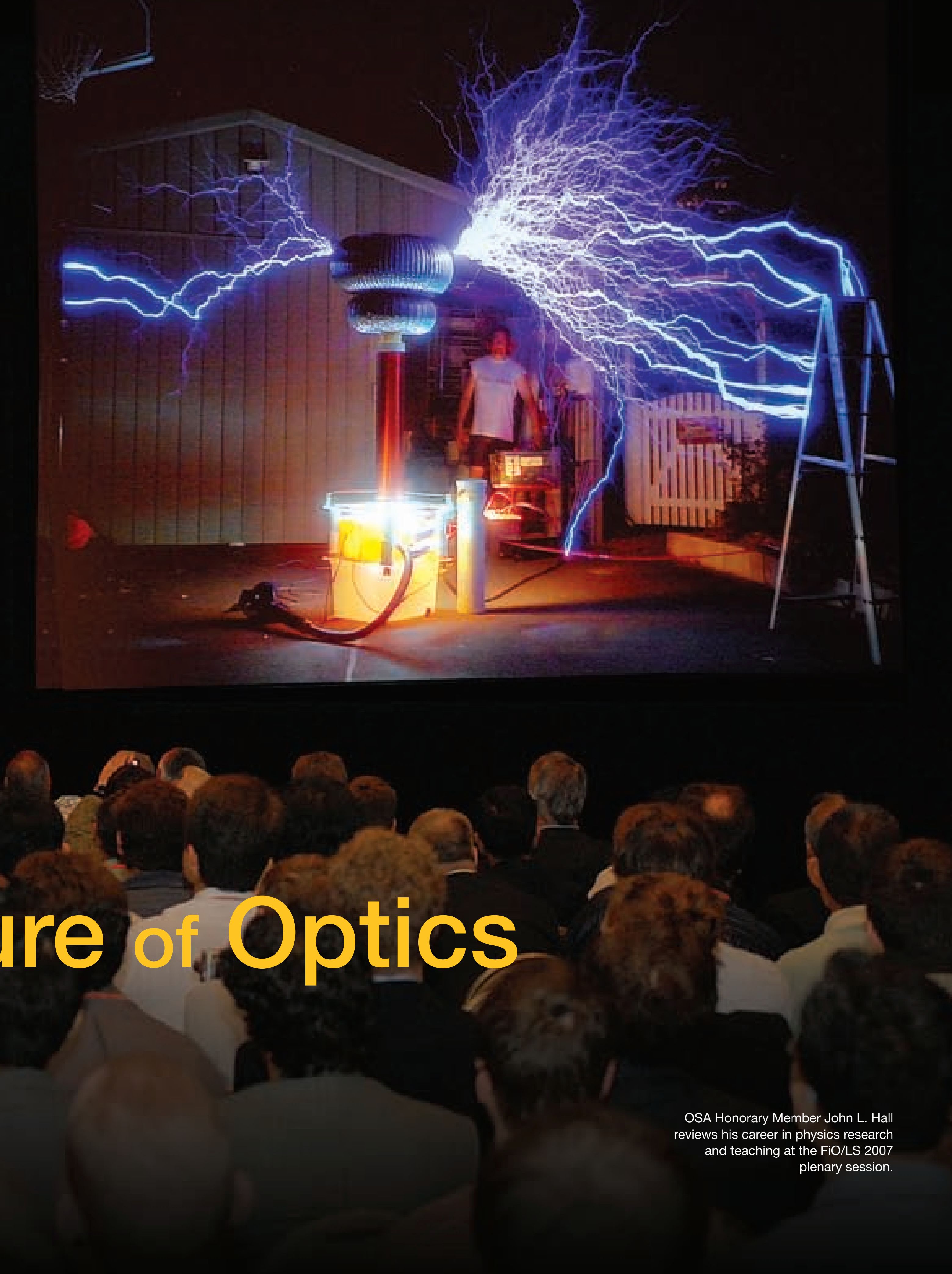
Report from FiO/LS 2007: Crystallizing the Futu

Patricia Daukantas

Frontiers in Optics (FiO) 2007, OSA's 91st annual meeting, brought the latest research in optics and photonics to San Jose, Calif. Among other topics, the conference focused on nanophotonics and photonic crystals, optical materials, optics for energy production and biomedical applications.



ure of Optics

OSA Honorary Member John L. Hall reviews his career in physics research and teaching at the FiO/LS 2007 plenary session.

Silicon Valley may have gotten its name from electronics, but FiO showed the region that photonics is here to stay. The OSA annual meeting brought together scientists and engineers, academic researchers and telecom entrepreneurs, Nobel Prize winners and undergraduate students. Attendees also had plenty of time to exchange ideas at multiple poster sessions, OSA division meetings and networking events.

At the FiO plenary session, Eli Yablonovitch, who is widely considered the father of photonic crystals, emphasized the integration of silicon with photonics. Yablonovitch, who recently left the University of California, Los Angeles, to join the University of California at Berkeley, took the plenary audience on a tour of structures far smaller than the wavelength of light.

A three-dimensional photonic crystal is a semiconductor for light waves, with structures that are half a wavelength apart. Its edges must be accurate to sub-wavelength dimensions. Given the tiny size of light waves, this sounds like a daunting task, but it is actually quite doable with today's technology, Yablonovitch said.

Scientists have created a "tremendous zoology" of photonic crystals with a "fabulous number of structures," according to Yablonovitch. For example, the silicon-on-insulator used in microprocessors is made for electronic reasons and not for optical reasons, but the layers of silicon and silicon dioxide, with a triangular lattice of holes, can also act as a two-dimensional photonic crystal.

Nanophotonics crossed an important milestone in 2003, when the size of integrated circuits dropped below the critical dimension for a photonic crystal, which is approximately 100 nm. "Electronics and optics have become one thing," Yablonovitch said.

Today's engineers can place edges of photolithographic features with ±3 nm of accuracy. "This is a phenomenal achievement, and it is an achievement of optics," according to Yablonovitch.


Yablonovitch

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Despite the lack of an integrated silicon laser, the full toolkit for integrated optoelectronics is at hand. In traditional electronics, the electricity comes from the outside, so the laser acts as an external cw power supply for the silicon technology. Remaining research opportunities include developing ever more sensitive photodetectors, more cw optical power at lower cost, mode-locked optical power and a true silicon-based light source.

In the emerging field of plasmonics, researchers work with circuit sizes much smaller than the wavelength of light. Although traditional optics incorporates path elements that are quite a bit longer, Yablonovitch pointed out that in conventional electricity it is normal for circuits to be subwavelength. After all, American standard 60-Hz alternating current has a wavelength of 5,000 km.

John L. "Jan" Hall of JILA, the University of Colorado and the National Institute of Standards and Technology, is as well known for his long history of training and mentoring young researchers as he is for his high-precision spectroscopy studies. Two years after he and his fellow newly minted Nobel physics laureates, Roy Glauber and Theodore Hänsch, appeared for congratulations from the FiO/LS plenary audience, Hall returned to the OSA annual meeting for a plenary talk that showcased the highlights of his storied career.

One of Hall's own mentors was Ali Javan of Bell Laboratories, whose team built the first working gas "optical maser" a few months after the first-ever laser. At the time that they got the gas laser to work on December 12, 1960, their manager was on the brink of shutting their project down.

Javan's team also combined two laser beams with nearly the same frequency and shone the mixed beam into a photodetector, which converted the beat frequency into sound. "Hearing the lasers' optical beat as an audio whistle changed my life," Hall said.

Hall reviewed the evolution of the world's length standards and their increasing precision—due in no small part to the invention of the laser frequency comb. By the spring of 1999, Hall knew about frequency combs but not how to make them. A Bell Labs postdeadline paper at OSA's 1999 Conference on Lasers and Electro-optics (CLEO) gave him and other researchers the idea of using a certain kind of microstructured fiber for the synthesis of femtosecond pulses that have a repeatable shape.

That CLEO talk sparked a friendly but intense competition between the JILA/NIST researchers and Hänsch and his colleagues in Garching, Germany, Hall said. During the next few years of productive research, postdoctoral fellows

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Scott Diddams and Thomas Udem shuttled between the two locations to create "positive interference between the two groups."

The optics-energy connection

Two special sessions on "Optics for Energy" shone light on this special concern to society. One of the presiders, Alan Kost of the University of Arizona, said that the sessions were intended to kickoff OSA's own efforts to promote and practice energy efficiency.

According to Greg Smestad, associate editor of the journal *Solar Energy Materials and Solar Cells*, the current interest in solar energy should be self-sustaining, due to economies of scale, new silicon supplies and processes, and an understanding of the requirements for economical, efficient solar converters. In fact, there has been so much recent demand for solar cells that there is a silicon shortage. (New capacity is expected later this year, however.) The eight-year-old Condé Nast building at 4 Times Square in Manhattan provides an example of integrated photovoltaic panels in a modern 48-story office building.

Optical concentration reduces the amount of semiconductor material needed for each solar cell and increases cell efficiency, said Sarah Kurtz of the National Renewable Energy Laboratory (NREL).

Despite its exponential growth rate, solar power still provides less than 0.1 percent of U.S. electricity, Kurtz said. No one knows how long the rapid expansion of solar technology will continue, but the growth curve extrapolates out to about 5 percent of the country's total electricity consumption—indicating that solar could become a major energy source during our lifetimes.

Semiconductor costs are still a substantial fraction of overall photovoltaic costs, so one could reduce the amount of semiconductor material by concentrating the light. Not only would that save money on semiconductor material, it could also permit the use of more efficient but costly materials. To obtain the highest efficiency, a photovoltaic panel should absorb each color of light with a material that has a bandgap equal to the photon energy. Multi-junction cells use multiple materials to match the solar spectrum, and concentrators for these cells have the highest efficiency growth slope curve.

Hall

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For high-concentration photovoltaic systems—those with an aperture-to-solar-cell area ratio exceeding 100—the technical requirements are fairly stringent, said Patrick Y. Meada of Palo Alto Research Center Inc. Such systems must have precise two-axis tracking to follow the sun's path across the sky and provide protection from wind and hail. Nevertheless, companies that produce concentrated photovoltaic systems report system efficiencies of up to 28 percent with triple-junction cells.

Hydrogen is often cited along with solar power as a renewable energy source. However, scientists are still working to find ways to extract it in an energy-efficient manner. (Currently, it must be gleaned from a non-renewable natural gas.) Tasios Melis, a biology professor at the University of California Berkeley, hopes to enhance the production of hydrogen and other renewable fuels by manipulating the optical properties of tiny plants.

The green microalga species *Chlamydomonas reinhardtii* exhibits differential interference contrast and red chlorophyll fluorescence, according to Melis. He and his colleagues at Berkeley and NREL are growing their small-scale test cultures of greenish algae in glass bottles. Each bottle contains a different density of cultures, and H_2 bubbles up to the top of each closed bottle for later collection.

According to Melis, hydrogen is not the only product of the metabolic reactions inside these bottles. The algae can generate various types of hydrocarbons: sugars, terpenoids and fatty acids.

For the large-scale production of either hydrogen or hydrocarbons, Melis envisions a low-cost tubular racetrack photoreactor setup to hold the tiny plants. However, once the density of algae gets high enough, sunlight penetrates only a couple of inches into the tube. Fully pigmented cells over-absorb and wastefully dissipate bright sunlight. In fact, 80 percent of the incoming photons are lost in heat dissipation, while the rest of the culture remains inactive.

Melis and colleagues want to improve the algae's solar conversion efficiency under bright sunlight and do some gene manipulation to permit greater

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transmittance of light and to improve the algae culture's overall solar utilization.

Biomedical optics

Linda Shi and colleagues at the University of California, San Diego, have been developing an annular laser trap for sperm sorting and analysis. Sperm analysis is important for human fertility assessment, animal husbandry and the preservation of endangered species. The single-spot laser trap is used to immobilize individual sperm, study laser-sperm interactions and quantify the motility of sperm.

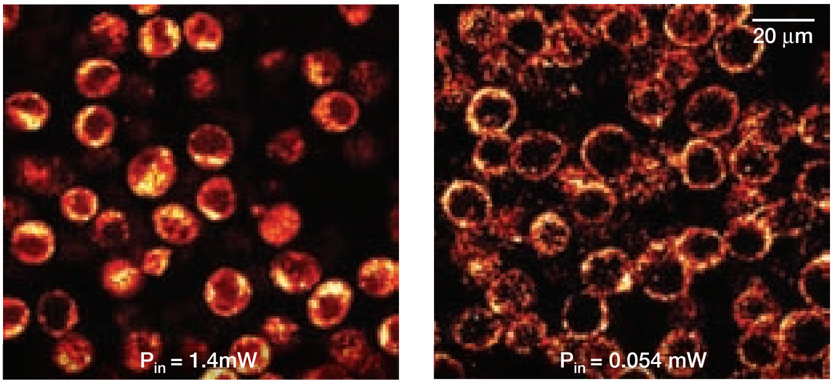
The team proposes an axicon-based ring-shaped trap for parallel sorting with respect to motility or chemotaxis. This requires low laser power (tens of milliwatts) and demonstrates the effect of optical force on sperm swimming. She showed her FiO audience a movie of human sperm sorting using a non-invasive annular laser trap.

Two-photon luminescence (TPL) imaging could prove useful in early detection and treatment of epithelial cancer. Adela Ben-Yakar and colleagues at the University of Texas at Austin are studying the use of gold nanorods and nanoparticles as contrast agents for imaging cancer cells with TPL.

Unlike two-photon auto-fluorescence and confocal imaging, the group's technique produces no background noise. The researchers prepared gold nanorods with a longitudinal surface plasmon resonance of 760 nm and used them to label human skin-cancer cells growing at different depths in a collagen matrix. Images taken with the group's custom-built TPL microscope show a lack of signal degradation with depth compared with unlabeled cells under two-photon auto-fluorescence. In fact, the TPL images showed three orders of magnitude more emission intensity than the auto-fluorescence images.

Esophageal cancer is the fastest-increasing type of cancer in the United States, said Eric J. Seibel of the University of Washington. More than 80 percent of all cancers originate in the epithelial layer and become deadly when they metastasize through the bloodstream. There are no easily detectable biomarkers for early cancer screening of the lung, pancreas and esophagus.

Seibel and colleagues at the university's human photonics lab have been designing ultrathin, flexible endoscopes for guiding biopsies, imaging and perhaps laser ablation of early cancers in the hard-to-reach areas of the human body, such as the lungs and parts of the gastrointestinal system. He described his team's instrument as "a laser-scanning microscope at the end of a very long piece of spaghetti," and he showed stunning images of a living pig bile duct and



(Left) Two-photon autofluorescence image of untagged human skin-cancer cells in a collagen matrix. (Right) Two-photon luminescence image of gold-nanorod-tagged cells buried 55 mm deep in tissue.

a breathing pig bronchus. The team is also developing three-dimensional imaging techniques to use on extracted cell samples to catch cancer at earlier stages.

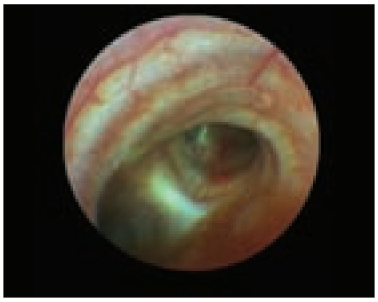
Lidar applications

A team headed by Jean-Pierre Wolf of the University of Geneva, Switzerland, claimed the most powerful white-light femtosecond lidar experiment to date using the 30-TW Alise laser beamline of the Commissariat à l'Énergie Atomique (CEA) in France. The 30-J pulses can send lidar signals up to 20 km in altitude. Using the European Teramobile, which is the first mobile terawatt laser, the group also demonstrated two-photon fluorescence lidar detection of bioaerosols in the field.

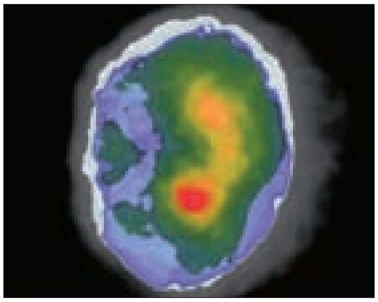
The absorption spectra of multi-component white-light lidar can aid in remote identification of air pollutants. With bioaerosols, the problems are both detection and identification. For example, the fluorescent spectra of some bacteria resemble those of water laced with the vitamin riboflavin. Organic compounds from diesel exhaust, soot and other sources can also add noise to spectra. Naphthalene has almost the same spectrum as tryptophan. One can discriminate between different types of bioaerosols and background interferents using the pump-probe method, Wolf said.

The United States is projecting a 150 to 250 percent increase in air traffic by 2025, and the Federal Aviation Administration is seeking new precision navigation and vision technology to decrease the buffers between planes in altitude and time. Mary E. Ludwig and colleagues at RL Associates Inc. of Chester, Pa., are proposing a near-infrared (NIR) lidar system for hazard detection onboard aircraft.

An NIR system would be ideal because it is eye-safe, covert and relatively insensitive to light scattering from particulate matter, according to Ludwig. The company has produced a tabletop prototype using a 1.57-µm laser and with a mass of less than 5 kg. A signal-to-noise ratio of 100 or better is the metric the researchers used to model the returned signal through various scattering media (haze through heavy rain).



Scanning fiber bronchoscope image from a living pig airway using 442-, 532- and 635-nm backscatter signals.



A human cancer cell imaged in white light with 3D microscopic analysis.

Early days of computer-aided design

Kevin P. Thompson, vice president of Optical Research Associates of Littleton, Mass., introduced the Optical Design and Instrumentation Technical Group to a little-known set of reports on lens design with an early electromechanical computer, the IBM ASCC or Harvard Mark I.

The Mark I—now in the Smithsonian—was a huge calculator, not an electronic digital computer. Mark I was an electromechanical calculator of 5 tons driven by "components" linked by a 50-foot shaft that sounded like a textile mill. It was only 10 times faster than Charles Babbage's 19th-century "difference engine."

The late James G. Baker, an astronomer at Harvard University, had written the 11 volumes, which were classified in the early 1950s and declassified in the early 1960s. He had been working with the military to optimize lens design with the primitive computer. His efforts helped transform optical design from an art to a science, Thompson said.

The "magic decade"

A joint symposium of FiO and its sister conference, the American Physical Society's Laser Science XXIII, explored the influence of optics on the second "magic decade" of quantum mechanics, which occurred roughly between 1972 and 1982. At that time, new optical capabilities had made it possible to test for the first time whether the Bell inequality could be violated, and physicists laid the foundation for modern quantum information research.

Unlike the first "magic decade" of quantum mechanics (1922-1932), most of the second decade's principal participants are still around, and a good number of them—including Abner Shimony of Boston University, Richard A. Holt of the University of Western Ontario, and John F. Clauser and Stuart Jay Freedman of Berkeley—gave their candid perspectives on the Bell inequality and other tests of quantum mechanics.

In September 2008, OSA will return to Rochester, N.Y., for the Society's 92nd annual meeting. More information will be announced at www.frontiersinoptics.org later in the year.

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>> J.L. Hall. "Defining and Measuring Optical Frequencies: The Optical Clock Opportunity—and More," online at nobelprize.org/nobel_prizes/physics/laureates/2005/hall-lecture.pdf (2005).

>> More information on the Condé Nast building is available at www.eere.energy.gov/buildings/database/energy.cfm?ProjectID=32.