Light Years Ahead

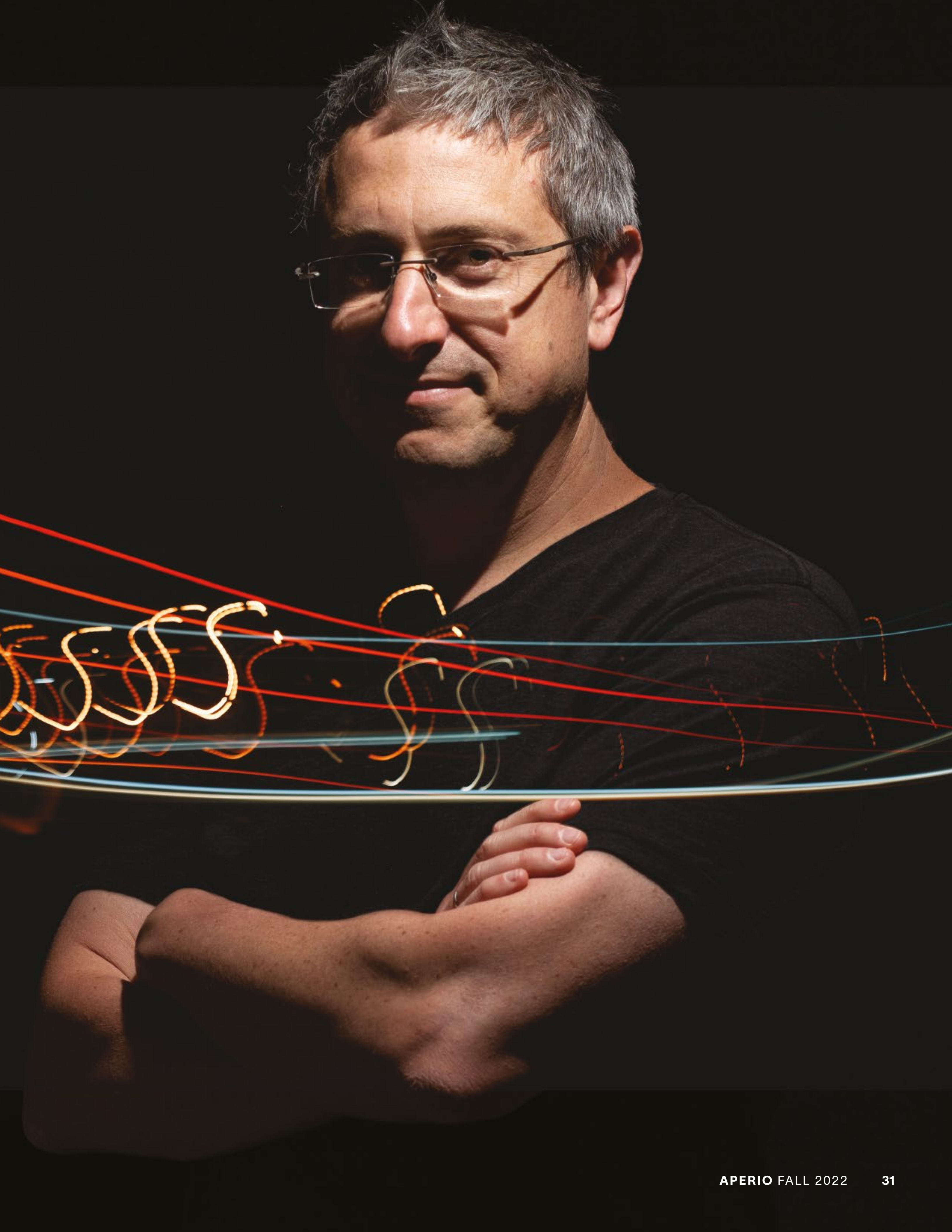
Physicist Mikael Rechtsman wants to channel photons for a spectrum of possible applications

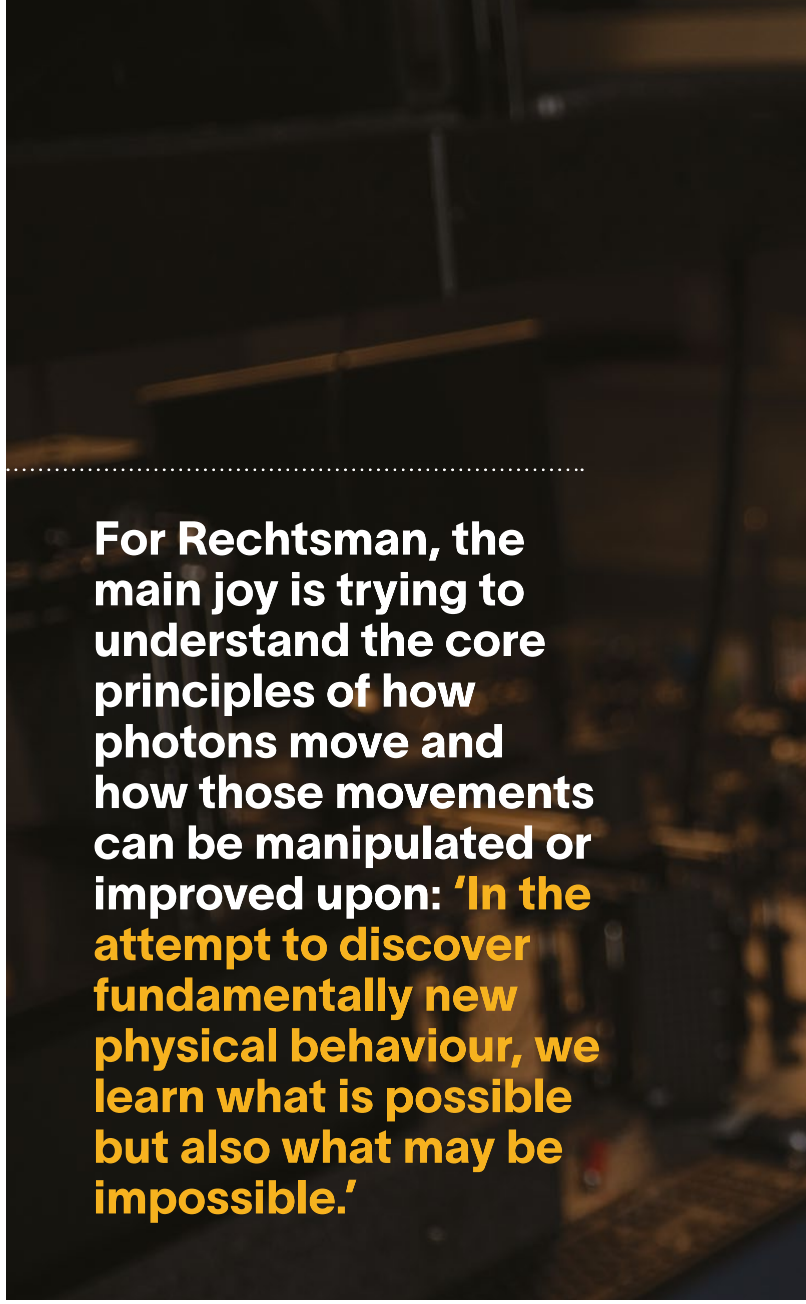
We spend our lives surrounded by light, yet few of us have even a rudimentary understanding of how it moves through space. Instead, we make analogies to water, something we can readily see and touch: light "streams" through clouds, "flows" through windows and "bathes" us in its brilliance. But truly comprehending the movement of photons — massless elementary particles that are the basic unit of all light — requires a rarefied level of math and physics that's accessible to only a select few scientists.

One of those is Pennsylvania State University's Mikael Rechtsman, a leading figure in the field of topological physics who, a decade ago, was an Azrieli International Postdoctoral Fellow at Technion–Israel Institute of Technology. Topology is the mathematical study of shapes and their arrangement in space. Simply put, Rechtsman explores not just how light moves through open space, but also how light moves through substances such as glass and how that travel can be manipulated by materials with complex geometries.

Perhaps the best example of this movement is in optical fibres. These long, thin glass "tubes" guide light in much the same way that wires guide electricity. In fact, they can carry dramatically more information than wires and require far less power to do so. As a result, optical fibres form the backbone of the modern internet's infrastructure. This technology and other developments have pushed forward the photonics industry, which augments and complements parallel developments in the electronics industry.

By Zac Unger
Photographs by Michael Fleck





For Rechtsman, the main joy is trying to understand the core principles of how photons move and how those movements can be manipulated or improved upon: ‘In the attempt to discover fundamentally new physical behaviour, we learn what is possible but also what may be impossible.’

In recent years, scientists have dramatically improved their ability to trap and manipulate light, particularly through the use of “photonic crystals” — microfabricated structures in which light propagates in a similar manner to how electrons move in solid-state materials such as silicon. However, since these and other photonic devices have to be manufactured using methods that are still imperfect, defects always threaten to hinder performance.

When light passes through glass, it essentially runs into a series of blockades, causing the light to scatter randomly. As far back as 1980, physicists knew that when electrons are confined to a two-dimensional plane and then immersed in a strong magnetic field, they propagate in a manner that is completely insensitive to defects and disorder. When Rechtsman was a postdoc in Moti Segev’s internationally renowned lab at Technion between 2010 and 2014 (as an Azrieli Fellow for the first two years), he and his colleagues demonstrated that the ability to be impervious to defects wasn’t just limited to electrons but could also be applied to light. This new knowledge provided a route to making photonic devices that were both more robust and far cheaper than was previously possible.

The foundational experiment that Rechtsman and his colleagues performed, a collaboration with Alex Szameit’s group at the University of Jena, involved a piece of transparent glass inside which they built a complicated network of “waveguides,” which act like optical fibres. Each of these waveguides is a little larger than the wavelength of light; they act like a series of parallel tunnels, each big enough for a single car to pass through at a time. In the experiment, a laser beam is focused on a piece of glass about the size of a microscope slide you might find in a biology lab. Light emerges from the back of the glass and enters a lens. Similar to a microscope’s lens, this magnifies the light that comes through and sends it to a camera, allowing scientists to analyze the pattern that emerges from its journey. (Rechtsman’s 2013 paper about this project “started the field of topological photonics,” says Segev, one of his co-authors.)

“If you want to make light behave in the way that electrons behave, you’ve got to do it with these structured objects, essentially scaffolding that you build that is on the correct scale,” Rechtsman explains. With the correctly constructed latticework, photons can act like electrons, making it through objects by overcoming the obstacles that would normally cause scattering. The nuts and bolts of the experimental process Rechtsman uses involve focusing a laser beam into a piece of glass, a technique known as “femtosecond direct laser writing,” so named because the lasers used have pulse durations measured in femtoseconds, or one quadrillionth of a second. This entire process is somewhat similar to 3D printing and leaves the glass with a network of hundreds of waveguides running through it, along which the photons will travel.

The potential applications of this work in topological photonics are still largely unknown. Advancements in the field could prove useful in fibre optics, solar energy, more efficient lasers, or lidar, the light-based “vision” employed by self-driving vehicles. “If you can make light impervious to disorder,” says Rechtsman, “you could make devices function much, much better, or with a higher yield at lower costs because you don’t have to control for defects.” One of the most tantalizing possibilities is that, as Rechtsman says, “we can generate quantum states of light much more efficiently,” potentially allowing quantum devices made of light to operate at a scale and complexity that vastly eclipses current technologies. “These are basically computer chips for light,” he says. “There are new start-up companies that are using waveguide arrays to run machine learning algorithms at light speed.

“Right now, I think we’re still at the fundamental science stage,” continues Rechtsman, who in spring 2022 led a team that won a $7.5-million USD grant from the U.S. Air Force Office of Scientific Research to probe the properties of systems that are “beyond conventional physics” and strive toward tunable systems of photons. “We’re showing one another how these things can work in principle and what the constraints are.”

For Rechtsman, the main joy of this work is in the pure science, trying to understand the core principles of how photons move and how those movements can be manipulated or improved upon. "In the scientific competition to discover fundamentally new physical behaviour," he says, "we learn from each other what is possible but also what may be impossible."

Rechtsman was always fascinated by the terrestrial aspects of physics. "Not particle physics or cosmology, but how materials work, how light functions," he says. "I always loved physics, ever since I was a teenager. There are beautiful theories of nature and, in particular, the understanding of how light works has been one of the most profound." Rechtsman was able to continue and deepen that lifelong love as a result of his Azrieli fellowship at Technion. "That was one of the main reasons I decided to go to Haifa," he says. "I wanted to join a team that could be the first to observe these topological effects with light. Moti's group at Technion was the place."

In addition to his faculty colleagues, Rechtsman also found that his graduate students were a particularly motivated, hard-working group. "They were very mature," he says, "and they had life experiences that gave them a lot of wisdom. Our ultimate discovery was a team effort."

It's easy to take light for granted; we flip a switch, we pull back the curtains, or we wait for sunrise. But for those who understand the breathtaking complexity of photonics, practising science at the edges of human understanding (as well as the limits of the laws of physics) comes with its share of both frustration and elation. "We'll try a hundred different ideas before we find one that is both scientifically meaningful and actually works," Rechtsman says. "You've made a prediction, you've done the calculations, you've sweated blood over it, spent years and years on something, and then all of a sudden it's actually physically there, and you can see it working and it feels magical." ▲●■