The Full Spectrum of Color Analysis

Flexibility, performance, and innovation—LightTools delivers it all.

### Performance and Reliability
Integrated optimization automatically determines the best design that meets color specifications and ensures performance and reliability when manufactured. Evaluate the lit or unlit true color appearance of your system with photorealistic rendering.

### Innovation
Smart output smoothing uses a unique algorithm to reduce statistical noise and provide rapid, accurate color analysis results. Verify your design’s compliance with performance requirements at any stage of the design process.

Unsurpassed color definition, comprehensive color analysis—from the optical design innovation leader you’ve trusted for over 45 years.

### Color Definition
- Full-spectral sources and chromaticity calculations based on real colors using CIE coordinates
- Spectral-dependent materials, reflectors, and diffusers
- Color ray data, wavelength or tri-stimulus based
- Fully dispersive ray tracing
- Backward ray tracing for illuminance, intensity, and spatial and angular luminance calculations
- Wavelength-dependent bulk absorption, reflecance, and transmittance

### Color Analysis
- Color meshes and points
- RGB true-color plots
- Smart output smoothing
- Spectral power distribution and CRI
- Photorealistic rendering
- Individual or combined CRI calculations on any receiver

---

Tel: (626) 795-9101  E-mail: info@opticalres.com  Web: www.opticalres.com

©2012 Synopsys, Inc.  LightTools is a registered trademark of Synopsys, Inc.
What is Your Constellation?

Coherent Receiver Lab Buddy

- Quad Linear Balanced Receivers with Optical Hybrid
- Automatic (AGC) or Manual Gain Control
- User-adjustable RF Bandwidth for Optimum Signal to Noise Ratio (SNR)
- Plug and Play
- Versatile for your Coherent Lab Setup: Intradyne, Homodyne, and Heterodyne

Live 25 Gbaud QPSK Constellation using Coherent Receiver Lab Buddy

Discovery Semiconductors, Inc. www.discoverysemi.com
119 Silvia Street, Ewing, NJ 08628 U.S.A.
26 Sensing Trouble: Fiber-Optics in Civil Engineering
A wave of new fiber-optic sensing techniques takes advantage of the sensitivity of telecom-grade fiber optics to stress, strain, temperature and other factors in order to ensure the long-term safety of civil structures. Lynn Savage

34 Next-Gen Quantum Networks
Get ready: the quantum Internet is a next-generation disruptive technology that is now closer to fact than fiction. Researchers predict that practical quantum communications may be here within 10 to 15 years. Valerie C. Coffey

42 Saving Hubble
Shortly after the launch of the Hubble, NASA scientists couldn’t bring its images into focus—and a bright hope became a grim fiasco. But behind the scenes, optical engineers were devising an ingenious fix that would transform Hubble into the world’s most successful telescope. Jeff Hecht
**President’s Message**

**Contributors**

**Optical Feedback**

**Product Profiles**

**After Image**

---

**DEPARTMENTS**

**Scatterings**

**9 Headliners:** Mimicking fireflies in LEDs and more. *Yvonne Carts-Powell and Pat Daukantas*

**13 Policy News:** Something new on the EU horizon, Congressional committee guides. *Sarah Michaud*

**14 Industry Updates:** OLED TVs reach consumer market, optical component growth. *Valerie Coffey*

**15 Book Reviews:** Nanostructured and Subwavelength Waveguides and more. *K. Alan Shore and others*

**Pulses**

**16 Optics Innovations:** Inrad Optics: new name, new mission. *Amy Eskilson*

**18 Global Optics:** Optics in Toruń, Poland. *Danuta Bukowska*

**20 Career Focus:** A curriculum vitae makeover. *Matthew Weed and Jean-luc Doumont*

**23 Conversations in Optics:** OPN talks with Brian Protiva. *Brielle Day*

**24 Member Lens:** Images from Adam K. Glaser and Samuel F. Pellicori.

**Backscatter**

**50 Member News:** New editors, Sir David Payne and more. *51 In Memory:** OSA remembers Peter Domachuk.

**52 Events Calendar:** Upcoming OSA meetings.

**53 Crossword Puzzle:** Famous names in optics.

---

**COVER:** Artistic interpretation of fiber-optic sensing in buildings. Thinkstock/Composite image Alessia Kirkland
When we think about optical fiber, communications is probably the first thing that comes to mind. But the sensitivity of telecom-grade fiber optics to stress, strain and temperature has also opened them up to a new world of applications in sensing. This month’s cover story explores how fiber optics is being used to provide real-time monitoring of the integrity of civil structures such as buildings, dams and bridges. It’s a wonderful example of how a mature technology can move into new application areas that no one could have predicted.

Meanwhile, the field of fiber optic communications continues to advance beyond what many of us ever thought possible as well. As this month’s OFC/NFOEC conference in Anaheim, Calif., U.S.A., will highlight, 400G networks are now emerging from the planning stage; 1Tb and photonic integrated technologies are driving tomorrow’s networks; and the IT industry is increasingly deploying dynamic cloud computing environments.

On p. 23 of this issue, Brian Protiva describes another key trend that will be explored at OFC/NFOEC this year: software-defined networking (SDN)—which challenges the vertically integrated approach to the switch-and-router design of the past 20 years. SDN may be a key component of the Internet of the future. To learn more about the meeting or to register, visit www.ofcnfoec.com.

Another striking possibility for future networks is the application of quantum physics to computing technology. As the article on p. 34 describes, some researchers predict that a quantum Internet could be a reality within the next 15 years. This form of computing would enable the transmission of massive volumes of data and complicated computations and searches—all with zero lag time.

If you like a good detective story, you will likely enjoy Jeff Hecht’s article on p. 42, titled “Saving Hubble.” While today we think of the Hubble as a resounding optics success story, around the time of its launch scientists feared that the telescope might go down in history as one of NASA’s most expensive flops. Spherical aberration in its primary mirror caused its images to come back no clearer than those captured from a high-elevation ground telescope.

OSA Past President Duncan Moore was charged with diagnosing the optical problem and designing repairs. Fortunately, optical engineers were able to pinpoint the issue using ingenious “forensic” optics and then devise a clever fix, transforming Hubble into the world-class telescope we know it as today.

What all these stories have in common is their ability to challenge our assumptions—and imaginations—about what can and cannot be accomplished through optics. As you read through your issue, I hope you will bring from it a sense of optimism that you can apply to your own lab, classroom or business. Anything is possible.

—Donna Strickland
OSA President
Our cover story explores how fiber optics is being used to monitor the health of civil structures such as buildings, dams and bridges. Fiber sensors react to changes in their environment through minute alterations of the refractive indices as light travels through them, signaling if a structure is damaged or strained, according to author Lynn Savage. For the article, he spoke with Branko Glisic, a professor of civil engineering at Princeton University whose lab is focused on structural health monitoring. “For the first time, fiber optics is providing very large volumes of structures with durable, precise and stable sensors, ensuring drastically improved spatial sensitivity to damage and long-term reliability,” Glisic says.

Most magazines can’t resist a good makeover story, and Optics & Photonics News is no exception. Our career column highlights before and after versions of young OSA member Matt Weed’s curriculum vitae, which was critiqued by science communication expert Jean-luc Doumont.

According to Jean-luc, Matt’s CV already had a lot going for it. “Compared to many I have seen lately, Matt’s CV is a solid start, emphasizing competencies and going beyond the mere research experience,” he says. “Still, it is long and visually suboptimal. With some trimming and a better use of space, Matt’s impressive experience becomes apparent at a glance.” Matt took the feedback in stride: “Jean-luc helped me to design a CV that better communicates what I have to offer prospective employers.”

A quantum internet could offer many advantages over standard networks, including the secure transmission of mass volumes of data in minimal time. While it seems hard to believe, this and other aspects of quantum communications are moving from speculative science into the realm of the possible. “Quantum communications technology is definitely coming—it’s only a matter of time,” says freelance writer Valerie Coffey. “According to the researchers I interviewed, a more secure and powerful Internet based on quantum physics will be practical in only 10 to 15 years,” she says.

“I still remember the dismay I felt when I first heard that Hubble’s main mirror was flawed,” says Jeff Hecht, who chronicled the story of Hubble’s first big repair in our final feature. “But I would rather recall the utter awe I felt when the Hubble Ultra Deep Field image showed me the edge of the universe.” For the article, he spoke with engineer Mark Kahan, who was integrally involved with the fix. Kahan compares the diagnostic process to that of an ophthalmologist who finds out that his patient has a problem that started a decade ago—and can’t come in for an exam. “If your ‘glasses’ can’t fix it, you, your company and NASA will all have hell to pay,” he says.
Changing the Lights—and the Measure

Keeping readers informed about trends in optics and photonics is something that Optics & Photonics News generally does well. I believe your content is useful not only for specialists, but also younger readers who might be interested in pursuing a career in optics.

In that context, I would like to share my (belated) feedback on two 2012 articles—“Changing the Lights” and “Better Solar via Photonic Crystals” (OPN, March 2012). While I found them very interesting, I was disappointed from an educational point of view because both articles use the obsolete unit degree kelvin (°K) instead of the right unit, kelvin (K) to refer to thermodynamic temperature.

The old and obsolete unit degree kelvin was abrogated and replaced with the currently valid one, kelvin, as part of the 13th meeting of the Conférence Générale des Poids et Mesures 1967/68. Moreover, in its 1980 meeting, the French Comité International des Poids et Mesures approved the report of the 7th meeting of the Consultative Committee for Units, which requested that the use of the symbols “°K” and “deg K” no longer be permitted.

Note also that the kelvin is one of the only seven base units of the International System of Units, or SI (from the French Le Système international d’unités), which is mandatory to use in any scientific, technical and educational paper, by international agreements. It is used in high schools and universities around the world. To still find the unit degree kelvin being used sends a confusing message to your readers.

George Nemes
Sacramento, Calif., U.S.A.
gnemes98@hotmail.com

THE EDITOR RESPONDS: Thanks for your letter. I agree with you that it is critical to use the current correct unit of measure in Optics & Photonics News. One of our reviewers alerted us to the same issue with Jeff Hecht’s article on LEDs. We will ensure that all subsequent articles contain the accurate measure.

Christina Folz
OPN Editor & Content Director

Mars Attacks

I keep looking at the January cover showing a robot zapping Mars with a laser. I have seen this many times in books and movies, and it is always followed by an invasion of Earth. Mark your calendars; it takes 18 months to travel from Mars to Earth.

Dana D. Dlott
Urbana, Ill., U.S.A.
dlott@Illinois.edu

THE EDITOR RESPONDS: Thanks for the heads up. Maybe the Mayans forgot to factor in the travel time from Mars to Earth. In any case, thanks for your message. We hope you enjoy the magazine over the next year and a half ... and hopefully beyond that! —Christina Folz

Correction: On p. 48 of the January OPN, we incorrectly stated that S.N. Bose had collaborated with Louis de Broglie and Albert Einstein. In fact, Bose worked only with Maurice de Broglie, Louis’s older brother. In addition, he did not collaborate directly with Einstein; the latter merely translated Bose’s first paper. We regret the errors. Thanks to OSA Fellow Barry Masters for setting the record straight.
CALL FOR PAPERS

Present your research to colleagues in an environment that fosters one-on-one interaction and offers you the opportunity to network with leaders in industry and academia. This event guarantees five days of cutting-edge presentations, renowned FiO and LS invited speakers and an array of special events.

Submit Your Research

- Optical Design, Fabrication and Instrumentation
- Optical Sciences
- Optics in Biology and Medicine
- Optics in Information Processing
  - Fiber Optics and Optical Communication
  - Integrated Photonics
  - Quantum Electronics
  - Vision and Color
  - Laser Science

SUBMISSION DEADLINE: Monday, 6 May 2013 12:00 noon EDT (16.00 GMT)

VISIT www.frontiersinoptics.org TO SUBMIT PAPERS.
Taking a cue from master engineer Mother Nature, researchers have figured out how a type of firefly gives off light (Opt. Express 21, 764) and used the results to raise the light-extraction efficiency of an existing LED by 55 percent (Opt. Express 21, A179).

Annick Bay, a doctoral student at the University of Namur (Belgium), and her colleagues studied the morphology of the segments of the luminescent abdomens of fireflies of the genus Photuris. They modeled the propagation of 560 nm light—close to the peak wavelength of the flies’ emission—within these structures, and they experimentally checked their calculations by measuring the radiance of light beamed through pieces of the insects’ abdomens.

The team found that Photuris has “misfit” chitin scales, with one edge of each scale protruding a few micrometers outward. The scales create a corrugated “factory roof” surface that improves light extraction from the abdomen over a flat surface with the same refractive index. They used this pattern to design an LED overlayer, which increased light extraction by 55 percent. The researchers speculate that, with achievable modifications to current manufacturing techniques, it should be possible to apply these novel, energy-saving design enhancements to current LED production within the next few years.

—Patricia Daukantas
Light Labyrinth

Coordinating random scattered photons.

Can something be both random and organized? Apparently so. Although light scattering is a random process, photons emitted in a complex and disordered structure can travel mutually coordinated paths, according to researchers at the Niels Bohr Institute at the University of Copenhagen (Denmark). The findings provide new ways of enhancing light-matter interaction for quantum electrodynamics and energy harvesting and may find applications in subwavelength diffuse-wave spectroscopy for biophotonics.

Researcher David Garcia and his team tracked photons emitted by a quantum dot embedded in a disordered photonic crystal (Phys. Rev. Lett. 109, 253902). Due to the wavelike nature of light, the photons took different paths but were interdependent in the sense that the chance of observing a photon at one outlet was increased if another photon is seen at the other.

The method might someday be used to measure the spatial properties of complex disordered materials such as biological tissue. —Yvonne Carts-Powell

Garcia explains: “The photons are scattered in all directions ... But photons are not just light particles, they are also waves, and waves interact with each other. This creates a link between the photons, and we can now demonstrate in our experiments that the photons’ path through the material is not independent from the other photons.”

The emitters probed the microscopic details of the medium and imprinted the near-field properties onto the far-field correlations.

Optical clocks can slice time into quadrillionths of a second—which is a million times smaller than a billionth of a second.
Mechanical Switching
Inside Optical Fibers

Once drawn, optical fibers are usually mechanically rigid—in other words, frozen forever. But scientists in the United Kingdom have used tiny mechanical interior movements to switch light between the two cores of a single glass fiber (Opt. Express 20, 29386). The experiments could lead to “smart fibers” for many telecommunications and sensing applications.

Research associate Zhenggang Lian and his colleagues at the University of Southampton’s Optoelectronics Research Centre constructed the nanomechanical fiber out of lead silicate glass, with the two cores independently suspended and yet optically coupled. At one point along the fiber, the researchers etched away the cladding to provide the outside environment with access to one of the cores.

The altered section was passed through a nitrogen-filled pressure chamber, which the team used to apply selective pressure on one of the cores. The researchers beamed polarized diode-laser light at a standard telecom wavelength (1,550 nm) down the fiber. By varying the chamber pressure by a few hundred millibars, the team moved one core by as much as 8 nm and switched the light between the two cores.

In future applications, electrostatic actuators, which are now used in many micro-electro-mechanical systems, could perform the tiny mechanical movements more quickly than the external pressure changes. Such nanoscale devices within fibers could move some of the switching, buffering and routing functions of a network from optoelectronic chips to the fibers themselves. Sensors could benefit from the fibers’ ability to detect minuscule pressure changes or vibrations in the environment. —Patricia Daukantas

Optical Fiber Solutions for Telecommunications

SPEAK WITH THE EXPERTS! OFC 2013 | Anaheim Convention Center, CA | Booth #2627 | March 17-21

RightWave™ Erbium-Doped Fibers | TruePhase® Polarization-Maintaining Fibers | Multicore Fibers
AllWave® Single-Mode Fibers | LaserWave® Multimode Fibers | AccuRibbon® Optical Ribbons
Coupler Fibers | FITEL® Fusion Splicers | Dispersion Compensation Modules | TruePhase® Polarimeter

OFS | 732 748 7400 | info@specialtyphotronics.com | www.SpecialtyPhotonics.com
New solar power installations in Germany hit a record high in 2012—capacity grew by more than 7.6 gigawatts.

Focusing Light to a Nanoscale Point

Squeezing light down to the smallest possible space is crucial for integrating tiny devices onto a single photonic chip and performing biomedical imaging. Scientists in California have built a tiny plasmonic waveguide that “nanofocuses” near-infrared light to a point less than 100 nm wide (Nature Photon., doi: 10.1038/nphoton.2012.277).

The tapered structure, consisting of silicon dioxide sandwiched between two layers of gold, is less than 2 μm in overall length, says Hyuck Choo, assistant professor of electrical engineering at the California Institute of Technology in Pasadena. The waveguide compresses light in the two dimensions perpendicular to the propagation of the radiation.

Computer simulations revealed the optimal geometry for the taper to produce nanofocusing. The bottom of the device remains flat for ease of on-chip implementation, with the sides and top narrowing from front to back.

The team focused 830-nm light from a femtosecond laser into a spot 14 nm by 80 nm, with an intensity 400 times greater than the original beam. By the group’s calculations, the smallest possible pinpoint of light that the tapered waveguide could produce would be 2 nm wide and 5 nm long, although they have not yet achieved that experimentally.

—Patricia Daukantas

Beating the Quantum Limit in Optical Communications

Teasing meaningful information out of a weak signal—whether in a child’s game of “telephone” or an optical network—can be difficult or impossible due to intrinsic noise. Now, scientists at the Joint Quantum Institute (JQI; U.S.A.) have devised a method for lowering the error rate of a quantum system below the standard quantum limit, which could lead to more efficient communications (Nature Photon, doi: 10.1038/nphoton.2012.316).

An ideal, 100-percent-efficient receiver can distinguish nonorthogonal coherent states down to a certain minimum level of error probability known as the standard quantum limit, according to Francisco Elohim Becerra, a postdoctoral researcher at JQI. Scientists can squeeze more information into a signal by encoding the data into multiple phases of light, but the higher the number of states or phases, the more difficult it is to distinguish them at the receiver, especially with low-intensity signals.

To “beat” the standard limit, the JQI team devised an adaptive feedback system that makes multiple assessments of the phase of the incoming signal. The receiver uses the first measurement to adjust itself before making the next measurement. The researchers tracked the experimental error probability involved in distinguishing among four states in the format known as quadrature phase-shift keying. The experiment yielded error probability that is 6 dB below the standard quantum limit for an ideal receiver. —Patricia Daukantas

Beating the Quantum Limit in Optical Communications

Teasing meaningful information out of a weak signal—whether in a child’s game of “telephone” or an optical network—can be difficult or impossible due to intrinsic noise. Now, scientists at the Joint Quantum Institute (JQI; U.S.A.) have devised a method for lowering the error rate of a quantum system below the standard quantum limit, which could lead to more efficient communications (Nature Photon, doi: 10.1038/nphoton.2012.316).

An ideal, 100-percent-efficient receiver can distinguish nonorthogonal coherent states down to a certain minimum level of error probability known as the standard quantum limit, according to Francisco Elohim Becerra, a postdoctoral researcher at JQI. Scientists can squeeze more information into a signal by encoding the data into multiple phases of light, but the higher the number of states or phases, the more difficult it is to distinguish them at the receiver, especially with low-intensity signals.

To “beat” the standard limit, the JQI team devised an adaptive feedback system that makes multiple assessments of the phase of the incoming signal. The receiver uses the first measurement to adjust itself before making the next measurement. The researchers tracked the experimental error probability involved in distinguishing among four states in the format known as quadrature phase-shift keying. The experiment yielded error probability that is 6 dB below the standard quantum limit for an ideal receiver. —Patricia Daukantas

Beating the Quantum Limit in Optical Communications

Teasing meaningful information out of a weak signal—whether in a child’s game of “telephone” or an optical network—can be difficult or impossible due to intrinsic noise. Now, scientists at the Joint Quantum Institute (JQI; U.S.A.) have devised a method for lowering the error rate of a quantum system below the standard quantum limit, which could lead to more efficient communications (Nature Photon, doi: 10.1038/nphoton.2012.316).

An ideal, 100-percent-efficient receiver can distinguish nonorthogonal coherent states down to a certain minimum level of error probability known as the standard quantum limit, according to Francisco Elohim Becerra, a postdoctoral researcher at JQI. Scientists can squeeze more information into a signal by encoding the data into multiple phases of light, but the higher the number of states or phases, the more difficult it is to distinguish them at the receiver, especially with low-intensity signals.

To “beat” the standard limit, the JQI team devised an adaptive feedback system that makes multiple assessments of the phase of the incoming signal. The receiver uses the first measurement to adjust itself before making the next measurement. The researchers tracked the experimental error probability involved in distinguishing among four states in the format known as quadrature phase-shift keying. The experiment yielded error probability that is 6 dB below the standard quantum limit for an ideal receiver. —Patricia Daukantas

Beating the Quantum Limit in Optical Communications

Teasing meaningful information out of a weak signal—whether in a child’s game of “telephone” or an optical network—can be difficult or impossible due to intrinsic noise. Now, scientists at the Joint Quantum Institute (JQI; U.S.A.) have devised a method for lowering the error rate of a quantum system below the standard quantum limit, which could lead to more efficient communications (Nature Photon, doi: 10.1038/nphoton.2012.316).

An ideal, 100-percent-efficient receiver can distinguish nonorthogonal coherent states down to a certain minimum level of error probability known as the standard quantum limit, according to Francisco Elohim Becerra, a postdoctoral researcher at JQI. Scientists can squeeze more information into a signal by encoding the data into multiple phases of light, but the higher the number of states or phases, the more difficult it is to distinguish them at the receiver, especially with low-intensity signals.

To “beat” the standard limit, the JQI team devised an adaptive feedback system that makes multiple assessments of the phase of the incoming signal. The receiver uses the first measurement to adjust itself before making the next measurement. The researchers tracked the experimental error probability involved in distinguishing among four states in the format known as quadrature phase-shift keying. The experiment yielded error probability that is 6 dB below the standard quantum limit for an ideal receiver. —Patricia Daukantas

Beating the Quantum Limit in Optical Communications

Teasing meaningful information out of a weak signal—whether in a child’s game of “telephone” or an optical network—can be difficult or impossible due to intrinsic noise. Now, scientists at the Joint Quantum Institute (JQI; U.S.A.) have devised a method for lowering the error rate of a quantum system below the standard quantum limit, which could lead to more efficient communications (Nature Photon, doi: 10.1038/nphoton.2012.316).

An ideal, 100-percent-efficient receiver can distinguish nonorthogonal coherent states down to a certain minimum level of error probability known as the standard quantum limit, according to Francisco Elohim Becerra, a postdoctoral researcher at JQI. Scientists can squeeze more information into a signal by encoding the data into multiple phases of light, but the higher the number of states or phases, the more difficult it is to distinguish them at the receiver, especially with low-intensity signals.

To “beat” the standard limit, the JQI team devised an adaptive feedback system that makes multiple assessments of the phase of the incoming signal. The receiver uses the first measurement to adjust itself before making the next measurement. The researchers tracked the experimental error probability involved in distinguishing among four states in the format known as quadrature phase-shift keying. The experiment yielded error probability that is 6 dB below the standard quantum limit for an ideal receiver. —Patricia Daukantas
**POLICY**

113th Congressional Committee Guides

Between the 2012 U.S. elections, retirements and committee chairmanship term limits, the new Congress holds a lot of changes for House and Senate committee rosters. To keep track of who’s who and what’s in store for the upcoming term, the OSA public policy team has put together committee-by-committee guides for both chambers. You can find them online at www.osa.org/about_osา/public_policy/washington_updates/.

Something New on the EU Horizon

“Horizon 2020” is the new, integrated funding system that will cover all research and innovation funding currently provided through the Framework Programme for Research and Technical Development, the Competitiveness and Innovation Framework Programme and the European Institute of Innovation and Technology. It combines these funding mechanisms in a way that allows for more award flexibility. Horizon 2020 is a seven-year program that will evolve to incorporate a broader economic and policy framework as it progresses, with the goal of delivering ideas, growth and jobs for the future. It also will be a key tool in implementing the Innovation Union flagship initiative, which is aimed at securing Europe’s global competitiveness.

The proposed support for research and innovation under Horizon 2020 will:
- strengthen the EU’s position in science
- bolster industrial leadership in innovation, including major investments in technology and small- and medium-sized enterprises; and
- address concerns shared by most Europeans, including climate change, affordable renewable energy, elder care and food safety.

For information on funding opportunities, visit www.osa-opn.org/home/#tab-ranld.

---

Salary Watch

In early 2013, the U.S. National Center for Science and Engineering Statistics released data on doctoral-level scientist and engineer salaries. The report includes information from 2010 on full-time employees in several sectors. Engineers reported median annual salaries ($115,000) that were higher than those reported by health and science doctorates ($95,000 and $93,000, respectively).

<table>
<thead>
<tr>
<th></th>
<th>Science</th>
<th>Engineering</th>
<th>Health</th>
</tr>
</thead>
<tbody>
<tr>
<td>All full-time employed</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>4-year educational institution</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Private, for-profit</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Private, non-profit</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Federal government</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>State/local government</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Self-employed</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Other</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Median annual salary ($)

<table>
<thead>
<tr>
<th></th>
<th>0</th>
<th>20,000</th>
<th>40,000</th>
<th>60,000</th>
<th>80,000</th>
<th>100,000</th>
<th>120,000</th>
<th>140,000</th>
</tr>
</thead>
<tbody>
<tr>
<td>All full-time employed</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>4-year educational institution</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Private, for-profit</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Private, non-profit</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Federal government</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>State/local government</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Self-employed</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Other</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

By 1662, Pierre de Fermat perfected his least-time proof of the sine law, which treats light as a particle shooting through space.

A Beautiful Mind

"Brainbow" is a neuroimaging process developed by researchers at Harvard University to illuminate over 100 individual neurons in the brain using fluorescent proteins. Older techniques only illuminated a few neurons at a time. One of brainbow's creators recently published research showing extensive “pruning” of neuron connections to muscle fibers shortly after birth in mouse models, often reducing the ratio of neurons to muscle fibers from 10:1 to 1:1 (Neuron doi: 10.1016/j.neuron.2012.04.017). Although the pruning theory has been around since the 1970s, researchers are now able to use brainbow to view this phenomenon.

The image to the right shows brainbow-engineered cells randomly expressing fluorescent proteins in a mouse hippocampus, which plays an important role in forming new memories.

INDUSTRY

Strong Component Growth Predicted through 2019

A report released by Wintergreen Research (Lexington, Mass., U.S.A.) estimates that the optical component market will grow from $3.6 billion in 2012 to $12.3 billion by 2019. Optical Components: Market Shares, Strategy, and Forecasts, Worldwide, 2013 to 2019, available for purchase at www.ResearchandMarkets.com, covers optical communication network elements and infrastructure, which are expected to surge along with the growth of smart phone use and Internet data transmission. —Valerie Coffey

OLED TVs Reach Consumer Market

LG Electronics (Korea) launched a commercially available organic LED (OLED) television at this year’s Consumer Electronics Show (CES). The 55” OLED screen TVs will go on sale for about KRW 11M (US $10,000).

OLED TV technology enables the elimination of a backlight, resulting in ultra-thin displays only 4 mm thick compared to the conventional flat-screen thickness of 15 mm. The weight of the set is thus reduced to 10 kg (22 lb). OLED TVs also use less power to produce brighter and sharper images compared to LCD and plasma displays.

Samsung introduced a 55” OLED TV prototype at CES 2013, but a commercial launch date had not yet been announced as of press time. —Valerie Coffey

Patricia Daukantas, Yvonne Carts-Powell and Valerie Coffey are freelance science writers who specialize in optics and photonics. Sarah Michaud is OPN’s associate editor.
BOOK REVIEWS

Nanostructured and Subwavelength Waveguides: Fundamentals and Applications
Maksim Skorobogatiy, Wiley, 2012; $155.00 (hardcover).

This book stands at the confluence of a number of fast-flowing streams in physics research: metamaterials, polar materials, plasmonics and nano-optics. Skorobogatiy provides a comprehensive range of mathematical and analytical approaches to treat nanostructured and subwavelength waveguides in widely different contexts. —K. Alan Shore

Springer Handbook of Lasers and Optics, 2nd Edition
Frank Träger, ed., Springer, 2012; $339.00 (hardcover).

I recommend this modern, comprehensive handbook to students, educators, engineers and scientists. The chapters are clearly written and include sophisticated illustrations that augment the text. The tables of data are also exemplary. The authors strike a good balance between theory and implementation. —Barry R. Masters

Nanostructured and Subwavelength Waveguides: Fundamentals and Applications
Maksim Skorobogatiy, Wiley, 2012; $155.00 (hardcover).

The chapters are clearly written and include sophisticated illustrations that augment the text. The tables of data are also exemplary. The authors strike a good balance between theory and implementation. —Barry R. Masters

Nanophotonic Fabrication: Self-Assembly and Deposition Techniques
Takashi Yatsui, Springer, 2012; $129.00 (hardcover).

Nanophotonics is a novel optical technology that utilizes the local interaction between nanometric particles via optical near-fields. This introduction to nanophotonic fabrication is aimed at readers who are interested in various functions that differ depending on the device. —Lisa Tongning Li

The Emergent Multiverse: Quantum Theory According to the Everett Interpretation
David Wallace, Oxford University Press, 2012; $75.00 (hardcover).

David Wallace, a physicist and philosopher, has written a modern account of the Everett interpretation of quantum mechanics, and its logical consequences and extensions. Readers who are familiar with basic quantum mechanics, probability theory and decision theory would be well-suited to tackle the mathematical and logical arguments presented here. —Barry R. Masters

FREE Youth Education Materials!

The Optical Society (OSA) and the OSA Foundation offer a variety of optics and photonics education materials to inspire tomorrow’s young scientists. Many of these fantastic resources are available free of charge to teachers, students, parents and science education enthusiasts.

Resources include:
- Classroom demonstration kits
- Lesson plans and guidebooks
- DVDs
- Web sites
- Posters
- And more!

To request your materials, visit: www.osa.org/educationmaterials

Lisa Tongning Li is from Livermore, Calif., U.S.A. Barry R. Masters is a Fellow of AAAS, OSA and SPIE. He is with the department of biomedical engineering at the Massachusetts Institute of Technology in Cambridge, Mass., U.S.A. K. Alan Shore is from the Bangor University School of Electronic Engineering, Wales, United Kingdom.
Inrad Optics: New Name, New Mission

Amy Eskilson

Since 1973, the Inrad name has symbolized expertise in crystalline optics. With its name change, Inrad Optics will also communicate the company’s focus on metal and custom optics.

The company Photonic Products Group is reclaiming its past and redefining its future with a new name: Inrad Optics. Founded in 1973 as Inrad, the company was one of the seminal nonlinear crystal growth companies in the United States. The most recent name change is part of a rebranding strategy that leverages its positive reputation—historic and current—while clearly communicating its focus on both the photonics marketplace and the investment community.

What’s in a name?

Inrad Optics is a publically held, vertically integrated photonics manufacturer that supplies crystal-based optical components and devices, custom optical components from glass and metal, and precision optical and opto-mechanical assemblies. It also offers a set of capabilities and services that compliments those product areas. Customers come from a wide variety of fields, including defense, aerospace, laser, medical, process control and metrology.

Inrad was founded by Warren Ruderman, an early leader in novel materials development. The business was originally focused on crystal products, and later included the fabrication of optical glasses. In 2003, the company acquired Laser Optics and in 2004, MRC Precision Metal Optics.

This growth-by-acquisition strategy set the stage for a name change from Inrad to Photonic Products Group in 2003. In 2011, company leaders conducted a thorough review of its brand and concluded that the name “Photonics Products Group” had not achieved the level of brand recognition they had hoped for—in other words, no one could remember the name! Anecdotal experience was backed up by marketing science. It seems that when a company name is composed of common words used within a particular industry, it becomes very difficult to create a strong and memorable brand around that name.

Weathering the economic storm

Inrad Optics faces some of the same challenges that many small photonics companies do in today’s economy: Its core capabilities and resources must be maintained in order to offer a valuable product...
to our customers. Most of the company’s business is custom in nature, and in this economic environment not all of its capabilities are fully utilized at all times. The Inrad Optics team works to eliminate downtime and conserve funds by cross-training on the production floor and maximizing production planning wherever possible.

Over the last several years, the company has been working to diversify its business, and it continues to push into other markets, chiefly the medical and industrial laser markets.

Areas of expertise
Inrad Optics prides itself on its broad and deep optical materials expertise. Its production facility in Sarasota, Fla., has experience in unique materials like beryllium and AlBeMet (aluminum beryllium metal matrix), as well as in aluminum and stainless steel. They process electroless nickel and electrolytic gold plating.

The facility in Northvale, N.J., possesses a diverse materials expertise that runs from traditional glass materials to thin film coating expertise to nonlinear crystals and devices.

Inrad Optics has a long history of collaborating with universities and U.S. national labs.

Inrad Optics is one of only a few companies in the world that grow zinc germanium phosphide, a material well-suited across the IR spectrum as an optical parametric oscillator and harmonic generator.

Inrad Optics also specializes in multi-element optical assemblies and large optics, glass up to 24” in diameter, and metal up to one meter. In early March the company will commission their new 2.5-m Plasma Assist Deposition coating chamber, vertically integrating all steps of large optic fabrication and thin film coating processes. Our customers rely on us to help them through every manufacturing stage—from choosing materials to optimizing production.

Collaboration
Inrad Optics has a long history of collaborating with universities and U.S. national labs. One of its well-known collaborations is with Lawrence Livermore National Lab (LLNL), beginning in the mid-1990s. This effort resulted in a novel crystal growth technique called fast solution growth, and the company grew potassium dideuterium phosphate crystals on the order of 600 lbs. in 54 days.

Recently, Inrad Optics has partnered with LLNL on solution growth techniques for radiation detection crystals, specifically materials to identify fast neutrons. The company was awarded an SBIR Phase II grant from the U.S. Domestic Nuclear Detection Office of the Department of Homeland Security to further develop this material.

True to a name that is both new and old, Inrad Optics plans to draw on its traditional strengths and relationships to meet the challenges of the future.
Optics in Toruń, Poland

Known for its beautiful buildings and view of the Vistula river, the city of Toruń is also home to Nicolaus Copernicus University—where a proud legacy in physics and astronomy began more than 50 years ago.

Poland’s traditions in optics date back to the 1200s. Over the centuries, the country has produced some of the world’s finest scientific minds, including Nicolaus Copernicus, Johannes Hevelius, Albert Abraham Michelson and Marie Sklodowska-Curie.

But our story begins a bit more recently—shortly after World War II, in the city of Toruń, a fascinating microcosm for exploring optics in Poland. The war had exacted tremendous losses, especially among the well-educated. As it drew to a close in 1945, a group of almost 200 scientists of Polish origin were traveling through the country by train. They had come from the Stephen Batory University in Vilnius, Lithuania.

The scientists stopped in Toruń and were amazed that it had not suffered too badly—so they decided to set up a scientific unit there. Although the plan for Nicolaus Copernicus University (NCU) had been in place before the war, it wasn’t until afterwards that it actually took shape; astronomers and physicists from this group were among its founders.

**Humble beginnings**

The astronomers soon found there weren’t enough books or instruments available to conduct research. Thus, they continued the work they had brought from Vilnius and engaged in a publication exchange with nearby observatories. As they began to publish, word spread that a new observatory had been established; the scientists made an appeal for catalogues, books and instruments.

They didn’t have to wait long for a response. Among those keen to help was Harold Shapley from Harvard College Observatory in Cambridge, Mass., U.S.A., who sent a spare 8-in. Draper’s telescope, one of the first astrographs in the world. Built in 1891, it remains among the crown jewels of today’s Observatory. Alexander Wolszczan, discoverer of the first planets beyond the Solar System, worked on it alongside many others.

Meanwhile, Alexander Jablonski, who was deeply involved in the post-war restoration of Polish science, was asked to head the department of experimental physics. Jablonski was well known for proposing a diagram of the energy states of a molecule, which had been published by *Nature* in 1933; it became the basis for the world literature in physics and chemistry.

Danuta Bukowska
Organizing the department wasn’t easy. There wasn’t enough space or equipment initially, and there were too few scholars. But eventually Jablonski found modest accommodations where both teaching and scientific research could take place as well as people who would help him develop experimental and theoretical physics. It was thanks to Jablonski that research on different forms of luminescence; atomic, molecular and optical physics; and spectroscopy began in Toruń. For example, in the 1970s, Toruń’s physicists pioneered the construction of efficient dye lasers.

Toruń today
Many of the recent achievements made by optical scientists in Poland are the result of the hard work of Alexander Jablonski’s scientific “grandchildren” and “great-grandchildren.” Many of the optics achievements in Poland are the result of the hard work of Alexander Jablonski’s scientific “grandchildren” and “great-grandchildren.” For example, Andrzej Kowalczyk and Maciej Wojtkowski made the first demonstration in the world of retinal imaging with Fourier domain optical coherence tomography, a technology that was successfully commercialized in 2006.

In NCU’s department of atomic and molecular physics, researchers are working on using cell and tissue fluorescence to detect pre-cancerous and cancerous lesions. Sebastian Mackowski conducts research into how to use inorganic nanostructures, such as semiconductor nanocrystals and metal nanoparticles, to control the optical properties of photosynthetic systems.

Since 2001, the university has hosted the National Laboratory for Atomic Molecular and Optical Physics, known as the FAMO group. FAMO scientists use sophisticated instruments that are unique in Poland (and in some cases the world) to study trapped cold atoms and quantum engineering. The Center of Quantum Optics was established in 2011; it includes six labs dedicated to ultrafast and ultrahigh spectroscopy, optical imaging for medicine and quantum photonics, among other things.

Since Poland joined the European Union in 2004, NCU scientists have received enormous research grants and prestigious European awards. They have taken part in numerous conferences and published in the best scientific journals.

And they keep coming up with new ideas, which they study in well-equipped modern laboratories. They are helping Poland to be ready to stand up to new challenges and living up to the demands and expectations of the world of today.

Danuta Bukowska (danbu@fizyka.umk.pl) is a Ph.D. student at Nicolaus Copernicus University in Toruń, Poland. She belongs to the optical biomedical imaging group guided by M. Wojtkowski.

To Learn More ...
- NCU Institute of Physics: www.fizyka.umk.pl/wfaiis_en/
- NCU Optical Biomedical Imaging Group: http://obig.fizyka.umk.pl
- NCU OSA Student Chapter: http://osa.fizyka.umk.pl
- FAMO group: www.fizyka.umk.pl/famo_en/
- WELCOME program of the Foundation for Polish Science: http://welcome.fizyka.umk.pl

Witelo’s De Perspectiva
In the 13th century, Witelo—the first scholar born in what is today Poland—began exploring optics. While studying at the University of Paris, he familiarized himself with Latin, Arabic and Greek works on light but found them incomplete.

That encouraged him to study and understand light himself, giving rise to his masterpiece De Perspectiva—a 10-volume work devoted to optics. It sums up Greek and Arab knowledge and contains Witelo’s own observations.

For example, he explores the formation of shadows and rainbows. He was also the first to discuss spherical aberration, which occurs when light from the margin of a lens with a spherical surface comes to a shorter focus than light from the center. The significance of Witelo’s work is underscored by the fact that it was studied by da Vinci, Copernicus and Kepler.

[Above] Page from Witelo’s De Perspectiva, with a miniature showing the author.
A Curriculum Vitae Makeover

Whether on paper or in electronic format, the résumé or curriculum vitae plays a crucial role in job applications. This analysis of a draft CV offers some dos and don’ts toward effective communication.

BEFORE: Great Experience, Long Read

Experience is organized in competencies—an approach that makes sense for someone who did more than just research. It focuses first on the institution, then on the job done (the reverse is justifiable, too), hence it could usefully group the two mentions of RPI.

The title "CURRICULUM VITAE" is unnecessary: this is visibly a CV.

Space is essential in page layout, but the white space here serves no purpose. Listed degrees and dates are needlessly far apart. For well-known universities, the location is unneeded.

The career objective is vague (basically, "use the skills I have"), hence not useful. It is best left for the job-specific cover letter.

Lists of one item make little sense; they are best rephrased as short sentences, using the action verbs already there.

The full name may confuse people outside the United States who are not used to middle names.

Lists of one item make little sense; they are best rephrased as short sentences, using the action verbs already there.

"Usefully group the two mentions of RPI."
Despite being set in small caps bold, headings do not stand out.

In general, the dates on the right are a little lost in the paragraphs. They would be more visible (and easier to scan) in the left margin. Indicating the month does not add much (and it is done inconsistently). A period such as Jun 2009 – Aug 2009 can be shortened to Summer 2009, which is more intuitive for a summer job.

Although it is visually meaningful to be able to fit each item of a list onto a single line, the lines are too long to read quickly. A wide left margin would shorten them and accommodate the dates.

Phrases such as “Orange County schools” or “Annually visit DC” are U.S.-centric.
**CONVERSATIONS**

**Network Transformer**

**Brian Protiva** sees change on the horizon for optical networking technologies.

Brian Protiva, CEO and co-founder of ADVA Optical Networking, has led the German-based company to become a global leader in Ethernet access devices and metro wavelength division multiplexing (WDM). Protiva will be a plenary speaker at OFC/NFOEC 2013, 17-21 March, in Anaheim, Calif., U.S.A.

**Q. How do you maintain ADVA’s market share?**

ADVA has grown on average more than 18 percent per year for the past decade by expanding geographically and addressing new market segments. We took a metro-based product and amplified it to address regional and long-haul optical networks. Technical differentiation helps us to maintain market share. Our approach has enabled us to build a single network element that can support 100G long-haul networks and address enterprise-managed services and scaled metro optical infrastructures.

**Q. How is ADVA capitalizing on cloud services?**

Connectivity is a big issue when businesses move critical applications to a cloud platform. Our carrier Ethernet technology enables our cloud service providers to connect customers with high-bandwidth access solutions and offer service-level agreements for connectivity, higher-layer performance and synchronization. We also offer service providers the ability to expand their optical cloud efficiently with state-of-the-art 100G optical platforms as well as inter-datacenter connectivity solutions.

**Q. What’s the most exciting emerging technology in your field?**

Software defined networking (SDN) is one of the most exciting developments in years. SDN will enable competitors in all layers of the network to drive a higher degree of software differentiation and resulting revenues. This will allow carriers to optimize and monetize their network infrastructures in new ways. However, only the most nimble network equipment providers will see dramatic changes.

**Q. What’s the take-away from your OFC/NFOEC presentation?**

It will highlight the impact of new technologies, the enormous scale of change and the significant opportunities available. Our industry has forged a path to business models that support software-centric selling and opportunities to add value to our customers. Yet, if we don’t support consolidation and focused spending, great ideas and good intentions will not be enough to transform networks. 

Brielle Day (bday@osa.org) is OSA’s public relations specialist.
Induced scintillation from a phosphorescent sheet irradiated with an X-ray photon beam at ± 30 degrees from the vertical.

—Adam K. Glaser, Dartmouth College, U.S.A.

Color effects around a scratch in an optical coating.

—Matthias Feinaeugle, Optoelectronics Research Centre, United Kingdom
EDITOR-IN-CHIEF: Andrew M. Weiner, Purdue University

OSA’s premier open-access journal, **Optics Express** (OpEx) publishes peer-reviewed, open-access, interactive online articles that emphasize scientific and technology innovations in all aspects of optics and photonics.

OpEx is one of the highest impact journals in optics with a 3.587 impact factor and over 54,000 citations in 2011. Manuscripts are published fast – less than 68 days after submission.

SUPPLEMENT EDITOR: Christian Seassal, CNRS, University of Lyon

**Energy Express**, a bi-monthly supplement to **Optics Express**, is dedicated to rapid developments in the science and engineering of light and its impact on sustainable energy development, the environment, and green technologies.

EDITOR-IN-CHIEF: Joseph A. Izatt, Duke University

**Biomedical Optics Express** (BOEx) serves the biomedical optics community with rapid, open-access, peer-reviewed papers related to optics, photonics and imaging in the life sciences. The journal scope encompasses theoretical modeling and simulations, technology development, and biomedical studies and clinical applications.

The journal received recently its first impact factor of 2.33, ranking it #11 among all optics journals. It is indexed by Google Scholar, PubMed, PubMed Central and Thomson Reuters’ Web of Science, among others.

EDITOR-IN-CHIEF: David J. Hagan, CREOL, University of Central Florida

OSA’s newest open-access journal, **Optical Materials Express** (OMEx) focuses on advances in novel optical materials, their properties, modeling, synthesis and fabrication techniques; how such materials contribute to novel optical behavior; and how they enable new or improved optical devices.

Indexed by Google Scholar and Thomson Reuters’ Web of Science, among others. And OMEx content has already been highlighted in Nature, Scientific American, New Scientist and other press outlets.

Submission instructions and content freely available on OSA’s Digital Library, Optics InfoBase – www.opticsinfobase.org
Sensing Trouble
Fiber-Optics in Civil

Lynn Savage
A wave of new fiber-optic sensing techniques takes advantage of the sensitivity of telecom-grade fiber optics to stress, strain, temperature and other factors in order to ensure the long-term safety of civil structures.
Unless you’re sitting in a building that is not to alarm you, but the building you’re sitting in may not be safe. The same holds true for the bridge you drove over getting to work and the dam just outside of town. These structures and others are continuously subjected to both common and uncommon stresses and strains that produce flaws. Everything from the weight of people, furniture and machinery to the forces exerted by fires, floods and earthquakes have an effect. Simple cracks and fissures may appear at first due to heavy loads; over time, these will lead to failure.

Manual inspections are par for the course when engineers are trying to determine the safety of buildings and other edifices. However, they are time-consuming and labor-intensive. Moreover, most city, town and state governments are not able to pay for enough inspectors to perform the work on a regular basis. Even if they were, inspections would cover only the easy-to-see exteriors. Most wear and tear, however, starts between walls, or even inside them.

Fortunately, fiber-optic technology provides another alternative. Since standard telecom-grade fiber optics are sensitive to stress, strain, temperature and other deleterious factors, they can be used to monitor buildings, bridges and dams in real-time. The field is known broadly as civil structural health monitoring or simply structural health monitoring (SHM).

Fiber-optic sensor systems react to changes in their environment through minute alterations of their refractive indices as light travels through them. Often, this is achieved by adding fiber Bragg gratings at discrete points along the length of the system. Passing light through depending on the design of the fiber and the method of reading the output spectra, an engineer can determine the total forces acting on a structure and thus judge whether it is in need of repair.

Depending on the design of the fiber and the method of reading the output spectra, an engineer can determine the total forces acting on a structure and thus judge whether it is in need of repair.

Feeling Scattered
The optical effects most often analyzed in fiber sensors are:

- **Rayleigh scattering:** Light is elastically scattered in all directions by subwavelength variations in the fiber’s index of refraction. This scattering can be affected by local strain and temperature changes. Strain and temperature can correlate with the intensity of the backscattered light.

- **Brillouin scattering:** Light is scattered due to the interaction between photons and thermal sound waves, causing frequency shifts. The spectral details of the backscattered Brillouin frequency are sensitive to local variations of silica density due to strain, temperature and vibrations.

- **Brillouin optical time-domain analysis:** Acoustic waves are generated by injecting two counter-propagating light waves with a frequency difference equal to the Brillouin shift. If one of the beams is a short light pulse and its position is determined by time of flight, local variations of strain can be measured along the fiber.

- **Raman scattering:** In this inelastic process, light is scattered by thermally activated molecular vibrations. The intensity of the blue-shifted anti-Stokes backscattered wave provides a temperature measure.
a fiber that is attached to a wall, floor or other surface reveals nothing until the surface changes.

However, when a wall shifts—through simple settling or perhaps via a mild temblor—its shape is minutely displaced, resulting in a similarly tiny variation in the light path provided by the fiber. The way in which these changes are measured depends on the anticipated effect, such as stress or temperature. The three optical effects most often analyzed in fiber sensors are Rayleigh, Raman and Brillouin scattering.

Depending on the design of the fiber and the method of reading the output spectra, an engineer can determine the total forces acting on a structure and thus judge whether it is in need of repair.

When the input light is provided by a pulsed laser, the location of the spot on the fiber that experienced the change can be determined with relatively good spatial resolution—usually depending on the distance between the stress point and the scanner reading the output.

**System options**

Bridges, buildings and anything else made of concrete and steel are constantly subjected to static and dynamic loads. Even a stiff breeze against an empty office building sets off a sequence of stresses, strains and temperature changes within the floors, walls and foundation. Over time, these forces take their toll, cracking and shearing the materials.

Selecting the correct fiber-optic sensor to monitor these forces is important for maintenance, as well as for giving civil engineers insight into how to adjust future designs.

“There are several technologies that allow monitoring of these parameters,” said Branko Glisic, a professor of civil and environmental engineering at Princeton University, “and selection of (the) right technology depends on several factors.”

Other technologies, including piezoelectric sensors, are used in some structures as stress gauges. Telecom-grade optical fiber, however, was found to be more durable than electromechanical devices, less sensitive to humidity and corrosion and, perhaps most important, completely impervious to electromagnetic interference.

Fiber optics are also preferred for monitoring structures—including pipelines—in the oil and gas industry, Glisic said, because they are electrically passive and therefore won’t ignite stray gasses.

Discrete point sensors are used to monitor small pockets of localized material, whereas discrete long-gauge sensors assess more global structures, especially where the construction material is not homogeneous, such as with concrete. Distributed sensors, which are sensitive at every point along their length, are largely used for assessing the integrity of large structures, including long bridges, pipelines and dams, especially where integrity loss is equally likely to happen at any cross-section of the structure, Glisic said. One distributed sensor can replace a multitude of point sensors, but the latter have their advantages as well.

“Fiber optics is the only technology that provides true long-gauge and distributed sensors,” he noted.

The most popular discrete sensors are based on fiber Bragg gratings because they offer in-line multiplexing and the ability to measure both static and dynamic forces. Interferometric sensors intrinsic to the fiber may be used in certain circumstances, such as when a large number of sensors is necessary, when very long gauge lengths are needed, and when extreme precision is required. Extrinsic interferometric sensors are mostly used when a limited number of sensors are needed and measurements are performed manually. They are also used when miniature sensors are necessary.

The method used to scan the spectral signal is significant as well. Distributed sensors based on Brillouin scattering (especially Brillouin optical time-domain analysis, or
BOTDA) are most often used to measure strain and temperature together, whereas Raman-based sensors are limited to temperature monitoring, which is performed to detect leaks in dams and pipelines, for example. Rayleigh measurements are used when very fast distributed sensing is required; however, this method suffers from a lack of available sensors, Glisic noted.

The right fiber-optic sensor system can be used to measure pressure, acceleration, tilt, displacement and pore pressure in soil and corrosion.

A bridge, strained

Glisic has a civil engineering background, but he has been working in the world of fiber optics since 1996. Prior to teaching, he spent seven years at Smartec SA in Switzerland, a company devoted to developing commercial possibilities for early fiber-optic sensors. When he moved to Princeton four years ago, though, a new application for fiber sensors was beginning to take shape.

The Streicker Bridge, which now provides a pedestrian walkway between two areas of the Princeton campus, was about to be built. Glisic and other members of the university’s SHM team took advantage by installing a pair of novel fiber-optic sensor systems into the concrete of the pedestrian bridge as it was poured.

The Streicker Bridge, which now provides a pedestrian walkway between two areas of the Princeton campus, was about to be built. Glisic and other members of the university’s SHM team took advantage by installing a pair of novel fiber-optic sensor systems into the concrete of the pedestrian bridge as it was poured.

Built in the campus’s “natural sciences neighborhood,” the bridge connects two sections of buildings divided by a road. It is uniquely shaped, stretching like a pudgy stick figure performing yoga across a distance of 300 ft. The bridge gets its unusual shape via a main span and four limb-like approaching segments composed of curved girders supported by steel columns.

The deck is just under 23-in. thick and has an arch constructed of tubing with a diameter of only 12.75 in. The SHM team has been using the pedestrian bridge for a variety of experiments ever since construction began on it in October 2009.

“Most of my sensors look for strain,” Glisic said. “Strain relates to stress; when you get to a certain amount of stress, you have a (structural) failure.” In these applications, strain is the distance a material deforms as compared to its original length, and the resulting dimensionless figure is rated in epsilons (ε).

Using the fiber-optic strain gauges, Glisic said, engineers can look for failure cracks as well as overall strain. In the Streicker Bridge, gauges are set to detect temperature as well as strain.

One of the installed systems is a discrete, long-gauge device, which collects strain (or temperature)
data at individual points within the poured concrete. The other system is a distributed sensor in which data can be collected from any point along the fiber’s length. The long-gauge system gets readouts using fiber Bragg spectrometry techniques, while the distributed sensor uses BOTDA.

In one experiment, Glisic and his colleagues attached a few pairs of discrete sensors close to the axis of symmetry in several cross-sections of the southeast leg of the bridge. The sensors monitor the normal and bending forces placed on the structure, focusing on the most heavily loaded parts, the sections above each column and the middle of each span between columns.

In addition, the group has installed distributed sensors between the main columns of the southeast leg, which are used to monitor strain (and temperature) along the entire span, not just the spots with the heaviest loads.

On a somewhat different scale, Farhad Ansari and his associates at the University of Illinois at Chicago have installed fiber-optic sensors on the brick masonry vaults of the iconic Brooklyn Bridge in New York City. These vaults, which support the bridge structure on the Manhattan side of the East River, have supported huge loads since the bridge was completed 130 years ago, but they are now riddled with longitudinal cracks along their crowns. Ansari’s group needed to set up a monitoring system and assess whether there is safety issue related to these cracks.

The group used a series of fiber-Bragg-grating-based sensors to measure crack formation, displacement, temperature and other forces. The crack sensors, in particular, were placed along the longitudinal cracks along the vaults’ crowns, but also along cracks in the vaults’ three-story-tall walls. In addition, the researchers installed fiber-optic accelerometers on each side of the longitudinal cracks. The sensors were designed by the group to measure an opening from 0.02 to 10 mm with 0.5 nm/mm sensitivity.

Over time, the sensors measured negligible ongoing perturbations in the structure of the vaults, finding maximum displacements of 36 μm per week. The sensor data also enabled the group to assess that the vault cracking does not yet warrant further maintenance or repair, but that continual monitoring would likely tell when the vaults were approaching their safety limits.

**Fighting corrosion**

At the University of Malaya, the focus is not on cracks but rather decay—specifically, corrosion that takes place on metal structures and substructures, such as the metal rebar used in reinforced concrete. Faisal Rafiq Mahamd Adikan, who formed the Photonics Research Group at the university’s faculty of engineering, leads the charge there.

“We saw a growing acceptance of photonics-based sensors in structural health monitoring...
in general,” Adikan said. But not in Malaysia—which is odd because the country is perpetually hot and humid, especially along the coasts. If the corrosion of rebar and similar structures goes undetected for too long, the metal weakens and ultimately fails.

Detecting corrosion
Setup used by researchers in Malaysia to study corrosion in the rebar used to reinforce concrete. The fiber is etched to allow a portion of guided light to sample the environment.

Adikan and his team attached fibers etched with fiber Bragg gratings directly to rebar samples and placed them into a corrosive liquid. The caustic environment alters the refractive index of the region within the immediate vicinity of the gratings, thus altering their effective refractive index. This held true even when the corrosive material couldn’t reach the rebar because of the placement of the fiber. Adikan’s group believes that the resulting change in the spectral signal is due to both localized and non-localized effects.

“The non-localized (effect) is mainly in the form of stress,” he said. “The localized one is probably due to refractive index changes following oxidation.”

He added that the underlying cause of corrosion is of no consequence to the spectral changes that occur, although there are as-yet-unexplained “jumps” in the spectral behavior.

Ultimately, working on rebar will provide a proof of concept that will provide insight into how to address the persistent problem of corrosion experienced in any sea-wrapped locale. The group also has installed a fiber Bragg grating sensor into a bridge south of the capital, the first such installation in Malaysia.

“The vision is to have these sensors installed in offshore oil platforms, ports, vessels, underground water pipes (and) chemical process reaction chambers,” Adikan said.

Hybrid systems
Distributed and point-sensing techniques provide strain and temperature readouts separately, but as the SHM model takes hold, building designers will want to keep watch on every parameter possible. The various techniques needed to acquire every desirable data point would seem to preclude using just one fiber system in any given installation, but one group of researchers in Italy has other ideas.

Fabrizio Di Pasquale of Scuola Superiore Sant’Anna in Pisa and his colleagues are exploring systems that would provide both distributed and discrete readouts simultaneously. The group is working with FiberSens S.r.l., a spin-off company of the applied sciences university, developing and marketing fiber-optic sensor systems.

Simultaneous measurement of distributed temperature and discrete dynamic strain fields would be useful for several applications, including industrial plant monitoring, micro-leakage detection in oil and gas wells, and fire detection in long rail and road tunnels. For that reason, Di Pasquale’s team decided to develop hybrid sensor systems.

In the 1 Nov. 2012 issue of Optics Letters, the investigators describe a system that uses a single pulsed laser to generate both Raman
and fiber Bragg grating signals. The laser generates a telecom-standard wavelength of 1,550.5 nm, drives it through an attenuator, and generates pump pulses of 33 dBm peak power at a width of 10 ns. The hybrid device is a bit less sensitive than stand-alone systems, but it produced a temperature resolution of 2° C at nearly 11 km away in lab tests and a dynamic strain resolution of approximately 60 nε/Hz½.

The light source used to drive any fiber-optic sensor is an important consideration. Systems based on fiber Bragg gratings are the simplest; they run satisfactorily either with broadband incoherent light sources or with narrow-band pulsed lasers, depending on the multiplexing technique. Raman-based systems, however, may demand high peak power broadband pulsed lasers.

Di Pasquale’s hybrid system requires even more. “The light sources to be used in hybrid sensor systems for simultaneous distributed temperature and discrete dynamic strain measurements have rather demanding specific requirements,” he said. “In particular, (both) high peak power levels and narrow band laser sources are needed.”

**Stress-ful challenges**

The market for fiber-optic sensors for SHM is small at present, Princeton’s Glisic said, so fiber makers aren’t in a hurry to tailor their products to the field. Sensors and related equipment, such as Brillouin scanners, are less expensive now than they were 10 years ago, which is helping to advance research—and this trend is expected to continue in the next decade or two.

Current fiber-optic sensor technology is based on a complex set of discrete optical and electronic components, including pulsed lasers, photodetectors, modulators, switches, optical filters, electrical current and voltage amplifiers, and more, Di Pasquale said. He contends that these features, especially the requirement of discrete optoelectronic components, make current fiber-optic sensor systems bulky and costly, limiting their use to low-volume niche applications.

“We believe that a key point to increase the market volume of fiber-optic sensors is integration,” he said. “Emerging technologies like silicon- and InP-based photonics will allow the integration of most sensor reading unit functions at (the) chip level, strongly decreasing the fabrication cost and opening the way to mass-scale applications, such as smart structures embedding fiber Bragg gratings, as well as distributed fire-detection systems.”

The field could progress faster, Glisic added, but for the natural “conservatism of civil engineering.”

“I think that the conservatism is related to structural health monitoring in general rather then to the SHM with fiber optic systems,” he said. “Thus, I think that bridging (the) educational gap between researchers and practitioners is one of the important factors.”

He added that two equally important issues are the development of better SHM methods, including the sensors themselves, the sensor network architecture and the algorithms used to analyze data, as well as sound proofs of cost-effectiveness.

“The overall aim of the Streicker Bridge project is to address all three factors,” he said.

Yet more novel applications are coming. Some groups are looking at using fiber optics to detect acoustic signals within structures. It would also be useful to monitor pH, chloride concentration and sulfate penetration in concrete, Glisic added. In addition, there is interest in making fiber-optic systems wireless at the sensor level, in creating Bragg gratings that are less temperature dependent, and in developing reading units that are less energy-dependent.

“Some people want to study strain; others, displacement or vibrations,” Glisic said. “For some of these techniques, fiber optics are more expensive; however, their longevity makes them worthwhile.”

Lynn Savage (lynn@savage-editorial.com) is a freelance writer who specializes in science and technology. He is the owner of Savage Editorial Services, Northampton, Mass., U.S.A.
GET READY: the quantum Internet is a next-generation disruptive technology that is now closer to fact than fiction. Researchers predict that practical quantum communications may be here within 10 to 15 years.

It’s conceivable yet fanciful: a quantum Internet. It would be exponentially faster and more secure than current technology. Hackers and identity thieves would have no way of uncovering national secrets or personal information. Complex calculations and searches could be done with imperceptible lag time.

The foundation for these possibilities lies in the fundamental unit of information in quantum computing systems—a photonic quantum bit (qubit). As opposed to a binary digit (bit) in existing computing systems, which is visible in programming code as either a “1” or a “0,” the qubit could be either a “1” or a “0” until it’s received and measured, but we don’t know which. It’s this property of “superposition” that ensures that a message is not read by anyone other than the recipient.

Another reason why quantum mechanics is brilliant for computing is that a single photon encoded with polarization or phase information can be “entangled” with another photon encoded the same way. Even after separating the two photons by a long distance, detecting the state of one tells us the state of the other. This “spooky action at a distance,” as Einstein called it, is an important key to secure quantum communications. The encryption
The encryption of sensitive data is particularly valuable to the banking sector, hospitals, and in urban communications, giving quantum technology strong commercial potential.
Stretching the path

To become practical reality, quantum communications must work over long distances. Quantum experiments typically use single-photon sources to generate the signal. The problem is that single photons are very small and dim points, so they can only be transmitted so far down a fiber or across free space optical links before they become undetectable. The photons tend to decohere and get lost in the noise. Researchers must progressively extend the transmission distance to prove that quantum communications is viable.

Distributing entangled photon pairs enables secure communication between two remote parties and could offer the possibility of interconnecting quantum computers. The vast transparency band of the installed global fiber-optic network, consisting of over a gigameter of optical fiber cables, presents a particularly attractive opportunity for this next-generation technology. The bond between entangled photons is, however, very fragile and can be easily lost. In a series of recent papers Misha Brodsky (then of AT&T Labs) and coworkers addressed the following question—how far apart could one send entangled photons while still maintaining the connection between them? They formulated a comprehensive approach for studying polarization-mode-dispersion (PMD) induced disentanglement and described, theoretically and experimentally, some of its most important and intriguing features, including the phenomenon of “entanglement sudden death” and a scheme for nonlocal PMD compensation. The new insights into the richness of the observed phenomena allow future quantum network designers to determine the reach of their entanglement-based cryptographic systems.

In September, researchers led by a team from the Austrian Academy of Sciences announced a successful high-fidelity test of independent qubits over two free-space optical links, quantum and classical, spaced 143 km apart between the two Canary Islands of La Palma and Tenerife—a record distance. The technique used a frequency-uncorrelated polarization-entangled photon pair source, ultra-low-noise single-photon detectors, and entanglement-assisted clock synchronization. Free-space optical links have particular promise for quantum communications via satellite; qubits do well in the atmosphere and even better in outer space.

Co-author Rupert Ursin, deputy director of the Institute for Quantum Optics and Quantum Information at the Austrian Academy of Sciences, says that the biggest barriers to practical quantum teleportation are the source and the detector. “The sources suitable for quantum
teleportation are not as advanced as those for quantum cryptography experiments,” says Ursin. “Because coherence time is an issue in teleportation, the challenge is to build a source bright enough for the high loss and to archive a sufficient signal-to-noise ratio (SNR) in the end.” Nevertheless, he believes it’s very likely that quantum computing and quantum networks will come to fruition within the next decade. “All the scientific principles are sown; the technology is down to which disciplines are best for scaling up to a real computer.”

A new quantum-entangled photon-pair light source from telecom manufacturer OKI of Tokyo claims the highest level of purity achieved to date with an SNR more than 100-fold better than optical fiber light sources. Quantum-entangled photon-pairs were successfully transmitted over a distance of 140 km using this light source with standard optical fiber, demonstrating the feasibility of next-generation quantum-cryptography communication systems over a metropolitan area.

The source, based on cascaded nonlinear optical effects using a proprietary periodically poled lithium niobate (PPLN) ridge-waveguide, also addresses cooling issues by operating at room temperature at the common optical communications wavelength of 1.5 μm. Tests using a semiconductor-based single-photon detector demonstrated that the signal-to-noise ratio for the photon pairs generated is one to two orders of magnitude greater than for conventional light source and detector combinations.

Hybrid systems
Free-space communications from Earth to satellite is one way to transmit shorter-wavelength optical photons over a long distance. Another is to send qubits via fiber-optics, which would be convenient since we have an existing infrastructure that forms our current optical network. But creating a hybrid system and devices that enable information exchange between two dissimilar systems is a major challenge.

To do this requires a conversion technique to change the wavelength of the photons of the quantum system to a telecom-band wavelength—while maintaining the entanglement information. Optical signals must travel from station to station through the network and sometimes be regenerated or amplified as they degrade. For quantum signals, special quantum regenerators or repeaters are necessary, much like an optical amplifier regenerates classical optical communication signals to prevent them from degrading over a distance. A quantum repeater is essentially this type of tool; generally it contains two lines of memory, one to receive an entangled message and a second line to copy it.

Storage
A major obstacle to quantum repeaters (and quantum communications in general) is storage and memory: catching an entangled photon and holding it without destroying its fragile quantum state. If you can’t queue up a message long enough for retransmission through a station, the whole way that information is processed through fiber goes out the window. The storage of photonic polarization qubits is difficult, however, because many materials are birefringent and have polarization-dependent absorption.

Of course, longer storage times are needed for long-range quantum networks over 100 km, simply due to the propagation time required over such distances. Applied physicists at the University of Geneva in Switzerland have made progress with these challenges in experiments with storing light in a biaxial yttrium orthosilicate (Y$_2$SiO$_5$) crystal doped with rare-earth ions. Storage times have moved from 100 ns to the millisecond regime in a short period, says co-author Mikael Afzelius, senior researcher at the University of Geneva.

The new material, called Eu$^{3+}$:Y$_2$SiO$_5$, allows for a longer coherence period and
therefore extended storage times. But scattering and fluorescence can mask the output signal at the single photon level. Once filtering techniques solve the noise problem, storage experiments of quantum states will be possible. The team has also demonstrated a method for storing qubits encoded with various degrees of polarization. Crystals are a good choice because they are solid-state materials that would be scalable to high-volume manufacturing, says Afzelius.

“Our long-term ambition is to demonstrate entanglement between two crystals,” says Afzelius, “but over a much longer spatial separation and for much longer times.” Then researchers will be close to a device that could be the technology basis of future quantum networks, he says.

In a 2010 *Nature Physics* paper, professor of physics Alex Kuzmich at the Georgia Institute of Technology and colleagues demonstrated a memory lifetime in excess of 0.1 s. “A memory lifetime on the order of several seconds is expected to be sufficient for quantum networks at intercontinental distances,” says Kuzmich, adding that the exact value required will depend on factors such as efficiencies of detectors, losses, and so on. “We have also demonstrated high (>65 percent) efficiency and low-noise wavelength conversion between near-infrared (795 nm) and telecom (1,367 nm) photons,” he says. “This allowed us to create and observe entanglement of quantum memories with telecom photons.”

Kuzmich and colleagues then built on this development to develop a quantum memory element confined in an optical lattice cooled by cold rubidium. When combined with quantum repeater protocols, the longer memory enables a 30-fold increase in transmission distance. A series of such devices could enable a quantum network.
An experimental measurement of photoemission from a quantum dot placed in a magnetic field, excited above-band, and detected with a rotatable polarizer is subject to polarization-selection rules. The polarization of an emitted photon, whether horizontal, \( H \), or vertical, \( V \), results in only a few allowed transitions between the states.

**Signal**

A signal to reach more than 1,000 km. The task was accomplished via wavelength downconversion from 795 nm to 1,367 nm, a traditional wavelength for fiber-optic-based telecom. This critical ability will be ideal for encryption key applications over larger distances.

**Dots and holes**

One approach to long-distance quantum transmission is to make a detector sensitive enough to measure the photon without washing it out. Toward that end, researchers led by a team at Stanford University have demonstrated coherent control of a single quantum-dot-hole qubit, a promising type of candidate source. Coauthor and Stanford researcher Kristiaan De Greve and colleagues used picosecond optical pulses to demonstrate coherent control of the spin phase of an arbitrary single-hole superposition in a hole-based qubit. One result is that the undesirable hyperfine interaction is suppressed, which eliminates strong nuclear effects. Controlling the dynamics of the qubit and suppressing the noise makes the photons easier to detect.

Another approach is to develop an interface between the quantum dot and a long-haul fiber-based telecom system at 1,550 nm. An international team led by scientists at Stanford implemented a downconversion quantum interface that converts single photons from 910 nm to 1,560 nm using a fiber-coupled PPLN waveguide and a 2.2-\( \mu \)m pulsed pump laser. The matter qubits are single electrons generated in an InAs/GaAs quantum dot, one of the brightest and fastest types of single-photon sources. “This approach is interesting,” says coauthor and HP Labs researcher Jason Pelc, “because such quantum dots can also be controlled at very high speed relative to other qubit candidates such as nitrogen-vacancy centers, ions and superconducting systems.”

**Quantum networks**

Researchers have worked hard to generate and manipulate quantum entanglement. Bringing it all together into a network is one of the last, biggest hurdles. Physicists in Germany announced in April the setup of the first elementary quantum network using single atoms in optical cavities. Scientist Stephan Ritter of the Max-Planck-Institut für Quantenoptik in Garching, Germany, and colleagues showed that an efficient atom-cavity–based approach enables nodes that can send, receive, store and release qubits between separate labs.

Communication between nodes is done via fundamental coherent exchange of a single photon. The team found they could generate entanglement remotely between the two nodes and store it for approximately 100 ms. This cavity-based approach to quantum networking is promising due to its scalability toward large-scale quantum networks and their applications.

Other quantum-information scientists question whether it’s possible to eliminate the need for memory altogether in the scheme of the quantum Internet. Quantum physics allows for new ways to create, manipulate and store...
information, according to a team from Japan and the United Kingdom. The time it takes to form and send a classical signal between entangled links at remote locations is what necessitates long-lived quantum memories.

So W.J. Munro at NTT Basic Research Laboratories in Kanagawa, Japan, and his collaborators proposed a design in which qubits are transmitted directly across the network without entanglement, eliminating the process of teleportation, which is, ironically, time-consuming. The approach also removes the need for quantum repeaters at intermediate locations. The qubits at remote nodes don’t have to wait for a classical signal to confirm whether they are entangled or not, saving hundreds of microseconds across tens of kilometers. The scheme has the potential to provide faster communication rates than previously thought possible.

The idea that quantum networking may not depend on entanglement is also the focus of two recent experiments at Oxford University in England. Scientists had previously pondered the role of quantum discord as an alternative resource to entanglement, says physics researcher Animesh Datta. The studies used discord to demonstrate quantum-enhanced information processing.

What is quantum discord? As every student of quantum mechanics knows, one of the unique features of a quantum system is that you cannot observe it without disturbing it. “Quantum discord is the quantity that captures this mathematically,” says Datta. “For certain quantum systems, called pure states, it is equivalent to entanglement.” Otherwise, discord is a more fundamental form of quantum correlation that may not be captured by entanglement, he says. “But it’s easier to generate and manipulate. And now we have experimental proof.”

The use of a new measure of what it means for a system to be quantum has profound technological and philosophical ramifications for the field of quantum information processing.

The primary application of quantum discord will be in quantum networks and computation. Like other quantum information scientists, Datta thinks it’s only a matter of time before real-world quantum computing and networks come to fruition. “Over the next 10 years we may expect to have an operational quantum network outside the lab.” He believes it will happen via a combined use of discord and entanglement.

But how long it takes before we have a practical, working quantum-based network depends, to a large extent, on the intellectual and financial investments we make, Datta says. He describes the work that’s been done so far as akin to “having laid the quantum equivalent of the first telegraph lines.” Fortunately, getting to the first quantum networks with many nodes should be faster since scientists now have a better understanding of the underlying physics and engineering. In other words, we’re poised to make a quantum leap in progress.

Valerie C. Coffey [stellareditor@gmail.com] is a freelance science and technology writer and editor based in Boxborough, Mass., U.S.A.

References and Resources

Jeff Hecht

Saving Hubble

Shortly after the launch of the Hubble, NASA scientists couldn’t bring its images into focus—and a bright hope became a grim fiasco. But behind the scenes, optical engineers were devising an ingenious fix that would transform Hubble into the world’s most successful telescope.
Hubble against Earth’s horizon.

NASA
When the Hubble Space Telescope launched from the shuttle Discovery in April 1990, it carried with it the hopes and dreams of astronomers everywhere. The state-of-the-art NASA instrument was expected to show scientists their clearest view ever of the cosmos.

It was the culmination of a 25-year effort that had begun with a 1965 proposal from a panel headed by astronomer Lyman Spitzer Jr. After many iterations, the plan to build a large space telescope was approved by the U.S. Congress in 1977, with a launch scheduled for 1983. However, that date was delayed for seven years due to shifting government priorities and the 1986 Challenger explosion.

So when Hubble’s time finally came, expectations were high among both scientists and the public.

The bad news started rolling in right away ...

In public disgrace
Radiation from the Van Allen belts knocked out the guidance system’s electronic memory for up to 10 minutes of every 98-min. orbit. The solar arrays shook as they warmed in sunlight and cooled in the dark, making pointing difficult. Worst of all, fine-tuning the optics did not bring starlight to the sharp focus expected in the vacuum of space. An analysis of the light surrounding the star images revealed that the telescope optics had suffered from a root-mean-square (RMS) spherical aberration of 275 nm. Disheartened officials announced the problem on 21 June.

Yet Hubble’s design gave NASA hope for recovery. The telescope’s instruments were packaged in modules designed for in-space replacement—although nobody had expected the optics would need to be fixed.

NASA named a panel of experts led by Lew Allen, director of the Jet Propulsion Laboratory (JPL), to find the cause of the optical systems’ failure and determine why it had not been spotted before launch. Duncan Moore, the director of the Institute of Optics at the University of Rochester, headed the Hubble Independent Optical Review Panel; he was charged with diagnosing the optical problem and designing repairs.

Comparing images from the Wide Field Planetary Camera and the Faint Object Camera confirmed that the problem was spherical aberration in the Ritchey-Chrétien telescope at the heart of Hubble. This resulted in images no better than those produced by a high-elevation ground telescope. Its Strehl ratio was only 0.15, far from the optically perfect 1.0.

What was the source of the aberration?
Only limited tests were possible in space, but test equipment and records were available, mostly at the Danbury, Conn., plant where the Perkin-Elmer Corp. had fabricated the primary mirror and polished it to its final shape. Among the hardware was a back-up primary mirror, made and finished to its final shape by Eastman Kodak, but not polished. Tests of the back-up showed that it met optical specifications, so the error had not been in design; thus, it must have been in fabrication and testing.

Meanwhile, Moore’s group found spherical aberration both on and off axis in Hubble images, showing the figure of the primary was in error. However, they did not see the coma expected from serious errors on the secondary. That left NASA in the embarrassing position of having launched a flawed primary when a perfect back-up was available. Swapping mirrors was not feasible in space.

Forensic optics
Investigators pored through NASA and Perkin-Elmer documents on design, fabrication and testing of the primary. Perkin-Elmer tests found that the primary mirror was within tolerance after it was polished and coated in 1981. Records also revealed that the complete optical system had never been tested end-to-end after assembly.

The rationale was that realistic simulation of the space environment is very difficult and expensive. For Hubble, it would have required $100 million to construct a huge special-purpose vacuum chamber. With the telescope already over budget, such testing had seemed a luxury when measurements had shown the component optics to be perfect. That decision looked much worse in hindsight.

The Moore panel sent expert optical trouble-shooters to the Danbury plant. Perkin-Elmer had sold the division to Hughes Aircraft in 1989, but test equipment
and records had been untouched since the optics were shipped in 1984 to Lockheed Missiles and Space in California for assembly of the Hubble spacecraft.

“The place looked like a crime scene,” recalled Mark Kahan of Optical Research Associates (ORA, now Synopsys). Federal marshals had secured all Hubble-related files and gathered the paper files in a cafeteria. “It was a scary process,” said Kahan, whose job was to sort through the records to deduce what had happened, why, and how that information could help repair Hubble.

The stakes were high for NASA management. Critics howled about the misfigured mirror and talked about scrapping Hubble. The agency desperately needed an affordable way to fix it. Kahan also had personal stakes. He knew people at Perkin-Elmer and realized that mistakes on crucial tests could end careers.

Another ORA optical specialist, William Wetherell, focused on the equipment used to test the main mirror. The crucial device used to figure the primary was a null corrector, an optical assembly designed to generate a wavefront to serve as an optical template for interferometric measurements of the mirror shape. The mirror is polished to match the wavefront; when that happens, tests produce a characteristic fringe pattern.

The standard design used in the 1970s was a refractive null corrector, in which a plano-convex lens focused light from a point source through a three-element field lens onto the mirror being tested. Its performance depended crucially on both the positioning and the optical properties of the lenses. That worried Perkin-Elmer managers because it was difficult to verify that the refractive null corrector was producing the desired optical template for the mirror.

To avoid that problem in fabricating a 1.5-m test mirror for NASA, Perkin-Elmer engineers designed a novel reflective null corrector with a single field lens and a pair of spherical mirrors instead of the usual single mirror. That design offered an important advantage: It had fewer surfaces and on paper was more accurately testable. The shape of the optical template it produced could be calculated from the dimensions of the mirrors and field lens, as well as the refractive index of the lens and the spacing of the optical elements. Optical-element spacing had to be within 10 μm to meet specifications, but optical metrology achieved that for a prototype mirror. That result, and an aggressively low bid of $69 million, helped Perkin-Elmer win the Hubble contract in 1977.
The reflective null corrector was modified in 1980 to test the larger Hubble primary during figuring, polishing and coating—a process that was completed in December 1981. Then it sat in place atop the Hubble test tower until the trouble-shooters arrived eight years later.

The reflective null corrector could not perform all needed measurements, so the team at Perkin-Elmer used a refractive null corrector for initial figuring and polishing of the primary. They reserved the reflective null corrector, expected to be more accurate, for final mirror polishing. They also used an inverse null corrector to simulate a perfect mirror so they could check that the reflective null did not change during its measurements of the primary.

Perkin-Elmer’s tests with the reflective null corrector showed the primary mirror exceeded NASA specifications. But 1981 data from the refractive null corrector in the old files told a different story. “We found spherical aberration roughly equal to what was found on station,” says Kahan. The test results didn’t match those taken with the reflective null at the same stage in the fabrication process even when test-equipment tolerances were considered. Standard procedure is to repeat the tests until the problem is identified, but documents showed the Perkin-Elmer test engineers decided the less-precise refractive null had to be wrong.

Trouble-shooters in 1990 first tested the refractive null, which they found to be accurate to within 0.02 wave RMS. That pointed to an error in the reflective null corrector. On 22 July, they put the inverse null corrector in the primary-mirror test tower with the reflective null and produced interferograms showing spherical aberration, which were virtually identical to those taken with the same setup in 1982. This bolstered the case against the reflective null corrector.

**Federal marshals had secured all Hubble-related files and gathered the paper files in a cafeteria.**

---

The crucial test equipment

---

Phil Saunders/Adapted from NASA, Hubble Space Telescope Optical Systems Failure Report.
Examination of the reflective null ruled out the two causes of the problems that initially seemed most likely: installing the field lens backwards or using glass with the wrong refractive index. While incorrect spacing of the optical elements initially had seemed unlikely, new measurements revealed that the field lens was about 1.3 mm too far below the lower mirror. This, the Allen panel found, accounted for the observed spherical aberration. In other words, Perkin-Elmer had fabricated the main mirror perfectly, but to the wrong shape.

The records did not reveal exactly what went wrong, but by mid-September 1990 the Allen panel had worked out the likely cause, with key evidence coming from Hughes-Danbury staff working for the panel. Originally used to test a 1.5-m test mirror, the reflective null had to be modified for the 2.4-m Hubble primary, and Perkin-Elmer used custom-made invar metering rods with rounded ends to accurately space the field lens. To make their optical measurements from the right point and to protect the invar rod, technicians had mounted a black cap with a small central hole over the rounded end.

What they didn’t notice was that a chip had flaked off the black paint and they mistakenly measured distance to the exposed metal glint rather than to the spacing rod. Trying to correct the spacing to that point, they inserted washers at the field lens, causing a 1.3-mm error in spacing between the field lens and the lower mirror.

The washers were inserted in May 1980, and the NASA investigators who dug through the mountains of paperwork found that the refractive null showed aberrations then. Tests with the inverse null corrector showed aberrations in August, when polishing began. A refractive null test in April 1981, at the end of polishing, still indicated aberration.

On 19 May, an internal Perkin-Elmer review suggested a “sanity check” for an incorrect null. Testing manager Lucian Montagnino tried to pin down the discrepancy, and every month from May 1981 to March 1982 he reminded Hubble optics manufacturing manager Bud Rigby of the need to certify the reflective null. But it never happened.

With NASA unwilling to pay Perkin-Elmer more than their $69 million contract, Perkin-Elmer deputy program manager Robert W. Jones closed the primary mirror project in March 1982. In 1990, he and two higher-level managers told NASA investigators that they didn’t know about the measurement discrepancies. NASA sued for damages and later recovered $25 million from Perkin-Elmer and Hughes in an out-of-court settlement.
Prescribing corrective optics

The plan to save Hubble began as soon as aberration was recognized, although it took several more months to pin down the optical errors tightly enough to compensate for them.

The first plan was to build the corrective optics into a new generation of instruments. JPL was already building a new Wide Field Planetary Camera (WFPC) for the 1993 service mission. It was a relatively straightforward process because the needed correction could be figured onto the camera's secondary mirror, where Hubble focused light.

However, that would have left the four instruments along Hubble's axis uncorrected, so Holland Ford and Robert Brown of the Space Telescope Science Institute (STSI) figured out how to fix them with their strategy team. The task was tougher than fixing WFPC because new optics had to be added to serve the axial instruments.

In the end, Ford recalls, they picked “two simple but genius ideas” suggested by James Crocker of STSI. He proposed sacrificing one axial instrument to make room for a module holding pairs of corrective mirrors. Once the module was installed, an optical bench would slip out and rods would slide one pair of corrective mirrors into the optical path to each of the other three instruments.

Crocker later said he got the idea of sliding the little mirrors on rods from a fancy shower in the hotel where he had stayed during a meeting. By November, they had sketched out the design of COSTAR (for Corrective Optics Space Telescope Axial Replacement) and decided it would replace the High-Speed Photometer, a first-generation axial instrument rendered almost useless by Hubble's vibration problem.

Murk Bottema, a veteran designer of space instruments at Ball Aerospace, did the design work on the aspheric COSTAR mirrors, which had to be precisely positioned to bring the three remaining axial instruments into focus. Investigators spent months more determining the main mirror’s flaws, so the 10- to 30-mm mirrors could provide exact corrections.

The COSTAR might sound simple, but it took a total of 5,300 parts to slide the six small mirrors in place so that they could focus exactly onto the three remaining axial instruments. Specifications called for the aspheric surfaces to be accurate within 6 nm of Ball’s design and smooth to within 1 nm, better than Hubble’s main mirror. Tinsley Optics took the job. The company created surfaces that were accurate to within 3 nm and smooth to within 0.5 nm.

Meanwhile, NASA tried to find some good news from Hubble despite its optical flaws. One achievement was recording Pluto and its moon as widely separated objects rather than blurry spots that appeared in ground photos. Aberration scattered light across the background of these images. NASA tried to enhance them, but could not recover the faint galaxies obscured by the stray light. Astronomers complained bitterly.

Hubble continued to experience technical and organizational failures. The telescope was shut down in May...
1991 because part of its main computer memory failed. The following month, a second gyroscope malfunctioned, leaving only one spare. Power-supply problems hobbled the Goddard High Resolution Spectrometer instrument in July. In early 1992, veteran astronaut Richard Truly was forced out as a NASA administrator. The first Hubble servicing mission had to repair reputations as well as hardware.

### Choreography in space

NASA planners had envisioned Hubble service missions as an orderly process of replacing old instrument modules with better ones. They had not expected the cascade of problems that surfaced after launch. In the spring of 1992, NASA picked veteran astronaut Story Musgrave to head the complicated first Hubble service mission.

Repairs in space need to be carefully choreographed, and the work is cumbersome and tiring. Musgrave was an expert; he had helped develop NASA space suits and worked on space servicing techniques since 1976. He knew work in space had to be planned far in advance, so he rehearsed in simulation tanks. That August, well over a year before the planned Hubble repair, fellow astronauts Tom Akers, Kathy Thornton and Jeff Hoffman joined Musgrave’s mission team.

The group faced new complications. Previous spacewalks had been largely in sunlight, so space suits had been designed to avoid overheating. But Hubble had to be kept out of the sun to prevent outgassing from the black insulation that absorbed stray light. After Musgrave suffered frostbite while spending hours in a space suit testing tools and procedures in a vacuum chamber, NASA had to redesign the mission and adjust the suits to keep astronauts warmer.

NASA scheduled five spacewalks for the 2-13 December 1993 repair mission, the most on any shuttle mission. The long list of tasks started with replacing the wobbly solar arrays and defective gyros, and installing COSTAR and the second WFPC. Thanks to careful planning, the astronauts completed their work with only minor glitches. When they were done, they had clocked 35 hours and 28 minutes in space.

After a few weeks of re-commissioning, Hubble was working well for the first time. “It’s fixed beyond our wildest expectations,” said program scientist Ed Weiler. The difference was obvious in pictures. The Faint Object Camera showed Pluto and Charon crystal-clear with COSTAR in place on 21 February 1994. The light scattered by spherical aberration was gone; Hubble’s Strehl ratio is now estimated at 0.90 at 500 nm and 0.98 at 1,200 nm.

Soon Hubble became a favorite with both astronomers and the public. The National Aeronautic Association gave the recovery team its 1993 Robert J. Collier trophy, “for outstanding leadership, intrepidity and the renewal of public faith in America’s space program ...”

Hubble has far exceeded its planned 15-year lifetime. In 2005, after its fourth service mission, it discovered two previously unknown 100-km moons of Pluto. The decision to ground the shuttle in 2009 made the 2009 upgrade the Hubble’s last, and allowed it to spot a smaller fourth moon in 2011 and a fifth in July 2012. That little moon, as yet unnamed, was only 10 to 25 km across, yet it clearly appears beside Pluto, says its discoverer, Mark Showalter of the SETI Institute. “I’m still struck by just what an amazing instrument Hubble is,” he said.

The telescope is expected to continue functioning until 2014. At that point, its successor, the James Webb Telescope, should be nearing completion and preparing for a 2018 launch.

Jeff Hecht (jeff@jeffhecht.com) is a freelance writer who covers science and technology.

### References and Resources

David Payne Knighted

OSA Fellow David Payne, director of the Optoelectronics Research Centre at the University of South Hampton, United Kingdom, received a knighthood on the Queen's New Year honors list. He received the recognition “for services to photonics research and applications,” reflecting his important work in using light for applications in telecommunications, sensing and lasers for manufacturing. One of his major contributions to the field is the erbium-doped fiber amplifier, which is a key component in the backbone of the optical fiber transmission systems that power the Internet and carry voice calls around the world.

Congrats to the 2013 Russ Prize Winners

OSA Fellow James Wynne and his colleagues Rangaswamy Srinivasan and Samuel Blum are the recipients of the 2013 Fritz J. and Dolores H. Russ Prize from the National Academy of Engineering (NAE). They received the prize for their development of laser ablative photodecomposition, enabling LASIK and photorefractive keratotomy eye surgery. Modeled after the Nobel Prize, the Fritz J. and Dolores H. Russ Prize is a $500,000 biennial award recognizing a bioengineering achievement that significantly improves the human condition. It was presented at the NAE awards dinner and ceremony on 19 February 2013.

Who Will Receive the 2013 Goodman Book Writing Award?

Know any outstanding optics authors? Consider nominating them for the 2013 Goodman Book Writing Award. This biennial distinction is funded by a personal gift from Joseph W. and Hon Mai Goodman; it recognizes a recent and outstanding book in the field of optics and photonics that has contributed significantly to research, teaching or the optics and photonics industry. Co-sponsored by SPIE and OSA, the award is presented to the author or authors of the most influential scientific or technical book on optics published in the preceding six years. R. Barry Johnson was the 2012 recipient for Lens Design Fundamentals, Second Edition.

The nomination deadline is 1 October 2013 for presentation in 2014. Contact the OSA Awards Office for more information (awards@osa.org).

Bonenfant Scholarship Exceeds Fundraising Goal

The Paul Anthony Bonenfant Memorial Scholarship fundraising campaign was recently completed, surpassing the total fundraising goal of $190,000. This scholarship provides $8,000 a year for undergraduate students enrolled in engineering or physical science programs to attend semester-abroad programs offered through their college or university.

It was bolstered by an anonymous donor who matched donations up to $62,000. There was also a series of 5K runs organized by Kelly Skelton, son of Lightwave magazine staffer Kathleen Skelton, along with telecom marketing agency Pacific Bridge Marketing and OSA Foundation staff. The first scholarship will be awarded during OFC/NFOEC 2013 in Anaheim, Calif., U.S.A. For more information, visit the OSA website.

OSAF Announces Major Donor Program

The Optics Circle, the OSA Foundation’s major donor recognition program, will provide special acknowledgements to the Foundation’s strongest supporters. Thanks to these committed individuals and companies, we fund important student-focused programs that inspire the next generation of optics and photonics leaders. To find out more about the Optics Circle, visit www.osa-foundation.org.

Corning Student Paper Competition Under Way at OFC/NFOEC

The OSA Foundation will conduct the Corning Outstanding Student Paper Competition during OFC/NFOEC in March 2013. This student program was established in 2007 to recognize innovation, research excellence, presentation abilities and future leaders in optical communications. Winners will be announced onsite during the conference. The competition is endowed by a grant from Corning Incorporated. Three awards will be presented, with the first prize recipient receiving $1,500 and two honorable mentions each getting $1,000. To learn more about the foundation and support a campaign, visit www.osa-foundation.org.
GLOBAL NEWS

Strickland in Australia
In December 2012, OSA President Donna Strickland attended the 20th Australian Institute of Physics Congress, co-located with the 37th Australian Conference on Optical Fibre Technology and sponsored by Australian Optical Society & Engineers Australia. During the conference, Strickland met with the officers of the Australian Optical Society, gave an invited talk and presented a best student paper award to Anna Wang from Harvard University, U.S.A. Afterwards, Strickland visited the OSA Student Chapter at Australian National University.

Laser Ceramics Symposium 2012 in Russia
The eighth Laser Ceramics Symposium (International Symposium on Transparent Ceramics for Photonic Applications) was held in Nizhny Novgorod, Russia, from 4-7 December. The aim of the symposium was to provide a forum for material scientists, chemists and physicists to discuss the state of the art of optical transparent ceramics. The OSA International Council co-sponsored the conference. The 2013 symposium will be held in Seoul, South Korea.

IN MEMORY

Peter Domachuk, a talented young scientist and OSA member, passed away this January following a sudden illness; he was just 33 years old. He was an outstanding figure in optics despite his young age and a leading scientist in silk photonics.

Domachuk earned his undergraduate and postgraduate degrees in physics at the University of Sydney, Australia. Under the supervision of Ben Eggleton, he completed his Ph.D. work in optofluidics. He was one of the first Ph.D. students to graduate from the Centre for Ultrahigh Bandwidth Devices for Optical Systems (CUDOS) ARC Centre of Excellence program at the University and was well known in the CUDOS community.

In 2006 Domachuk took a postdoctoral position at Tufts University, U.S.A., with Fio Omenetto. His work focused on photonic crystal fibers and silk photonics. In 2009 he returned to the University of Sydney and received a prestigious ARC postdoctoral fellow position in the CUDOS group. There, he initiated a new program in biophotonics (silk photonics and optofluidics). He chaired the University of Sydney Institute of Photonics and Optical Science 2010 symposium on biophotonics, which attracted high profile international participants. Peter was a valued member of the photonics community, an active member of OSA’s Young Professionals program, and a great colleague and friend to those who knew him. He will be sorely missed.

If you would like to make a memorial donation to the OSA Foundation in honor of Peter Domachuk, please visit www.osa-foundation.org/give.

PUBLICATIONS

Welcome New Editors
We are happy to announce that Chao Lu of Hong Kong Polytechnic University has been appointed as a new associate editor for Optics Express. Andreas Mandelis of the University of Toronto, Canada, has recently joined the editorial board of Optics Letters. We thank these members of the optics community for their support of OSA publications.
Upcoming Call for Papers Deadlines

Imaging and Applied Optics
OSA Optics & Photonics Congress
23–27 June 2013
Arlington, Virginia, USA
Submission Deadline: 6 March 2013, 12:00 EST (17:00 GMT)
- Adaptive Optics: Methods, Analysis and Applications (ACO)
- Applied Industrial Optics: Spectroscopy, Imaging and Metrology (AOI)
- Computational Optical Sensing and Imaging (COSI)
- Fourier Transform Spectroscopy (FTS)
- Optical Molecular Probes, Imaging and Drug Delivery (OMP)
- Optical Trapping Applications (OTA)

Advanced Photonics
OSA Optics & Photonics Congress
14–19 July 2013
Rio Grande, Puerto Rico, U.S.A.
Submission Deadline: 3 April 2013, 12:00 EDT (16:00 GMT)
- Integrated Photonics Research, Silicon, and Nano-Photonics (IPR)
- Optical Sensors (SENSORS)
- Photonic Networks and Devices (NETWORKS)
- Signal Processing in Photonics Communications (SPPCom)

Nonlinear Optics (NLO)
OSA Topical Meeting
21–26 July 2013
Kohala Coast, Hawaii, USA
Submission Deadline: 3 April 2013, 12:00 EDT (16:00 GMT)
- Propagation through and Characterization of Distributed Volume Turbulence (pcDVT)
- Quantitative Medical Imaging (QMI)

CALENDAR

OSA Optics and Photonics Conferences and Meetings

Optics in Life Sciences Congress
14–18 April 2013
Waikoloa Beach, Hawaii, U.S.A.
www.osa.org/Life_Sciences_Congress
- Bio-Optics: Design and Application (BODA)
- Novel Techniques in Microscopy (NTM)
- Optical Molecular Probes, Imaging and Drug Delivery (OMP)
- Optical Trapping Applications (OTA)

European Conferences on Biomedical Optics [ECBO]
12–16 May 2013
Munich, Germany
www.osa.org/ecbo

International Photonics and Optoelectronics Meetings (POEM)
24–27 May 2013
Wuhan, China
http://poem.wnlo.cn/
- Nanophotonics, Nanoelectronics and Nanosensor (N3)
- Advanced Optoelectronics for Energy and Environment (AOEE)

CLEO: 2013—Laser Science to Photonic Applications (CLEO)
9–14 June 2013
San Jose, Calif., U.S.A.
www.cleoforum.org

Optical Interference Coatings
16–21 June 2013
Whistler, British Columbia, Canada
www.osa.org/oic

Imaging and Applied Optics Congress
23–27 June 2013
Arlington, Va., U.S.A.
www.osa.org/Imaging_Congress
- Imaging Systems Applications (IS)
- Applied Industrial Optics: Spectroscopy, Imaging & Metrology (AIo)
- Hyperspectral Imaging and Sounding of the Environment (HISE)
- Adaptive Optics: Methods, Analysis and Applications (AOI)

Hannah Bembia (hbembia@osa.org) is OSA’s publications administrative assistant.
Sarah Michaud is OPN’s associate editor.
FAMOUS NAMES IN OPTICS

The Stanford University Student Chapter has devised this crossword challenge to test your knowledge of who’s who in optics. Do you know your Bohr from your Boltzmann, or is it time to hit the history books—or at least the historical articles from OPN’s archives? For the answer key, visit www.osa-opn.org/home/puzzle_solution/. Additional puzzles are posted at OSA’s Optics & Photonics Latin America website (www.opticslatinamerica.org/crosswords).

### Across
1. German physicist; postulated that energy is quantized (6)
8. Enjoyed cages (7)
10. Foie gras minus ln(e^e) (4)
11. Stanford laser physicist; author of famous textbook on lasers (7)
13. Cheerful Scandinavian who brought together the great young minds of the time to put on a production of Goethe’s Faust and, oh yes, derive and describe quantum mechanics (4)
14. Disproved the existence of the ether, together with Morley (9)
18. Famous for his double-slit experiment and deciphering the Rosetta Stone (5)
20. Spontaneously named for a famed Baroque British composer (7)
21. Made fundamental contributions to the fields of negative-index materials, metamaterials and transformation optics (6)
22. His principle pertains to complementary screens (7)
23. Scottish physicist, has a famous angle named after him. (8)

### Down
2. Scottish nonlinearity (4)
3. German physicist, synonymous with plasmonic metals (5)
4. French for fish; setting the electric charge density to zero in his equation leads to Laplace’s equation (7)
5. His principle states that every point along a wavefront can itself be considered a source (6)
6. His functions come in both cylindrical and spherical varieties (6)
7. His polynomials are intimately related to spherical harmonics (8)
8. Made fundamental contributions to the theory of far-field diffraction (10)
9. Austrian physicist, founder of statistical mechanics, and noted suicide. (9)
12. Not to gloat, but he made fundamental contributions to the theory of X-ray diffraction (5)
15. British lord; perhaps first man in history who could explain why the sky is blue (8)
16. The constant relating a blackbody’s temperature to its total power is named after him and Boltzmann (6)
17. Maxwell added the displacement current term to his law in order to conserve charge. (6)
19. Got hit in the head with an apple (6)
20. Completes Fabry interferometer (5)

Puzzle courtesy of the Stanford University Student Chapter. If you would like to submit a puzzle, please email opn@osa.org.
TOPTICA scores from the red zone: a team of new and improved lasers deliver @ 633 nm

Record-breaking and the only one of its kind in terms of power, wavelength and coherence stability, TOPTICA’s sleek new Top-Mode laser replaces bulky, power-consuming gas ion lasers. The proprietary CoHerence-Advanced Regulation Method (CHARM) provides active stabilization of the lasers’ coherence and ensures relentless single-frequency operation for round-the-clock operation. **TOPTICA** www.toptica.com

Semrock Manufactures the World’s First 11-band Optical Filter

Semrock proudly announces the production of the world’s first 11-band filter with steep edges within a 100 nm wide spectral window. The filter has high transmission and exceptional blocking outside each of the eleven. The unmatched spectral complexity of this 11-band filter was designed specifically to match the corresponding formaldehyde fluorescence emission spikes over the 380-480 nm wavelength range. The filter can be utilized to investigate the homogeneous charge combustion ignition (HCCI) combustion process. **Semrock** www.idexcorp.com

Alluxa announces a new line of Ultra-flat dichroic and polychroic thin film filters

Alluxa is pleased to announce the production of ultra-flat dichroic and polychroic filters with very high levels of in-band transmission. These filters are unique because they achieve flatness by eliminating the high stresses of as-deposited traditional ion-based coating process such as Ion Beam Sputtering (IBS) and Ion Assisted Deposition (IAD). Alluxa’s new technique uses a novel plasma hard coating process that produces low-loss, fully dense dielectric films with essentially net zero stress on the primary coated side. **Alluxa** www.alluxa.com

Cambridge Technology introduces FlexScan-3D™

Cambridge Technology’s FlexScan-3-D Systems are application-flexible integrated 3-Axis solutions for scanning applications demanding excellent large field and 3-D processing speed and accuracy in a compact and cost-effective enclosure with industry standard interfaces. The flexibility of the FlexScan-3-D System comes from its configurability, programmability, diffraction-limited spot size and high power laser handling capability. **Cambridge Technology Inc.** www.camtech.com
Employment

WORKinOPTICS
Your Global Resource for Optics and Photonics Jobs

Browse Listings or Upload Your Resume to www.WORKinOPTICS.com

Optical Research Design Engineer ................................................. Thorlabs
VP Sales and Marketing .............................................................. Vytran LLC
Technical Leader, Optical Engineer .............................................. Cisco Systems
Manufacturing Engineer .............................................................. PFG Precision Optics
Director/VP of Development ...................................................... BinOptics Corporation
Optical Engineer ........................................................................ Lightwaves 2020, Inc.
Senior Opto-Mechanical Design Engineer ............................... LightPath Technologies, Inc.
Mechanical Engineer ................................................................. CVI Melles Griot

(AS OF FEBRUARY 2013)

Visit WORKinOPTICS.com to browse all positions
OSA’S ONLINE JOB BOARD

ADVERTISER INDEX

American Elements ................................................................. Cover 4
www.americanelements.com

CLEO 2013 ................................................................................. Cover 3
www.cleoconference.org

Discovery Semiconductor ......................................................... 1
www.discoverysemi.com

Edmund Optics ........................................................................... 13
www.edmundoptics.com/cage-system

Frontiers in Optics ...................................................................... 8
www.frontiersinoptics.com

Nextrom ....................................................................................... 7
www.nextrom.com

OFS ............................................................................................ 11
www.specialtyphotonics.com

OSA Education Materials ......................................................... 15
www.osa.org/educationmaterials

OSA Express Journals ............................................................... 25
www.opticsinfobase.org

OSA Topical Meetings .............................................................. 52
www.osa.org/meetings

Synopsis ...................................................................................... Cover 2
www.opticalres.com

Work in Optics ........................................................................... 55
www.workinoptics.com

For advertising information, please contact Regan Pickett, OPN’s Advertising Sales Manager, at +1.202.416.1474 or rpickett@osa.org.
This art represents a coherent (laser-like) X-ray pulse with the largest color spread generated to date. Such rainbows of color can support extremely short, few-attosecond light pulses, which are invisible to the human eye but important for capturing the ultrafast dynamics in materials and nanosystems.

—Tenio Popmintchev, JILA, University of Colorado at Boulder
Register Now

CLEO: 2013
Laser Science to Photonic Applications

Technical Conference:
9–14 June 2013

Short Courses:
9–11 June 2013

Exhibit:
11–13 June 2013

San Jose Convention Center
San Jose, California, USA

CLEO: QELS – Fundamental Science
CLEO: Science & Innovations
CLEO: Applications & Technology

Featuring:
CLEO: Expo
CLEO: Market Focus

CLEO: 2013 — The one conference for peer-reviewed, late-breaking and full-spectrum research, world-class engineering and market-ready applications presented by industry leaders and the next generation of optics innovators.

• 1,800+ Technical Presentations • 180+ Invited Speakers • Dynamic Plenary Session • 24 Tutorials
• 20 Short Courses • 12 Symposia • 10+ Networking Events • CLEO: Expo and more

Advance Registration Deadline: 13 May 2013
Visit www.cleoconference.org for more information
Now Invent.™