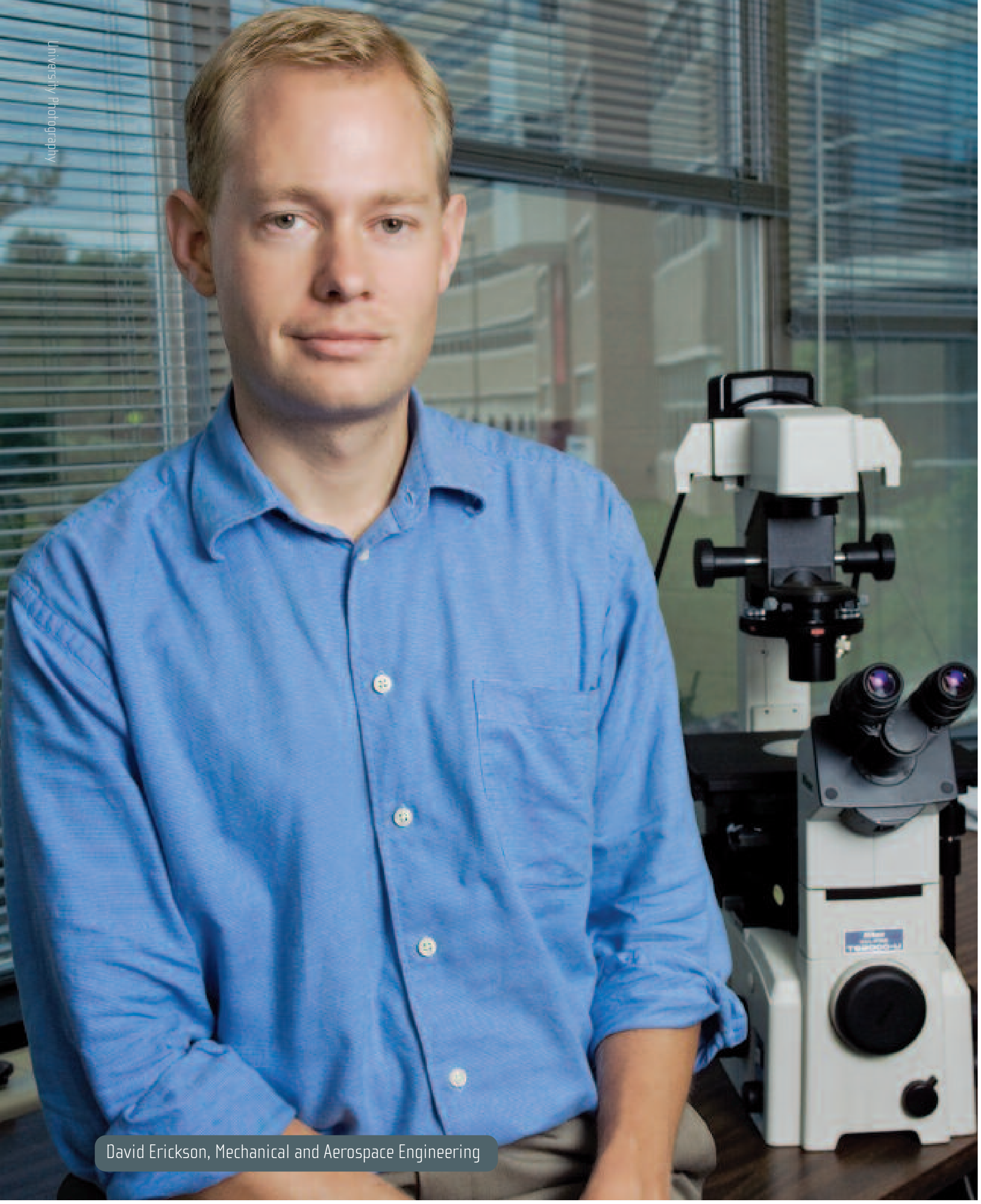
David Erickson, Mechanical and Aerospace Engineering

University Photography

Using Light's Schizophrenia
Optofluidic Devices

For most of us, light is the stuff whose absence or presence determines how easy it is to get to the bathroom in the middle of the night. It surrounds us and illuminates our world. However, beneath its seemingly mundane and ubiquitous presence, light is fundamentally peculiar stuff.

Most of us who have taken at least some high school science know that unlike sound, the speed of light is constant no matter how fast you are traveling toward or away from the source. Many are aware that the speed of light has something to do with nuclear weapons, or at least know Einstein's famous equation: $E=mc^2$, with c being the speed of light. But only those quite familiar with light's underlying nature know that it suffers from a serious form of schizophrenia—its so-called wave/particle duality. Sometimes it behaves like it is composed of tiny particles, and sometimes it behaves like a vibrating wave.

Exploiting Light's Duality

David Erickson, Mechanical and Aerospace Engineering, is familiar with light's nature, and he is exploiting both sides of its split personality to help life scientists and others manipulate and identify biomolecules and organisms easily and with extreme sensitivity. His work has already resulted in the disclosure of two inventions to the Cornell Center for Technology, Enterprise, and Commercialization (CCTEC) since his arrival in Ithaca in the fall of 2005. The first invention is a device for separating objects suspended in a liquid using a laser beam; this device exploits the particle-like behavior of light. The second invention is a device for detecting molecules and organisms of interest in a liquid; this device exploits the wave-like behavior of light. Erickson's student, Sudeep Mandal, is a co-inventor of both devices.

Starting Out

Erickson did not start out with an academic career in mind. He was born in Edmonton, Alberta, where his father was working as an electrician in the oil business. Erickson stayed in Edmonton to attend the University of Alberta, majoring in chemical engineering. For a short time it seemed that he too might end up in the oil business, but one of his co-op jobs just after college convinced him to pursue an academic career instead. The job was in an experimental bitumen plant for processing the tar sands into oil products. Erickson joined the other new workers on the bottom floor. He wondered why the new workers were assigned to the bottom floor, which was significantly cooler than the upper floors—each hotter and more oppressive than the one below. It did not take long to discover the reason; bitumen and the other nasty chemicals handled in the facility dripped downhill, covering everything with a coat of black gunk. "It would get all over you," Erickson remembers. "Most days it took less than an hour for clean outfits to become covered with black gunk. It started out being kind of fun," Erickson continues, "We were out there and getting things done, but after a while it was just hot and sticky."

So Erickson left Alberta and the tar sands behind to attend the University of Toronto. There he began to work in fluidics, focusing on microfluidic systems, lab-on-chip devices, and the fundamentals of microscale transport. He earned his master's degree and then his doctorate. His next stop was a postdoc assignment in Pasadena at the California Institute of Technology. Erickson began learning about optical physics and integrating optical devices and fluidic systems. It was this work that led to his innovations at Cornell. Optofluidics is the integration of fluidic and optical systems. Since arriving at Cornell, Erickson has been particularly interested in optofluidics in nanoscale devices where many of the approaches developed for microfluidic systems a thousand times larger fail to work. Part of the attraction for Erickson is that optofluidics on the nanoscale is a relatively new area where one can pursue risky research projects confident that some interesting physics will come out of it. Moreover, Erickson likes to aim for things with clear application bases and where his work, in his words, "can improve the state of the art by an order of magnitude."

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Using Light's Particles

Both of the recent inventions from Erickson's research group are optofluidic devices. The first invention of Erickson and Mandel is a technology that exploits the particle side of light to separate organisms suspended in a liquid sample. Particles of light, called photons, do not have any mass, but they do carry momentum. The momentum of photons can be transferred to the objects they strike, creating something called radiation pressure. Fortunately for us, the energy in each photon is miniscule (4 x 10^{-19} joules for visible light; joules themselves are quite small—it takes 360 million joules to power a 100 watt light bulb for an hour). It is enough to excite a single photoreceptor in our eyes as we enjoy a sunset, but not enough to make walking towards the sunset noticeably harder than walking away from it. Radiation pressure is, however, large enough that sunlight shining on satellite solar panels can be used to make minor corrections to the satellite's orientation and orbit, and, if a laser is used as a light source, to separate particles in a liquid.

Erickson was not the first to attempt using light energy to move materials. Optical tweezers are already used to manipulate objects ranging from single atoms to micron-sized particles, and lasers have been used to separate objects suspended in liquid. Optical separation (or chromatography) has been of great interest because the propulsive velocity of objects under optical stimulation has as much as a fifth power dependence on particle radius and is also highly sensitive to refractive index. Other researchers have used optical stimulation to demonstrate very precise separation between very closely related bacteria, deadly Bacillus anthracis (anthrax) and harmless Bacillus thuringiensis (found in soil and the source of genes for insect-resistant transgenic Bt crops), something difficult to achieve by other nonspecific separation means. However, optical separation devices have only been able to achieve small separations on the order of millimeters, separations too short to take full advantage of the power of optical separation techniques.

The problem with previous devices has been that in order to increase the intensity high enough to separate the particles, the light had to be focused down to a very small spot. Such tight focus means that the beam's useful "depth of focus" is very small, and the beams diverge very quickly after achieving a useable intensity. Erickson and Mandal's device solves this problem by using a separation column constructed of liquid-core photonic crystal fiber (LC-PCF). The construction of photonic crystal fibers is such that light is trapped within the liquid-filled core by total

Provided

INFO

Using Light


Frank DiMeo

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- Erickson's detector might be integrated into a portable and disposable detection device.

internal reflection, the same principle used in optical fiber for telecommunications (the holey structure surrounding the liquid core acts like a mirror). As a result, there is very little lengthwise dissipation of the laser's optical energy, and separations of several centimeters and more can easily be achieved.

Potential uses of their new device include the detection of waterborne bacteria and viral pathogens, which cause large numbers of deaths worldwide each year. It also has potential use in chromatography devices to separate and concentrate particles of varying sizes and compositions. As Erickson wrote in the disclosure received by CCTEC, "With further development this could be the first practical technology that can take advantage of the exception potential of optically driven separations."

Using Light's Wave Properties

The second invention is a device for detecting biomolecules and organisms by exploiting the wave properties of light. To understand how this device works, one must first understand a little about the implications of the wave side of light's split personality and how its wave properties make it behave in a waveguide such as optical fiber. Looking at optical fiber it is easy to imagine that light travels through the transparent glass core in the same way that water travels down a tube. It does not. There are a number of differences, of which two are critical to Erickson's detector. First, unlike a pipe, which can be filled with only one liquid at a time, light of different wavelengths (such as red and blue light) can travel down the same optical fiber simultaneously without interfering with each other. Second, when light travels through an opti-

Optofluidic Devices

Figure 1: Optofluidic Transport in a Liquid Core Photonic Crystal Fiber
(a) Hollow core photonic crystal fiber. (b) Demonstration of trapping and concentration of particles into a stable band structure in a liquid core photonic crystal fiber. Red arrow tracks 3μm bead. (c) Integrated system incorporates a flow through counter direction electroosmotic flow.

Figure 2: Detail of "Side Resonator" NOSA Platform
(a) SEM showing chain of side resonator devices with graphically superimposed boxes which illustrate functionalization channel location. (b) Experimentally obtained resonant dips in output spectrum of bus waveguide for a 5 resonator device integrated with microfluidics. (c) Close up view of a side resonator with FDTD simulations showing the intensity pattern at resonance. (d) 4x5 side resonator array. The scale bar is 1μm in this image.

Figure 3: Envisioned Autonomous Microsystem For Prognostic Detection of Viral Infection

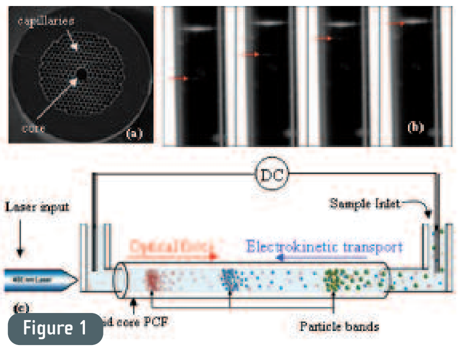

Figure 1

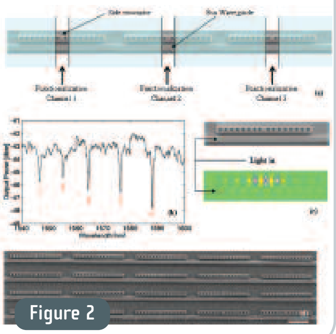

Figure 2

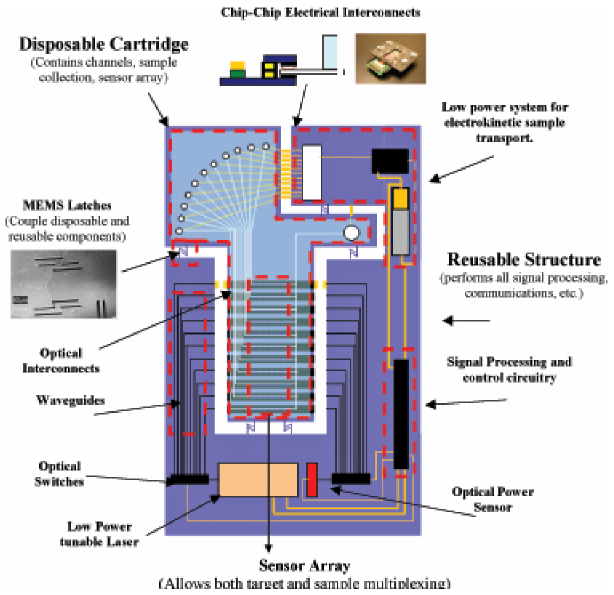

Figure 3

cal fiber, it is not contained completely within the clear core of the optical fiber; a portion of the light actually travels outside the glass core. The portion of the light traveling outside the glass core is referred to as its evanescent field.

The evanescent field makes possible two things essential to the operating of the sensor. First, the light in one waveguide structure can couple with another waveguide structure within its evanescent field. This means that light from one waveguide structure can jump to another nearby waveguide structure. Second, physical interference with the evanescent field affects the light signal in the waveguide. There is one further wave property of light that is essential to understanding the operating of the new sensor. Under proper conditions light waves, like sound waves, will resonate. Optical resonators, often consisting of a waveguide between two reflecting surfaces (called a cavity), have one or more frequencies, and light at those frequencies will resonate in the cavity (one or more standing light waves form such that the positions of their peaks and troughs remains constant).

Light in a resonator may travel back and forth hundreds or even thousands of times between entering and exiting the resonator. Optical resonators are actually familiar to most people, although they do not realize it: lasers are optical resonators that also amplify the light as it resonates. Figure 2 shows the resonators used to make the detector; the holes on either side of the middle section are actually wavelength-specific mirrors known as distributed Bragg reflectors. An explanation of how holes reflect light is beyond our scope here; suffice it to say that it is due to the wave properties of the light in the cavity.

Erickson and Mandal's detector, at its simplest, consists of a waveguide connected to a laser source of light at one end and a detector at the other end, a resonator located close enough to couple with light in the waveguide, and a channel for carrying a liquid sample that crosses the center of the resonator. The channel is functionalized with a detection site or trap for the biomolecule or organism (the target of interest) at the point where it crosses the middle of the resonator. The trap is typically a chemical entity that will bind specifically, only to some portion of the target's chemical structure.

In operation, a laser shines into the waveguide, and because the waveguide is optically coupled to the resonator, the laser light enters the resonator and travels back and forth many times before the light returns to the waveguide to continue on its way. A liquid sample is pumped through the channel past the binding site on the resonator. If the target biomolecule or organism is in the sample, it will attach at the binding site, and its presence will slightly change in the light signal in the resonator each time the light travels past the binding site. If the detection site was simply on a waveguide, that slight change would probably be too small to detect. However, since the light in the resonator travels back and forth many times between entering and exiting the resonator, and the captured targets effect the light on each of those many passes, the slight effect of one pass is amplified hundreds- or thousands-fold, and can now be detected.

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Prototype devices with multiple waveguides coupled to multiple resonator-detectors crossed by multiple liquid channels—Figure 2 (d)—have already been built. The liquid channels deliver samples to multiple detection sites, each of which can be functionalized to detect the same target or different targets. A multiplexed light signal (consisting of separate beams of light, each having a different wavelength) is used, and each of the resonators is constructed to resonate at the wavelength of one of the multiplexed signals. The downward spikes in Figure 2 (b) show the frequency dependence of each of the five resonators shown in Figure 2 (d). Future devices are planned with 20 resonators per waveguide for expanded detection. These devices are not only extremely sensitive, but a single device is able to detect multiple biomolecules and organisms of interest. Figure 3 shows how Erickson's detector might be integrated into a portable and disposable detection device.

Improving the State of the Art

Erickson's foray into optofluidics has so far been very productive. Optofluidics at the nanoscale is a long way from the tar sands and bitumen plants of Alberta, and Erickson is happy with the academic path he has chosen. He is excited by the potential of his work, although he does state somewhat wistfully, "My friends who stayed in the oil business were there when the price of oil rose and made the tar sands economical. They are all millionaires now." CCTEC is already working with Erickson and Mandal to find commercialization partners for these two inventions, and with luck, both will become successful products that help advance our knowledge and improve our health and safety.

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