 depending on power and wavelength.

IV – Never eye or skin safe. Even minor reflections can cause permanent and severe damage to skin or eyes. Now in Category 4.

Table 2. Older Laser Hazard Classifications (Pre 2000 ANSI Z136.1)

Precautions to Be Taken

Appropriate eye wear to provide attenuation through use of filtering should be used with any Class 2M through Class 4 laser. Special care must be taken to choose lenses with the appropriate amount of attenuation at all wavelengths that may emit from a given laser. If more than one laser will be used at the same time or be used by multiple people in the same area, this becomes even more difficult.

An issue that can arise when choosing protective eyewear is maintaining enough visible light. If filtering gets too broad in wavelength, it is often difficult to create filters that allow sufficient light for viewing your work. Some laser protective eyewear can make a very bright room look like dusky night with no moonlight. This also causes the temptation to look over or around your glasses, making them useless and increasing the risk of eye damage by the beam or reflections.

The use of blockades, curtains or other barriers are required along with signage to keep bystanders from entering the laser area without eye protection. People with access to the room may come in unannounced. They must be made aware as they approach. Two-way communication with the operator is needed to interrupt the work or they need glasses with them so they are protected as well. These are the most common near misses in laser laboratories. They can be prevented by keeping the laser area appropriately small or removing the ability for anyone to walk in on a test.

One last area that is often overlooked is stray or on purpose reflections. Precautions must be taken to know where your beam and any reflections are at all times, especially when doing alignment or adjustments to Class 4 laser systems. While making adjustments to lenses or mirrors with an open beam setup, reflections can be created that reflect right back into your face or hit an arm or hand. Keep your eye level above the beam path and perpendicular to it at all times. Use laser safety eyewear with side guards and do not continue working if the eyewear does not stay in place on your face well.

Skin must also be safeguarded. Most common injuries to the skin are burns from reaching across an open beam path or through a side path. These are especially painful and damaging in pulsed laser system work. Again, always be aware of your beam path(s) and splits and reflections when working with lasers in the Class 3 or 4 subcategories.

Documents With Laws And Standards For Laser Safety Program

The rules implemented in the safety standards are there to protect you and bystanders that may come into a laser test area unaware. By properly setting up the area and maintaining strict controls, laser work can be performed in complete safety. Good practices and thinking through how you will do your laser work can allow you to prepare the area and your own practices to make this a relatively inexpensive and safe job.

If added motivation is needed to take laser safety seriously there are some great resources that you should check out and share.

- Laser Institute of America (www.LIA.org) The Laser Institute of America (LIA) provides specifications, guides, training and signage to fully equip any company to the level required to meet safety standards and apply appropriate controls to a laser endeavor.
- Department of Labor, OSHA Technical Manual (OTM), Chapter 6 - OSHA Instruction TED 01-00-015 [TED 1-0.15A] lists U.S. government regulations concerning laser safety.
- Rockwell Laser Industries – Laser Accident Database (www.rli.com/resources/accident.aspx) This site has been collecting accident reports and is shared to reduce the number of accidents in the future. Rockwell Laser Industries offers all types of training and certification courses for optics and laser engineers.
- Navy Laser Safety Program Information - (www.public.navy.mil/navsafecen/Pages/acquisition/LaserRadiation.aspx) The Navy site has many pointers and good suggestions for setting up a strong laser safety program and operations.

Laser systems are diverse. These references and links show how to tailor a laser safety program to the specific application.

Find or become a Laser Safety Officer

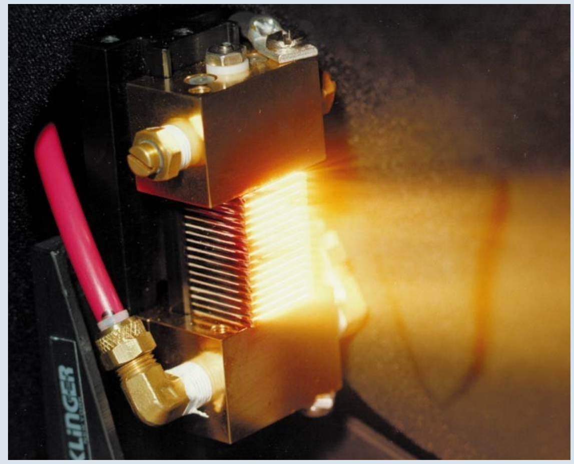
If this project is a onetime event, then work closely with your safety department to ensure all laws are complied with and safety is maintained. If this is just the beginning, then you should consider becoming a Laser Safety Officer (LSO). To become a LSO will require training and getting certified through a program like the one at LIA. The duties of the LSO are simple:

1. Identify the hazards of a given laser system (proposed or existing)
2. Understand and apply appropriate safeguards for the Laser Hazard Classification rating of the given system
3. Train any personnel who will working with or be around the laser activities at your company

This is an official certification. It documents that you have studied and understood all the safety considerations and laws for working with lasers and laser optics. You will be a very important part of the safety and laser team working in your company.

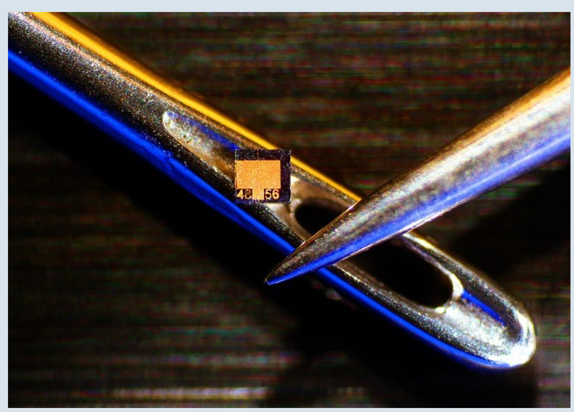
Summary

Working with lasers or even developing and testing lasers is very exciting. Many laser engineers started out as electrical engineers and fully understand the hazards with high voltage or high current systems. They may be asked to work with lasers when there are no other laser engineers in the company. This article was intended to help you make the leap to create a proper work area and to work with lasers responsibly and safely.



High power laser diode emission is usually invisible due to wavelength. Image Credit: Lawrence Livermore National Laboratory

CD-ROM read and write components contain a laser diode that is not safe if viewed directly during operation.



Since Tunable Diode Lasers (TDLs) can produce more than one wavelength of light, they require special attention to safety. Image Credit: NASA

Spend some time getting to know the various rules and precautions as well as view examples of how others have solved their problems. Always keep in mind what wavelengths you are working with and if there are any wavelengths present in the system (even if they are not normally in the exiting beam). Be prepared that something can change and the other wavelengths may be emitted as well. Choose appropriate eyewear, get training and train others who will be in the area. In no time you will be another laser engineering expert.

Joining The Optical Society (OSA) and/or SPIE, the international society for optics and photonics, would also help you in having mentors in the laser optics field to help with difficult or unclear situations. Or your expertise will be invaluable to others as your experience increases in working safely with lasers.

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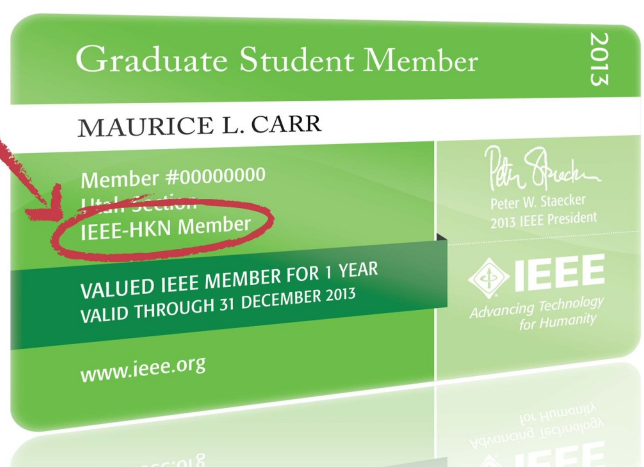
About the Author

David Brown is an electrical engineer with many years experience in testing all types of electrical and optical systems. EaglePicher Technologies LLC in Joplin, Missouri employs David as a Principal Engineer. Prior to this, he was the Chief Engineer at Oklahoma State University – University Multispectral Laboratories in Ponca City, Oklahoma for two years. He was a Principal Engineer at Honeywell FM&T in Kansas City, Missouri for 17 years where he built and evaluated various types of laser systems for the Department of Energy. He holds a Master’s of Science degree in electrical engineering from MS&T in Rolla, Missouri. He also attended Missouri Southern State University in Joplin, Missouri before attending MS&T. David is a member of IEEE-HKN, IEEE, OSA and SPIE.



Nominate Candidates for the Outstanding Student and Chapter Awards

IEEE-Eta Kappa Nu offers opportunities for exceptional members and Chapters to be recognized via the Alton B. Zerby and Carl T. Koerner Outstanding Student Award and the Outstanding Chapter Award. The deadline to submit nominations for these awards awards are 30 June and 15 October, respectively.

IEEE-HKN's Outstanding Chapter Awards for the 2011-2012 year

The Alton B. Zerby and Carl T. Koerner Outstanding Student Award recognizes outstanding scholastic excellence and high moral character, coupled with demonstrated exemplary service to classmates, university, community, and country. This program is administered by the Los Angeles Area IEEE-HKN Alumni Chapter.

The purpose of the Outstanding Chapter Award is to recognize excellence in college Chapters for their activities. The award is based on the contents and description of Chapter activities that are contained in the Annual Chapter Report (submit your form here: http://bit.ly/HOGr8O). The Annual Chapter Reports are due by 30 June of each year and summarize all activities for the previous academic year from 1 July to 30 June.

In bestowing an award, the standing committee attaches less importance to the number of a Chapter's activities than to their nature and quality. Of critical concern to the committee in judging a Chapter are activities to improve professional development, to raise instructional and institutional standards, to encourage scholarship and creativity, to provide a public service, and generally to further the established goals of IEEE-HKN.

Please note: though college Chapters are under no obligation to contend for this award, all Chapters are required to submit at least the short-form Annual Chapter Report summarizing their officers and activities. Chapters wishing to contend for the award are encouraged to submit a more comprehensive report covering their activities. The award submission deadline is 15 October. More information about these awards, including information on the application process, is available on the IEEE-HKN website (www.hkn.org).

Did you Know?

The Greek letters HKN were chosen from the 1st, 4th, and last letter of the Greek word for amber or electron: **HΛEKTPON**

SUPPORT OUR STUDENTS AND IEEE-HKN WITH A DONATION TO THE IEEE FOUNDATION

Each year, IEEE-HKN holds the IEEE-HKN STUDENT LEADERSHIP CONFERENCE to offer our students the opportunity to participate in opportunities for professional development, career advancement and networking. To assure that as many IEEE-HKN students as possible are able to attend, there is no registration fee.

However, hosting the IEEE-HKN STUDENT LEADERSHIP CONFERENCE costs in excess of $52,000, thus, we need your help to continue to offer this benefit to our students.

As you consider a donation, remember your days as a student, and imagine what attending an event like this would have meant to you.

Consider the following:

- -- $47 contribution pays for the Conference meals for one student
- -- $108 contribution supports the cost for one student to participate
- -- $250 contribution covers the travel reimbursement for one Chapter

By supporting the Conference, you will help impart the knowledge and skills needed by this generation of IEEE-HKN to make a difference in the world. For ease of donation, you can donate online using the IEEE Foundation's secure site at www.ieee.org/donate and selecting the IEEE-HKN Student Leadership Conference Fund (note: the IEEE Foundation is a tax exempt 501(c)(3) organization).

The attendees of the IEEE-HKN 2013 Student Leadership Conference.

Student Leadership Conference attendees participate in roundtable discussions on professional development topics.

Attendees of the Student Leadership Conference gather to learn from each other.

IEEE-HKN HISTORY SPOTLIGHT

ENGINEERING - A CAREER FOR TOMORROW

In 1953, as a way of commemorating its 50th anniversary, Eta Kappa Nu produced a career guidance film to interest high school students in engineering careers. The 50th anniversary movie committee was formed, with Dean William L. Everitt, College of Engineering, University of Illinois, as chair. He provided valuable guidance and support and enlisted the aid of the university's motion picture and television unit to produce the movie "Engineering — A Career for Tomorrow." Daniel F. Hang, also a member of the committee, engineering students, and others from the campus appeared in the film. Scenes were filmed also in the Chicago area at Illinois Bell Telephone and Commonwealth Edison. The film was completed in 1954 and can be viewed on the IEEE-HKN Virtual Campus.

– Call for Articles –

November 2014 Issue Theme: Undergraduate Student Research

- **Have you written an article resulting from your undergraduate research?**
- **Would you like to publish an article in THE BRIDGE?**

The theme of one of the 2014 issues of THE BRIDGE is "Spotlight on Student Undergraduate Research." IEEE-HKN seeks to honor excellence in engineering by recognizing the leaders of today and tomorrow. This issue of THE BRIDGE will spotlight articles written by IEEE-HKN student members, and is a great way for you to be recognized.

Qualifications:
Must have worked on a research project as an undergraduate in a topic area of IEEE interest that was supervised by faculty.

Things to know:

- Both feature length (2000-4000 word) and shorter length (800-1000 word) articles are solicited
- Copyright must be available for all images and figures
- Previously published articles are eligible if reprint permission is available
- Editorial staff of THE BRIDGE will work with you to edit submittals that are accepted

Next Step: If you are interested in submitting an article, send the following to info@hkn.org: 1) proposed article title, 2) abstract, and 3) a statement as to why the research would be of interest to readers. This information must be submitted by 15 April. Selected papers must be finalized in May/June 2014.

IEEE Educational Activities Board Awards

Presented November 2013

IEEE-HKN Honors Exceptional Leaders for Achievements in Engineering and Technical Education

The annual IEEE Educational Activities Board (EAB) Awards recognize and honor individuals and companies for major contributions to engineering and technical education. Awards are given for meritorious activities in accreditation, continuing education, educational innovation, pre-university education, service to the IEEE EAB, standards education, employee professional development, and informal education systems and related achievements that advance the practice of engineering and of engineering education.

Members from New Jersey IEEE-HKN Chapters and Amy Recine from IEEE-HKN Headquarters at the IEEE Educational Activities Board Awards Dinner in New Brunswick, NJ.

In addition, IEEE-Eta Kappa Nu presents several awards and recognizes Eminent Members. These awards honor excellence in engineering and the IEEE fields of interest by recognizing the leaders of today and tomorrow.

In this event, held in November in New Brunswick, New Jersey, IEEE-HKN presented awards to the following individuals:

-- IEEE-HKN Outstanding Young Professional Award
Sampathkumar Veeraraghavan "for inspiring leadership and exemplary seminal contributions in addressing global Humanitarian challenges through technological innovations in electrical and computer engineering"

-- C. Holmes MacDonald Outstanding Electrical and Computer Engineering Teacher Award
Sayan Mitra "for exemplary classroom teaching, outstanding dedication to students' learning, including substantial personal engagement with both undergraduate and graduate students, and major innovations in computer engineering courses and laboratories"

IEEE-HKN also recognized three Eminent Members at the November event.

-- N. R. Narayana Murthy "for technical attainments and contributions to society through outstanding leadership in the profession of Electrical and Computer Engineering"

-- Susan L. Graham "for technical attainments and contributions to society through outstanding leadership in the profession of Electrical and Computer Engineering"

-- Martin Cooper "for technical attainments and contributions to society through outstanding leadership in the profession of Electrical and Computer Engineering"

In addition, IEEE-HKN held a special separate ceremony for an Eminent Member in October in Cambridge, Massachusetts.

-- Faqir Chand Kohli "for advancing engineering education in India at undergraduate levels to world standards and serving as the 'Father of the Indian Software Industry'"

IEEE-HKN members from local Chapters Gamma Epsilon (Rutgers University), Iota Delta (Stevens Institute of Technology) and Gamma Kappa (New Jersey Institute of Technology) attended the New Jersey event. IEEE-HKN members from local Chapters Beta Theta (Massachusetts Institute of Technology), Gamma Delta (Worcester Polytechnic Institute), Epsilon Delta (Tufts University), Delta Eta (University of Massachusetts – Amherst) and Kappa (Cornell University) attended the Massachusetts event.

MA students and Kohli: IEEE-HKN Eminent Member Faqir Chand Kohli with IEEE-HKN members at the Eminent Member Ceremony in Massachusetts.

Award winners, from l to r: S. K. Ramesh (IEEE-HKN Board of Governors), Sampathkumar Veeraraghavan, N. R. Narayana Murthy, Susan L. Graham, Martin Cooper, Sayan Mitra, John Orr (IEEE-HKN President), Michael Lightner (IEEE Vice President-Educational Activities).

Quantum Optics for the 21st Century Electrical Engineer

A new mainstay of electrical engineering?

By Sean J. Bentley
Gamma Theta Chapter

Abstract

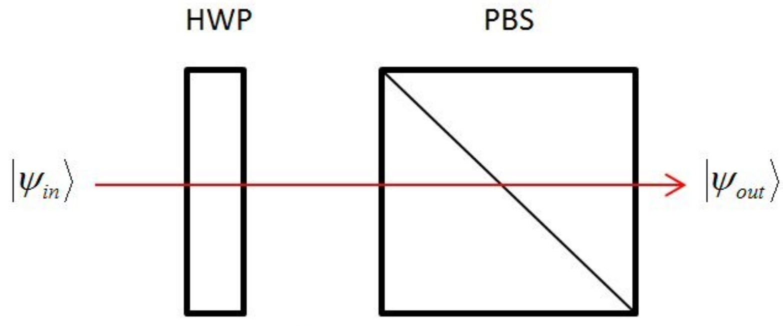
Quantum optics and electrical engineering—perhaps not two things you often think of as a perfect combination. However, just as advanced fields of study such as semiconductors and electromagnetics have become mainstays of electrical engineering and critical to so many of the technologies society takes for granted, I believe that quantum optics will soon be just as embedded in the field. Quantum mechanics has played an increasingly important role in electrical engineering over the past several decades, and this is sure to continue with quantum optics being a sub-field ready to step into the forefront of technology.

Quantum Mechanics & Quantum Optics

Quantum mechanics is the science behind the most impactful and far-reaching technological developments of the 20th century—transistors, lasers, solar cells, LEDs, quantum dots, and many more. Essentially all modern electronics, photonics, and nanotechnology rely critically on the principles of quantum mechanics. As devices continually get pushed to the limits of technology and science, the importance of engineers with knowledge of quantum theory will grow. However, very few electrical engineering students take quantum physics. When I was an undergraduate 20 years ago, I was the only electrical engineer in my year that took a full quantum mechanics course. The primary exposure most electrical engineering students get to quantum mechanics is a couple of weeks in a modern physics survey course, and a short introduction at the beginning of a semiconductor devices course. In many programs, even these courses are electives. While many recognize the importance of having more engineering students develop a solid working knowledge of key quantum principles, as seen by books specifically for electrical and mechanical engineering students (yes, even mechanical engineers face a growing need to understand the principles of quantum mechanics, primarily due to the growing importance of nanotechnology for that field), very few electrical engineering students learn quantum mechanics in any depth. In a field that is known for rapid development and the need to stay knowledgeable on the latest technologies to remain competitive in the workforce, I feel many electrical engineering students will open up a successful and exciting career by studying quantum mechanics and quantum optics.

Quantum optics is an important area of quantum physics that is becoming central to many new technologies.

Quantum optics is an important area of quantum physics that is becoming central to many new technologies. While some applications in quantum mechanics involve light (lasers and LEDs as two obvious examples), in most of the cases there the optical field is large enough to be treated as a classical electromagnetic field, with only the atomic system needing to be treated quantum mechanically. However, when the optical field is very weak, it becomes necessary to treat it in a quantum manner as well. This is often referred to as second quantization. To treat such problems where a weak optical field interacts with matter, the theory used is known as quantum electrodynamics, an example of a quantum field theory. That is an intimidating subject for any undergraduate, and something I will not explore here. Luckily, however, there are many important problems in quantum optics where only the optical field needs to be accounted for, allowing a much simpler approach for treating the photons quite similar to treating electrons in quantum mechanics (the details of the interaction of the light with matter in such cases can be hidden in the process used to generate the quantum states of light and to detect the light—these are important processes and must be understood in detail by some, but such an understanding is not critical for the discussion here). There are a few major differences that of course must be taken into account when studying photons rather than electrons. Three of these are that photons are massless, uncharged, and are bosons rather than fermions. While these are important to keep in mind and are key to certain applications, the focus here will be on the basic idea of manipulating the state of the photon.



(a)

$$A = \begin{pmatrix} 1 & 0 \\ 0 & 0 \end{pmatrix} \begin{pmatrix} \cos\theta & -\sin\theta \\ \sin\theta & \cos\theta \end{pmatrix} = \begin{pmatrix} \cos\theta & -\sin\theta \\ 0 & 0 \end{pmatrix}$$

(b)

Figure 1. (a) A simple example of a quantum optical system, where the input and output states are two complex numbers related to the polarization state of the photon being represented. Here, the photon is passed through a half wave plate (HWP) and a polarizing beamsplitter (PBS). (b) The operator, *A*, of the quantum system from (a) is given by the product of the operators that represent the two physical components (first matrix is for second component).

The state of any quantum object (whether an electron, photon, or other particle) is a description of the properties of the system in a mathematical way. Quantum theory gives a mathematical description for how the state of the quantum object evolves due to its interaction with a given physical system. For those of you who have studied quantum mechanics, there is a good chance your course focused on a differential equations approach to describe the object-system interaction. This is still common in most introductory courses and is useful for developing certain conceptual foundations of quantum theory. However, there is an equivalent approach to quantum mechanics that focuses on the use of linear algebra rather than differential equations. There are many advantages to the linear algebra approach, and it often makes the description of physical systems appear simpler and more transparent. While I will avoid going too heavily into the mathematics here, I will favor the linear algebra approach for most discussions of quantum optics and will use it to a limited extent here. This linear algebra approach, though, does make it look very much like linear systems analysis familiar to many electrical engineers:

$$|\psi_{out}\rangle = A|\psi_{in}\rangle$$

where ψ_{in} gives the initial state of the particle, ψ_{out} gives the state of the particle after being acted on by the system, and *A* is the linear operator which mathematically models the physical effect of the system on the particle (see Figure 1 for an example). As I mentioned earlier, creating and measuring the quantum states is an important area in its own right, but much of the key to any application of quantum physics is being able to create a physical system that can operate in a desired manner on your particle — that is, being able to find a physical realization for a desired *A*. For example, what if you want to perform an operation on a quantum state analogous to a digital logic operation one would perform on a logic variable? Scientists have learned methods to do exactly that, at least for certain logic operations. The difficulty of this varies greatly with the complexity of the problem, but researchers have now brought many very useful technologies to reality in the quantum realm. A few of these, including quantum computing, quantum cryptography, and others will be discussed briefly here.

Quantum Computing & Information

There are major advantages to quantum information. In traditional digital logic used in all modern electronics, every piece of information, known as a bit, can take on the value 0 or 1. Through operations built on Boolean relations AND, OR, and NOT that act on those bits, computers perform all of what we see from games to word processing to simulations of differential equations. While engineers and computer scientists have used this technology to do amazing things (which has been greatly aided by the continued miniaturization of integrated circuits—something that quantum mechanics also looks to aid as will be discussed later in this article), for certain types of functions the speed and power of traditional computing will always be limited. Quantum computing has as its major advantage its fundamental element, the quantum bit, known as a *qubit*. Unlike a standard bit that is either 0 or 1, a qubit is simultaneously both 0 and 1, represented as:

$$|\psi\rangle = \alpha|0\rangle + \beta|1\rangle$$

where ψ gives the quantum state of the qubit, with α and β known as the amplitudes for 0 and 1. The amplitudes are in general complex numbers, with the only restriction being that the state is normalized:

$$|\alpha|^2 + |\beta|^2 = 1.$$

For many of the traditional types of procedures you may want to do on computer, you may not see how this would be an advantage, and you could be right. However, there are particular types of problems for which the qubit holds great advantage in computing speed and power when compared to traditional computing. One such problem is in factoring large numbers, the key to cracking current cryptography codes (and there are many other complicated physical models that could be ideal candidates to be mathematically solved much faster by quantum computers than traditional computers). This power is held in the two facets of the amplitudes. First, the squares of the magnitudes of the amplitudes give the probabilities of being 0 or 1. The states being inherently probabilistic gives great robustness for quantum computing. Additionally, the amplitudes are not just real numbers, but in general complex numbers. Thus, not only do 0 and 1 have certain probabilities, but also relative phases. Like any quantities with relative phase, this means that qubits can interfere! This opens up a wide variety of computational methods not available to traditional computers. While it may never be economically and technologically practical to have a quantum computer inside your tablet or smart phone, quantum computers are now a reality, and their applications and uses will continue to grow. In fact, as some believe that much like storage the majority of your computing power will someday exist in the cloud, then perhaps you indeed will be using a quantum computer someday when playing your favorite game on your phone.

You may be wondering how you would physically implement a qubit. It turns out there are many possible implementations, with common examples being polarization states of photons and spin states of electrons. As particles have more than one property that can simultaneously carry information, it turns out that a single particle such as a photon or electron can actually carry multiple qubits. There are also higher-order qubits (for example, qutrits, which are in states 0, 1, and 2 simultaneously), but you get the idea—quantum computers can hold large amounts of very robust information in a few elementary particles. Physicists in laboratories are happy to deal with the level of precise equipment needed to do proof-of-principle quantum computing using elementary particles, but engineers would quickly point out the difficulty of working with such systems. (Figure 2 shows a typical quantum entanglement experimental set-up using photon entanglement.) Therefore, the one company currently building commercially available quantum computers, D-Wave, uses superconducting loops with Josephson junctions to create the qubits. When I was an undergraduate in the early 90s there was still great excitement over the possibility of room-temperature superconductors which would revolutionize the world. While many have now given up the search as the highest temperature semiconductor found to date is still a frigid 138K, superconductors are still very important for high-end applications and are the primary system for creating macroscopic quantum states. The fact that D-Wave uses their superconductors at 20mK means the systems

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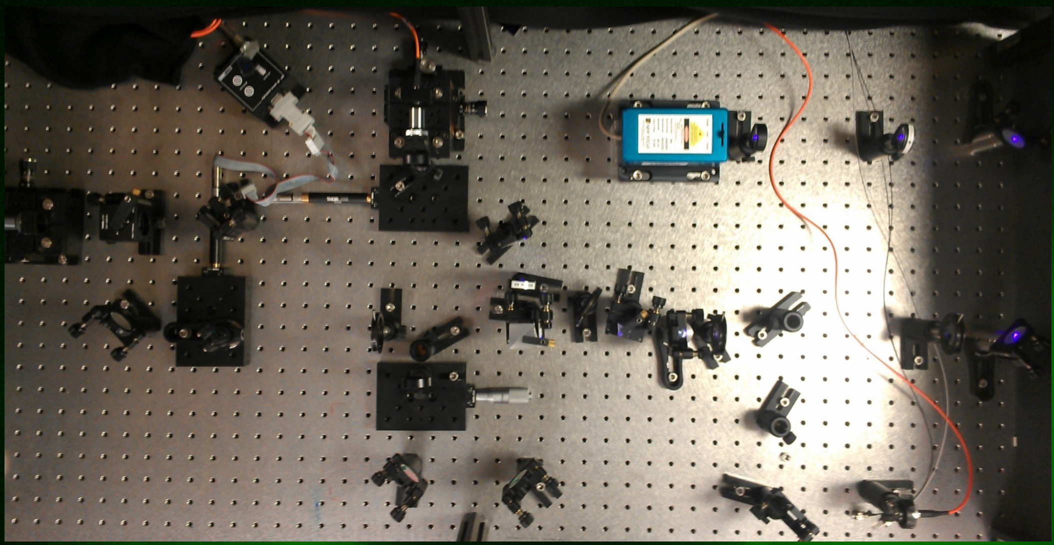

Figure 2. A typical experimental configuration for the generation, manipulation, and detection of entangled photons. The particular configuration shown is implementing a spatial quantum eraser for a double-slit interference measurement.

continue to be large, expensive, and not something you will find at your local store, but nonetheless the systems exist and are available for use. While the current implementation is not directly using quantum optics, much of the foundational research was done (and continues to be done) with photons, and it is possible that some future commercial systems may be optical. Either way, continued development of quantum computers depend on the next generation of engineers and scientists, and hold the promise of elevating computing to levels that even now are hard to imagine.

Quantum Cryptography

For those who take the above discussion of quantum computing to heart, one concern that may come to mind is that quantum computers could be the ultimate hacking machine, capable of cracking the highest level of encryption in a flash. Once again, quantum rises up to solve the problem (even problems it "created"). A concept known as quantum entanglement leads to many new ideas and technologies, and one of the leading such technologies is quantum cryptography. Unlike traditional cryptography that relies on the difficulty of brute-force factoring large numbers into primes (something that quantum computers can do rapidly), quantum cryptography is in principle unbreakable. It sends the information through quantum particles (for example, a stream of photons is sent, with each photon carrying one bit of information) which are entangled with another set of particles. Entanglement goes far beyond simple classical correlation to the point that if you make a measurement on one of the particles (in any basis system that you choose, which is something that makes it inherently quantum—the basis could for instance be what angles about you would measure the photon's polarization state), you can say something definitive about the outcome of a similar measurement on its entangled partner. Without going too deeply here into the physics and mathematics, the information to be sent is mixed with the random states of the entangled particles. One set of the particles is measured, with the information recorded locally, while the other set of particles is sent to the destination of the information. After the receiver confirms that they received all of the particles, then the results of the measurements are sent over a classical channel to them so that they can decode the information. However, if any of the particles are not received, then rather than sending the decoding information, the process is repeated until successful transmission is achieved. Thus, if any of the particles are "stolen" along the way, the decoding information is never sent, meaning that what was stolen is nothing more than random bits containing no meaningful information. So why could the hacker not just grab the information, copy it, and send it on to the intended receiver so that their crime is not detected? Quantum comes to the rescue again with the no-cloning theorem, which says that it is impossible to make an exact copy of a quantum particle without destroying the original. So how about just making the measurement of the particle, then create a new particle in that state? Fortunately the measurement depends critically on what basis to make the measurement in, which is only known to the sender and receiver. Since the hacker doesn't know what basis the measurements will be made in, the best they could do is to take a wild guess, something they could do just as well without grabbing the particles at all. Putting all of these pieces together, quantum cryptography is indeed "unhackable."

In practical applications, though, there is a limitation. Assume that your system uses photons as the quantum particles, and that you want to send the information from New York to London. You could imagine having a dedicated fiber to send the photons through, but fibers have loss. How many times would you have to perform the above procedure to get the entire packet to London without losing any photons? How long would this take? You could end up with terribly low effective data rates. For sending small amounts of very sensitive information, perhaps this would be acceptable, but for most applications this would be a major drawback. Thus, some quantum cryptography systems (yes, these also are commercially available and are being used in some systems around the world) actually allow for a small amount of loss by building in redundancy to greatly increase effective data rates. Once any loss is allowed, the system is no longer perfect, and allow (extremely high-tech) hackers a chance of stealing the information. Lossless systems are used primarily in short-range systems where fiber losses can be negligible, and in loss-forgiving systems used for long-range systems one must decide how much risk they are willing to take in exchange for speed. With the ever-increasing concerns over information security as virtually all of our information and transactions travel through the internet, quantum cryptography could hold the answer. Engineers are needed here as well to help develop systems that can work to simultaneously minimize the risk of data theft and maximize data transfer speeds.

More Advanced Quantum Technologies

As we keep pushing the bounds on all technologies, quantum mechanics continues to find its way into more applications. One of these is quantum lithography. It is a proposal to extend the limits of optical lithography by using quantum states of light. The basic idea of quantum lithography is to use an *N*-photon recording substrate and entangled states of light to write features that have an *N*-times higher resolution than would normally be allowed. If one were to do this with classical light, you would get sharper fringes, but without tighter fringe spacing. Limitations to practical implementation of quantum lithography have caused many researchers to look for classical alternatives, but at the very least research into quantum lithography has led to an increased effort to find new ways to push the limits of optical lithography.

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Another leading area of quantum optics research is quantum imaging. In this application, entangled photons are used to create an image of an object in a non-traditional manner. One of the entangled photons is sent into the region containing the object, and a detector determines if the photon makes it through. Its entangled pair is spatially resolved, while never interacting directly with the object. Possible applications could include imaging through turbid material. This is one of the oldest areas of quantum optics research, and the most well developed. While the original research was done with entangled photons as described above, due to the difficulty of using entangled photons in real-world applications other sources have been investigated. One major breakthrough this has led to is the deeper understanding of the quantum properties of thermal light. While the use of entangled photons is a powerful research tool, it would be difficult to implement widely in applications in uncontrolled environments. Thermal light, on the other hand, is a cheap, robust, easy to use source. You may think of thermal light as being one of the most classical things you could imagine, but the quantum fluctuations of such light could be key to many next-generation applications. At the very least, it broadened the thinking in the field of quantum optics.

Quantum optics research is touching on many more key areas, and it is nearly impossible to predict which ones will find their way into mainstream technological application. However, it is clear that for these areas to become well developed, engineers trained in quantum theory will be at the center of the effort.

Electrical Engineers & Quantum Mechanics

Electrical engineers who work in the area of semiconductors have long needed at least a solid foundation in quantum theory, and this will always be the case. The growing area of nanotechnology is bringing more electrical and mechanical engineers into the quantum family. As discussed here, quantum optics is bringing many more areas of electrical engineering into the quantum realm, including computing, cryptography, imaging, and more. Clever scientists and engineers will continue to find new applications for quantum optics and quantum mechanics. While certain areas of electrical engineering such as motors and power transmission may never feel the influence of quantum physics, the need for more electrical engineers trained in quantum theory will almost definitely grow in this century. If you want to be on the cutting edge, then perhaps you should take the quantum leap.

About the Author:

Sean J. Bentley earned his BSEE ('95) and MSEE ('97) from the University of Missouri-Rolla (now Missouri University of Science and Technology), and his Ph.D. in Optics ('04) from the University of Rochester. He is an Associate Professor of Physics at Adelphi University, where he was awarded the Teaching Excellence Award for 2012-13. He serves on the National Council of the Society of Physics Students, is authoring a text on quantum imaging, and holds a patent in nonlinear lithography. He was elected to membership in IEEE-HKN as an undergraduate.

Does Your Chapter Have the Keys to Success?

New Recognition Available in 2014

Each Chapter is encouraged to complete the requirements to be named a Key Chapter. Participation and activity in the areas identified are the best practices that successful Chapters follow. Every Chapter has the potential to earn the Key Chapter recognition! Key Chapters will receive recognition on the IEEE-HKN website and social media, celebrated by their peers, and receive a prize. The prize will be identified annually and promoted to each Chapter along with the requirements.

Mandatory requirements:

- Submit the Annual Chapter Report
- Submit the Notice of Election of Officers within one week of the election
- Submit the induction paperwork either before or within one month of their induction ceremony

Fulfill two of the following requirements:

- Send a representative to the Annual Student Leadership Conference
- Participate in one of the IEEE-HKN competitions or challenges
- Contribute workshop content to the IEEE-HKN Virtual Campus Conference Center
- Complete a Chapter activity or program to reconnect with alumni
- Host a regional meeting of Chapters (based on Chapters that are geographically accessible)

The Key Chapter recognition period will start on 1 January and complete on 31 December of the same year. The ceremony to recognize Key Chapters will be held during the Annual Student Leadership Conference of the following year. For example: 1 January, 2014 – 31 December, 2014 will be presented at the 2015 Student Leadership Conference. Questions? Contact info@hkn.org.

IEEE-HKN Board of Governors Election Results

IEEE-Eta Kappa Nu held elections this past October to fill open positions for the IEEE-HKN Board of Governors for 2014. The results were as follows:

- President: John Orr
- President-Elect: Evelyn Hirt
- Governor-at-Large: Nita Patel
- Governor, Regions 7-10: Dr. Mohamed El-Hawary
- Governor, Regions 1-2:Dr. Kenneth Laker
- Student Representative: Kyle Lady, IEEE-HKN Beta Epsilon

These representatives will join Dr. David Jiles (Governor – West Central Region), Dr. S. K. Ramesh (Treasurer and Governor – West Region), Dr. Timothy Kurzweg (Govenor-at-Large), Dr. Mark E. Law (Governor – East Central Region) and Dr. Catherine Slater (MGA Governor-at-Large) as the 2014 IEEE-HKN Board of Governors.


John Orr


Evelyn Hirt


Nita Patel

THE BRIDGE editorial team asked each of the recently-elected representatives to share their IEEE-HKN-related goals for 2014. Below are their responses.

John Orr, President

- Continue the growth in numbers of Chapters and in numbers of inductees in each Chapter.
- Introduce new programs and activities that add value for our student and professional members.
- Begin the implementation of the Strategic Plan developed by past president Dr. Steve Goodnick and his committee.
- Increase involvement by alumni, both with student Chapters and on Board-level committees.
- Enhance the support and recognition of Chapter officers and Faculty Advisers.
- Enhance the visibility of IEEE-HKN within IEEE and promote greater synergy with IEEE activities.
- Support Nancy Ostin and Amy Recine at IEEE-HKN Headquarters in their great work with the Chapters.

Evelyn Hirt, President-Elect

- Integrate IEEE-HKN fully into IEEE: Help to build stronger relationships and collaborations between IEEE-HKN Chapters and their local and regional IEEE geographic units (Region, Areas, Sections, Subsections, technical

Chapters, and Affinity Groups) around the world as well as with IEEE-USA for those Chapters within the United States

- Grow alumni participation: Facilitate increased interaction and involvement of IEEE-HKN and HKN alumni in their local (student or alumni), or home IEEE-HKN Chapters.
- Encourage and recognize service to the profession and to society / Realize sustained membership growth: Work with Chapters to identify professionals among the IEEE membership and their alumni for induction who's professional achievements, commitment to service, and volunteerism to the profession and to society as a whole demonstrate IEEE-HKN Core Values.

Mohamed El-Hawary

Nita Patel, Governor-at-Large

- Integrate with and leverage the broader IEEE resources for mutual success.
- Strengthen and deepen our engagement with and between our strong, core membership.
- Focus on our mission of honoring/recognizing technical excellence.

Kenneth Laker

Mohamed El-Hawary, Governor, Regions 7-10

- Lead a campaign to establish new IEEE-HKN Chapters in Regions 7-10, beginning with all of region 7, United Kingdom and Republic of Ireland Section in Region 8, India, Australia, Hong Kong, New Zealand and Taiwan.
- Develop Spanish/ French/ Portuguese/ German material promoting the creation of IEEE-HKN Chapters.
- Seek best practices from well-established IEEE-HKN Chapters to use with IEEE-HKN Chapters in Regions 7-10.

Kyle Lady

Kenneth Laker, Governor, Regions 1-2

- Use my IEEE experience and network to help IEEE and IEEE-HKN realize win-win opportunities that were foreseen by those who worked tirelessly to achieve the IEEE-HKN merger
- Help improve areas where both our student and professional members can benefit from each other, such as taking advantage of the global IEEE and honor associated with being inducted into IEEE-HKN, deploying IEEE-HKN students to appropriate IEEE committees and boards and enabling IEEE-HKN Chapters to enhance their impact on their campus communities.

Kyle Lady, Student Representative

- Working with Chapters of all shapes and sizes to ensure that we're providing the resources that can enable chapters to carry out their missions.
- Help the annual conference expand into an event for student members to express their views on IEEE-HKN's priorities, governance, and procedures, in addition to the programming and small-group activities that already exist.

Chapters Celebrate First Founders Day

In a shady spot under a large cottonwood on the campus of the University of Illinois at Urbana-Champaign, IEEE-Eta Kappa Nu's founders saw the need for an honor society - one that by invitation would recognize scholarship, attitude and character. The vision of these inspired young men was to promote the highest ideals of the engineering profession and form an organization where professionals and students help each other.

More than 100 years later, IEEE-HKN celebrates Founders Day on 28 October to honor the society, its members and its accomplishments. In October 2013, Chapters were encouraged to host a special activity or meeting to celebrate Founders Day and tell the IEEE-HKN story.

Twenty-two Chapters, including our Chapters in Canada, Mexico, and India, took to the cause and participated in a Founders Day event. Each Chapter received $100 from IEEE-HKN for their efforts. These events raise awareness of the value of IEEE-HKN Chapters, informed interested potential members of the benefits of joining IEEE-HKN and helped reconnect alumni, department and faculty of the importance of IEEE-HKN.

Members of the Iota Epsilon Chapter joined members of the University of Hartford IEEE student branch to host Dr. Charlotte Blair, Senior Application Engineer at ANSYS, Inc., for a presentation on wireless system modeling.

The Beta Phi Chapter hosted a social event for both current members and eligible students.

Members of the Alpha Chapter had a booth outside their electrical and computer engineering building and shared trivia and candy with fellow students.

The Beta Alpha Chapter held a general information session to educate the university community on IEEE-HKN and the Chapter's events for the year.

Members of the Delta Omega Chapter hosted a BBQ and games for members of the school's College of Engineering to promote IEEE-HKN and tell the Founders Day story.

The Kappa Theta Chapter held a pizza social for both current and prospective members. Attendees brainstormed ideas for future events and watched the IEEE-HKN movie, "Engineering: The Challenge of the Future."

The Lambda Rho Chapter promoted IEEE-HKN and the benefits of membership to prospective members.

The Lambda Zeta Chapter held an event with members, faculty and all students in the electrical engineering department to promote IEEE-HKN. The event included refreshments and a special IEEE-HKN cake.

Epsilon Theta Chapter Reactivates with 24 Inductees in Fall 2013

After a period of inactivity, the Epsilon Theta Chapter at California State University, Long Beach inducted 24 students on 23 November 2013. Despite facing several obstacles, the Chapter leadership put forth great effort and time to execute a nearly-flawless induction ceremony. The Chapter executive board now looks forward to planning activities for the future, including creating an alumni database, preparing a handbook of Chapter procedures (to help future Chapter leadership), connecting with other local Chapters and attending events such as the IEEE-HKN Student Leadership Conference.

The fall 2013 Epsilon Theta inductees, as well as Faculty Advisor Dr. Chin Chang, Chair of Electrical Engineering Dr. Anastasios Chassiakos and IEEE-HKN Board of Governors members Dr. Catherine Slater.

The Epsilon Theta's newly-elected 2013-2014 Executive Officer Board. (Left to right) Edwin Almeida (Recording Secretary), Rafi Koutoby (Treasurer), Andros Nguyen (Corresponding Secretary), Victoria Hatfield (web correspondent), Anh Do (Vice President Internal), Juan Montano (Vice President External) and (front-center) Raul Rodriguez (President).

Visit the New IEEE-HKN Store!

Share your IEEE-Eta Kappa Nu pride and recognize your exceptional academic achievements!

The following items are available for purchase in the IEEE-HKN store:

- ♦ **IEEE-HKN pins:**
  - **Crest ($12)**
  - **Emblem ($12)**
  - **Key ($12)**
- ♦ **IEEE-HKN key pendant ($14)**
- ♦ **IEEE-HKN medal ($20)**
- ♦ **Scarf ($22)**
- ♦ **Necktie ($25)**
- ♦ **Honor stole ($20)**
- ♦ **Honor cord ($30)**
- ♦ **IEEE-HKN 6" Table Covers ($99)**

These distinctive items are available for you to use at Chapter events, at graduation and at any official IEEE-HKN ceremony.

Special discounts are available for combination and bulk purchases:

- Save $10 by purchasing the "honor combo" – one honor cord and one honor stole for $40
- Save $21 by purchasing 10 of the same style pin for $99
- Save $51 by purchasing 20 of the same style pin for $189

All items are available for purchase through the IEEE-HKN store.

Interested in a bulk purchase for other items? Email info@hkn.org for pricing.

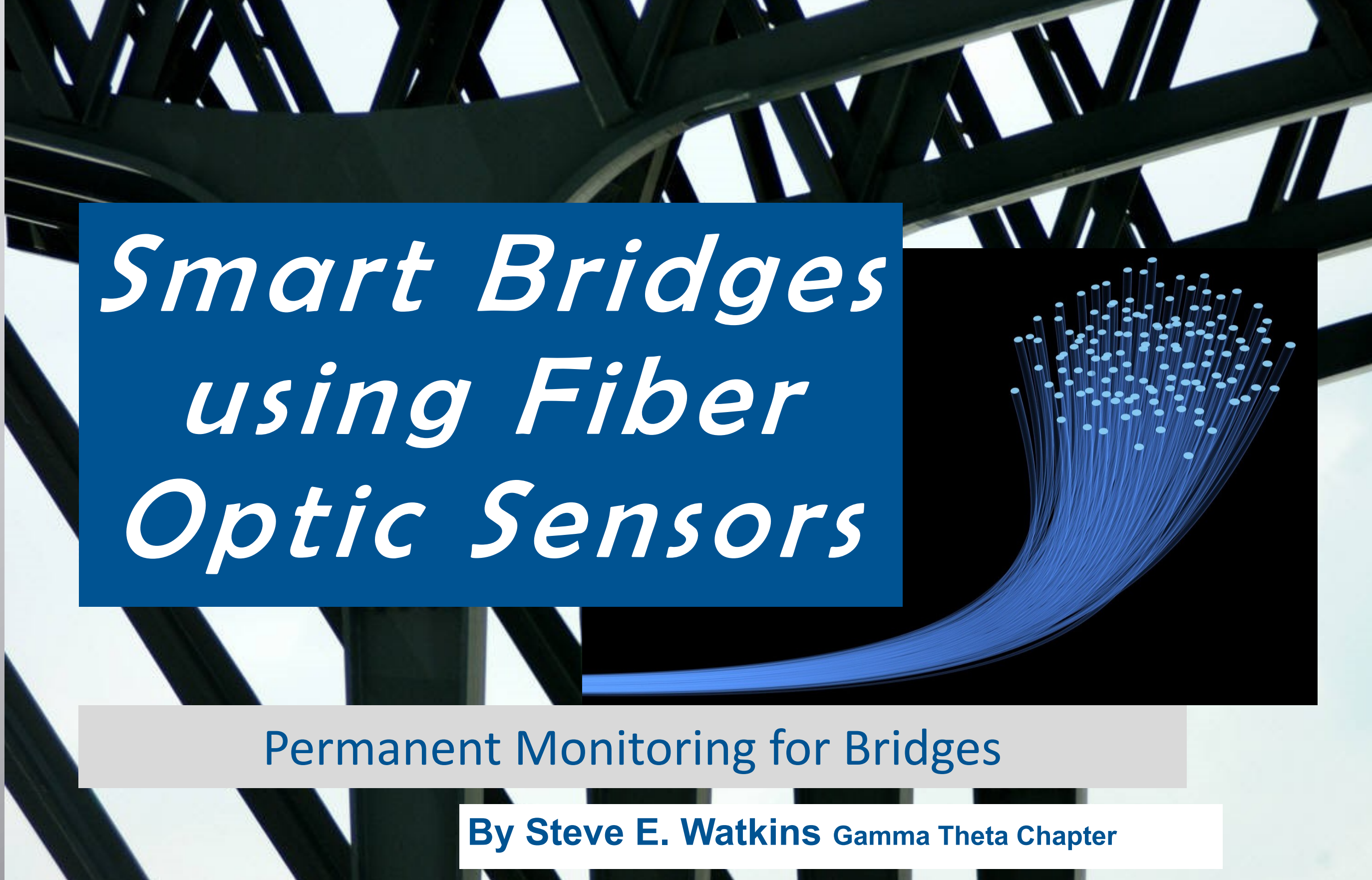
Want your purchase by a specific date? Please order at least 2-3 weeks before your event (or 1 week before with expedited shipping) to receive your purchase in time.

Share your IEEE-HKN pride with (from left to right): the IEEE-HKN emblem pin ($12), the IEEE-HKN crest pin ($12), the IEEE-HKN medal ($20) and the IEEE-HKN key pendant ($14).

IEEE-HKN offers two forms of honor regalia: the honor cord ($30) and the honor stole ($20). The two may be purchased together for $40.

Need the perfect accessory? Look no further: scarves ($22), ties ($25) and the IEEE-HKN key pin ($12) are available for purchase.

Represent IEEE-HKN at meetings and events with a 6" navy blue IEEE-HKN table cover ($99).



Smart Bridges using Fiber Optic Sensors

Permanent Monitoring for Bridges

By Steve E. Watkins Gamma Theta Chapter

I. INTRODUCTION

Bridges represent an enormous infrastructure investment across the nation. Maintenance, repair, upgrade, and replacement of these structures are ongoing expenses. The management of these resources is particularly acute today. Many structures, especially those built in the first half of the twentieth century, are at or near the end of their service life and are carrying unanticipated traffic loads. [1] The possibilities of vehicular accidents, earthquakes, and terrorism add to the management difficulty. Engineers are turning to improved materials and techniques in conjunction with permanent instrumentation to decrease costs and increase service life in both old and new structures.

Effective structural instrumentation can be based around fiber optic systems. Initially a spin-off of optical telecommunication developments, fiber optic sensing technology has advanced and matured. [2] Many types of sensors have been developed with various characteristics. Common approaches use interferometry, Bragg gratings, scattering mechanisms, and fluorescence. [3] They all benefit from the low profile and low loss of optical fiber. The sensors can be placed in otherwise difficult locations and the information sent over long lengths of fiber. The result is a permanent, flexible capability for nondestructive testing.

Advanced instrumentation for civil engineering structures must address a wide range of interdisciplinary issues. Effective implementation requires the integration of sensor technology, advanced signal processing techniques, materials science, and structural mechanics. Also, field demonstrations are critical to developing practical protocols and to establishing confidence in long-term system performance. This article describes a smart structures approach to bridge improvements, introduces key technologies used in fiber-optic-based health monitoring systems, and gives an overview of three instrumented bridges. A sensing system in the first example bridge monitors general performance and health, the system in the second bridge interrogates the behavior of a major structural repair, and the systems in the third bridge verifies the performance of a bridge retrofit.

II. SMART BRIDGES

A smart structure is one in which integral sensors add control or interpretation attributes to a structure. In addition to the basic load bearing function, the structure will intelligently adjust or interpret its state with respect to environmental conditions similar to biological systems. [4] Figure 1 shows a typical system for fiber-optic-based smart sensing. The physical condition being measured, i.e. the measurand, interacts with the sensor to create an optical signal. The signal is transmitted over the optical fiber to the processing support instrumentation for demodulation and analysis. The resulting information can be used to control some physical aspect of the structure or to evaluate some management aspect of the structure. For instance, actuators could damp unwanted vibrations or managers could be warned of deterioration. With a smart system, an automated, fast response is possible and internal conditions that may be difficult to assess otherwise are detected.

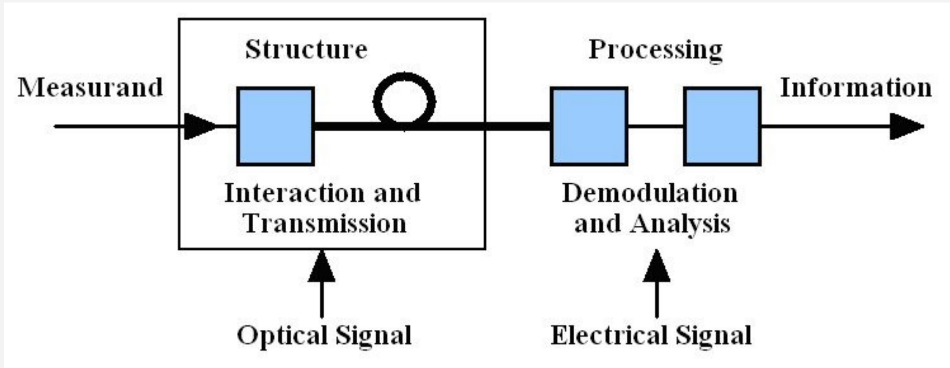


Fig. 1 Fiber-optic-based system for a smart structure.

The primary measurement needs for bridges involve management rather than control. Although, concerns such as damage mitigation during earthquakes would be addressed by a smart sensing and control system. Management concerns include [4]

- Verifying that the construction and the load distribution meets design expectations,
- Characterizing the extent and location of accidental damage,
- Determining the safe load posting after repair or upgrade, and
- Monitoring the remaining service life.

These functions are traditionally handled through conservative design, qualitative inspections, statistical analysis, risk-intolerant maintenance, and one-time testing. The weaknesses of the traditional approach, in addition to cost, are the difficulty of quantitative assessment and the slow use of innovations. Cost/performance optimization, new techniques, and new materials, such as fiber-reinforced-polymer (FRP) composites, cannot achieve widespread use without an assurance of safety and performance. Reliable monitoring can encourage the early use of innovations by decreasing risk and increasing confidence.

In a smart bridge, the relationships among component technologies must be understood. First, an embedded or attached sensor must be compatible with the host material. For instance, the performance of fiber optic sensors in concrete is a function of the fiber coating. [5] Similar considerations exist for metal and FRP composite materials. Second, the system analysis may be facilitated by different sensing architectures. Choices include detection of the measurand field at a single point, for an array of points, and along an integrated path. [5] Point detection resolves spatial variations or localized effects such as midspan strain and integrated sensing provides a view of global characteristics such as average temperature. Other interdisciplinary challenges are in the areas of constructability, system identification, data acquisition, information technologies, and field studies. [6]

III. FIBER-OPTIC STRAIN SENSOR SYSTEMS

The sensing process transforms a physical quantity into a useable signal. The characteristics of a fiber-optic sensor system are determined by the physical interaction, the sensor design, the signal interpretation, and the smart structures integration. The use of optical fiber as part of the system will influence most or all of these factors. In addition, one or more of these factors may recommend optical signals and optical fiber systems over other alternatives in a given application.

A key parameter of interest in structural applications is the measurand of strain. The dimensional deformation due to load, temperature, or other variables can be related to various performance, health, and safety issues. An optical strain sensor must encode this physical change on some aspect of the light wave. Phase changes and interferometric detection approaches are especially useful since they can resolve displacements and deformations on the order of an optical wavelength. Effective approaches that are based on interference include fiber-based Fabry-Perot interferometers and Bragg gratings. They can make point measurements and do not depend on a reference arm as do Mach-Zehnder interferometers. An alternate approach is Rayleigh scattering in the optical fiber. Information gained from Rayleigh scatter sensors provide distributed strain measurements along the optical fiber.

FIBER OPTIC SENSORS

The sensor interaction and design can be classified as extrinsic or intrinsic. An extrinsic sensor is one in which the sensing occurs outside of the fiber and the role of the fiber is only to transmit the data optically. An intrinsic sensor is one in which the sensing interaction occurs within the fiber itself. Three successful sensor types are Fabry-Perot sensors, Bragg grating sensors, and Rayleigh scattering sensors. The Fabry-Perot type can be extrinsic or intrinsic, while the Bragg grating and Rayleigh scattering types are intrinsic. For intrinsic and extrinsic sensors, the gage or interaction length tends to be long and short, respectively. Strain is integrated over this length. Hence, a short gage length is best for point measurements. A long interaction length can give integrated measurements.

An extrinsic Fabry-Perot fiber-based sensor is shown in Figure 2(a) [3]. An extrinsic cavity can be formed by cutting the fiber and separating the ends. (An intrinsic cavity can be formed by incorporating partially reflecting interfaces along the fiber.) Multiple-reflections occur between the two fiber end-faces. The total reflected interference signal varies in response to changes in the cavity spacing. A capillary tube is bonded to the two fibers and maintains the alignment of their end faces. The tube is bonded to a material under strain. As the material and attached tube is strained, the optical phase between reflections changes and returned signal varies periodically.

The extrinsic Fabry-Perot interferometric (EFPI) sensor has several desirable features. A single-ended sensor is given by use of the reflected signal (as shown), although the strain information is also in the transmitted signal. The sensor has little transverse coupling and effectively evaluates the axial component of strain. The reflection coefficient of the end-faces can be easily modified with a coating to enhance the return signal. The gage length is determined by the length of the capillary tube rather than the cavity. The tube length is typically limited to less than a centimeter. The fiber transmission path may be long, but the reflected signal is insensitive to environmental changes that could cause noise in other sensor systems. This sensor design can also measure temperature if attached to a material with a known thermal expansion characteristic.

A Bragg grating sensor is shown in Figure 2(b). Periodic index variations are incorporated along a length of the fiber. This Bragg grating structure will strongly reflect light of a particular wavelength, while other wavelengths have negligible reflections. As the interaction length is subject to strain, the period of the grating is modified and the reflect wavelength is directly modulated. Multiple gratings of different periods may be placed in the same optical fiber. A broadband optical input can excite all sensors along the fiber each of which reflects at a different center wavelength. Thereby, a single fiber can be used to

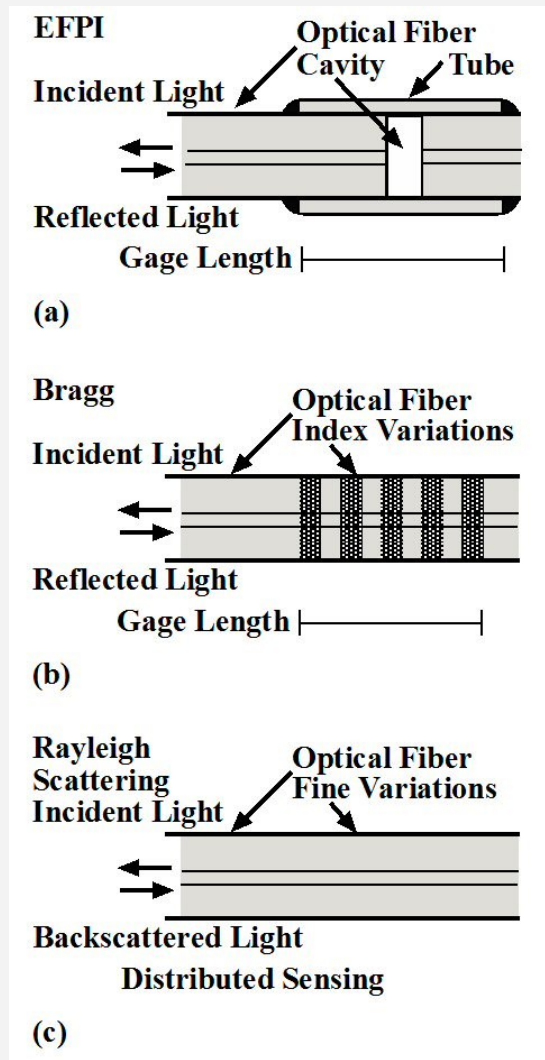


Fig. 2 Sensor Types: (a) Extrinsic Fabry-Perot interferometric (EFPI) sensor with an external air-gap cavity between fiber end-faces. (b) Bragg fiber optic sensor with periodic index variations within the fiber. (c) Rayleigh scattering sensor with distributed sensing capability.

perform multiple measurements as long as the spectral reflections can be resolved.

A Rayleigh scattering sensor is shown in Figure 2(c). This intrinsic sensor is based upon the local refractive index variations in the fiber glass and can measure distributed strain or temperature simultaneously along the fiber. These local variations are stable and produce a weak Rayleigh backscattered signature signal. As any point along the fiber is stretched or compressed due to load or temperature, the signature in the backscatter can be resolved and correlated to the strain or temperature. The spatial resolution of the measured depends on the capability of the data processing.

SENSOR DEMODULATION AND SMART STRUCTURE INTEGRATION

Interpretation of the signal has a number of levels. The most basic signal processing is to demodulate a strain value from a single sensor. More advanced signal processing may demodulate strain from a network of sensors and perform advanced analysis. Networking can be done simultaneously with dedicated instrumentation for each sensor or sequentially with a single instrument that connects to each sensor in turn. Also, optical wavelength-division multiplexing may be performed at the cost of wavelength-sensitive fiber couplers and connections. Advanced analysis depends on the application needs.

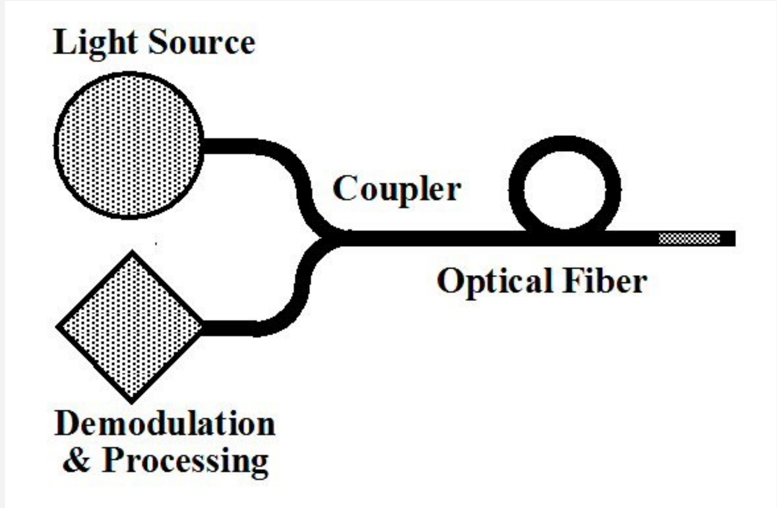


Fig. 3 Typical support instrumentation for fiber-optic sensor systems.

Sensor demodulation depends on the sensor type and measurement needs. The typical components of these sensor support systems are illustrated in Figure 3. An optical source such as a laser diode or an LED excites the system, the sensing interaction in the optical fiber modulates a return signal, and the processing instrument converts the optical information into electrical form.

The application imposes diverse criteria on the sensing solution. The incorporation of the sensor system must not adversely affect the structure, the environment must not significantly degrade the signal, the demodulated information must be readily available, and the system cost must be less than alternative methods of inspection. The use of optical fiber addresses the first two integration concerns. Fiber advantages include small size, low weight, low loss, environmental ruggedness (e.g. to corrosion, temperature, and vibration), and immunity to electrical noise. Also, in laboratory and field tests, fiber sensors have been shown to function during and after catastrophic failure in reinforced concrete structures. The final two integration concerns must be satisfied primarily by the support instrumentation. Performance and cost must be balanced. For instance, the number and placement of sensors, the testing schedule, and the complexity of signal analysis are considerations.

Artificial neural networks are often coupled with fiber optic sensing systems due to their capabilities in pattern recognition, classification, and prediction. These parallel processing architectures have been shown to provide advanced processing and analysis functions accurately and robustly. The implementation of neural networks in smart structures is an active research area.

IV. BRIDGE IMPLEMENTATIONS

Permanent fiber-optic-based instrumentation in bridges provides capability for performance monitoring, health indicators, and warning functions. The following examples use EFPI strain sensor networks for long-term quantitative assessments. The on-site physical components are the sensors and a patch box. Data acquisition and processing equipment for the sensors are brought to the sites during tests. Initial testing gives base-line data for interpretation. Periodic measurements can be taken with little setup or disruption of traffic.

MISSOURI S&T SMART COMPOSITE BRIDGE

A nine-meter-span bridge and associated test articles were designed, analyzed, manufactured, and tested as a comprehensive research project. The structures are modular assemblies of fiber-reinforced-polymer (FRP) composite tubes. These pultruded square-tubes have standard 76-mm square cross-section and are reinforced with either carbon or glass fibers. Seven alternating layers of tubes form structural I-beam elements within the bridge. The approach results in an extended lifetime due to all-FRP construction and relative economy due to standard off-the-shelf tube elements. The strength and deflection of the bridge assembly was tailored by the balanced use of higher-cost, higher-stiffness carbon tubes and lower-cost lower-stiffness glass tubes. Although rated for highway loads, the prototype structure, the first all-FRP bridge in Missouri, is part of a pedestrian walkway located on the Missouri University of Science and Technology campus. The development was a cooperative development effort that was led by the university with industry and government partners (see reference [8] for details and partners). The project goals were to develop a novel FRP-composite approach for extended life-time highway bridges and to implement a permanent performance and health monitoring system as a long-term technological demonstration for industry and a field laboratory for engineering students.

The fiber-optic strain sensing system was incorporated as a primary feature of the bridge. Research issues included installation protocols, sensor accuracy, and sensor lifetime. The measurement objectives of the fiber optic instrumentation were:

- To monitor flexure strain during destructive laboratory tests of tube assemblies,
- To monitor flexure strain during near-rating load tests of the installed bridge,
- To record strain characteristics during dynamic and static load tests, and
- To provide a capability for field remote monitoring developments.

Sensors were embedded to monitor internal strain in the main load carrying layers, i.e. the top and bottom layers of carbon-FRP tubes. (1) A four-layer test article and a full-scale seven-layer structural I-beam element were loaded past failure to verify design strength and investigate failure characteristics. Fiber optic sensors along with companion electrical resistance strain gages and linear-variable-differential-transformers (LVDTs) monitored the tests. (2) The bridge was field loaded to near its design rating using the weighted dump truck shown in Figure 4. These tests are periodically repeated to document long-term bridge behavior. (3) The strain signals are analyzed for various loading conditions during academic laboratory exercises. (4) The instrumented bridge is a test-bed for remote monitoring developments.

Fig. 4 Missouri S&T Smart Composite Bridge during a near-rating load test with a weighted truck.

Fiber optic sensors were incorporated within the structure during assembly as shown in Figure 5. They were placed in small grooves on the tube surfaces to provide protection from impacts during assembly steps and to move the sensors away from the interface between tubes. The strain measurements by each sensor should be associated with only one tube and not complicated by possible interface effects. The sensors were tacked in place after cleaning the groove with acetone. The sensor leads were routed toward the end of the bridge along the interface between tubes. Then, the sensors and leads were covered with epoxy during the surface preparation of the next layer of tubes. A fiber optic sensor patch box is located at one corner of the bridge deck. The ends of the leads were carried inside transverse tubes to the sensor patch box.

SENSOR PERFORMANCE FOR SMART COMPOSITE BRIDGE

The EFPI sensor network performed well in the Smart Composite Bridge project with respect to monitoring of failure events, to agreement with other sensor measurements, and to sensitivity for small loads. [8] For a four-layer test article, the sensors survived the entire load test including catastrophic failure. For an I-beam test article, the sensors displayed excellent correlation to co-located electrical resistance gages. For the bridge tests, the fiber optic sensors differed from a finite element model prediction less than four percent (worst case). Also, the sensors recorded elastic behavior for loadings below the design threshold. Figure 6 shows the mid-span strain on the top layer as a Ford F150 truck drives across the bridge. The truck had a front axle weight that was 8.4 percent of the highway load rating of 142.4 kN (32,000 lbs.). Note that the unloaded strains before and after the test are the same. The maximum compressive strain occurred when the truck's center of mass was at mid-span. Load tests with heavier trucks, cf. Figure 3, produced strain measurements that fit a linear load-verses-strain relationship. Hence, the internal fiber optic sensors verified the elastic behavior expected for normal loading of the bridge.

Fig. 5 Fiber optic sensors are embedded in the bottom layer of the Smart Composite Bridge during assembly. The full-scale I-beam test article is shown in the background.

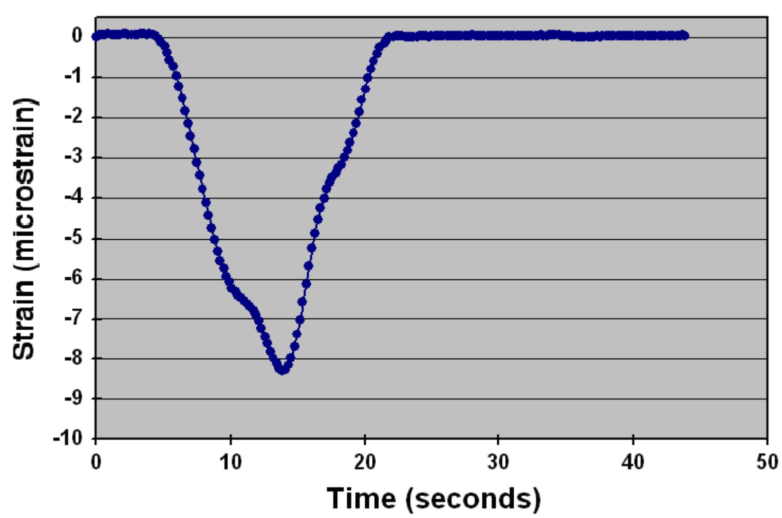


Fig. 6 Compressive strain in the top layer of the Smart Composite Bridge for a moving pickup truck. The front-axle load was 8.4 percent of the design load rating.

INTERSTATE OVERPASS REPAIR

A highway overpass on Interstate 44 in south-central Missouri was repaired following a major accident. The bridge is a reinforced concrete structure that is part of the Missouri Department of Transportation (MODOT) system. A vehicular impact severely damaged both piers in the median and the associated pier cap structure. The repair consisted of replacing the damaged piers, reconstructing the pier cap, injecting cracks with epoxy, and reinforcing the concrete with carbon-fiber-reinforced-polymer (carbon-FRP) composite sheets. A research aspect of the repair was the field demonstration of the ability of the carbon-FRP confinement to increase load carrying capacity. An effective repair was obviously less expensive and less disruptive than a total replacement of the bridge. However, there were concerns about possible degradation of the repair over time. Conventional testing and inspections involve considerable setup and time. The bridge was instrumented with fiber-optic sensors as a cost-effective means of confirming safety and an appropriate load rating.

The in-situ system was designed to monitor possible degradation of the reconstructed pier cap and the carbon-FRP patch. Figure 7 is a schematic of the repaired piers, pier cap, and carbon-FRP reinforcement. The three objectives of the fiber optic instrumentation were:

- To measure potential propagation of cracks in the pier cap,
- To monitor potential delamination of the carbon-FRP reinforcement, and
- To record a signature strain during load tests.

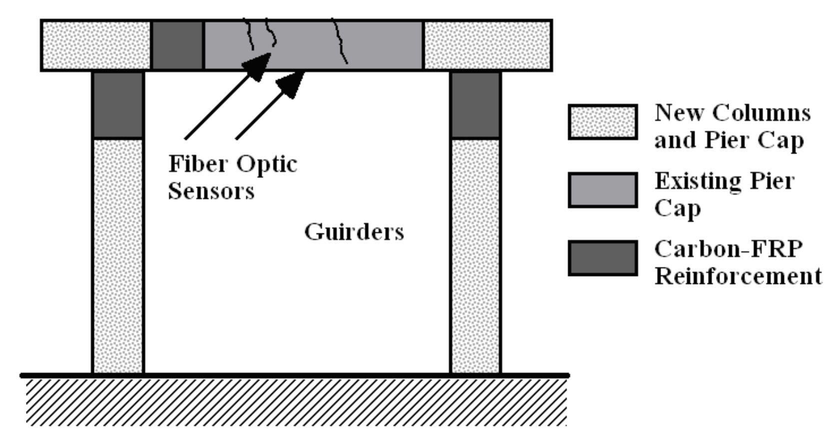


Fig. 7 **Schematic of the piers and pier cap of an instrumented concrete bridge. Fiber optics sensors monitor cracks in concrete and delamination of FRP reinforcement.**

Fig. 8 **Fiber optic sensors installed on the reconstructed pier cap of an I-44 Overpass. The crack sensors and the patch box are visible on the face and the delamination sensors are placed on the blue reinforcing sheet on the bottom.**

All sensors were applied to the pier cap as shown in Figure 8. (1) Three major cracks were present in the pier cap. A fiber optic sensor was attached at the base of each crack. Any further propagation of these cracks will produce a major change in the strain signal. (2) A sheet of reinforcement was placed on the bottom of the pier cap where it would experience maximum flexure strain. A circular bubble of diameter 12-cm was incorporated in the sheet. This intentional delamination reduces the effectiveness of the reinforcement. Sensors were surface-mounted on the delamination and at the edge to detect any spreading of the delamination. (3) The overall strain characteristics from all five sensors during a standard load test are an indication of the structural health. Changes from this signature could indicate a reduction in the bridge's load capacity.

The sensor installation consisted of preparing the surface and of routing the optical fiber to the patch box. The sensors were attached with epoxy and the fiber leads tacked in place. Sensors and fibers were covered with caulking for extra environmental protection. Also, the sensors mounted to the concrete were placed in small grooves to provide protection from impacts during testing. A sealed patch box was located on the pier cap to limit general access.

STATE HIGHWAY BRIDGE REHABILITATION

A three-bay bridge that serves a rural two-lane highway in Missouri was showing evidence of decay and was the object of a research collaboration between the Missouri University of Science and Technology and the Missouri Department of Transportation (MODOT). [9] The structure was 49 years old at the time of rehabilitation. This reinforced-concrete structure was strengthened by conventional repair using new steel rebar and concrete patches and by advanced techniques involving fiber-reinforced-polymer (FRP) composite sheets. The rehabilitation upgraded the bridge rating for higher traffic loads and extended the lifetime of the bridge. Fiber optic EFPI sensors were installed on the steel rebar and in the FRP wraps at various locations in the bridge deck and girders. Electrical strain gages were co-located with selected fiber-optic sensors to obtain a field comparison of performance.

Fig. 9 Fiber optic sensors and patch box installed on the rehabilitated highway bridge. Sensors monitored both the bridge deck and girders.

Figure 9 shows the underside of the bridge after installation with some of the fiber runs and the fiber patch box visible. The fiber runs were placed in grooves of the concrete and sealed to provide protection from weather and vandalism. The three objectives of the instrumentation were:

- To measure load-induced strain characteristics during dynamic and static testing,
- To correlate experimental measurements and theoretical modeling (including fiber optic sensors, electrical strain gages, and finite element analysis), and
- To monitor performance changes over time.

A comprehensive set of strain measurements was recorded both one year after installation and two years after installation. Since the bridge was subject to traffic loadings that were not recommended for the original design, the field performance of the rehabilitation had to be verified for a new load posting. The testing confirmed that the bridge was stiffer than before strengthening. The performance of the sensor network over time was observed. The fiber optic and electrical resistance gages showed general agreement in the field environment. However, the fiber optic sensors exhibited less noise and better longevity. No fiber optic sensors failed during the two years of service, but multiple electrical gages failed. The sensitivity of the fiber optic instrumentation allows greater in-situ assessment of structural performance and insight into structural changes over time (or due to damage events).

V. SUMMARY

Smart bridges are possible in which structural, geometric, environmental, and health characteristics are evaluated with permanent sensing instrumentation. Cost/performance optimization, new techniques, and new materials can be managed with greater safety and assured performance. This interdisciplinary field addresses critical needs for maintenance, repair, upgrade, and replacement of structurally deficient or functionally obsolete bridges. Fiber-optic-based instrumentation is particularly well suited for civil engineering applications. Measurements are possible at hard-to-access locations and the information can be transmitted over long lengths of fiber. The optical sensors do not perturb the structure and can handle the environmental extremes while providing reliable, high-resolution information.

ACKNOWLEGEMENTS

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S. E. Watkins, “Smart Bridges using Fiber Optic Sensors,” *IEEE Instrumentation and Measurement Magazine*, 6(2), 25-30, (2003).

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Students test the health of the Missouri S&T Smart Composite Bridge. Photo Credit Missouri S&T

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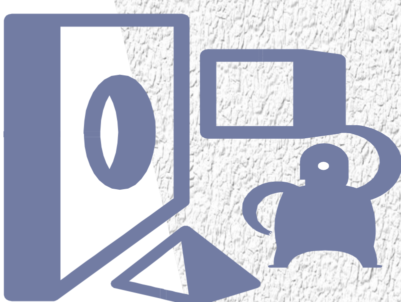
Amy Jones Gamma Theta Chapter

Amy Jones holds a B.S. in Electrical Engineering from Missouri University of Science and Technology, and is currently pursuing an M.S. in Electrical Engineering from Purdue University. She is employed as a Product Engineer in John Deere's Construction and Forestry Division. Amy is the Software Verification Engineer and Electrical Team Lead for the Excavators Outside of the Americas product line, as well as the Verification Team Lead for WorkSight Solutions, which focuses on cutting-edge telematics offerings. In her spare time, Amy is a passionate advocate for STEM outreach in the community, serving as the Dubuque Area Site Coordinator for John Deere's Inspire initiative. She was recently selected as the IEEE-USA 2014 New Face of Engineering.

Why did you choose to study the engineering field?



I chose to study engineering because of the opportunities that it offered. There aren't many careers that offer the flexibility and breadth of engineering, and yet offer an opportunity to make an impact on the world.

What do you love about engineering?

I love that engineering is a career based on problem solving. The challenges that the world is facing, particularly in the areas of food production and infrastructure, are huge and impactful. I love that I have the opportunity to come to work every day and do something that improves the lives of people around the world. I also love the camaraderie between engineers. We all speak a similar language, and that connection makes me feel like a member of a very exclusive club.

What don't you like about engineering?

In general, engineering is not a diverse field. In my experience, being the only female engineer on a team (or in a company) is an isolating and intimidating experience. I'm grateful for the engineers who reached out to mentor me and for the organizations (like the Society of Women Engineers) who provide opportunities to network with other women.

Whom do you admire, and why?

I admire my father, an engineer with an industry-spanning 30+ years of experience. Despite his vast technical knowledge, he still embodies the kind of curiosity that typifies engineering for me. Dad's favorite part of any gift is the instruction manual, and he is always eager to learn about my industry. From the customer needs of a Chinese construction company to the regulations regarding medical devices, Dad's passion for learning is an example that I strive to follow.

Emmy Noether

From a historical perspective, I admire Emmy Noether (1882-1935). She was a brilliant mathematician who was so dedicated to her field that she taught without pay for seven years, during a time when women were largely excluded from academic positions. Her work has been cited as "one of the most important mathematical theorems ever proved in guiding the development of modern physics" and includes one of the deepest results in theoretical physics.

How has the engineering field changed since you started?

The average person now has more access to technology and information than any time previous. There is no longer an emphasis placed on memorizing information—it's all available in seconds. This makes communication and project management skills increasingly important to success in the engineering field. In my industry, that instant information has enabled a 24 hour work cycle, with close integration of teams all over the world.

What direction do you think that the engineering field is headed in the next 10 years?

Personal information will be created and uploaded in exponential qualities, and I believe that we'll see thus-far unimagined integration between personal computing devices and the world around us. Privacy will be a thing of the past. This data will be a key driver in technology facilitating day-to-day life and will hopefully lead to a more optimized society.

What is the most important thing you have learned in the field?

The most important thing that I've learned in the field is that attitude and the ability to contribute to a team is just as integral to success as technical knowledge. I don't know any engineers who work alone; being unable to collaborate with others is a career-ending handicap.

What advice would you give to recent graduates entering the field?

Companies have personalities just like people do. Use internships and the interviewing process to find an organization that is a good fit for you. The highest salary in the world won't compensate for a job that makes you miserable.

Also, I see lots of recent graduates complaining about how heavy their workload is, in an effort to be perceived as important. This is a mistake-opportunities are given to those who demonstrate an enthusiastic attitude, not to the people who talk about how busy they are.

If you were not in the engineering field, what would you be doing?

If I weren't in engineering, I think I would have pursued a career in psychology. I'm fascinated by why people do what they do, and I would want to learn more about the motivations behind behavior.

Finish this sentence: "If I had more time, I would…

……volunteer more! Engineering has given me amazing experiences, like operating a nuclear reactor, traveling to China, and driving bulldozers and excavators. With a career that exciting, I can't help but want to share that opportunity with as many people as possible!"

Karen Panetta *Kappa Sigma Chapter*

Dr. Karen Panetta is a Fellow of the IEEE. Dr. Panetta received the B.S. in Computer Engineering from Boston University, and the M.S. and Ph.D. in Electrical Engineering from Northeastern University. She is the IEEE-USA Vice President of Publicity and Public Relations. She is the Editor-in-Chief of the IEEE Women in Engineering Magazine. During 2009-2007, she served as the World Wide Director for IEEE Women in Engineering. She is the Associate Dean of Graduate Engineering Education and Professor of Electrical and Computer Engineering at Tufts University and Director of the Simulation Research Laboratory. Her research focuses on developing efficient algorithms for simulation, modeling, signal and image processing for security and biomedical applications. Before joining the faculty at Tufts, Dr. Panetta was employed as a computer engineer at Digital Equipment Corporation. Her research in Simulation and Modeling has won her research team five awards from NASA for "Outstanding Contributions to NASA Research" and "Excellence in Research." She is a NASA Langley Research Scientist "JOVE" Fellow, is a recipient of the National Science Foundation (NSF) Career Award and won the 2003 Fischer Best Engineering Teacher Award. She is the 2009 Norm Augustine Award recipient from the American Association of Engineering Societies and the 2011 recipient of the Anita Borg Institute, Women of Vision Award and the 2011 IEEE Harriet Rigas Award for Education. In 2010, the IEEE recognized Karen with the IEEE Educational Activities Board, Major Educational Innovation Award. In 2011, United States President Barack Obama awarded Karen the nation's highest award for engineering education and mentoring, the NSF Presidential Awards for Excellence in Science, Mathematics, and Engineering Mentoring (PAESMEM) award.

Why did you choose to study the engineering field?

I am the youngest of 3 children and am the only girl. I grew up playing with trucks, doing carpentry, masonry and helping my dad work on heavy construction equipment engines. He told me to become an engineer because he wanted me to have a job that would support my expensive shopping habits. He really wanted me to be a civil engineer and still gives me a hard time that I chose computer and electrical engineering over civil engineering. I had no clue what engineers did, but I did love robotics, animation, special effects and music. Computers seemed the thing to learn to get into these areas.

What do you love about engineering?

I enjoy taking on projects that can help people and preserve the environment. One of my Nerd Girls Team projects saved a national historic landmark using solar energy. Engineering is about always learning so we never get bored because we are always learning and developing new technology. It's even more awesome that something I develop here in my lab can save lives in a country without me ever having to physically be there in that remote village community where my work is being used.

What don't you like about engineering?

Unfortunately, many people still do not know what engineers really do. We've done such a great job of embedding technology into every day life, that oftentimes our contributions become transparent to the end user. The stereotype of the one-dimensional, anti-social engineer who "fixes broken electronics" still persists. I was really excited to see IEEE start highlighting all the talents and interests that our members engage in for fun. Dancing, music, art, sports, writing, photography, languages (spoken, not only computer languages) and a multitude of other hobbies that show that we are well-rounded, interdisciplinary and that these are essential ingredients for innovation.

Whom do you admire, and why?

My husband Jamie. He is so honest, kind, patient and thorough in everything he does. He really is the strength behind my energy. I have traveled around the world giving talks to help inspire young engineers and scientists (over 50 per year!) and he's been right there beside me. I am often asked how I can "do it all"….I don't do it all alone! Jamie is the team supporting my initiatives, my career and sharing family responsibilities. He genuinely loves learning new technology and brainstorming new ideas with me. He is my secret weapon that enables me to quickly ramp up on new innovations, new software, interesting research and good parenting practices. His software talents are the best on the planet and he is a great cook too! He married me for me and not for my power tools and woodworking workshop.

How has the engineering field changed since you started?

First, engineers today must be interdisciplinary. We have to interface with so many different technologies and disciplines that it requires us all to learn more about areas that are beyond our classical training. For instance, I am trained as a computer and electrical engineer, yet I have learned about medical imaging diagnosis, mechanical sensors and actuators and biological systems. I need to know this to develop effective research that is useful and practical to solving state of the art issues.

The second major change is that we never anticipated that we would have to worry about the technology we create NOT being used to benefit humanity, but rather to harm it. I know this is one of my driving motivations for my research in security and detection of threat objects.

Finally, engineering education used to be valued around the world because it was a great path that ensured a healthy future regardless of an individual's socio-economic background or ethnicity. Today, many young people don't appreciate, or realize how an engineering education can change their future. We need them to stay in school and thrive, if we are to remain world leaders in innovation and sustain our workforce. Unfortunately, what hasn't changed that SHOULD have changed by now is that in this day and age that there are still countries where women aren't allowed to be educated or are killed for trying to educate themselves.

What direction do you think that the engineering field is headed in the next 10 years?

We will see more modeling and simulation of human systems. When I pursued my Ph.D. in 1994, I told my professors it was my goal to model and simulate the human brain. They quickly dismissed me for thinking of such an outrageous goal that was deemed impossible. Today, the U.S. government has put millions of dollars into research to investigate exactly this topic. It's a good thing I didn't let them dissuade me and went ahead to pursue my own research initiatives. Now, I'm well ahead of the game. The other fields that will continue to demand attention are clean water and renewable power and energy. People don't associate the need for clean water with electrical engineering, but we have many essential roles to solving this problem. Renewable energy used to be considered too expensive and for poor countries with little resources, low-cost renewable sources of energy are recognized as life saving technology. Finally, mobile devices will become the key to economic freedom and equal access to education. Women that have been threatened for trying to attend school will be able to educate themselves and have access to health services as well as other support groups to help them and their children live healthier, happier lives.

What is the most important thing you have learned in the field?

I can learn about any topic and contribute my engineering skills to solve problems across any discipline.

What advice would you give to recent graduates entering the field?

Do not think what you have trained for in your specific discipline is what you will end up doing for the rest of your life. It breaks my heart when a student takes a circuit theory course their second year in college and says, "I don't want to do soldering for the rest of my life" and decides to switch out of the major because they don't see how what they are learning fits into the overall big picture. Honestly, does anyone out there know an engineer who solders all day? No!! When I graduated as a computer engineer, all my training was about programming and designing computers. I thought that this was what I would do and I actually did do for the first few years of my career. It wasn't until I went to graduate school part time and then became a professor that I realized that my skills could be used to develop solutions for so many other areas. I have worked on projects to help track and diagnose autism and blindness, helped create devices to assist the disabled and have produced algorithms and new mathematical operators that model the human visual system for use in recognition systems and security systems.

If you were not in the engineering field, what would you be doing?

I would have been singing like Sarah Brightman or dancing like Shakira.

Finish this sentence: "If I had more time, I would…

…Spend more time working out, dancing, gardening and writing a book about all my adventures."

IEEE-HKN Chapters Participate in Founders Day Photo and Video Contests

Several opportunities for Chapters to raise funds were offered by IEEE-HKN HQ during the fall to celebrate IEEE-HKN Founders Day. The IEEE-HKN photo and video contests encouraged Chapters to submit content representing their Chapter, their members and/or their recruitment tactics. Each Chapter that submitted a photo, video and/or hosted a Founders Day event received a monetary prize from IEEE-HKN. The results of the IEEE-HKN photo and video contests are as follows:

Students from the Beta Chapter re-enacted the early days of IEEE-HKN in their video.

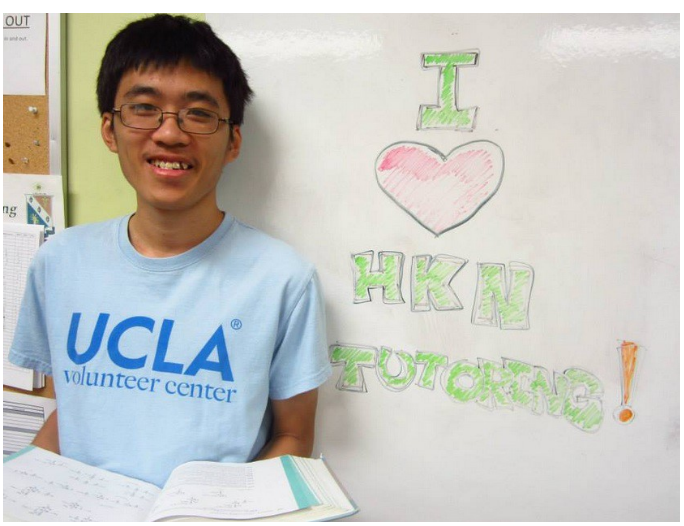
Video Contest:

- 1st) Beta
- 2nd) Lambda Eta
- 3rd) Delta Xi

Photo Contest:

The judges awarded each Chapter that submitted an entry a prize. Congratulations to the participants: Lambda Rho, Iota Gamma, Delta Xi, Beta, Lambda Eta and Lambda Zeta Chapters. View all photos on the IEEE-HKN Facebook page.

Congratulations to all Chapter participants!



Members of the Iota Gamma Chapter regularly tutor freshmen and sophomores in lower division classes.

A member of the Lambda Zeta Chapter mentors freshmen students on how a 555 timer circuit works.

A Brief History of High-Power Semiconductor Lasers

By David F. Welch
IEEE Senior Member

Significant technological demonstrations that shaped history...

ABSTRACT

The following is an historical perspective of the significant technological demonstrations that shaped the history of high power semiconductor lasers. This article is not meant to be a review article, as there are much better review articles and reviewers available, nor would the article try to cover all of the contributions to such a rich technology. Nonetheless, this article will, anecdotally, present a perspective on the technological advances that resulted in the enabling technology of high power semiconductor lasers for applications such as fiber optic communications, data storage, and material processing.

INTRODUCTION

The semiconductor laser, first discovered in 1962 [1]–[4], was thought to be a breakthrough invention that would revolutionize industry. As early as the late 1960s and early 1970s there were patents and articles proclaiming the utility of this technology for optical data storage and fiber optic and free space communications. However in its early form, the simple p-n homojunction device was a long way from realizing the dreams of these early inventors. To realize the capability of semiconductor lasers and specifically high-power semiconductor lasers a convergence of many technologies had to be realized. Advances in crystal growth technologies, the development of double heterostructure lasers and subsequently quantum well lasers, materials passivation technologies, heatsinking technologies, pseudomorphic materials; breakthroughs in device designs including single-mode lasers, laser arrays, distributed feedback lasers, and the simultaneous development of complementary technologies, the most significant of which is the rare earth doped fibers for fiber amplifiers and fiber lasers, all contributed to one of the most enabling technological industries today, that of high-power semiconductor lasers. In many ways semiconductor lasers are second only to the transistor and integrated circuit as to their impact on today's high-technology market place. The semiconductor laser is the conduit in which the internet became economically feasible and is the backbone of which the information age of tomorrow will depend. The following paragraphs will address specifically the technologies associated with the development of high-power semiconductor.

MATERIALS TECHNOLOGIES

By the late 1970s, semiconductor lasers had advanced to where double-hetereostructure lasers had been developed resulting in reduced threshold continuous wave (CW) emission [5], [6]. In addition advances in laser design included the breakthrough realization of distributed feedback lasers. Liquid phase epitaxy (LPE) was used to fabricate these lasers [7]–[10], however, the performance was limited by the inability of LPE to grow uniform thin epitaxial layers and accurately tailored doping profiles. Nonuniform materials from LPE-grown wafers resulted in current crowding and optical self-focusing, thus limiting the aperture size of the laser to a few micrometers, and the thick active regions (0.5µm) were lossy limiting the efficiency of the laser. The consequence was a laser that could only operate reliably to a few milliwatts in output power and a manufacturing process that resulted in low yields. The first key technology advancement necessary for the realization of high-power lasers was the development of two new growth technologies: metallorganic chemical vapor deposition (MOCVD) and molecular beam epitaxy (MBE). These two key technological advancements, developed nearly simultaneously, created a tool that enabled the laser designer to control the crystal deposition to atomic layer accuracy which resulted in two benefits: uniform material deposition and ultimately quantum well active layers.

Uniform material deposition is critical to both laser performance and yields. The more uniform epitaxial layers enabled the development of large aperture laser structures, the first such device was the evanescently coupled laser array. Large aperture devices dramatically broke through the barriers of power output from a single laser. Output powers well in excess of several watts were demonstrated. Over the course of the next decade, higher and higher output powers will be developed where outputs exceeded 10 W CW from a 200 µm laser source [11]–[16].

The second effect of the conversion from LPE crystal growth technology to that of MBE and MOCVD was the ability to grow thin active layers on the order of 10 nm. LPE was typically limited to active layers on the order of 0.1–0.5µm. Thin active layers were very difficult to grow by this technique. The consequence of a thick active layer laser structure was that there was a high overlap of the optical mode with the free carriers in the active layer. The propagation loss within the laser, being dominated by the free carrier absorption in the active layer, was therefore inherently high and consequently the threshold, efficiency of the laser, and the length of the laser cavity is limited. Fig. 1 depicts the impact of propagation loss on the efficiency of a hypothetical laser with a device with 4% and 100% reflectors and an internal conversion efficiency of 100%.

The consequence of a high-propagation loss in the laser cavity not only impacted the laser efficiency, but it also impacted the ability to fabricate long cavity length lasers and therefore the thermal resistance of the laser. The thermal resistance of the laser is a critical design consideration for high-power lasers. The short cavity length of LPE grown lasers, typically less than 250µm, increased the thermal resistance of the laser, limiting the ability to dissipate power and ultimately the output power of the laser.

The advent of MOCVD and MBE changed the way the research community could think about laser designs. The ability to control the crystal deposition on an atomic scale in a fashion that resulted in uniform epitaxial growth was the first major breakthrough for the development of high-power lasers. With this new tool the research community went to work and the first conceptual breakthrough was that of quantum well lasers. Quantum-well lasers, lasers with active layer thicknesses on the order of 10 nm, resulted in a number of advantages including a dramatic reduction in threshold current, a reduction in the free carrier loss, and a reduction in the temperature sensitivity of the threshold current. All of these effects increased the efficiency of the laser and the ability to make lasers with longer cavities and therefore lower thermal resistance. Furthermore, as the overlap of the optical mode with the active layer was much less, the power limitation caused by catastrophic optical damage of the laser was significantly improved. The net effect was the ability to demonstrate higher output power lasers.

A significant metric of semiconductor lasers as compared to other laser systems, and ultimately the determining factor in much of the performance of these lasers in ultrahigh-power applications such as welding, is the ability to demonstrate electrical to optical conversion efficiencies of greater than 60%. No other laser media can approach

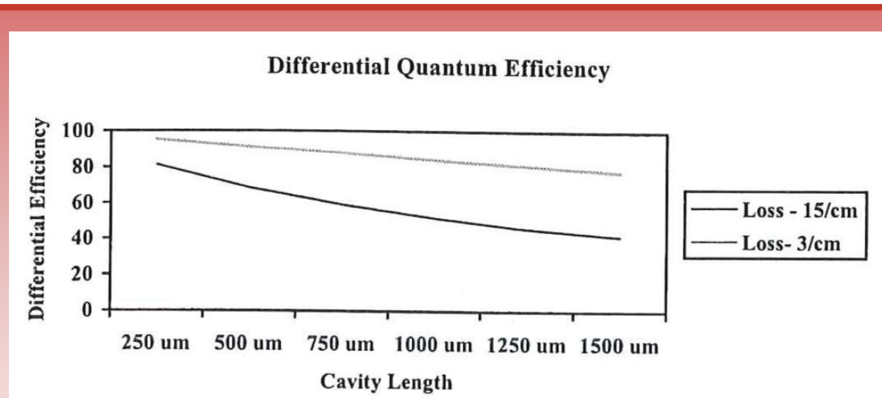


Fig. 1. Effect of distributed loss on a laser with reflectors of 4% and 100%, an internal conversion efficiency of 100%, and a distributed loss of 15 cm^{-1} (typical for thick active layer LPE materials) and 1.5 cm^{-1} (potential loss for quantum well lasers).

this type of efficiency (see Fig. 2) and therefore, in high-power applications where heat generation and removal are the limiting factors, semiconductor lasers have the distinct advantage.

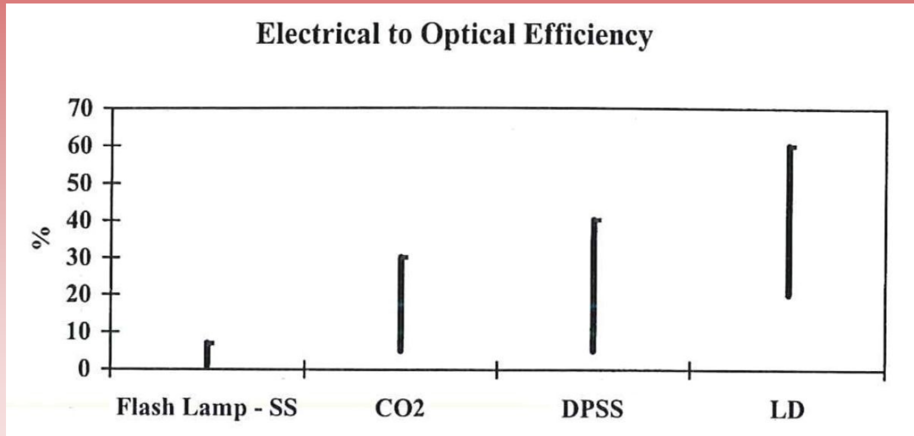


Fig. 2. Relative electrical to optical conversion efficiency.

CATASTROPHIC OPTICAL DAMAGE (COD)

The next limitation to output power for semiconductor lasers after the initial advances in crystal growth technology was that of catastrophic optical damage (COD) to the end facet of the laser. COD is a result of surface recombination sites on the cleaved facet causing a depletion of charge at the crystal surface. The depleted bands absorb the laser emission that, when the absorption is sufficient, causes thermal run away effect, melting the end facet of the laser. COD is especially prevalent in Al containing materials and as a result greatly impacted the reliability of AlGaAs lasers, and therefore inhibited the introduction of high-power AlGaAs lasers into applications like communications and optical data storage.

Extensive research by several laboratories was performed on both materials technology and passivation techniques to eliminate COD. Several research organizations were able to come up with process technology necessary to eliminate COD, each organization having a different approach to the problem.

Ultimately COD was eliminated as a reliability limitation for most laser diodes. It was these various techniques that enabled high-power lasers for both the communications market and the recordable optical data storage products. Furthermore, reduction in the impact of COD on reliability greatly improved the performance of high-power lasers for DPSS applications, enabling greater penetration of DPSS lasers into the material processing and thermal printing markets.

PSEUDOMORPHIC MATERIALS

The next major technology breakthrough for semiconductor lasers and specifically high-powered semiconductor lasers was the conceptual development and experimental realization of psuedomorphic materials [17]–[22], otherwise referred to as strained layer materials. Up to this time crystal growth was limited to the material systems that were lattice matched to a common substrate. In the mid-1980s, a series of conceptual developments occurred that resulted in the realization that a layer need not be lattice matched if its thickness was less than the critical thickness, at which point the material would no longer be single crystal. Layers that were on the order of 10 nm could be grown in the midst of a lattice match layer structure where the lattice mismatch could be significant. This concept lead quickly to the incorporation of In into AlGaAs quantum well material structures and was applied to all semiconductor laser material structures.

InGaAs active regions in AlGaAs layer structures resulted in several key benefits: higher gain from the materials, lower threshold current operation, higher efficiency, extension of the emission wavelength to longer wavelengths, and higher reliability. For AlGaAs lasers grown on GaAs substrates, emission wavelengths could then be extended from less than 780 nm to longer than 1100 nm, easily reaching the emission wavelengths necessary for pumping of Er doped fiber amplifiers (discussed in more detail below). It was further shown that the incorporation of In in the active region of an AlGaAs laser inhibited the migration of defects in the material thus improving the reliability of the material (Fig. 3). From these developments came high-power, highly reliable lasers operating at 980 nm and the first short wavelength laser that could meet the 20-year lifetime required for communication systems.

Pseudomorphic materials were critical to the development of another class of high-power lasers, that of AlGaInP lasers for the emission between 630 and 680 nm. AlGaInP lasers had been demonstrated for operation in the 680-nm region, however, these lasers when lattice matched resulted in high-threshold currents and limited their output power to a few milliwatts. With the introduction of pseudomorphic materials to the design of AlGaInP materials, the gain could be significantly increased resulting in lower threshold current densities. The result was the realization of high-power, high-efficiency lasers operating at 630 and 680 nm.

Pseudomorphic concepts have since been applied to most semiconductor material systems including GaInAsP/InP laser where efficiency, power, and polarization effects have been optimized, AlGaInN lasers for efficient operation in the 380 to 470 nm region and in AsSb-based materials for lasing properties in the mid-IR.

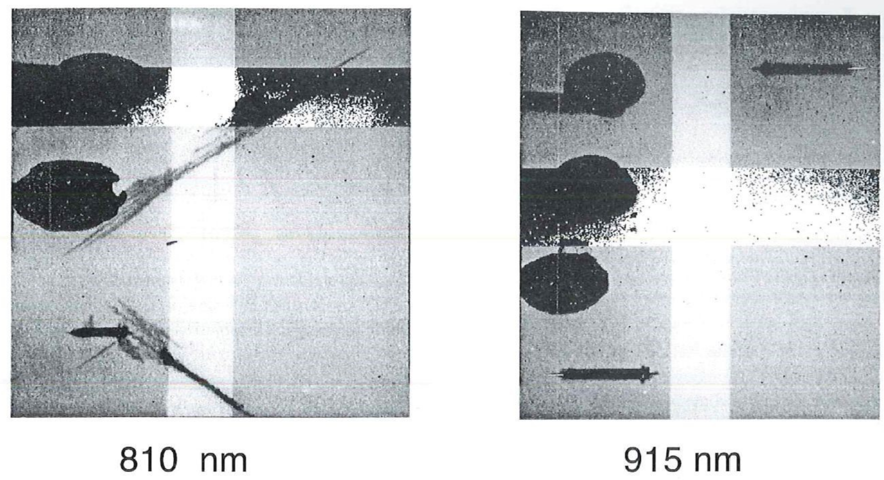


Fig. 3. Electroluminescent images of the surface of a broad-area laser operating at 810 and 915 nm. For this experiment defects were intentionally introduced in the chip and in the case of 810-nm lasers (no In) these defects are seen to propagate through the active region [22].

The above discussed material advances and the resultant laser design advances created the groundwork for a number of critical applications that were enabled by high-power semiconductor lasers. As each relevant application is discussed, high power is qualified as a relative term to the state of the industry prior to these advances. As an example, high power in the realm of industrial lasers is measured in watts and kilowatts, while high power for optical data storage is discussed as the advances necessary to take the technology from the few milliwatts level to 30 mW and beyond. Often the impact of achieving high power directly correlates the overall reliability improvement of the laser.

SINGLE-MODE SEMICONDUCTOR LASERS

Advances in materials technology and process technology as discussed above have made dramatic advancements in the ability to efficiently generate power at high reliability and across extensive wavelength coverage in semiconductor lasers. There is an entirely different branch of semiconductor laser development associated with the generation of multiwatt output power in a single spatial mode. Standard techniques for generating single-mode waveguides have been demonstrated in high-power materials resulting in the demonstration of greater than 1 W of single-mode operation from a few micrometers aperture. The motivation to achieve output powers in excess of 1 W from a monolithic device was driven largely by the perceived need for transmitters for free-space communications and direct diode material processing applications.

Semiconductor lasers, being highly nonlinear devices and having a large coupling between the gain of the laser and the index of refraction, made it difficult to fabricate a large aperture single-mode laser. Several conceptual techniques were pursued [23]–[38]: 1) coupled laser arrays through either evanescent or direct coupling of individual laser elements; 2) surface-emitting laser arrays where serial injection locking of multiple cavities were studied; 3) master oscillator power amplifier configurations on a monolithic chip; 4) externally injection locked lasers; 5) asymmetric gain profiles in large aperture lasers; 6) multimode large aperture devices with highly differentiated modal gain profiles; 7) external cavity lasers; and 8) unstable resonator lasers with large emitting apertures. Several general issues were barriers to a number of these potential solutions; first the output power needed to be efficiently coupled into a single emission radiation lobe, the radiation pattern, or far field pattern, needed to remain stable over all power and temperature operating conditions, the discrimination between modes of operation had to be sufficient to insure single-mode operation as the gain uniformity and index uniformity changed during operation of the laser and the laser had to be able to be made reproducibly with high yield. All of these conditions became very problematic in a material system that was highly nonlinear and the index and gain were highly coupled. Finally and more importantly, the need for an application that is economically large enough that would justify the expense associated with the migration from a DPSS solution to a semiconductor manufacturing solution. To date some exceptional work by a variety of research organizations has resulted in the demonstration of single spatial mode

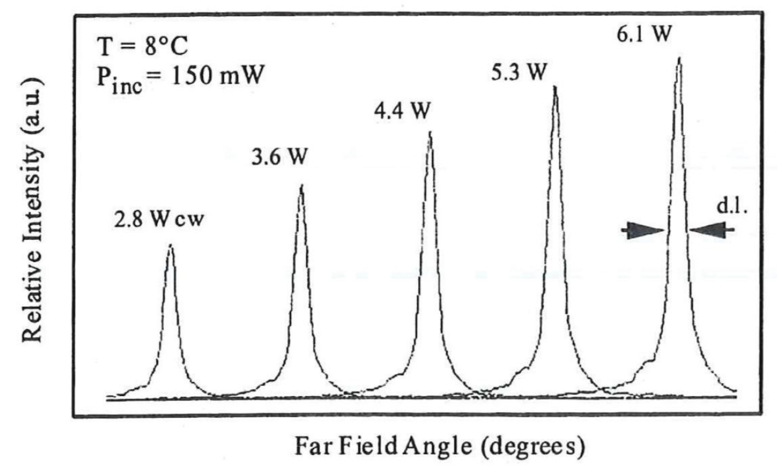


Fig. 4. Far field patterns from a broad area amplifier for output powers from 2.8 to 6.1 W CW with an injected power of 180 mW.

laser at output powers in excess of 5-W CW (Fig. 4).

In parallel with the development of monolithic single spatial mode lasers came the development of double-clad rare earth doped fiber. As discussed below, rare earth doped fiber originated around the need for optical amplification in the fiber where Er doped fiber amplifiers (EDFA) were developed. From the technology of Er fibers, which were originally developed for single-mode fibers requiring single-mode pump lasers, came the conceptual development of double-clad fibers. Double-clad fibers have a single-mode core surrounded by a second multimode optical cladding layer. In this configuration multimode light is injected into the outer cladding layer and the the light propagates over several tens of meters while it is absorbed by the rare earth dopant in the single-mode core of the fiber. This process has demonstrated to be a very efficient mechanism of conversion of the multimode radiation from the semiconductor laser to a single-mode output. While the Nd :YAG laser, discussed below, will result in optical to optical conversion efficiencies of 30%–50%, the double-clad fiber lasers could operate at optical to optical conversion efficiencies of 60%–80%. Although fiber lasers do not result in the broad wavelength coverage of semiconductor only solutions, fiber lasers have met the power and scaling requirements of most potential multiwatt single-mode applications. Currently, fiber lasers are used in marking systems, thermal printing systems, and Raman amplifiers.

DIODE-PUMPED SOLID-STATE (DPSS) LASERS

The first use of MOCVD and MBE was in the fabrication of AlGaAs lasers operating between 780 and 860 nm. From this material system came the first application of high-power semiconductor lasers, that of pumping Nd :YAG lasers at wavelengths around 810 nm. The use of diode pumping of Nd :YAG lasers enabled a dramatic reduction in size and a significant increase in operating efficiency as compared to flash lamp pumped solid-state lasers. In later years as the semiconductor lasers became more reliable, so did the solid-state lasers. A steady progression in DPSS technology over the past 15 years has transformed the laser-based material processing industry to where DPSS lasers now compete with high-power CO laser systems for cutting and welding applications, and a significant fraction of the market is the sale of DPSS lasers. High-power semiconductor lasers used for pumping of Nd :YAG lasers were first commercially introduced in 1984 at output powers of 100 mW CW. Nd :YAG lasers have several distinctions compared to semiconductor lasers; first they have a long excited state lifetime and can therefore store energy and are applicable to Q-switched operation resulting in high-peak power applications, and second they have the ability to efficiently convert multimode light into single-mode light. The designers of DPSS lasers looked to use of high-power semiconductor lasers to

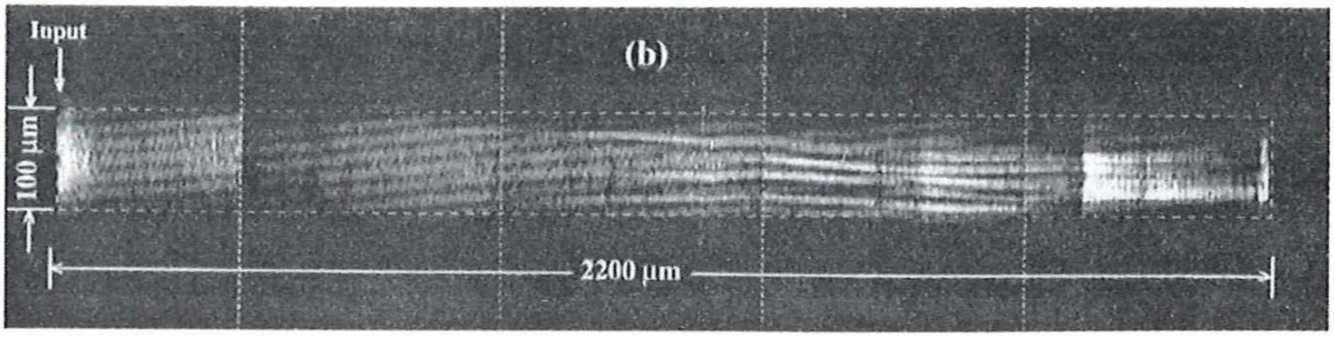


Fig. 5. Infrared image of the top of a broad-area gain region illustrating the effect of filamentation.

replace that of flash lamp pumping for the advantages of greater efficiency and higher reliability. This gave great design flexibility to the DPSS laser designer in the choice of format for the high-power semiconductor laser. Quickly, the market moved to a design of a 1-cm-long monolithic semiconductor laser array that could be stacked to create a two-dimensional (2-D) emitting aperture, Fig. 5. The 1-D and 2-D arrays were used in either CW or what was noted as quasi-CW mode, where the quasi-CW operation was a series of long pulses used to match the upper state lifetime of the solid state laser, on the order of a few hundred microseconds to a few milliseconds. Today, monolithic laser arrays have been demonstrated at output powers approaching 200 W CW where reliable operation of 60 W is commercially available.

Emerging from the DPSS systems were first lasers operating in the few watts average power region. Applications for these lasers included marking on electronic packages, thermal or ablative printing on plates for offset printing applications, micro- welding for various applications in the hard disk and semiconductor industry, heat treatment of micromechanical components, and many others. A second class of applications arose from the ability to efficiently convert the output of the DPSS to green and UV for application to photosensitive materials.

The second class of products, which is just beginning today, are the applications that require high average power operation including cutting and welding applications where the average powers are in the range of 100–1000 W (Figs. 6 and 7).

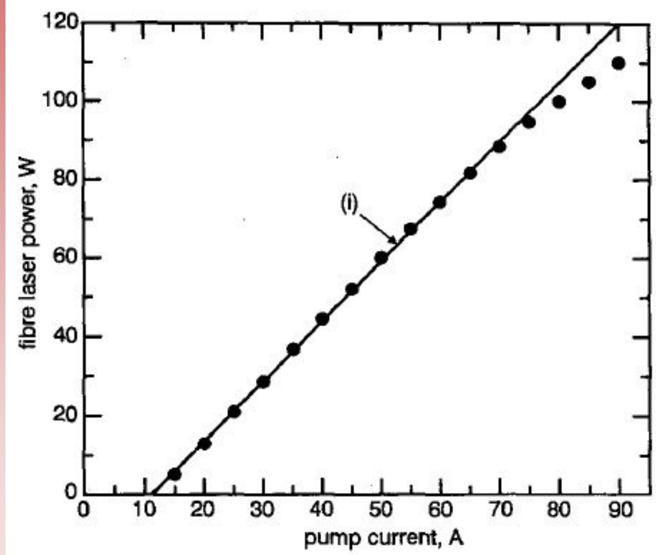


Fig. 6. Power output as a function of drive current for a diode-pumped fiber laser.

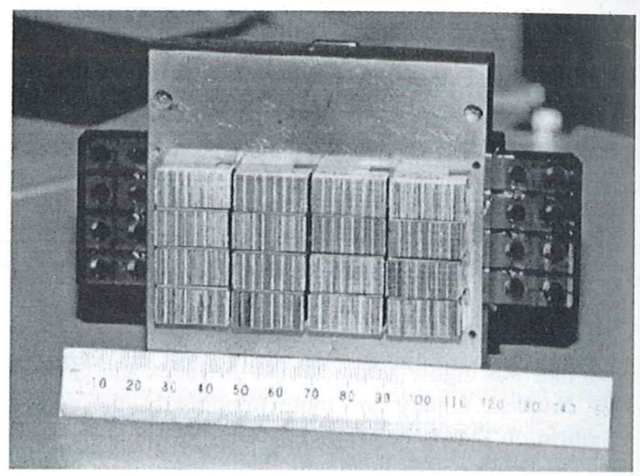


Fig. 7. Photograph of a 2-D array of laser diode bars; maximum output power of 2.56-kW average power.

OPTICAL DATA STORAGE

The second application that has been impacted by high-power semiconductor lasers has been optical data storage. Read-only applications within optical data storage have existed for a number of years at 830 and 780 nm. It has been the advances in high-power laser technology that have pushed the reliable output powers to greater than 30 mW that has enabled the ability to write on optical discs. Initially, this was introduced to that market at 830 nm, followed closely behind by 780 nm and more recently 650 –680-nm lasers, the movement to shorter wavelength for the benefits of higher storage densities. These devices are all single spatial mode operation.

Other applications that have benefited from higher power semiconductor lasers in the early years of their development include free-space/satellite communications, where extensive work and a number of demonstrations were successful at secure free-space optical links, direct diode material processing applications including heat treatment of metal surfaces, medical applications including photodynamic therapy, hair removal, and other therapeutic applications.

TELECOMMUNICATIONS

In parallel with the development of high-power semiconductor lasers was the development of rare earth doped optical fiber. Rare earth doped fiber in conjunction with the advances in high-power lasers are, in this author's perspective, the true enabler to WDM communication systems. It was the ability to amplify light in fiber that eliminated the need for expensive regeneration every 100 km, thus enabling an economic solution for WDM fiber optic communication. The development of rare earth fiber

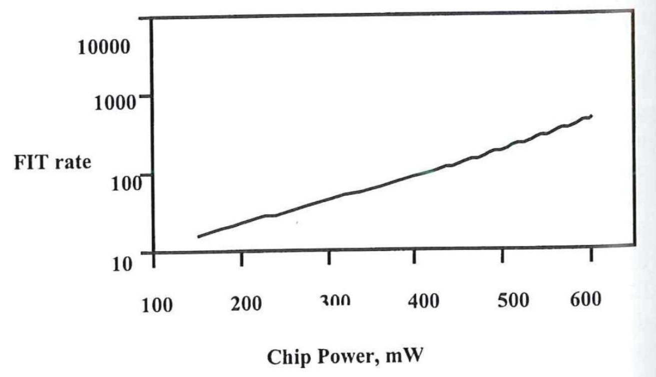


Fig. 8. FIT rate for 980-nm laser chips as a function of output power.

has had two primary areas of impact: the first being Er: doped fiber for amplification at 1550 nm.

The first demonstration of Er doped fiber amplifiers (EDFA) was in conjunction with 1480-nm semiconductor lasers. The conversion efficiency of the 1480 pump lasers to 1550 amplification of the signal source is in the range of 70%. Rapidly, the communication system designs pushed for output powers from the amplifiers on the order of 20mW(13 dBm), and for a variety of reasons due to multichannel inputs and multistage amplication, these amplifiers required pump powers of greater than 50 mW. As the channel count further increased over time the amplifier output power exceeded 23 dBm with some applications requiring greater than 30 dBm and therefore further driving the output power requirements from the semiconductor lasers. The research community implemented some of the technologies and designs discussed above, increasing the cavity length of the laser to 1 mm and beyond in research devices to handle the thermal dissipation of the high-power lasers. The communication industry had significant data on the reliability of InP-based lasers in the form of DFB lasers, and InP lasers did not demonstrate COD, therefore the communications industry adopted 1480-nm lasers as the first high-power laser for communications. The first EDFA was deployed in an undersea communication link in the early 1990s.

The second absorption band of EDFAs was at 980 nm. The advantage of 980-nm pumping was that the noise figure was much lower than 1480-nm pumping. As the development of the EDFA was nearly simultaneous with the development of pseudomorphic materials and the processing developments that lead to the elimination of COD, the next high-power application to develop was that of 980-nm laser for EDFA pumps. There are several inherent tradeoffs between 980-nm lasers and 1480-nm lasers: 1) 980-nm pumping results in a lower noise figure from the amplifier than 1480-nm pumps; 2) the optical conversion of the pump laser to 1550-nm light is more efficient in 1480-nm lasers; 3) the drive current requirements are higher for 1480-nm lasers, an important parameter in the design of undersea equipment; and 4) the initial reliability of 1480-nm lasers was greater than that of 980-nm lasers. The result was that the communication industry wanted to use 980-nm lasers in the EDFA, however, the reliability of the 980-nm pump laser needed to be improved to the same level of performance as the 1480-nm laser. Over a number of evolutionary growth, processing, and packaging developments, several organizations were able to develop highly reliable 980-nm pump lasers that met both the terrestrial and undersea reliability requirements. Today, high-power 980-nm lasers can be deployed with FIT rates less than 100 at powers of several hundred milliwatts (Fig. 8).

The combination of Er fiber, and high-power 1480- and 980-nm lasers are the essential elements of theWDM long -haul communication systems. The 980-nm laser provides the noise performance, while the combination of 1480- and 980-nm for power generation enable the multichannel architectures of today. Without these technologies there would be no high data rate communication systems capable of handling the traffic needed for internet applications.

The next generation of amplification technology for communication networks is Raman amplification. Raman amplification transforms the network from amplification at discrete points to a network where the transmission fiber becomes part of the amplification network, resulting in a dramatically reduced noise figure of the amplifier, thus enabling ultralong haul transmission and 40-Gb/s transmission (Figs. 9 and 10). Raman amplification grew out of two different high-power laser technologies. The first deployment of Raman amplification has come from the use of fiber laser-based pump sources. These amplifier pumps are currently being deployed in undersea festooning application and dry-side-based preamplifiers. As discussed above, the fiber laser configuration combines the technologies of high-power semiconductor lasers with that of double-clad fiber laser converting the multimode semiconductor light to single spatial mode output and subsequent Raman shifting to an output wavelength of 1455 nm at a power in excess of 1 W CW. These light sources were initially tools of the research community to investigate the properties of Raman amplification in fiber optic transmission. Optimum pump powers for fiber is dependent on the type of transmission fiber being used and the system implementation of the fiber and ranges between 500 mW and 1.5 W.

The alternative technology to fiber laser-based Raman amplification pumps is the use of direct high-power semiconductor lasers. For Raman amplification in the C and L transmission bands of the optical fiber, the semiconductor lasers need to operate in the 1450-nm range. To achieve the output power of 500 mW to 1W, organizations are both polarization and wavelength multiplexing four–six pump lasers in to a single-fiber output (Fig. 11). Raman amplification will require the output power of discrete 1455-nm pumps to approach 300 mW and beyond in order to optimize the performance and manufacturing cost.

Today, most next-generation long-haul transmission system designs will utilize Raman amplification. This technology is a breakthrough technology as it is the enabler for ultralong-haul transmission and high data rate (>40Gb/s) transmission. Currently, the Raman amplification is designed to complement the EDFA.

CONCLUSION

Over the past 20 years since the first work for high-power semiconductor lasers, the technology and market requirements have advanced dramatically. The market for semiconductor lasers has grown at staggering clips from 1980 to 2000 and is currently growing at greater than 40% per annum, the largest market being the communications market. The semiconductor laser is the largest market of all optical technologies (Figs. 12 and 13). High-power lasers as a segment of the overall market are growing even faster at a rate in excess of 90% per annum. For high-power lasers the growth and impact is substantial as high-power lasers enable dramatic cost reduction and performance enhancements in the communications systems. The trend is to shift value from the transmission products to the amplification products as a percentage of the overall systems cost. This trend represents the ability to replace the expensive repeaters with optical amplifiers.

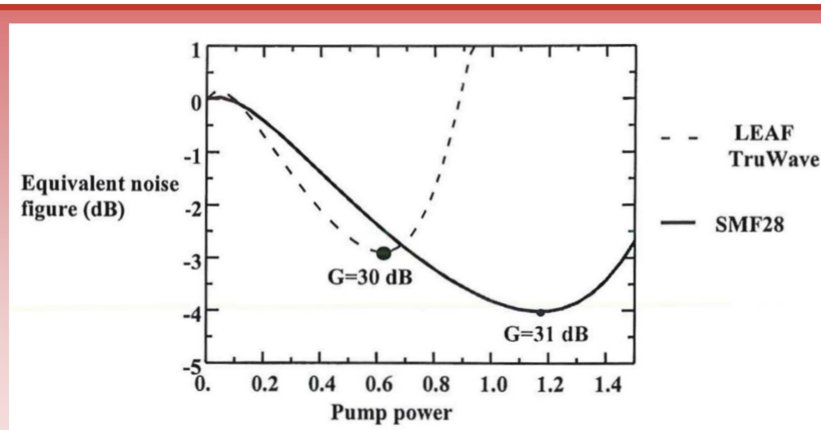


Fig. 9. Equivalent noise figure as a function of pump power for a Raman pump laser for both SMF28 and LEAF fiber.

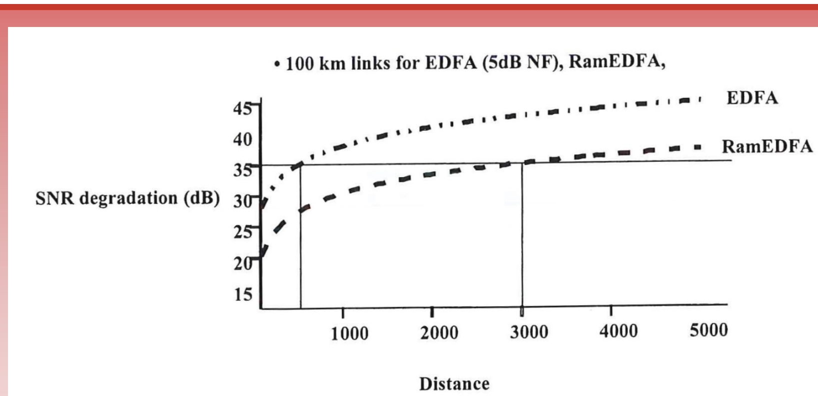


Fig. 10. Impact of Raman amplification on the SNR degradation in system performance. For a system designed for 35-dB degradation in SNR, the incorporation of Raman amplification in complement with EDFA (NF = 5 dB) extends the distance between repeaters from approximately 500 to 3000 km. For this example the amplifier spacing is 100 km.

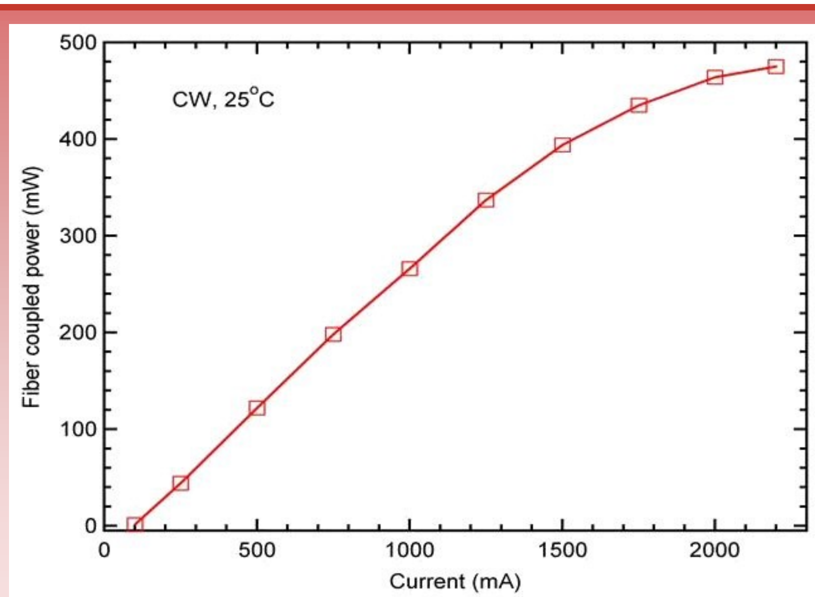


Fig. 11. Power output as a function of current for a fiber coupled 1455 nm laser [39].

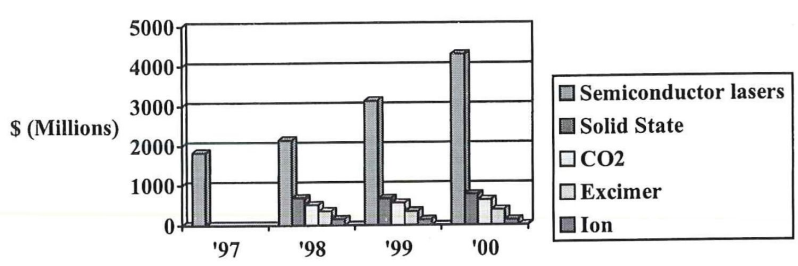


Fig. 12. Laser marketplace (Laser Focus World) [40].

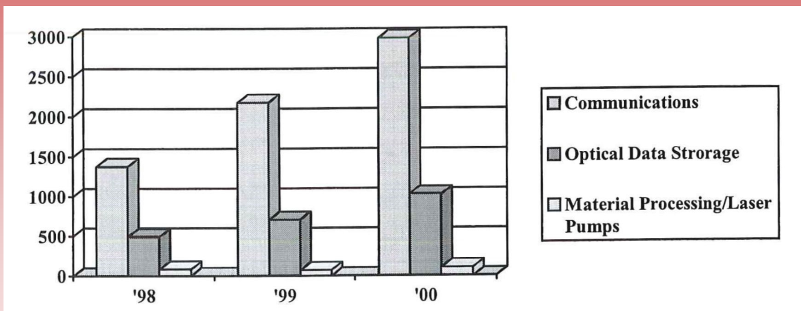


Fig. 13. Revenue by market sector for semiconductor lasers (Laser Focus World) [41].

High-power semiconductor lasers have become a pillar for a number of markets including fiber optic communications, materials processing/manufacturing technologies, printing, optical data storage, medical therapeutic and cosmetic applications, free-space communications, and many others. Research in this area has shifted from basic research to applications research as these markets have matured.

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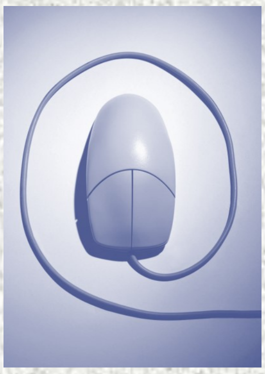

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