Digital Optics and Algorithms
FOR ART CONSERVATION

FACULTY HIGHLIGHT: Jungsang Kim, p.12
Welcome to the Spring 2016 issue of BROADBAND, the newsletter of the Fitzpatrick Institute for Photonics (FIP). Due to the dedication and contribution of its faculty, students and staff, the FIP has continued to grow in research, education, industrial activities, and membership. The membership of the Institute has increased to 110 faculty members belonging to 37 departments and institutions from the Pratt School of Engineering, the Trinity School of Arts & Sciences, and the Duke School of Medicine. The year 2015 was special for the photonics community worldwide as the United Nations (UN) General Assembly 68th Session proclaimed 2015 as the INTERNATIONAL YEAR OF LIGHT (IYL 2015). Supported by 100 partners from more than 85 countries, the “International Year of Light is a global initiative highlighting to the citizens of the world the importance of light and light-based technologies in their lives, for their futures and for the development of society” [www.light2015.org/home.html].

To celebrate IYL2015, our institute organized the 2015 World Photonics Forum (WPF), which was designed to provide a platform for international researchers in science, technology, art, and the humanities, and global leaders in management, policy and industry to discuss the challenges, contribution and potential of photonics-related activities and technologies in the next century. These distinguished guests provided their views, discussed and anticipated how photons will play a critical role by contributing fundamental and breakthrough technologies, and reviewed how these critical enabling technologies are at the heart of the scientific convergence that will define research progress in the 21st century. The WPF included several panels on critical and strategic topics of photonics: • Fundamental Breakthroughs in Light-based Science Technology (basic research and applied technologies, convergence of the New Light Age where photons replace electrons, etc.) • Light-based Technologies and Societal Impact and Human Development (education, arts, humanities, happiness, entertainment industries, next-generation global transportation, etc.) • Light-based Technologies on Global Economic Development (global health, global interconnectivity, renewable energies, the reshaping of geopolitics and global economics, etc.)

Technical sessions at the WPF and the Outreach Program organized at the WPF are highlighted in this special issue of BROADBAND. The IYL celebration underlines the fact that we are witnessing a very exciting period in the history of photonics science because there is an epochal convergence of many revolutions from the 20th century, such as the quantum revolution, the technology revolution and the genomics revolution. Riding on the crest of this convergence, light-based technologies influence our lives today in new ways that we could never have imagined just a decade ago. As we move into the next century, light will play an even more significant role, triggering a revolution in global photonics communications linking our entire planet, creating nanoscale biochips to unlock the inner world of the human cell, developing cost-effective medical cures for global health, inventing new energy sources and galvanizing human exploration at the frontiers of the universe.

I invite you to visit our website at www.fitpatrick.duke.edu to learn more about our faculty, research programs and activities. I hope you have a successful and enjoyable year.

Tuan Vo-Dinh
Director, Fitzpatrick Institute for Photonics
R. Eugene and Susie E. Goodson Professor of Biomedical Engineering
Professor of Chemistry

2015 FIP Symposium and World Photonics Forum
March 9-10, 2015 Duke University Durham, North Carolina, USA

The 2015 International Year of Light, as proclaimed by the United Nations, was an exciting, historic moment—and the Fitzpatrick Institute for Photonics (FIP) recognized this global event at its 2015 annual symposium. Key events included a roster of distinguished speakers—including two Nobel laureates, Professor Theodore W. Hänsch, and Professor John L. Hall, Nobel Laureates in Physics (2005). Dr. Hall and his wife, Marilyn Hall, co-creators of the Sci-Tek’s Discovery Program for Kids, also helped lead a pre-symposium open house to expose the general public to the latest in light-based science and technologies. In addition to lectures from world-renowned speakers, the symposium included contributed papers and posters by investigators from Duke and other academic and industrial institutions. Additional featured highlights were the International Year of Light poster and technology fair, industry booths, themed lab tours and the 2015 World Photonics Forum of special panel sessions on the influence and contribution of light-based technologies on science, human development and global economic development for the next century. The sessions were represented by our global community.
In honor of the momentous occasion of the International Year of Light 2015, the Fitzpatrick Institute for Photonics held a contest for non-Duke students to qualify for free registration to the symposium. The students had to submit a video, sound clip or essay to answer the following question: “How have light technologies positively impacted your life?” The winners of the competition were:

1st Place – Kapila Wijayarante, University of Virginia
2nd Place – Sam Migirditch, Appalachian State University
3rd Place – Niranjan Sridhar, University of Virginia
Honorable Mentions:
Ben Migirditch, Appalachian State University and Wenjiang Fan, University of Virginia

Check out their videos and essays on our website: www.fitzpatrick.duke.edu/fip-international-year-light-contest

FIP Photonics Pioneer Award
Dr. Theodor W. Hänsch, 2005 Nobel Laureate in Physics (jointly with Roy Glauber and John L. Hall) for his contributions to the development of laser-based precision spectroscopy, including the optical frequency comb technique, presented the keynote lecture at the annual Fitzpatrick Institute for Photonics (FIP) Symposium and World Photonics Forum held March 9-10, 2015. During the conference, Dr. Hänsch was recognized for his accomplishments in the field of photonics and awarded the prestigious FIP Pioneer Award.

SPEAKERS FOR THE 2015 FIP SYMPOSIUM AND WORLD PHOTONICS FORUM INCLUDED:

In the images:
1. Symposium Keynote Speaker
   Theodor W. Hänsch, PhD
   Nobel Laureate in Physics (2005) Max-Planck-Institut for Quantum Optics, Carl Friedrich-von Siemens Professor Chair, Faculty of Physics, Ludwig-Maximilians University of Munich, Germany.
   Dr. Hänsch was awarded the Nobel Prize in Physics along with Dr. Hall for their contributions to the development of laser-based precision spectroscopy, particularly the optical frequency comb technique.

2. Forum Keynote Speaker
   John L. Hall, PhD
   Professor Nobel Laureate in Physics (2005) JILA, University of Colorado National Institute of Standards and Technology Boulder, Colorado, USA
   Dr. Hall was awarded the Nobel Prize in Physics along with Dr. Hänsch for their contributions to the development of laser-based precision spectroscopy, particularly the optical frequency comb technique.

Left to Right: John Hall, Robert Lieberman, Eugene Arthurs and John Dudley all wearing their signature SPIE International Year of Light ties.

Left to Right: Federico Capasso, Michael Fitzpatrick, Theodore Hänsch, Robert Lieberman, Tuan Vo-Dihn and John Hall

In the text:

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For decades, art conservators have had a cradling problem. But thanks to some fancy mathematics and computer engineering work, their issues have been laid to rest. X-ray radiography is a standard technique widely used by art conservators, art historians and curators to discover information about the manufacturing process and the condition of a painting. A long-used preservation technique called cradling, however, often gets in the way of their work.

Cradling is the term used for wooden slats attached to the back of many old paintings executed on wooden panels. While the slats do provide support for the aging art works, it also creates lattice patterns that appear as grids or a series of stripes on an X-ray image. These patterns can obscure the image and distract art conservators from reading the image and analyzing paint layers. “Cradle patterns in X-ray images have been an ages-old problem for conservators studying collections of Old Master paintings, requiring many hours of tedious Photoshop manipulation or various other techniques that could damage the painting,” says William Brown, chief conservator at the North Carolina Museum of Art (NCMA). “We have been fortunate to work with world leaders in the fields of time-frequency analysis, informatics and image processing to come up with a practical solution to a difficult problem.”

The cradle pattern problem appeared while Rujie Yin, research assistant in Duke University’s Mathematics Department, was using X-ray images to research a 14th-century altarpiece by Francesco Ghissi for an upcoming exhibition at the NCMA. Yin, attempting to study crack patterns in the altarpiece for an image-processing component of the exhibition, was frustrated at the distracting cradling and decided to use mathematical algorithms to solve the problem.

But she couldn’t do it alone. Yin turned to Noelle Ocon, NCMA conservator of paintings to identify objectives of the project based on art conservators’ challenges with X-ray images. Then, with the help of Duke professors Ingrid Daubechies (mathematics and electrical and computer engineering) and David Dunson (statistics), the group developed an algorithm that removed the cradle pattern from the X-ray image. Compared to manually altering the image in Photoshop, the algorithm was not only quicker and more effective, but also much easier for art conservators to use.

Describing the algorithm, Daubechies explains, “The algorithm consists of a three-stage procedure. First, the cradled regions are located automatically. The second step consists of separating the X-ray image into a textual and image component. In the last step, the algorithm learns to distinguish between the texture caused by the wooden cradle and the texture belonging to the original painted wooden panel.”

With the support of a grant from the Samuel H. Kress Foundation, the collaboration was then able to convert the algorithms and coding into a user-friendly Photoshop plug-in tool. Dubbed Platypus, the program was introduced at a workshop in August 2015 attended by national and international art conservators. After receiving feedback from the conservators, the group worked to finalize the software and coding, which is now available free online.

The collaboration between the NCMA and Duke University is part of the NCMA’s Art + Science Initiative, which enlists local universities to research issues concerning both art and science, bringing technological advances to art conservation and demonstrating the importance of interdisciplinary studies. The Museum’s Conservation Center has partnered with Duke University on other conservation projects, including applying laser imaging technology to research materials used in paintings (designed by Warren S. Warren, director of Duke University’s Center for Molecular and Biomolecular Imaging).

The project is also part of the Information Initiative at Duke (iiD), an interdisciplinary program designed to increase “big data” (information characterized by tremendous volume, variety and rapid change) computational research and expand opportunities for student engagement in this rapidly growing field.
For my group, it’s about applying this kind of photoluminescence to building memory systems, sensors and computational logic,” said Dwyer. “And we build these components with self-assembling nanostructures using DNA.”

This approach has several benefits. For one, Dwyer and his group can use DNA structures to piece together logic gates just two nanometers wide. This leads to memory systems that are very dense. And the way light propagates also means that the amount of energy required to perform an operation is radically lower than a conventional computer.

Or at least it could be, once Dwyer’s group gets all of the components talking to one another. They can currently build logic gates and memory elements and network them together, but they still have to figure out how to optimize these devices so that they can compete with electrical silicon technologies.

“These devices blow silicon processors out of the water on paper, but getting the real world in line with the theory is easier said than done.”

For example, being made out of DNA, these tiny computational networks are biologically compatible. Perhaps scientists could put some computing power on a diagnostic assay inside the body—a feat which would greatly reduce the costs of such tests. Or in a future science fiction world, maybe scientists could conduct computations inside the bloodstream itself.

Dwyer also notes the idea of an encryptable drug, which would have a cryptographic algorithm run by a molecular-scale computer that would render it ineffective if it wasn’t presented with the correct challenge or response.

“I spent a great deal of my career trying to simply replace silicon in computing technology,” said Dwyer. “It probably took me the better part of six years, or half my career in academics, to figure out that a much better use of this technology is to bring computation to every niche of the physical world where silicon can’t go. I think that’s a much better use of our technology.”

The Genetic Codes That Create Optical Computers

FIP researchers are using self-assembling DNA to form the basic components for optical computing.

Optical computing has been around for decades, but the physical properties of light have limited its use to large scales. Wave guides that interact with and manipulate light have to be of the same order of magnitude in size. And for photons, that means nothing can be much smaller than a micron, which is huge compared to conventional silicon systems.

Dwyer, however, and others in his field have found a way around this problem—excitons. When individual molecules called chromophores interact with light, they quantum-mechanically absorb some of its energy, which gets turned into an exciton. And when that little nugget of energy moves from chromophore to chromophore in specific patterns, it creates light-based computational components.

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“I spent a great deal of my career trying to simply replace silicon in computing technology,” said Dwyer.
controlling its state with a high degree of reliability is very difficult. Kim’s group has demonstrated this feat with an accuracy on par with anyone in the world. Once an atom’s quantum state can be controlled, the system must be made quantum-mechanically coherent. If the atom interacts with the outside world even a little bit, it loses its “quantumness,” which is bad. Again, Kim’s laboratory has demonstrated this ability. They have also demonstrated the ability to initialize their system to a well-defined starting state. For example, in a laptop, each bit starts in the same place—a zero—until data is written to the chip.

Fourth, a quantum processor needs enough components to produce a universal set of gates, which allows one to implement arbitrary computational tasks. Kim’s setup combines a simple two-quantum-bit gate with the ability to control each quantum bit’s state to accomplish that.

Last but not least, a quantum computer needs to have the ability to report its solution. To do that, there must be good quantum measurements, which again, Kim’s laboratory has already demonstrated. “All of these criteria our system meets pretty much as well as anybody else’s can,” said Kim. “But those are just the components. If you want to build a computer, you have to put a large number of these things together in a way that you can control them and interact with them at will. And that system integration is something that we are currently working on.”

After scientists in the 1940s put together the first string of vacuum tubes, it wasn’t long before they filled rooms with tens of thousands of them to create the first digital computer. Kim hopes to demonstrate the first small string of “quantum vacuum tubes” within a year. After that, it will be up to the cutting-edge technologies developed for semiconductors and telecommunications to scale the system up.

“We do all of these quantum manipulations with atomic ions trapped on silicon chips, so we could actually start to think about systems where we have 100 atomic ions,” said Kim. “That’s a small processor, but we have ways of connecting multiple units to build large-scale systems. The result would be similar to data processing centers with thousands of processors linked together.”

“The challenge is getting today’s telecommunication technologies to work with our quantum systems, because they operate on different wavelengths,” Kim added. “I think we’re getting close. And if successful, not only could we make scalable quantum computing clusters, but also quantum networks that communicate over long distances.”
Tracking Electrical Storms with a New Light

FIP researchers are using radio waves to track miles of unseen channels of lightning to learn more about the common but enigmatic phenomenon.

The flash of light streaking between the ground and sky that catches onlooker’s attention is literally just the tip of the lightning bolt. During a typical strike, less than 10 percent of the total electrical activity is visible. The rest is hidden from view within different layers of the cloud extending for miles through the storm. This presents a major hurdle for studying lightning’s many enigmas that still confound researchers to this day. Because movements of electricity are hidden from view, scientists must turn to different portions of the electromagnetic spectrum for insights.

“If you have a really good high-speed imaging system, you can see all of this amazing, intricate detail in lightning flashes,” said Steve Cummer, professor of electrical and computer engineering. “But even with that technology, there are some things you can’t see that lightning does because it’s in the cloud. So you need some kind of non-optical way to see it.”

To study an electrical storm’s internal wiring, researchers watch for either Very High Frequency (VHF) waves caused by the breakdown of air in front of a bolt’s path or radio waves produced by the movement of electrons. Cummer is pursuing the latter.

Along with postdoctoral associate researcher Fanchao Lyu, Cummer has devised a ground sensor system and data processing system that can track the sources of radio wave emissions with more precision than ever before. The system works by cross-correlating radio wave signals from two stations during a 350-microsecond window to determine the difference in the waves’ time of arrival. The time window is then slid 50 microseconds and the process is repeated.

Because the radio waves travel at the speed of light, the difference in time it takes them to reach each sensor is extremely small—but it is detectible. That difference constrains the point from which the waves could have originated. And after getting time-of-arrival differences from seven different stations for a single event, the source of the radio waves can be pinpointed.

While this method has been used before, the greater number of sensors and the way the data are processed make Duke’s system more sensitive than any previously deployed, giving good mapping results on both continuous emissions and fast processes within the cloud. The tracking allows Cummer and Lyu to image more processes during a lightning strike than ever before, providing a more complete image of the event.

Besides giving new insights into basic aspects of lightning that are still not understood—like how lightning channels form across tens of miles of sky—the system can also help investigate some of the more extraordinary and rare phenomena produced by electrical storms. “Right now I am obsessed with terrestrial gamma-ray flashes, which is the process in which thunderstorms act as particle accelerators and launch very high-energy gamma rays out into space,” said Cummer. “The challenge is that the only terrestrial gamma-ray flashes ever detected are the ones that just happen to be seen by astronomy satellites.”

Because they are thousands of miles away from the source of terrestrial gamma-ray flashes, the satellites rarely manage to spot one. And when they do, they can’t directly image the processes at work. They can, however, measure some details of the lightning flashes that produce the bursts of gamma rays. Cummer hopes that by matching some of the characteristics of storms that produce terrestrial gamma-ray flashes with events he’s captured on his new radio wave system, he can begin to tease out the inner workings of the phenomenon.
The Fitzpatrick Institute for Photonics (FIP) is able to offer several graduate student fellowships through the continued support and generosity of the Fitzpatrick Foundation and John T. Chambers.

**Fellowships**

The Scholars program provides existing Duke graduate students within the FIP approximately $46,000 each year toward their stipend, tuition remission, grad school fees and health insurance for two years. This program is designed to reward the most outstanding individuals within FIP for their accomplishments and potential. Each candidate, nominated by a FIP Professor, was judged on the criteria of demonstrated excellence in their academic studies, research within FIP for their accomplishments and potential. Each candidate, nominated by a FIP Professor, was judged on the criteria of demonstrated excellence in their academic studies, research within FIP for their accomplishments and potential. Each candidate, nominated by a FIP Professor, was judged on the criteria of demonstrated excellence in their academic studies, research within FIP for their accomplishments and potential. 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FIP Faculty: 121 faculty members from 37 departments and institutes at Duke

ANESTHESIOLOGY
Allan Shang, M.D. Adjunct Prof.

ART, ART HISTORY & VISUAL STUDIES
Bill Seaman, Prof.

Biology
Adde DeCruz, Adj. Assist. Prof.
Steve Haase, Assoc. Prof.
Sönke Johnsen, Prof.
Daniel Kiehart, Prof.
Zhen-Ming Pei, Assoc. Prof.

BIOMEDICAL ENGINEERING
Ashutosh Chilkoti, Prof.
Mark Dewhirst, Prof.
Sina Faruqi, Assist. Prof.
Daniel Gauthier, Prof.
Ce Zhen, Assist. Prof.

BIOLOGY CENTER FOR GENOMIC AND COMPUTATIONAL BIOLOGY
Lingchong You, Assoc. Prof.

CENTER FOR APPLIED GENOMICS AND PRECISION MEDICINE
Geoffrey Ginsburg, M.D. Prof.

CENTER FOR COMPLEX SYSTEMS AND COMPUTATIONAL BIOLOGY
Lingchong You, Assoc. Prof.

CENTER FOR GENOMIC AND COMPUTATIONAL BIOLOGY
Lingchong You, Assoc. Prof.

CENTER FOR METAMATERIALS AND INTEGRATED PLASMONICS
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Steve Cummer, Prof.
Nan Jokir, Prof.
Junsang Kim, Prof.
David R. Smith, Prof.

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Emily Derbyshire, Assist. Prof.
Martijn Fischer, Assoc. Res. Prof.
Katherine Franz, Prof.
Jie Liu, Prof.

COMPUTER SCIENCE
Nikos Pitsianis, Adjunct Assoc. Prof.

DERMATOLOGY
Russell P. Hall, Prof.

DIVISION OF INFECTIOUS DISEASES AND INTERNATIONAL HEALTH
Steve Taylor, MD, Assoc. Prof.

DUKE COMPREHENSIVE CANCER CENTER
Neil L. Spector, M.D., Assoc. Prof.

DUKE HUMAN VACCINE INSTITUTE
Nathan Thrulman, Prof.

ELECTRICAL AND COMPUTER ENGINEERING
Martin Brooke, Assoc. Prof.

ENGINEERING AND COMPUTATIONAL BIOLOGY
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Leslie Collins, Prof.

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Joseph Izatt, Prof.

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Ken Kingery, and Emily Kowalski

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Xueliang (Steve) Zhang, Assist. Prof.

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Aoife Egan, Prof.

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Andrew Janjua, Prof.

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Anne Bensinger, Assoc. Prof.

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Hisham Massoud, Prof.

PHYSICS
Yi Zhong, Prof.

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G. Allan Johnson, Prof.

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