Photonics: Making light work for us

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Photonics is the science and technology of creating, controlling and using light. Like electronics in the 20th Century, photonics is the enabling technology of the 21st Century. It underpins the solutions to many of the world's current challenges, including high-speed communications, clean energy, advanced manufacturing, healthy ageing, and global climate change. The photonics industry is growing at a rapid pace, much faster than global GDP, with a global market size of over 600 billion euro predicted by 2020 (1). Truly, we are putting light to work for us to make the world a better place.

Photonics also provides an excellent example of how fundamental, cutting-edge scientific research can emerge from the laboratory and have a positive impact on our daily lives. At the time of its invention in 1960, the laser was characterised as a solution looking for a problem (2). However, within three years, laser sales had hit one million US dollars (3). Within 15 years, over 500 patents had been issued for laser technologies and applications (4). Laser welding, laser surgery, laser micromachining, laser barcode scanners, even laser applications in music were almost immediately invented and sold to consumers.

A scan of the Nobel Prizes awarded in Physics and Chemistry shows a remarkable dominance of discoveries related to light – over 25 Nobel Prizes have been awarded for photonics or photonics-enabled breakthroughs. Indeed, the 2014 Nobel Prizes in both Physics and Chemistry went to scientists who invented exciting new photonic technology, the blue LED, and methods to image at super-resolution using light, respectively (5). Closer to home, the smartphone is a powerful testament to photonics and laser processing (6). Virtually every component in this ubiquitous, high-tech device uses light, is made with light, or both.

In this article, we highlight some of the discoveries and applications of lasers in New Zealand. In particular, we focus on the recent development of some extraordinary new laser sources, how our understanding of fundamental light–matter interactions allows us to manipulate exotic laser pulses to improve laser micromachining efficiency, and two examples of how photonic technology is being commercialised here in New Zealand: Southern Photonics and Engender Technologies.

Nonlinear optics and novel laser sources

Because of the physics underpinning their key functions, many photonics applications require a particular wavelength of laser light. These needs have prompted decades of research into developing suitable materials and tailoring laser–matter interactions to produce laser emissions at new frequencies. Yet, despite significant efforts, gaps exist in the electromagnetic spectrum where the light of no laser shines.

Recently advances in this area have been made by the University of Auckland laser physics group through harnessing nonlinear optical effects. The exploration and development of advanced laser sources based on nonlinear optical phenomena is motivated by improving diverse applications such as medical imaging (7), micromachining (8), spectroscopy (9) and precision metrology (10).

Nonlinear effects are characterised by a polarisation in the nonlinear optical material that depends on the electric field of the laser to powers of greater than one. These effects become

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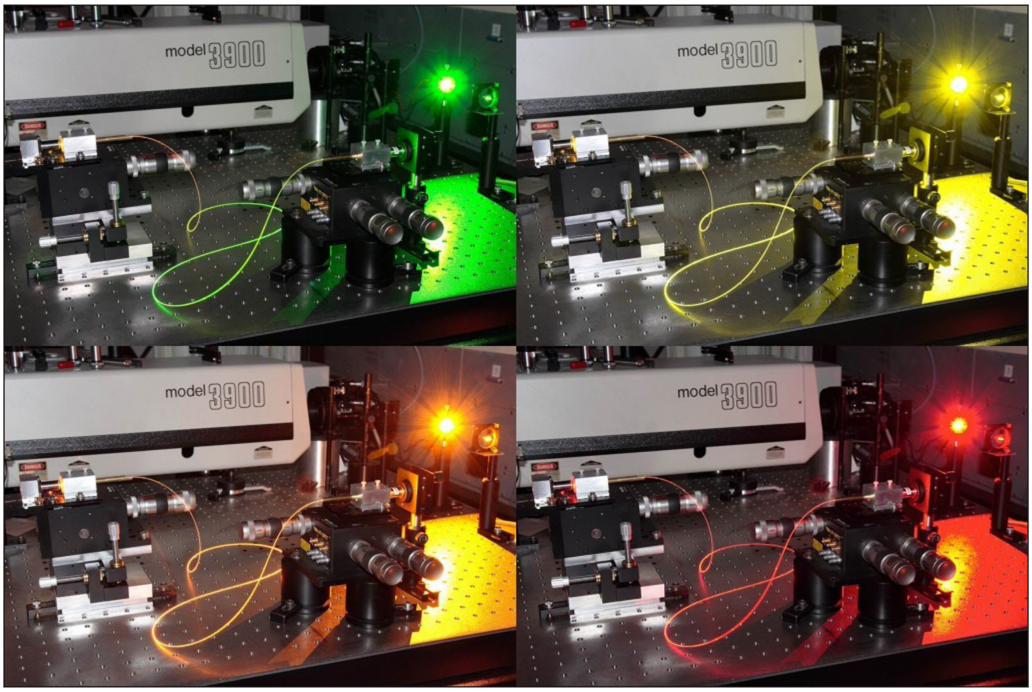

Figure 1. A fibre-based laser source that allows laser light to be converted to different wavelengths.

significant (and useful) when very intense laser light interacts with a nonlinear material.

Nonlinear optical effects make it possible to convert laser light from one wavelength to another. A typical green laser pointer used in a lecture is one example; the green results from frequency doubling an infrared beam. Other nonlinear optical effects include sum- and difference-frequency generation, self-phase modulation, four-wave mixing, and optical parametric amplification (11).

In one area, the Auckland laser physics group exploits the myriad of nonlinear interactions that occur when laser light propagates in optical fibres. When intense laser light is injected into a nonlinear optical fibre, it propagates along the length of the fibre generating multiple wavelengths through nonlinear processes. The longer the fibre is, the longer the interaction is between the nonlinear material and intense light. New frequencies are generated from the original laser frequency and cascading from the newly generated frequencies as well.

Over the past decade, many diverse and novel laser sources based on nonlinear effects in optical fibres have been designed, developed and tested. These include sources that emit laser light whose emission wavelength can be continuously tuned over broad regions of the electromagnetic spectrum (Figure 1) (12), and ultrafast pulsed fibre lasers that unleash laser pulses that are a few hundreds of femtoseconds long (13).

More recently, the group has ventured into exploring and developing sources based on microcavities (14). Advances in the fabrication of microscopically small structures for confining light have led to an entirely new paradigm for nonlinear optical sources. Microcavities allow light to resonate and build up tremendous laser energy. This resonant enhancement and the microscopic confinement volume have led to significant nonlinear phenomena.

When laser light is injected into a microcavity, it can be transformed into thousands of new frequencies, each of which exhibits laser-like properties (Figure 2). A sequence of such frequencies equidistantly spaced is called an *optical frequency comb*. Because of their microscopic size, power efficiency, and emission properties, optical frequency combs generated in microcavities offer advantages to many exciting applications. For example, more data can be squeezed through a single optical fibre by transmitting multiple frequencies. Currently, multiple frequencies are generated by multiple lasers; microcavity frequency combs would enable all of them to be created from a single laser.

The laser group's new theoretical models of optical frequency combs allow complex nonlinear interactions to be simulated on standard computers. These models are now being used by many researchers across the globe, and their introduction is widely considered a game changer in the field (15).

The Auckland laser physics group is learning to exploit fibre-behaviour in other ways as well. For example, a method for storing a sequence of ultrashort light pulses (i.e. an arbitrary stream of binary information) indefinitely, in a loop of optical

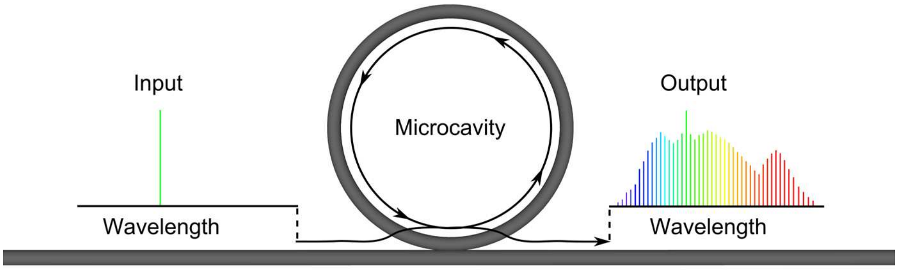

Figure 2. Laser light injected into a microcavity can be converted into thousands of different wavelengths.

fibre, was recently pioneered. Current technology stores data electronically. The new all-optical memory approach has the potential to improve both energy efficiency and speed. It may underpin a greener and faster future internet.

The novel approach to an all-optical form of data memory relies on solitons, or solitary waves. In the context of fibre optics, these are pulses of light that maintain constant shape. However, solitons are not found only in fibres; similar nonlinear waves appear in many other physical systems, including water waves, where they were reported as early as 1834 (16).

It may seem surprising that laser light in optical fibres can behave similarly to waves in water. However, under certain conditions, propagation of light in optical fibres and the evolution of waves in water obey almost identical mathematical model equations – nonlinear Schrödinger equations.

The analogy is not limited to water waves. Many fascinating physical systems, from ultracold atoms to hot plasmas, can exhibit similar wave behaviour. By harnessing these analogies, fibre-optic laser systems can be used as convenient laboratory platforms to gain a deeper understanding of wave behaviour in other physical systems.

Rogue waves provide just such an opportunity. These are rare, unusually large waves that can unexpectedly emerge far out in the open ocean, with great destructive power. For decades they were believed to be the lore of sailors, until one such wave was scientifically detected in the North Sea in 1995 (17). However, because rogue waves are rare and oceans are vast, studying ocean rogue waves *in situ* is very difficult.

Remarkably, experiments performed in 2007 at the University of California revealed that a fibre-optic system could give rise to a phenomenon resembling ocean rogue waves (18). These pioneering observations attracted great interest, essentially spawning an entirely new field of 'optical rogue wave' physics. The University of Auckland laser physics group has been at the forefront of this new field (19), providing a wealth of insights into the extreme instabilities that can occur in laser-based systems (Figure 3).

Thus, in addition to pioneering new classes of tuneable sources of laser-like light, ultrafast femtosecond fibre lasers, and microscopic optical frequency comb generators for a broad swath of existing and future applications, the Auckland laser physics group is leveraging laser physics to explore a myriad of interdisciplinary nonlinear wave phenomena.

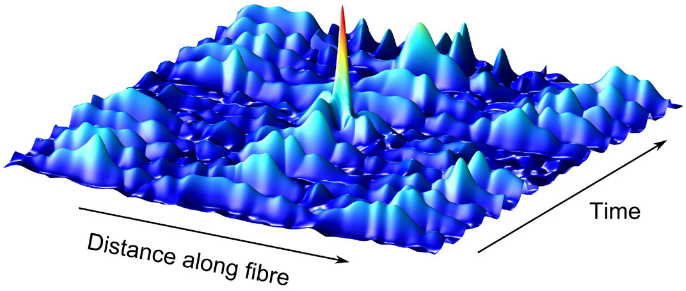

Figure 3. Light propagation in optical fibre can exhibit behaviour resembling giant ocean rogue waves. Here, an intense 'rogue' laser pulse emerges at a specific point along the optical fibre.

Changing the shape of laser micromachining for industry

A laser can pack a tremendous amount of energy in a precise, controllable volume. Very early after their invention, it was recognised that this would allow lasers to machine things in new ways. Today, lasers are used to cut and shape everything from automobile parts to living tissue.

Micromachining has been a particularly fruitful area of laser research and development. We can take advantage of pulsing the laser to increase peak powers without necessitating an increase in average power. Two pulse-duration regimes are important for micromachining: nanoseconds and femtoseconds. The former is useful for rapid micromachining of features that are tens of micrometres in size or larger. The latter is employed for creating higher-precision, smaller features, and when less collateral damage around the cut region can be tolerated (20).

The mechanism of ablation is different for the two regimes. Generally, nanosecond pulses are absorbed by the material and converted to heat in the lattice. The material then melts, is vaporised and ejected (21, 22). In contrast, the peak intensities of femtosecond pulses are so much larger that the interaction with the material is usually multiphoton (23, 24). Multiphoton ionisation and electron avalanche cascade generate a plasma at the interaction site (24). The pulse duration (usually 100 femtoseconds) is significantly shorter than the electron-phonon coupling time (usually a picosecond or longer), so minimal excitation energy is transferred to the lattice to generate heating – this is a 'cold cutting' method (8, 20). The plasma plume leaves the site and is followed by a Coulomb-driven ejection of the material left behind (ions, nanoclusters, nanoparticles) (24, 25).

These mechanistic differences have important consequences. For example, the type of material that can be cut with a given nanosecond laser is limited to those whose absorption bands overlap the laser wavelength. In contrast, multiphoton excitation with femtosecond pulses means that virtually any material can be machined with this approach (26-30). In addition, the temporal uncoupling of electronic and nuclear communication leads to much smaller heat-affected zones with femtosecond laser micromachining.

Unfortunately, femtosecond laser micromachining has not been adopted widely in industry because processing speeds are too slow. Although the peak powers of femtosecond pulses are extremely high – commonly in the gigawatts – pulse energies are nano- to microjoules. Until femtosecond laser micromachining can be made more efficient, the promise in this method will remain unrealised on an industrial scale.

At the Photon Factory, we exploit our deep knowledge of laser–matter interactions and our ability to tailor our femtosecond laser pulses across a wide range of variables to improve the efficiency of femtosecond laser micromachining. We vary the wavelength, pulse duration, frequency sweep within each pulse, multi-pulsing (pre and post) with single and multiple wavelengths and energies, and the temporal and spatial beam shape of each pulse.

One recent success involves optimising the beam shape – the cross-sectional intensity profile – of the femtosecond laser pulses to increase efficiency. Most laser beams are Gaussian; we have constructed a micromachining system that allows us to change the pulse to virtually any beam shape (Figure 4). More

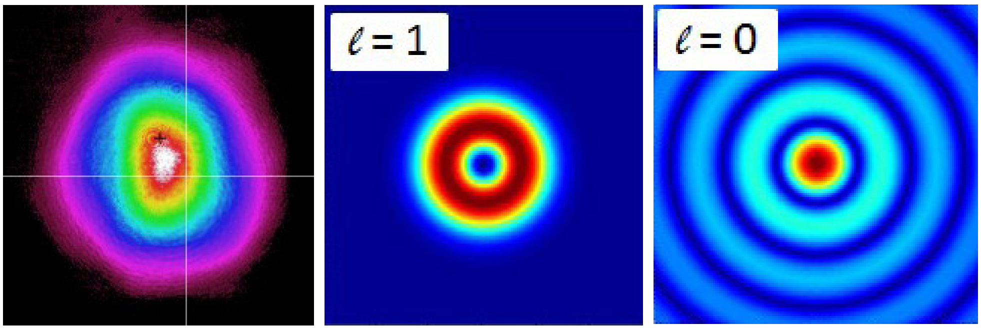

Figure 4. Three beam shapes: Gaussian (left), first order vortex (centre) and zero-order Bessel (right).

importantly, we have developed a method for quantitatively evaluating the resulting ablation efficiency changes.

The relevant efficiency metric is the ablation threshold, F_{th}, the minimum pulse energy density at which material is removed (31). Ideally, the ablation threshold would be a property of the material. In practice, though, it reflects the characteristics of the material (ease of removing electrons, electron-phonon coupling efficiency, thermal conductivity), the laser pulse (duration, shape, energy) and the machining conditions (laser repetition rate, temperature, pre-processing).

Measuring and interpreting the ablation threshold is thus surprisingly challenging, particularly for non-Gaussian beams. A few robust methods have been published, but all begin with the assumption that the beam is Gaussian (31–33). We have recently become the first group in the world to be able to measure the ablation threshold for non-Gaussian beams (34).

We recently reported that, other variables being constant, Bessel beams generally are more efficient than Gaussian or vortex beams for femtosecond laser micromachining (Figure 5) (34). Bessel beams have a cross-sectional amplitude described by a Bessel function of the first kind. The interesting properties of Bessel beams include their non-diffracting, self-healing nature (35, 36). Vortex beams are also known as Laguerre-Gaussian modes or helical wavefronts, as the phase of the beam rotates during propagation (37).

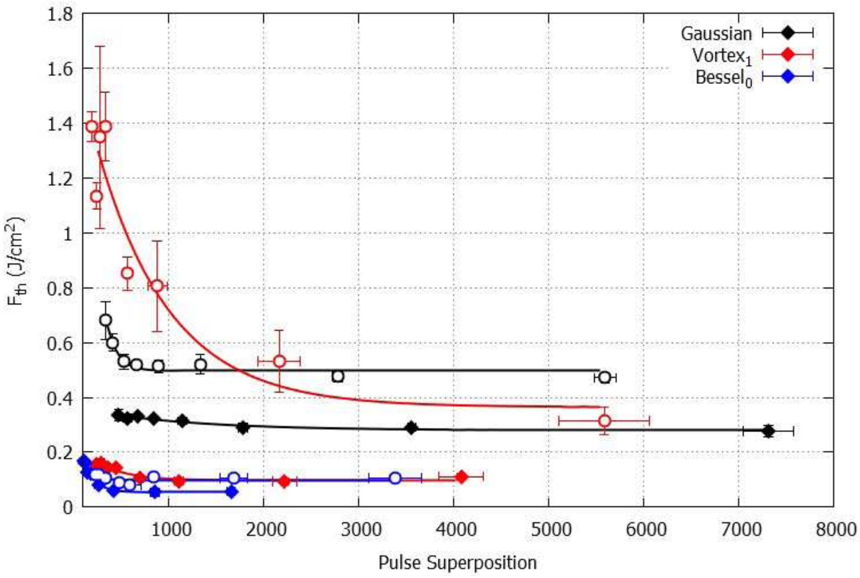

Figure 5. Ablation threshold measurements, F_{th}, as a function of the number of overlapping pulses delivered to the sample (pulse superposition) for silicon (filled symbols) and quartz (open symbols) using three different pulse shapes.

For some materials, excellent results can be obtained with simple beam shaping (tailoring depth of focus) and controlled machining parameters. For example, with an extended depth of focus, and carefully controlled laser power and stage motion settings, 250 µm thick sintered alumina wafers can be cut at speeds of up to 125 µm/s – almost four times faster than the highest previously reported cutting speed for this material (38, 39). That these speeds can be achieved, while leaving the surrounding area undamaged, is a testament to the ability of ultrashort pulse machining, and is extremely promising for future applications.

The femtosecond laser's ability to remove material without imposing excess thermal damage also makes it a prime candidate to replace mechanical tools for orthopaedic surgery. Extensive tests at the Photon Factory show that femtosecond lasers have exceptional tissue removal ability. Most importantly, the collateral damage to the tissue surrounding the laser ablated region can be virtually non-existent (30).

These results provide a path forward for the industrial use of femtosecond laser micromachining. They also open new avenues of exploration into the fundamental underpinnings of pulsed laser ablation. The dependence of laser ablation thresholds on beam shape, and on the other non-materials variables mentioned above, will give insight into the detailed mechanism of the laser ablation process.

Making light work –Two very different spin-off companies

Southern Photonics – one way to commercialise research from a laser laboratory

Towards the end of the 20th Century, a team of physicists at the University of Auckland were studying picosecond laser pulses. The 'telecoms boom' was in full flight, and these pulses were increasingly at the forefront of optical communications. The team developed a novel instrument for characterising short laser pulses through amplitude and phase, rather than intensity.

The success of this approach was followed by requests from other scientists for the technology. Initially, this was achieved through university research contracts. However, in 2001, Professor John Harvey and his team started up Southern Photonics to commercialise novel pulse characterisation instruments (40). Two key drivers underpinned this decision: (1) to capitalise on the tremendous growth in companies with photonics expertise, and (2) to respond to customers' preference for working with a company.

Over the next decade, Southern Photonics expanded its range of instruments. A new market in optical communications test and measurement equipment emerged, in which the information is encoded on the phase of the underlying carrier wave and in the amplitude of the optical signal. Because of its reputation, Southern Photonics was ideally placed to partner with a major international oscilloscope manufacturer to produce a combined instrument that analyses the new modulation formats.

By this time, the Southern Photonics product range extended beyond optical communications. The company was split: the daughter company, Coherent Solutions (41), focuses on telecoms; Southern Photonics concentrates on other photonic technologies, including femtosecond fibre lasers, optical fibre systems for temperature and strain measurement, and photonic gas sensors. Southern Photonics also provides consulting and prototype development through its partnership role in the new Dodd Walls Centre for Photonic and Quantum Technologies.

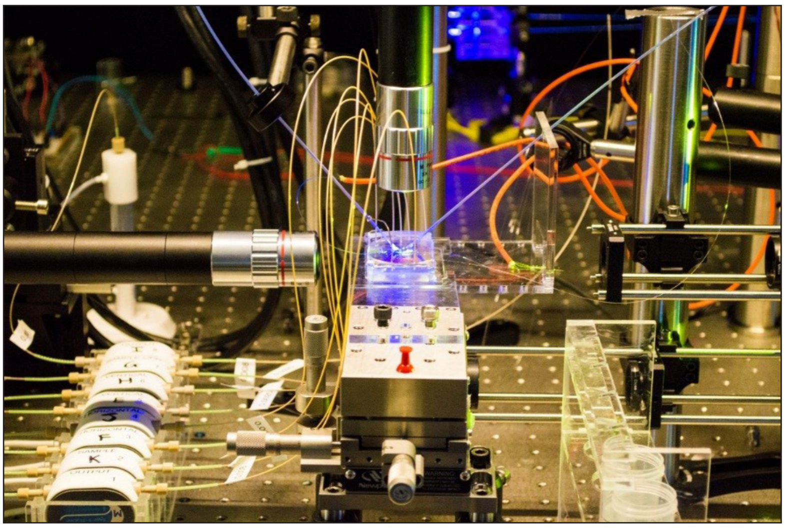

Figure 6. Photonic and microfluidic chip developed at the Photon Factory for sorting bovine sperm for the dairy industry.

We hope that our activities will continue to spur the formation of new companies, so that New Zealand can succeed in developing a photonics-enabled industry. One role model in this area is Scotland, a country similar in size to New Zealand. There, the photonics industry contributes over a billion dollars to the Scottish economy each year. In the next decade, we confidently expect the healthy growth of a photonics industry-based 'ecosystem' with clear career opportunities for graduates and all the excitement that constant startups brings.

Engender Technologies – ***a different way to commercialise research from a laser laboratory***

In 2010, Dr Cather Simpson and Dr Robert Feldman from Pacific Channel Ltd discussed how the Photon Factory's research might help the dairy industry. Sperm sorting by sex seemed like a promising challenge, and Engender Technologies was born.

In contrast to Southern Photonics, Engender Technologies was formed from the outset as a commercial project, co-funded by Pacific Channel and Auckland UniServices, to exploit and commercialise photonics expertise at the Photon Factory. Our goal is to provide an improved technology for sorting bovine sperm by sex, and thereby generate significant economic returns in New Zealand and globally. Success is forecast to create revenues for Engender in the range of hundreds of millions of dollars per year. The Engender project is thus high-risk, high-gain.

Engender, the company, is designed to provide a better option to artificial insemination companies that sell sexed sperm to farmers. The technology we develop must be significantly less expensive, easier to use, and have minimal effect on the sorted sperm viability and fertility relative to unsorted sperm.

Engender's technology is designed to successfully outcompete the only method currently available commercially: fluorescence-activated flow cytometry (FACS) (see p. 50–51). During the FACS sorting process, sperm are forced through a nozzle to form droplets that are then charged. The presence of an X or Y chromosome in the nucleus is detected using fluorescence from a DNA-binding dye. Finally, sperm are directed into different output chambers with an electric field. The interaction with the nozzle generates significant shear stress on the membrane of the sperm head. The electric field further damages the cells. This process thus leads to a significant reduction in sperm viability that translates directly into cost for the dairy farmer.

The team at the Photon Factory decided to use a combination of microfluidics and photonics to sort sperm (Figure 6). We, too, identify X- and Y-bearing sperm with a DNA stain. This method is not detrimental to sperm health, and is well-known; there is clear freedom to operate.

Flow through the microfluidic device is laminar, so there is minimal shear stress on the cell membrane. We have tested this on-site with one of the world's leading artificial insemination companies and demonstrated that sperm viability is unchanged by passing through our chip.

The truly innovative components of the Engender chip are orientation and sorting steps that employ the interaction of light with the cell (42). Bovine sperm heads are disc-shaped. To detect the small fluorescence intensity differences that indicate X- or Y-containing nuclei, the orientation must either be set or known. We use laser-light scattering forces in the orientation of the sperm. We also use a non-trapping force to 'nudge' the sperm into different laminar flow streams in the channels (43). The forces involved in this interaction are orders of magnitude smaller than the electric fields used in FACS sorting, and are not expected to damage the cells at all.

Engender Technologies is still a young company – we are not yet selling sperm sorting devices. However, we have demonstrated the feasibility of the ideas in the laboratory, constructed laboratory prototype chips that can indeed sort particles of different levels of fluorescence intensity, and demonstrated that our technology does not harm the sperm. These are all very positive advances, and the future is bright for Engender. We are in the last pre-commercial stage, and in a major fund raising campaign.

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