THE SPECTROGRAPH

Volume 23, Number 1 Fall 2006

George R. Harrison Spectroscopy Laboratory

Massachusetts Institute of Technology

Spectroscopy Laboratory sponsoring three workshops and seminars

●The **Seminar on Modern Optics and Spectroscopy** continues its tradition of inviting a broad spectrum of researchers to share their latest work in optics and spectroscopy. The seminar is held Tuesdays at noon.

●On Tuesday, Nov. 14, the Spectroscopy Laboratory, in collaboration with Massachusetts General Hospital and the Center for Integration of Medicine and Innovative Technology, will sponsor "**Bio-Optics of DNA: Shedding Light on Structure and Dynamics**", the latest in the series of Lester Wolfe Workshops in Laser Biomedicine.

●In addition, the Spectroscopy Laboratory will sponsor a program of lectures, posters and student talks during MIT's January Independent Activities Period. A lecture program, "**Spectroscopy for Alternative Energy**", will address the scientific underpinnings of proposed new sources of energy based on proton and electron transfer.

Posters with full details of the programs can be found inside.

Also in this issue

MIT technique reveals inner lives of red blood cells

Work could aid research on sickle cell anemia and malaria

Anne Trafton, MIT News Office

This article is reprinted in full from the Oct. 18, 2006 edition of TechTalk with permission from the MIT News Office

For the first time, researchers at MIT can see every vibration of a cell membrane, using a technique that could one day allow scientists to create three-dimensional images of the inner workings of living cells.

Studying cell membrane dynamics can help scientists gain insight into diseases such as sickle cell anemia, malaria and cancer. Using a technique known as quantitative phase imaging, researchers at MIT's George R. Harrison Spectroscopy Laboratory can see cell membrane vibrations as tiny as a few tens of nanometers (billionths of a meter).

But cell membrane dynamics are just the beginning.

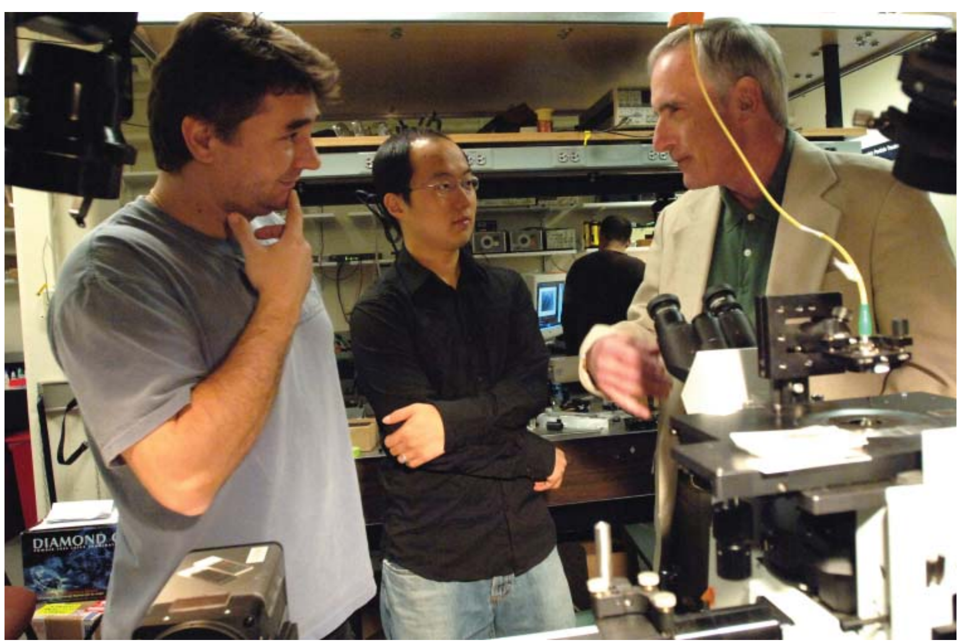
Soon, the researchers hope to extend their view beyond the cell membrane into the cell, to create images of what is happening inside living cells -- including how cells communicate with each other and what causes them to become cancerous.

"One of our goals is create 3D tomographic images of the internal structure of a cell," said Michael Feld, MIT professor of physics and director of the Spectroscopy Laboratory. "The beauty is that with this technique, you can study dynamical processes in living cells in real time."

Scientists have long been able to peer into cells using electron microscopy, which offers a much higher magnification than a traditional light microscope. However, electron microscopy can only be used on cells that are dehydrated, frozen or treated in other ways. Thus it cannot be used to view living cells.

Quantitative phase imaging, on the other hand, allows researchers to observe living cells for as long a time period

Red Blood Cells, continues on page 2



Postdoctoral associate Gabriel Popescu, left, mechanical engineering graduate student YongKeun Park, center, and Professor Michael Feld, right, use spectroscopy to study changes in the membranes of living cells. Photo courtesy of Donna Coveney, MIT.

Red Blood Cells, continued from page 1
as they want. After years of fine tuning, the MIT researchers can now create images with a resolution of 0.2 nanometers. (A red blood cell has a diameter of about 8 microns, or 8,000 nanometers.)

Drums in perpetual vibration

So far, the team has focused its attention primarily on red blood cells (Figures 1 and 3), neurons, and Epithelial cancer cells (Figure 2). Red blood cells are an especially good model to study cell membrane dynamics because they are relatively simple cells, with no nuclei or internal cell structures, says Gabriel Popescu, a postdoctoral associate in the Spectroscopy Laboratory.

In work that is soon to be published in Physical Review Letters, the MIT researchers show that the frequency of cell membrane vibration is related to the elasticity of the cell

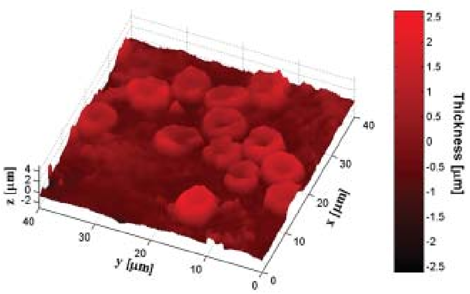


Figure 1. Image of red blood cells recorded using quantitative phase imaging

THE SPECTROGRAPH
Published by the George R. Harrison Spectroscopy Laboratory at the Massachusetts Institute of Technology, Cambridge, MA 02139-4307. Comments, suggestions, and inquiries can be directed to the editor.

Editors: Geoff O'Donoghue & Chung-Chieh Yu

GEORGE R. HARRISON SPECTROSCOPY LABORATORY
Director: Michael S. Feld
Assoc. Director for Scientific Coordination: Robert W. Field
Associate Director: Ramachandra R. Dasari

The Spectroscopy Laboratory houses two laser research resource facilities. The MIT Laser Research Facility provides shared facilities for core researchers to carry out basic laser research in the physical sciences. The MIT Laser Biomedical Research Center, a National Institutes of Health Biomedical Research Technology Center, is a resource center for laser biomedical studies. The LBRC supports core and collaborative research in technological research and development. In addition, it provides advanced laser instrumentation, along with technical and scientific support, free of charge to university, industrial, and medical researchers for publishable research projects. Call or write for further information or to receive our mailings.
(617) 253-4881
http://web.mit.edu/spectroscopy

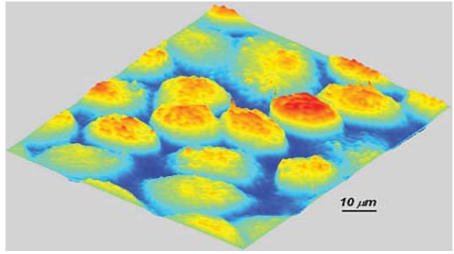


Figure 2. Epithelial cancer cells recorded using quantitative phase imaging.

membrane. Elasticity is important for red blood cells because they have to be able to squeeze through tiny capillaries in the brain and elsewhere, as they deliver oxygen.

"The elasticity of these cells is crucial for their function," said Popescu.

It has been known for more than a century that red blood cell membranes are continuously undulating, or as Popescu puts it, a red blood cell is "effectively a drum in perpetual vibration." This undulation offers a chance to study the mechanical properties of the membrane, including how the membrane provides the cell with both the softness and the elasticity needed to squeeze through narrow capillaries.

Red blood cell abnormalities, such as the twisting deformation seen in sickle cell anemia, also influence membrane dynamics. The researchers are now studying how sickle cell anemia and malaria infection affect the mechanical properties of red blood cell membranes.

Popescu gave a talk on the blood cell work earlier this month at a meeting of the Optical Society of America.

Another group in the Spectroscopy Laboratory is studying signal propagation in neurons. This project, a collaboration with Sebastian Seung, a professor of brain and cognitive sciences, and led by Chris Fang-Yen, a postdoctoral associate in the Spectroscopy Laboratory, is based on the fact that membranes undergo tiny mechanical deformations when an action potential (electrical current) travels along the neuron's axon.

The correlation between membrane vibration and electrical activity could "give us insight on how networks are organized on a neuron level," said Fang-Yen. They are especially interested in studying neural networks in the hippocampus, a brain area associated with memory.

The trouble with interferometry

Quantitative phase imaging builds on an optical phenomenon known as interferometry. With this method, a light wave passing through the cell is compared with a reference wave that doesn't pass through the sample. Combining those two waves creates an interference pattern that offers nanometer-scale images of individual cells.

The major problem with interferometry is that the apparatus is highly sensitive. Even breathing near the interferometer can disrupt the system, leading Popescu to observe that in a typical laboratory environment, trying to measure such tiny optical signals is "like trying to sense the waves of a jellyfish in a stormy ocean."

One way to overcome that is to mount the system in an isolated environment. Another technique, known as the "common path" approach, places both arms of the interferometer (through which the light waves are traveling) in close proximity so the noise in the signals cancel each other out.

Quantitative phase imaging has not yet reached the level of resolution that electron microscopy offers, but Feld said he believes it will someday.

Other Spectroscopy Laboratory researchers involved in the work are Wonshik Choi, a postdoctoral associate; Ramachandra Dasari, principal research scientist; Kamran Badizadegan, a faculty member in the MIT-Harvard Division of Health Sciences and Technology; Shahrooz Amin, a graduate student in electrical engineering and computer science; Seungeun Oh, a graduate student in physics; YongKeun Park, a graduate student in mechanical engineering; and Niyom Lue, a graduate student at the University of Massachusetts College of Engineering.

Michael Laposata and Catherine Best Popescu from Massachusetts General Hospital are also collaborating on the red blood cell studies.

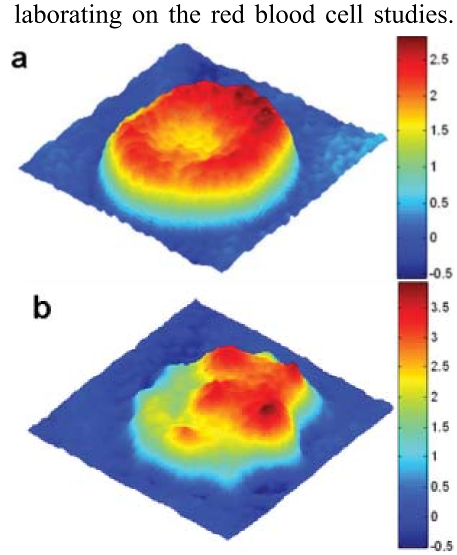


Figure 3. Images of a normal (a) and abnormal (b) red blood cell recorded using quantitative phase imaging.

Personality

Keith Nelson

Keith Nelson attended Stanford University as an undergraduate, earning a B.S. in Chemistry in 1976, and as a graduate student, earning a Ph.D. in Physical Chemistry in 1981. In a harbinger of his independent scientific career, Nelson's graduate work was marked by discovery and exploitation of new methods for pulsed optical excitation and time-resolved optical detection of coherent acoustic waves in molecular crystals and liquids.

> ***"Nelson discovered that acoustic waves could be generated in transparent materials through stimulated Brillouin scattering."***

The initial discovery came during experiments with what was at the time a new "transient grating" or transient four-wave mixing method on electronic excited states in organic molecular crystals. The measurements failed to reveal singlet exciton transfer in these materials, but showed strong, oscillating time-dependent signals due to acoustic waves that were launched through spatially periodic absorption of the crossed excitation pulses. Later Nelson discovered that even in transparent materials, without any optical absorption, acoustic waves still could be generated through stimulated Brillouin scattering. Going further, he remains hopeful that even without any sample present at all, acoustic electron/positron wave generation will ultimately be demonstrated.

During his graduate years Nelson was noted for energetic if perhaps ungifted play on the soccer field, self-described "totally unstructured jumping around" on the dance floor, and an abiding devotion to Patti Smith which continues to this day. He remains the only person on record to have danced to the song "Horses" in its entirety, in the presence of others, multiple times.

After finishing at Stanford, Nelson married and left for postdoctoral work at UCLA. The research group he had joined there dissolved within months of his arrival, leaving him time to order equipment and plan for the research that he would soon begin at MIT. His marriage has fared considerably better, aided perhaps at the time by his learning Spanish and his Mexican wife learning English so that the mutual impressions formed during their few weeks together on scant visits back and forth over a several-year period could be reinforced, and occasionally challenged, through increasingly fluent conversation.

At MIT, Nelson's enthusiasm for coherent optical spectroscopy and control of condensed matter elementary excitations and the collective rearrangements induced by them has blossomed from a mere research interest into the driving obsession that haunts him today. Coherent acoustic waves of every possible frequency and wavelength, coherent optic phonons and molecular vibrations, coherent phonon-polaritons (the topic of the accompanying article), electronic coherences – they must be excited, they must be controlled, they must be uncoupled, dissected, and recoupled, they must be monitored and, with some wisdom and some luck, their interplay that mediates collective structural and electronic properties and their evolution may be unmasked.

In the service of this agenda, Nelson and his group have been driven toward the development of ever more intricate and surprising optical methods including spatiotemporal femtosecond pulse shaping and spatiotemporal coherent spectroscopy and control, Deathstar multiple-pulse acoustic wave excitation, shaped shock wave generation, single-shot femtosecond spectroscopy, terahertz Death Ray generation, and polaritonics. In some cases these methods have enabled myriad applications outside the original research objectives. Nelson and his wife will celebrate their 25th wedding anniversary this fall.

At the Old Physicists' & Old Writers' Home.

Research Report

Cellular individuality in directional sensing

Azadeh Samadani, Jerome Mettetal and Alexander van Oudenaarden

Department of Physics and G.R. Harrison Spectroscopy Laboratory, MIT

It is generally assumed that single cells in an isogenic population, when exposed to an identical environment, exhibit the same behavior. However, it is becoming increasingly clear that even in a genetically identical population, gene expression levels can vary significantly from cell-to-cell [1-3] giving rise to non-genetic individuality [4]. It is an open question whether a conceptually similar individuality can be observed in other cellular activities, such as signal transduction. For example, it is unknown how the fidelity of sensing an extracellular cue varies from cell-to-cell. Here we explore this individuality in the gradient sensing response of single *Dictyostelium* cells when exposed to repeated spatio-temporal pulses of the chemoattractant cAMP. We find the response of a single cell to be highly reproducible from pulse-to-pulse. In contrast, a large variability in the response direction and magnitude is observed from cell-to-cell, even when different cells are exposed to the same pulse. We propose that the effective signal a cell detects is the product of the extracellular cAMP signal and an intracellular signal that varies in direction and magnitude from cell-to-cell. Using this model we successfully predict the observed variability in directional sensing.

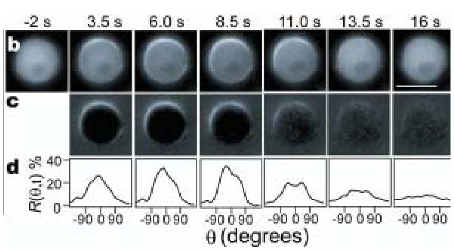
Starved *Dictyostelium* cells were immobilized and seeded into an observation chamber containing a known concentration of caged cAMP. The response of cells to a short pulse of cAMP was quantified by monitoring the spatial and temporal localization of the cytosolic regulator of adenylyl cyclase (CRAC) fused to green fluorescent protein (GFP). The pleckstrin homology (PH) domain of CRAC translocates to the leading edge of motile cells and therefore provides a convenient reporter of directional sensing at the single cell level [5-8]. A spatio-temporal cAMP gradient was formed by uncaging a known concentration of cAMP using a circular UV beam (Fig. 1a).

Figure 1b illustrates the dynamic trans-

van Oudenaarden, continues on pg. 4

van Oudenaarden, continued from pg. 3
location of CRAC-GFP to the membrane after stimulation with a 2 second UV pulse for a cell with a depolymerized actin cytoskeleton. The relative CRAC-GFP concentration in the membrane with respect to the pre-stimulus level was measured by subtracting the images taken after the release of the stimulus from the image taken just before the release of the stimulus (Fig. 1c). We defined a response function $R(\theta,t)$, in order to quantify the relative CRAC-GFP concentration in the membrane. Figure 1d displays $R(\theta,t)$ for the cell depicted in Fig. 1c.

We have characterized $R(\theta,t)$ with three parameters: localization L, polarization P, and polarization angle ϕ. These three parameters are determined by fitting the experimentally obtained response function $R(\theta,t)$ with $R_{fit}(\theta,t) = L(t) + P(t)\cos[\theta - \phi(t)]$. In Fig. 2, we quantify the cell-to-cell, versus pulse-to-pulse variability of $R(\theta,T_{max})$. $R(\theta,T_{max})$ is highly reproducible from pulse-to-pulse, when a single cell is stimulated with 10 identical pulses of cAMP (Fig. 2a). In contrast, $R(\theta,T_{max})$ for a population shows a large variability from cell-to-cell even though cells are stimulated with the same identical pulse (Fig. 2b). In Fig. 2c and Fig. 2d we present P and ϕ in a polar plot. For a single cell, ϕ is observed not to vary significantly from pulse-to-pulse (red dots in Fig. 2c), even when $\phi \approx 90^o$ (green dots in Fig. 2c). In contrast, a pronounced cell-to-cell variability of the polarization angle ϕ is observed in the population even though the cells are stimulated with the same pulse of cAMP (Fig. 2d).



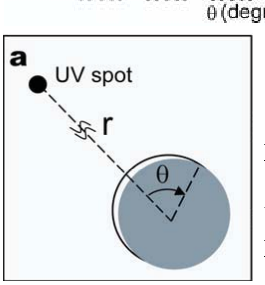


Figure 1. Dynamic translocation of CRAC-GFP at the plasma membrane after stimulation with a 2 second pulse of cAMP **a**, The UV uncaging location is positioned a distance r away from the cell center. The angle θ defines the coordinate along the cell's periphery. **b**, Unprocessed epi-fluorescence images displaying CRAC-GFP as a function of time. The scale bar denotes 10 μm and $r = 70$ μm. **c**, Subtracted images illustrates the relative change of CRAC-GFP concentration in the membrane with respect to the pre-stimulus level. **d**, Response function, $R(\theta,t)$ as a function of time for images in **c**.

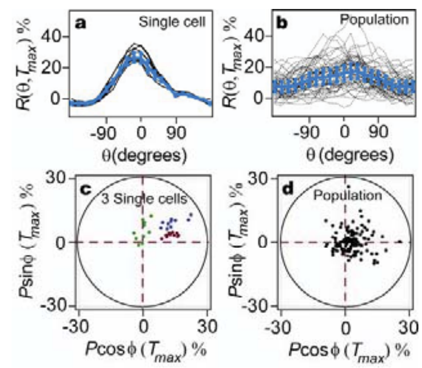


Figure 2. a, Comparison between $R(\theta,T_{max})$ for a single cell, which is stimulated 10 times and **b,** a population of 40 cells, which are stimulated once. **c,** Polar plot of the polarization at T_{max} for three single cells and **d,** a population of 100 cells. In this representation one data point represents data from a single cell

Existing models of eukaryotic directional sensing are commonly constructed from spatially symmetric and deterministic systems of partial differential equations, therefore it is predicted that a cell's polarization will always occur along the direction of the extracellular gradient. Therefore in order for a cell to polarize in a direction other than the direction of the extracellular gradient, an additional source of symmetry breaking must be present in the cell's gradient sensing network. To introduce a simple and general form of asymmetry, we assume that a cell has a static intracellular signal, $S_{int}(\theta)$. The main assertion of the model is that the extracellular cAMP signal $S_{ext}(\theta) = S_o + S_1\cos\theta$ is combined multiplicatively with the intracellular signal $S_{\text{int}}(\theta) = 1 + \varepsilon\cos(\theta - \phi_\varepsilon)$ to produce an effective signal $S_{eff}(\theta)$. Parameters S_o and S_1 reflect the average cAMP concentration and cAMP gradient, respectively. The parameters ϕ_ε and ε define the orientation and relative strength of the intracellular signal, respectively. The intracellular signal may for example, be caused by spatial inhomogenities in any of the signaling molecules in the gradient sensing pathway. Our model accounts phenomenologically for this intracellular asymmetry without making statements regarding the molecular origins of the asymmetry.

When cells are stimulated with a uniform extracellular stimulation, the effective signal retains the direction of the intracellular signal and the direction of the effective polarization simply matches the direction of the intracellular signal ϕ_ε (Fig. 3a). Figure 3b illustrates the case where a cell is stimulated with a directed pulse of cAMP. In this case, an effective signal, whose polarization is biased by the direction of an intracellular asymmetry causes a cell to polarize in a direction different from either the intracellular or extracellular signal.

This model can be geometrically represented in a polar plot. The polarization vector of the cell (black arrow, Fig. 3d) is proportional to the sum of a vector with length S_1 (red arrow, Fig. 3d) and a vector with length εS_o and angle ϕ_ε (blue arrow, Fig. 3d). This model predicts that for a uniform stimulation ($S_1 = 0$), the polarization angle ϕ equals ϕ_ε (Fig. 3c, 3e). For a directed pulse ($S_1 \neq 0$) one would expect a non-uniform ϕ-distribution with a maximum at $\theta = 0$ as was experimentally observed (Fig. 3f). It is encouraging that this

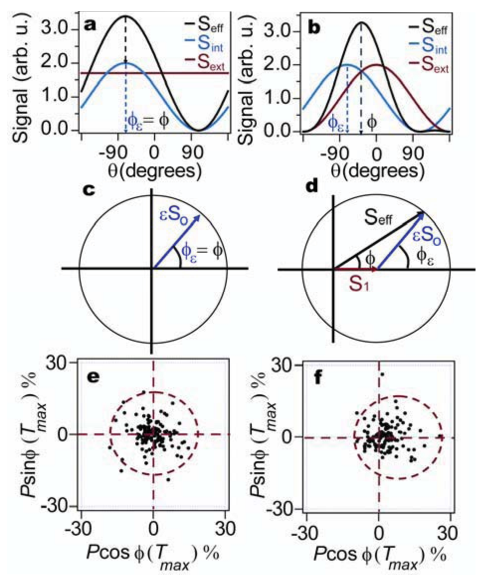


Figure 3. a, Schematic illustration of the effective signal (black), which is a combination of the intracellular signal (blue) and the extracellular signal (red) for a uniform cAMP stimulus and **b,** a directed pulse of cAMP. **c**, Graphical representation of the geometric model and the polarization angle ϕ, when cells are stimulated with a uniform pulse of cAMP and **d**, a directed pulse of cAMP. The effective polarization angle strongly depends on the direction of the intracellular signal ϕ_ε. **e**, Experimentally measured polar plots, as defined in Fig. 3c-d, for a uniform pulse of cAMP and **f**, a directed pulse of cAMP.

Research Report

Phonon-polariton excitation in ferroelectric slab waveguides and photonic crystals

E.R. Statz, D.W. Ward and K.A. Nelson

Department of Chemistry and G.R. Harrison Spectroscopy Laboratory, MIT

1. Introduction

Generation of terahertz radiation in ferroelectric $LiNbO_3$ (LN) offers several advantages over more traditional coherent THz sources, including large second order nonlinear susceptibilities, broad and narrowband frequency tunability over approximately a decade of frequencies, commercial availability of the host material, and high dielectric susceptibility in the THz regime. The THz waves in LN and similar materials are phonon-polariton waves, admixtures of electromagnetic and polar optic phonon modes whose characteristic dispersion properties are well known [1]. Both narrowband and broadband polariton waves have been generated in LN over a roughly 0.1-5 THz frequency range in the lowest phonon-polariton branch [2-4]. Higher branches also have been explored [4].

The large dielectric constant of LN for THz frequencies relative to that for 800 nm light results in THz wave propagation in primarily lateral directions relative to the optical excitation beam wavevector, with Cherenkov cone angles of around 65°. [2] A cylindrically focused excitation beam acts as a “line” source that results in THz plane waves propagating laterally away from the excitation region with modest (~ 25°) forward propagation angles in bulk crystals. Recently, exploration of polariton propagation in waveguides [5] and patterned crystals [6,7] has begun. Here we explore two important classes of systems in which THz polariton propagation is mediated by LN crystal boundary conditions and patterned structures. In the first, planar LN slabs of different thickness are studied to characterize the continuous transition from waveguide to bulk properties, highlighting the potentially useful dispersion properties of the modes in the intermediate regime. In the second, two-dimension polaritonic bandgap structures are examined. The unique dispersion properties of such structures have been treated theoretically [8]. In both cases, X-cut crystals are used and both the optical and polariton polarizations are along the Z-axis.

2. Methods

A home-built Ti:sapphire multi-pass amplifier (800 nm central wavelength, 50 fs, 1 kHz repetition rate, 700 μJ/pulse) seeded by a KM Labs oscillator was used. The ~100-μJ excitation pulse was cylindrically focused to a height of several mm and a width of ~100 μm to generate single-cycle polariton wavepackets with the desired wavevector and corresponding frequency bandwidths. Polariton propagation was recorded through real-space imaging using a variably delayed, 400-nm probe pulse that was expanded to pass through a large part of the crystal area. The transmitted probe light was imaged onto a CCD camera to reveal the full time-dependent polariton field distribution, as has been described

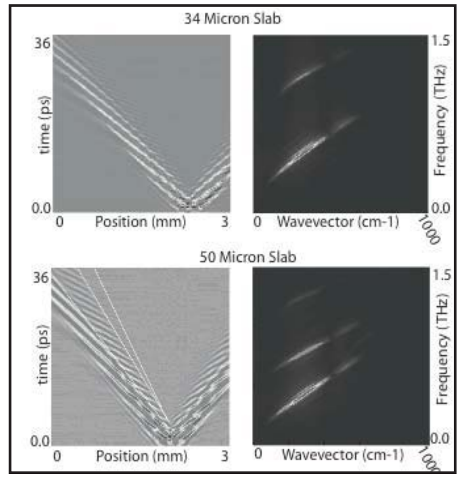


Figure 1. Space-time plots and their Fourier transforms showing multiple slab waveguide modes for 100 micron wide polariton wavepackets in 34 micron and 50 micron $LiNbO_3$

[9]. The time-ordered sequence of images may be played back in succession to show a “movie” that captures the full spatiotemporal evolution of phonon-polariton waves propagating through the crystal. When a cylindrically focused “line” excitation source is employed, the polariton response is often uniform in the direction of the line, and the 2D polariton images may be condensed to a single dimension by averaging over the uniform direction. This permits the entire sequence of compressed 1D images to be presented in succession in a single plot, with the uniform spatial dimension replaced by a time axis. Fourier transformation of this space-time plot along one or both dimensions reveals the wavevector or frequency evolution as a function of time or lateral position or the dispersion relation that is followed by the polariton response.

Polaritonic bandgap structures were fabricated through femtosecond laser machining of LN [6]. A periodic array of 30-μm diameter holes, separated by 100 μm, on a square or triangular lattice, was drilled.

3. Results

3.1 Multimode excitation of slab waveguides

Broadband phonon-polariton wavepackets were generated in 34 and 50 μm thick crystals, and using real-space imaging, the wavepacket evolution was recorded. The left-hand figures below show compressions of the image sequences, constructed as described above. The excitation beam reached the crystals at the zero of the time axes and

Nelson, continues on page 6

van Oudenaarden, continued from pg. 4

simple linear model correctly captures the key properties of the observed stochasticity in directional sensing. Our results show that there is a large cell-to-cell variability in the fidelity of directional sensing. Whereas some individual cells correctly detect the extracellular cue, most cells display a significant deviation from this direction. However, this does not hinder a population of many cells to accurately detect the direction of the extracellular cue (Fig. 3e). The geometric model provides an intuitive explanation for this. The model suggests that the effective signal is the product of a randomly oriented intracellular signal and the extracellular cue.

References

1. Rao, C. V., Wolf, D. M. & Arkin, A. P. *Nature* **420**, 231-237 (2002).
2. Raser, J. M. & O’Shea, E. K. *Science* **309**, 2010-2013 (2005).
3. Kaern, M., Elston, T. C., Blake, W. J. & Collins, J. J. *Nat. Rev. Genet.* 451-464 (2005).
4. Spudich, J. L. & Koshland, D. E., Jr. *Nature* **262**, 467-471 (1976).
5. Kimmel, A. R. & Parent, C. A. *Science* **300**, 1525-1527 (2003).
6. Meili, R. & Firtel, R. A.. *Dev. Cell* **4**, 291-293 (2003).
7. van Haastert, P. J. & Devreotes, P. N. *Nat. Rev. Mol. Cell Biol.* **5**, 626-634 (2004).
8. Manahan, C. L., Iglesias, P. A., Long, Y. & Devreotes, P. N. *Annu. Rev. Cell Dev. Biol.* **20**, 223-253 (2004).

Nelson, continued from page 5

at a location of about 2 mm on the position axes shown. The resulting wavepackets propagated away from this location in both lateral directions, and the left-propagating wavepackets appear within the field of view of the images shown. The wavepackets are superpositions of several planar waveguide modes that separate spatially after a short time due to their differing group velocities. This is particularly apparent in the lower left-hand figure which clearly reveals three modes, outlined with white lines, that propagate with distinct group and phase velocities.

The dispersion relations resulting from Fourier transformation of the space-time plots in both dimensions are shown in the right-hand plots of Fig. 1. Several trends, consistent generally with waveguide theory [10], are apparent from the results. First, the frequency gap between distinct waveguide modes decreases with an increase in film thickness. In the limit of a bulk crystal, we expect a dense manifold of modes spaced closely enough that their discreteness may be neglected and a continuum model used instead. Second and related to this trend, the number of modes accessible within the wavevector range generated increases with crystal thickness. Calculations and finite difference time domain simulations confirm that three modes should be accessible in the 50 µm film and two modes in the 34 µm film for the 100-µm excitation beam width used. Third, the group velocity becomes progressively smaller in higher order modes, a trend that is apparent from the gradual reduction in the slopes of the successive dispersion curves shown in Fig. 1. Waveguide modes can be expressed as superpositions of waves with forward and backward wavevector components that reflect off of the front and back crystal surfaces with well-defined bounce angles. Interference between such waves gives rise to the nodal patterns characteristic of the different waveguide modes. Higher order modes with more nodes in the crystal plane arise from waves with more oblique bounce angles, which lead to slower lateral propagation speeds than those of lower order modes. Finally, the phase velocities are faster than those of the bulk LN crystal, i.e. the refractive index values are smaller than the bulk value (n = 5.2) even for the lowest-order modes and more so for those of higher order since their dispersion curves to not extrapolate to zero frequency at zero wavevector. In the 34 µm thick film, the effective indices of refraction are 3.0 for the lowest-order mode (p = 0) and 1.5 for the second mode (p = 1). In the 50 µm thick film, the values are 4.0, 2.0, and 1.2 for the three modes p = 0, 1, and 2 respectively.

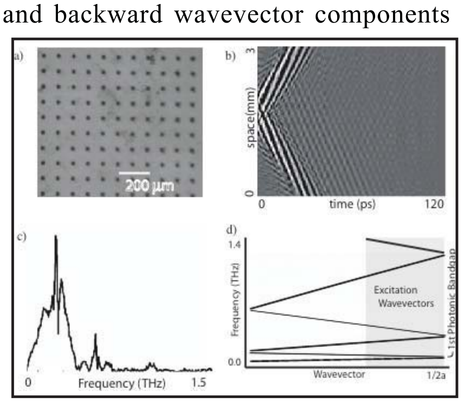


Figure 2. a) Polaritonic bandgap crystal, b) Space-time plot of polariton resonse. c) Fourier transform of a of Fig. 2b at a selected crystal location. d) Theoretical polaritonic bandgap dispersion curve

3.2 Polaritonic bandgap crystals

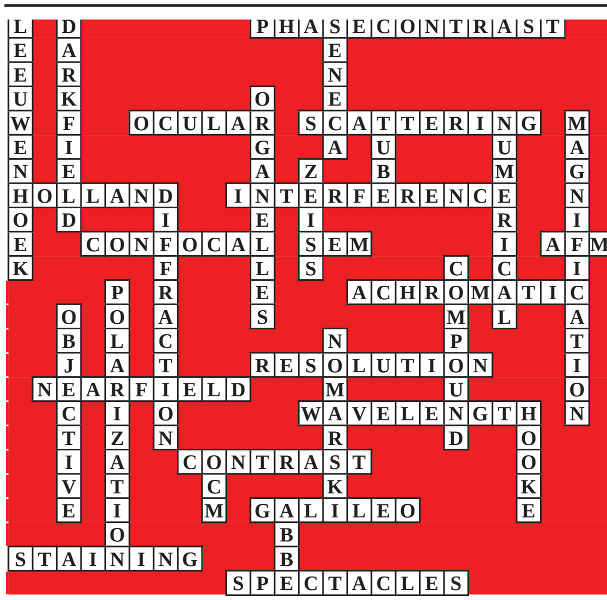
Broadband phonon-polaritons with a center wavelength in the material of twice the lattice periodicity were generated in the polaritonic bandgap crystal shown in Fig. 2a. A condensed display of the resulting propagation is shown in Fig 2b, with the Fourier transform of the response at a selected crystal location, ~2 mm on the space axis of Fig. 2b, shown in Fig 2c. The excitation polariton wavevector range is indicated on the right-hand side of the theoretically calculated dispersion curve shown in Fig. 2d. Although a single line of excitation light produces a broadband polariton wavepacket in an unpatterned crystal, the bandgap structure strongly filters the response, resulting in a narrowed bandwidth as is evident by the multiple cycles revealed in Fig. 2b. Note the high LN:air index contrast of 5.2:1.

The lowest six branches of the photonic dispersion curve (Fig. 2d) are evident in the Fourier transform, with the lower frequency mode of each pair having higher signal strength due to its field localization primarily in the crystalline material (where it is observable in our images) and its counterpart's localization primarily in the air regions.

References

1. Barker, A.S.; Louden, R.; Phys. Rev. 158, 433 (1967)
2. Auston, D.H.; Nuss, M.C.; IEEE Journal of Quantum Electronics 24, 184 (1988)
3. Dougherty, T.P.; Wiederrecht, G.P.; Nelson, K.A.; J. Opt. Soc. Am. B. 9, 2179-2189 (1992)
4. Stoyanov, N.S.; Feurer, T.; Ward, D.W.; Nelson, K.A.; Appl. Phys. Lett. 83, 674-676 (2003)
5. Ward, D.W.; Statz, E.R.; Nelson, K.A.; Roth, R.M.; Osgood, R.M.; Appl. Phys. Lett., 86,
6. Stoyanov, N.S.; Ward, D.W.; Feurer, T.; Nelson, K.A.; *Nat. Mat.* **1** 95 (2002).
7. Ward, D.W.; Beers, J.D.; Feurer, T.; Statz, E.; Stoyanov, N.; Nelson, K.A.; *Opt. Lett.* **29** (2004) 2971-2673
8. Huang, K.C.; Bienstman, P.; Joannopoulus, J.D.; Nelson, K.A.; Fan,

Answers to the previous issue's crossword puzzle



Congratulations to Luis Galindo, winner of the Spring issue crossword puzzle.

Please send your solution of this issue's crossword puzzle on page 16 to Gabi Popescu (gpopescu@mit.edu).

Lester Wolfe Workshop in Laser Biomedicine

Bio-Optics of DNA:
Shedding Light on Structure and Dynamics

Tuesday, November 14, 2006
4:00-6:00pm

Massachusetts Institute of Technology
HST Lecture Hall
Building E25 (Whitaker College), Room 111
45 Carleton St,
Cambridge, MA

Refreshments served at 3:30pm

The central importance of DNA to all of biology has led researchers to study its structure and function at the single molecule level. This symposium will cover some optical approaches for studying and manipulating DNA molecules, particularly concerning laser tweezers and fluorescence resonance energy transfer techniques.

Introductory remarks
Brian Seed, Harvard Medical School and Massachusetts General Hospital

Taking Movies of DNA Actions: From *in vitro* to *in vivo*
Sunney Xie, Harvard University

Analyzing DNA Dynamics Using Nanopores and Single Molecule FRET
Amit Meller, Boston University

Watching Tweezed Hairpins with FRET
Matthew Lang, MIT

PLEASE POST

Seminar on

Modern Optics and Spectroscopy

Fall Semester 2006

September 26	Art Utz, Tufts University **Probing methane dissociation dynamics with selectively energized reagents**
October 3	Gabriel Popescu, MIT **Quantitative phase imaging: Watching cells waltz**
October 17	Marlan Scully, Texas A&M University and Princeton University **Single-photon Dicke super and sub radiance**
October 24	David Pritchard, MIT **Confined atom interferometers**
October 31	Eric Statz, MIT **Polaritonic structure imaging**
November 7	Pablo Jarillo-Herrero, Columbia University **Low temperature electronic transport properties of graphene**
November 21	Hans Bechtel, MIT **Partner swapping: Another reason to pump and dump**
December 5	Tom Foster, University of Rochester **Optical signatures of response to photodynamic therapy**
December 12	Sam Achilefu, Washington University **Spying cancers with colorful molecules**

Tuesdays, 12:00 - 1:00 p.m., Grier Room (34-401)

Refreshments served following the seminar.

Sponsored by the George R. Harrison Spectroscopy Laboratory, Department of Electrical Engineering and Computer Science, and School of Science, MIT

PLEASE POST

GEORGE R. HARRISON SPECTROSCOPY LABORATORY
MICHAEL S. FELD, DIRECTOR
77 MASSACHUSETTS AVENUE, ROOM 6-014
CAMBRIDGE, MASSACHUSETTS 02139-4307

TELEPHONE: (617) 253-7700
FAX: (617) 253-4513
URL: http://web.mit.edu/spectroscopy/

G.R. Harrison Spectroscopy Laboratory

Independent Activities Period Lectures and Poster Presentations

January 11, 2007; 9:30 am-3:00 pm, Grier Room (34-401, A & B)

Spectroscopy for Alternative Energy

IAP lecture program, 9:30 am - 11:30 am

Daniel Nocera, MIT Department of Chemistry
On the global energy future

James McCusker, Michigan State University:
Spectroscopy of charge injection in solar cells

Vladimir Bulovic, MIT Department of Electrical Engineering and Computer Science
Organic photovoltaics for solar energy conversion and lighting

Poster session and lunch

11:30 am - 1:30 pm

Prizes awarded for the posters with the most science, the most spectroscopy, and the most originality!

Graduate Student Talks

1:30 pm -3:00 pm

Jeffrey Kay, Field group
Rydberg states of CaF and NO: Structure and dynamics

YongKeun Park, Feld group
Nanoscale live cell imaging using optical interferometry

Michael O'Kelly, van Oudenaarden group
Noise analysis in yeast ribosomal DNA

Darius Torchinsky and Christoph Klieber, Nelson group
Structural correlation length and time scales of complex materials

PLEASE POST

Spectral Lines

Mediocrity and Illumination

by Stephen R. Wilk
Textron Defense Systems
Wilmington, MA

Stephen R. Wilk

Now I go to become a ghost myself. I will stand in the shadows when you come here to this earth in your turn. And when you feel the dreadful bite of your failures – and hear the taunting of unachievable, uncaring God – I will whisper my name to you: 'Salieri:Patron Saint of Mediocrities!' And in the depth of your downcastness you can pray to me. And I will forgive you….Mediocrities everywhere – now and to come – I absolve you all. Amen!

Playwright Peter Shaffer never claimed that his play *Amadeus* was historically accurate. *Amadeus* was no more the true story of Wolfgang Amadeus Mozart and Antonio Salieri than his *The Royal Hunt of the Sun* had been the story of Francisco Pizarro and the Incan Emperor Atahuallpa, nor *Equus* the story of a British boy who blinded six horses. Shaffer took his inspiration from real incidents, but he wove these facts into allegories about the relationship between God and Man. *Amadeus* asks how it could be that a just and loving God bestowed his Gifts of Music upon an undeserving and ungrateful boor, while leaving the virtuous and devoted Salieri a mediocrity. And so Salieri, slighted, as he thinks, by God, wages war upon Him in the person of Mozart.

Except, of course, that Salieri was not a musical mediocrity. He was *Kapellmeister* to Emperor Joseph II in Vienna for 36 years, was president of the Musical Society, taught an array of famous pupils (including Beethoven), and composed a great many Operas and pieces of Church Music. Since the play appeared, and especially since the appearance of Milos Forman's film version, there have been re-stagings of Salieri's Operas and concerts of his music. New CDs of his works have been released in recent years, including Cecelia Bartoli's *The Salieri Album*. Salieri was not mediocre – simply overlooked.

In the world of Physics, I have often felt as if Thomas Young (1773 – 1829) was the Patron Saint of Mediocrity. Not, I hasten to point out, because he or his work were mediocre. Young has an enviable track record, championing the Wave Theory of Light, doing important work on the Accommodation of the Eye, expounding on Elasticity, writing numerous articles for the new Encyclopedia Britannica, helping found Egyptology, and being a practicing physician on top of all that. But in two of his most famous endeavors, Young came out second-best. His work on translating the Rosetta Stone has been overshadowed by Champollion's work, and his formulation explaining the Supernumerary Rainbow was incorrect.

In the first case Young had no need to be ashamed. He was an expert on languages, speaking over a dozen of them. His was the first successful work on the Rosetta Stone, and he succeeded in translating the Demotic Script (which he called "Enchorial") and made the first inroads into Hieroglyphics. His work was published well before that of Champollion, who eventually succeeded in deciphering the Hieroglyphics completely, but who never acknowledged Young's prior achievements.

"In two of his most famous endeavors, Young came out second-best. His work on translating the Rosetta Stone has been overshadowed by Champollion's work, and his formulation explaining the Supernumerary Rainbow was incorrect."

As for the latter, that is one of the rarely-told stories of physics. All too often in the history of science the work of scientists past is glossed over. They become figures like prairie dogs, invisible until and unless they surface to grant their name to a formula or a principal or a constant. I knew of Young because of his Modulus of Elasticity and his two-slit experiment and even his work on hieroglyphics[1] I had to wonder about the sort of person whose claims to fame were in areas as widely scattered as Optics, the Physics of Materials, and Egyptology.

Thomas Young started as a classically-trained scholar, whose interests could go in any direction. Early on his interest in the Eye took him to study accommodation, and from there his interest in light lead him to study that subject, and to challenge the then dominant *corpuscular* theory of light. Today, with the advantage of hindsight (and knowing the Einstein and the photoelectric effect wouldn't come around to bedevil the issue for another century), the Wave Nature of Light seems to be an obvious thing. But it was a live issue at the time, and many objected that no conceivable medium could support light rays yet offer no other physical manifestation, or that the wave theory could not explain the fact of extraordinary refraction. Against these objections, Young struggled to produce convincing demonstrations and explanations. He looked for evidence of the Wave Nature of Light everywhere, and found it in reflections from fine scratches, soap films and oil films, diffraction around edges[2] , and the supernumerary rainbow.

The Supernumerary Rainbow is the name given to the "extra" rainbow arcs located within the curve of the Primary Rainbow, after Red, Orange, Yellow, Green, Blue, Indigo, and Violet. Under the right conditions, one may often see extra bands within these, alternating in purple-pink and blue-green. Newton did not mention these, and may have been unaware of them, although Edme Marriotte had described them in the 17th century. Others tried, without success, to explain them.

To the modern opticist, the alternating green-blue and purple-pink coloring suggests multiple order white light interference, characteristic of oil films and all but the thinnest soap bubbles. Young, too, may have made the analogy with these effects, and surmised that the effect was due to the superposition of light waves traveling different paths and *interfering* with each other (a term he was the first to use).

In the cases of thin films and plates, Young explained the variation in color as being due to interference between reflections from the front and rear surface of the plate or film. If light was a wave, as he surmised, then the two reflections would be of opposite sign and cancel each other when the optical path length between the two reflections was equal to half a wave. This effect was inexplicable using the corpuscular theory of light, but developed naturally from the wave theory of light.

Young explained the supernumerary rainbow in the same way. The rainbow

Mediocrity, continues on page 14

Mediocrity, continued from page 13

occurs, as Rene Descartes showed, where rays exiting the spherical raindrop form the smallest angle relative to the line between the drop and the sun. rays passing through the center of the drop are undeviated, but the angle of deviation increases as the distance between the point where the ray enters the drop and the center of the drop increases, until the point where the ray strikes the drop at 86% of the drop radius. The angle between the outgoing ray and the line to the sun is then about 42˚, the smallest it will get. If the ray strikes the drop farther from the center than this, the angle begins to increase again. Descartes's view was that the rainbow appeared where it did because, although rays are emitted from the drop in almost all directions, the bulk of them are directed near this minimum deviation angle. That explains the one bright peak, but not the supernumeraries.

Young's explanation was that pairs of rays, one impacting on either side of that critical ray, would exit from the drop along the same angle relative to the sun, but with different path lengths. Along directions where the path length difference amounted to an integral number of waves, these rays would reinforce each other, and you'd get a bright supernumerary band. There would be a great many such subsidiary bands, all located inside the main rainbow and weaker than it, just as observed. What's more, such supernumerary rainbows would only be visible when the drops were very nearly the same size, since only then would there be a large effect from many drops adding together and giving maxima along the same direction. If the sizes of the drops varied, then the path length differences along any given direction would vary as well, and there would be no cumulative effect. The competing sets of Supernumeraries from each different size of drop would "wash out". That explained why supernumerary rainbows were not always seen. You needed to not only have a collection of drops in the right place, as for the major rainbow, but you also had to have a restricted range of droplet sizes.

A ***Supernumerary Rainbow*** *can be seen roughly on the diagonal in the picture above. (Thanks to http://www.museum.vic.gov.au/scidiscovery/light/interfere.asp).*

Young's explanation seemed to cover all the observed facts. I was therefore surprised when I saw in Charles Boyer's book a reproduction of a graph from George Biddell Airy's important paper "On the Intensity of Light in the neighbourhood of a Caustic" from 1849. It showed three plots of rainbow intensity vs. emergence angle. One represented Descartes' rainbow, with a smooth curve starting out low and gradually increasing toward infinity at the Cartesian Rainbow Angle. Another showed Airy's physical Optics calculation, with a series of oscillations – the Supernumerary Rainbows that Young sought to explain. The peak intensity is near, but not at , the Cartesian Rainbow angle, and the intensity does not stop at the Cartesian angle, but gradually tails off outside it. The third plot, however, showed the predicted intensity from Young's theory. It has the Supernumerary peaks, but they are out of phase with those of the Airy function by about 1/8 of a cycle. The intensity reaches up toward infinity at the Cartesian rainbow angle, and it ceases abruptly at the Cartesian angle. It appears, in other words, as if Young was wrong. He had the right idea going in, but failed in the execution, just as with the Egyptian Hieroglyphics. Like Salieri to Airy's Mozart.

"Young's explanation was that pairs of rays, one impacting on either side of that critical ray, would exit from the drop along the same angle relative to the sun, but with different path lengths. You needed to not only have a collection of drops in the right place, as for the major rainbow, but you also had to have a restricted range of droplet sizes."

How could Young have miscalculated so badly? Having found a satisfactory explanation in general, how could he fail in execution? I obtained a copy of Airy's original paper. Airy is careful to not attribute that graph to Thomas Young. He never refers to it as "Young's Theory", but as "the imperfect theory".

It's clear that Airy is criticizing the direct and uncritical application of Young's explanation to the calculation of the intensity. If you assume that you only need consider the pair of rays – one from each side of the Cartesian ray – that emerge parallel from the raindrop in calculating the intensity, then you will get that "imperfect theory", with its sharp cutoff and phase error. The true calculation must take into account that every point on the wavefront acts as a nucleus for wave formation, as in the Huygens-Fresnel theory, and so one must integrate the contributions from each point on the wavefront, not merely from the two points the geometrical optics predicts will contribute to that angle.

A little thought shows that the Imperfect Theory really is demonstrably erroneous in a number of ways. It is not a geometrical or a physical optics formulation, but an incomplete combination of the two. It assumes strictly geometrical wave propagation only in a direction normal to the wavefront, but assumes that the light is in the form of waves that interfere. It assumes waves of all wavelengths, down to infinitesimal, high-frequency waves. A real wave calculation must show the limitations imposed by the finite size of the waves. An infinitely high peak in the intensity at the Cartesian angle, and the sharp and complete cutoff beyond are impossible unless waves of all wavelengths, including those of vanishingly small size are included. Yet the rainbow must be limited to wavelengths of visible light, as Young well knew.

Young never saw the graph of intensity vs. emergence angle. If he did, the unphysical nature would surely have struck him with force. He did make the mistake of assuming geometrical propagation in his verbal description of the interference phenomena, it is true, but his point was made. In all other examples – the single-slit and double-slit experiments, Newton's Rings, Interference from Parallel Scratches (very nearly diffraction gratings) all properly take into account the Huygens-Fresnel nature of wave propagation. In these cases the wavefronts are all planar or spherical (or cylindrical). Young ran afoul of the Huygens-Fresnel principle in the case of the rainbow because the wavefront is *not* a simple planar or spherical wave in this case – it is a cubic (to first order, as Airy calculated it), with a pronounced cusp. He assumed that the same explanation of path length differences along parallel rays would suffice as it had before. This time, however, it did not.

Mediocrity, continues on page 15

Mediocrity, continued from page 14

Thomas Young (1773-1829)

Young is famous for his experiments on and advocacy for the wave theory of light, including his double-slit experiment (1801), but he made an error in his analysis of the Supernumerary Rainbow

Young was interested in providing evidence for the wave nature of light, and that was foremost in his mind when he proposed his explanation of supernumeraries. Having found an excellent example from nature to bolster his case, along with a simple, intuitively grasped explanation, he sought no further to explain his observations. He was still in the thick of defending his case for the mere existence of the wave theory. Airy was able to perform his calculations 35 years later, when the arguments had cooled down and the wave theory was in the ascendant.

So Young's theory of the rainbow did contain a flaw which he missed in the more immediate fight over the Nature of Light. Airy himself acknowledged Young's achievements and genius: "…I well knew that in writing on *any* physical subject it is but ordinary prudence to look at [Young's work] first." (Robinson, p. 186). Young was no mediocrity. To cite his most recent biographer, Andrew Robinson, "Young made mediocrities uneasy, and to cover their unease, they belittled and ridiculed him."(p. 63)

Endnotes

1. If there is any comfort in the afterlife, it is that most people I've talked to not only don't know of Young's contributions, they had never heard of Champollion, either. The rivals are now united in obscurity.
2. His first lecture on the topic, surprisingly, did *not* feature his famous two-slit experiment, but an observation of light diffracting around a thin obstruction. The two-slit experiment was described six years later in print. It has recently been suggested that Young never even performed the experiment, but used it simply as a *Gedankenexperiment* to explain the principal.

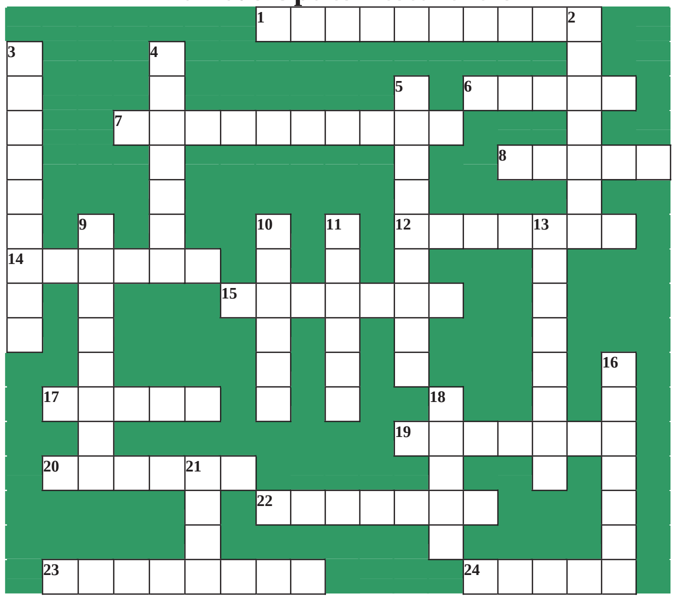
References

1. **Amadeus** Peter Schaffer Penguin Books 1981
2. There are three book-length biographies of Thomas Young (and countless briefer ones). The most recent is **The Last Man Who Knew Everything** Andrew Robinson , Pi Press (2006) **;** The others are **Thomas Young, Natural Philosopher** by Alexander Wood and Frank Oldham, Cambridge Univ. Press (1934), and **Life of Thomas Young, M.D., F.R.S. &c.** by George Peacock, D.D. , publ. John Murray of London (1855) Peacock was an acquaintance.
3. An excellent and very accessible treatment of both the geometrical optics rainbow and the Airy Theory is in R.A.R. Tricker's **Introduction to Meteorological Optics** American Elsevier Publ. (1970)
4. Young's own work is available in **miscellaneous Works of Thomas Young, M.D., F.R.S., &c.** , edited by George Peacock, publ. John Murray of London (1855), but reprinted in 1972 by Johnson Reprint Co. of New York & London. The critical paper on interferen, "Experiments and Calculations relative to Physical Optics" appears there, and in the Phil. Trans. Of the Royal Soc. London **94** pp. 1-16 (1804)
5. George Biddell Airy's Paper appeared in the Trans. Cambridge Phil. Soc. **6** 397-403 (1838), with Addendum in **7** 595-600 (1849). Both are reprinted in two different editions of the SPIE Milestones series, but without graphs or illustrations. **Selected Papers on Scattering in the Atmosphere MS-7**, Craig F. Bohren, ed. (1989) pp. 329-357; and **Selected Papers on Geometrical Aspects of Scattering MS-89** ed. Philip L. Marston (1994); The graph appears in **The Rainbow: from Myth to Mathematics** by Carl B. Boyer Princeton Univ. Press. It also appears (without the Decartes result) in M.V. Berry "Exuberant Interference" **Phil. Trans. Royal Soc. London A 380** 1023-1037 (2002).

Mildred Dresselhaus honored with Harold Pender Award

Mildred Dresselhaus, Institute Professor and Professor of Physics and Electrical Engineering, was honored with the Harold Pender Award from the University of Pennsylvania School of Engineering. The award was recieved in February 2006 and covers the period Spring and Summer 2006. "The Harold Pender Award, initiated in 1972, is given by the Faculty of the Moore School to an outstanding member of the engineering profession who has achieved distinction by significant contributions to society. The Pender Award is the School's highest honor and is celebrated with a guest lecture by the honoree and a reception." Ms. Dresselhaus was cited "for pioneering contributions and leadership in the field of carbon-based nanostructures and nanotechnology, and for promoting opportunities for women in science and engineering." Previous winners include John Mauchly and J. Presper Eckert (1974), inventors of ENIAC, Nobel Prize winner John Bardeen (1988), co-inventor of the transistor and contributor to the theory of superconductivity, and Nobel Prize winner Arno Penzias (1991), discoverer of the background microwave blackbody radiation of the universe. For more information on the Harold Pender award, visit http://www.seas.upenn.edu/pubs/pender-award.html.

Famous Optics Researchers



Across

1. Formulated the uncertainty principle
6. Discovered the effect of inelastic photon-phonon interaction
7. Derived the formula for far-field diffraction
8. Invented holography
12. Introduced a mathematical transformation used in Kramers-Kronig relationships
14. Polarization vector
15. His equations are on the first page of optics textbooks
17. Invented the HeNe laser
19. His transform applies in optics, too.
20. Defined the principle of minimum action in geometrical optics
22. Approximated the spherical wave front with a parabola
23. Discovered scattering from tiny particles
24. Worked with Perot

Down

2. Received the 2005 Nobel Prize in Physics for "his contribution to the quantum theory of optical coherence"
3. Performed with Morley the famous "failed experiment" on ether
4. Invented phase contrast microscopy
5. The wave equation in the frequency domain has his name
9. The polarization sphere is named after him
10. Gave the law of black body radiation
11. Although he got the refraction wrong, has an equation named after him in geometrical optics
13. Explained the photoelectric effect
16. Discovered the effect of polarization rotation due to magnetic fields
18. Introduced a complex matrix formalism for describing polarization
21. Wrote first theory of microscope imaging

MASSACHUSETTS INSTITUTE OF TECHNOLOGY
G. R. HARRISON SPECTROSCOPY LABORATORY
CAMBRIDGE, MA 02139-4307

Nonprofit Organization
US Postage
PAID
Cambridge, MA
Permit No. 54016