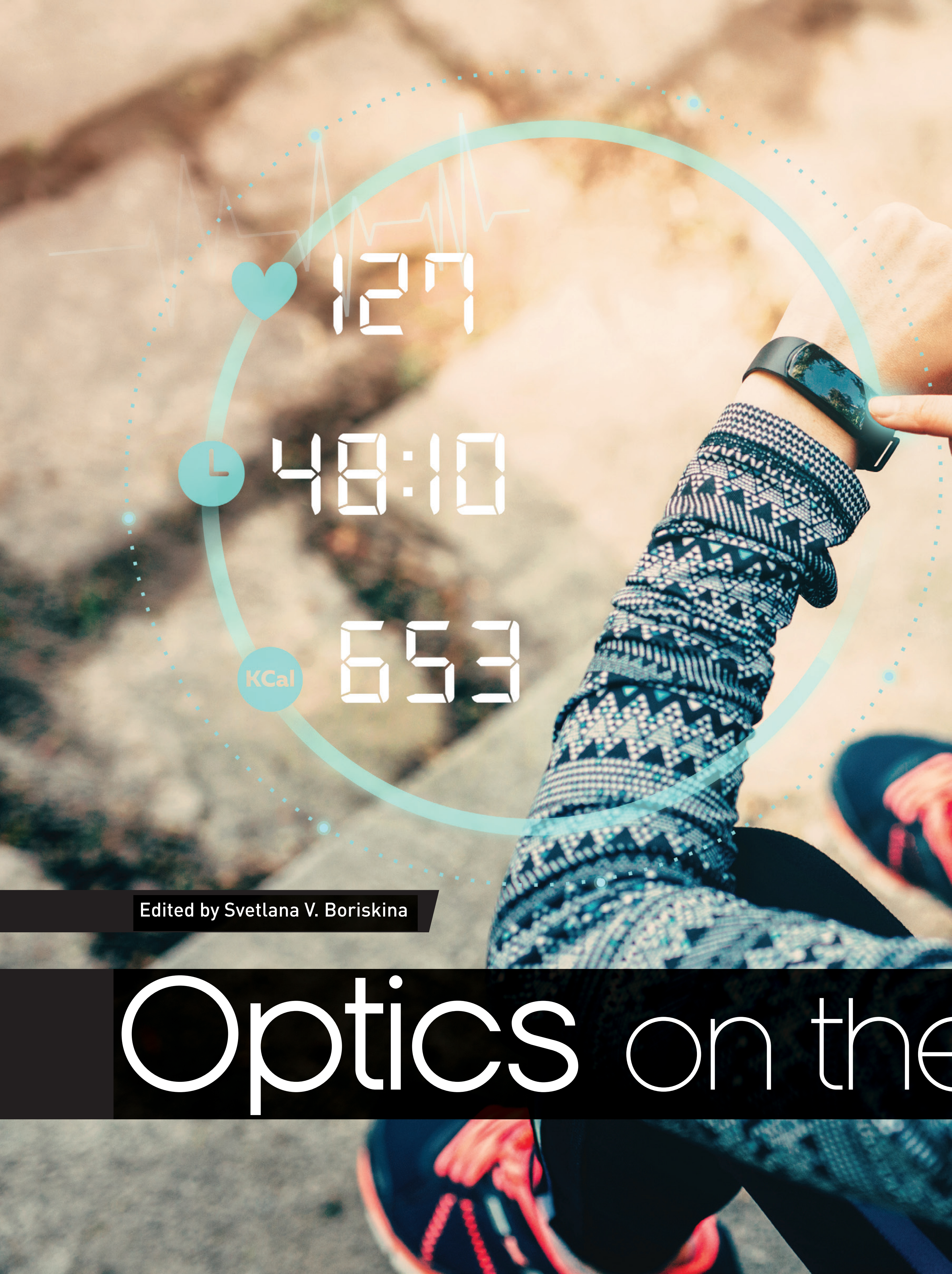

Edited by Svetlana V. Boriskina

Optics on the

Wristwatch-style health trackers are just one area where optics and photonics are expanding the horizons of wearable tech.
Getty Images

e Go

Wearable optical technologies are emerging to keep users safe, powered-up and entertained.

Shimmering, structurally colored garments can now be made using fabrics that mimic the microstructure of the blue morpho butterfly's wings **(see p. 41).**

Donna Sgro / Teijin Japan / (Inset) Getty Images

People like to take their essentials along wherever they go—and that list of essentials increasingly includes optical technologies. The trend, which started years ago with glasses and sunglasses, has accelerated as optical devices have become more and more miniaturized. Personal electronic devices, including smart watches, mobile phones and tablet computers, fuel consumer demand for lighter, brighter and more flexible optical displays. Fitness enthusiasts rely on optical sensors to monitor heart rates and optimize workout schedules. And active optical sensors, which can noninvasively track multiple vital signs in real time, are fast becoming indispensable for personalized medicine as well.

While visible light plays a key role in our communications with each other and the environment, ultraviolet (UV) and infrared (IR) photons can strongly affect our personal comfort and wellbeing. Wearable technologies for detecting and controlling these non-visible photon emissions span a wide frequency range, from monitoring harmful UV radiation from the sun to IR-sensitive night-vision capabilities for military and law enforcement personnel.

As optical technologies develop, so does consumer demand—and the demand for portable devices is morphing into a taste, among some users, for fully wearable devices integrated into glasses, jewelry, clothing and even the skin itself. The entertainment and fashion industries have blazed the trail in this area—blending fiber optics with solid-state lighting sources into spectacular wearable art displays; harnessing photoluminescence to achieve glow-in-the dark clothing, footwear and even tattoos; delivering streams of visual information through high-tech glasses.

These emerging devices require portable or renewable power sources to operate—and the lack of cheap, long-lasting and lightweight sources has proved a big hurdle to wider adoption. While offering a free energy source, sunlight's dilute and intermittent nature strictly limits the amount of power that wearable energy conversion devices can harvest. In this context, fully passive optical solutions that do not rely on external power sources can truly revolutionize wearable technologies.

In the following pages, researchers from the academic, industry and military spheres offer a snapshot of where things are headed for a number of emerging wearable optical technologies.

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References and resources can be found online at www.osa-opn.org/wearables/references.

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Smart Glasses and AR Vision

Technicolor R&D France

Recent advances in optical technologies have realized a long-lived science fiction dream: that of "smart glasses" that can add information and imagery to the existing environment. From the systems of a few decades ago—consisting of bulky helmets wired to remote computing modules—augmented-reality (AR) devices have evolved into stylish, fully autonomous headsets that can be used indoors and outdoors under different lightning conditions. Modern headset shapes range from motorcycle helmets to lightweight glasses that are barely distinguishable from ordinary sunshades.

Fueling this remarkable transformation has been both consumer demand and a revolution in optical engineering. Smart glasses offer a microcosm of optical technologies: cameras that scan the environment; a wearable computer generating digital data shown by a microdisplay; imaging optics; see-through displays. Embedded optical technologies transform the ordinary vision-correcting and protective eyeglasses into the interface between the user's personalized digital universe and the larger physical environment.

Ideally, the transition between those two realms should be seamless: images overlain on see-through displays should not block the outside world. In reality, many commercial smart glasses do not yet offer complete transparency, and most have reduced field of view and low angular resolution. However, the technologies for image formation and aberration correction continue to improve, evolving from polarized beam combiners and "bird bath" optics, to freeform prisms that reduce eye fatigue, to wedge optics and waveguide diffractive gratings and holograms that shrink volume and weight. Embedded spectral filters permit use of broadband light sources such as LEDs, and new bright and compact organic and inorganic LEDs allow outdoor use.

It's not difficult to envision applications for smart glasses today: navigation supported with real-time digital notifications, geolocation tags, and performance statistics; personalized education enhanced by the computer-generated graphics; co-development of new technologies and digital art by users working in the same office or across the globe. A new generation of AR wearables, however, aims at a truly immersive user experience that complements the physical world by attaching digital information to real objects. Those objects, detected via image processing and geolocation data, can be augmented by projecting images of 3-D virtual objects that appear next to them. Engineers continue to develop additional functionalities, such as tracking of head position and orientation, eye tracking to identify the objects in the focus of the user, and gesture recognition to enable manipulation of virtual objects along with real ones.

Before smart glasses become an affordable, everyday essential, however, they will need to overcome a number of challenges. See-through displays capable of translating digital images with sufficient quality, field of view and depth information need to improve, as do micro-display, optical sensor and energy storage technologies. New plasmonic and metamaterials approaches promise flat, lightweight and aberration-corrected lenses and displays that could open up the design space. These and other recent innovations in smart-glasses technology suggest that, notwithstanding the challenges, the days of routine consumer AR could come soon.

Artem Boriskin, Research and Innovation Center, Technicolor, Rennes, France

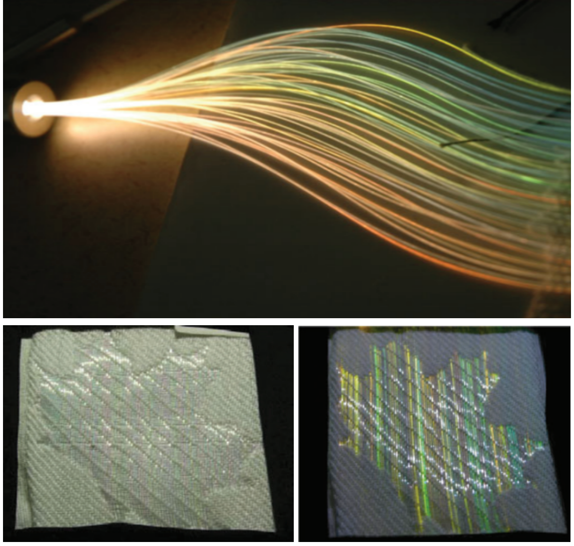
A new generation of AR wearables aims at a truly immersive user experience that complements the physical world by attaching digital information to real objects.

Active-Color-Changing Textiles

Consumer demand for unique appearance, increased performance and multifunctionality in woven items has driven active research in smart photonic textiles—woven materials that integrate light-emitting or light-processing elements into a mechanically flexible matrix. Such textiles have potential applications in wearable sensors, in monitoring the condition of structures, in large-area illumination, in clothes with unique aesthetic characteristics, and in flexible and even wearable displays.

Some photonic textiles, already demonstrated, combine compact light-emitting diodes and conventional total-internal-reflection optical fibers to let colors change dynamically. For the color to be visible outside of the fiber, the light guided along the fiber must be scattered and emitted sideways through the fiber walls. Corrugating the fiber surface or fiber microbending can allow such scattering, but introducing such mechanical imperfections degrades the fiber's robustness and durability. Moreover, achieving a certain color may require the fiber to be impregnated with coloring agents that fade over time.

By contrast, photonic textiles based on Bragg fibers, which guide light using photonic band gap (PBG) effects, have some unique properties that allow their appearance to be actively manipulated. When broadband light is launched into a Bragg fiber, only a specific color, defined by the spectral position of the reflector band gaps, is guided; all other colors are scattered out of the fiber after propagating only a few centimeters. Scattered light gradually leaks out from the fiber core, with the leakage rate controllable by changing the number of reflector layers. The spectral position of the reflector band gaps, and hence the guided color, might also be changed by tuning the thicknesses of the reflector layers when the fiber is drawn. The underlying materials can be completely transparent, and no mechanical deformation is needed to extract the light, as PBG fibers are inherently leaky.



(Top) Scattered light from optical fiber can produce multiple, tunable colors. (Bottom) The color of a Bragg fiber can be varied by mixing the emitted guided color with the reflected color from ambient illumination.

An example of a PBG fiber suitable for photonic textiles is a plastic Bragg fiber that features a hollow or solid core surrounded by a periodic sequence of high- and low-refractive-index layers forming the Bragg reflector. Fabrication of these fibers starts by co-rolling two different polymer films around a plastic rod, to create a fiber preform. The reflector multilayers can comprise various thermoplastic materials including polymethyl methylacrylate/polystyrene or polyvinylidene fluoride/polycarbonate combinations. The Bragg fibers are then manufactured via preform heating and drawing.

Under external illumination, the Bragg fibers themselves have a color, mainly determined by the diffraction properties of the Bragg reflectors. The fiber color under ambient illumination thus commonly differs from the color caused by the selective scattering of the guided light. This opens an intriguing opportunity of tuning the overall fiber color by controlling the relative intensities of the ambient and propagating light, thereby realizing an active-color-changing functionality. With such functionality, PBG-fiber-based textiles could find applications in many fields, including decorative fabrics, security apparel, dynamic signage and environmentally adaptive coloration.

Hang Qu and Maksim Skorobogatiy, Ecole Polytechnique de Montréal, Montréal, Quebec, Canada

PBG-fiber-based textiles could find applications in many fields, including decorative fabrics, security apparel, dynamic signage and environmentally adaptive coloration.

Inward and Outward Monitoring

Accelerating advances in optical sensing technology have driven increased demand for, and adoption of, lightweight and flexible display technologies. Advances in integration, packaging and software/algorithms for smartphones are creating new opportunities for wearable optical technologies.

Of particular interest are portable displays that use ambient-light sensing (ALS) to approximate the human eye's response to light, allowing for better power management and battery life. As display technology has moved from white LED backlighting to RGB LEDs—which can deliver a full color gamut and produce different color temperatures of white—these new ALS displays will require very accurate qualification of light sources to adequately match the eye's response and reflect colors appropriately. To meet that demand, RGB LED technology is giving way to advanced XYZ RGB solutions, yielding optical spectrometers with more than 100 channels.

Having this number of peak frequencies to draw from opens new opportunities for wearable sensors that accurately characterize what is happening on or even beneath the skin. The largest organ in the human body, the skin plays a crucial role in health, continuously monitoring the body's hydration, sun exposure and vitamin D production. And just beneath the skin is a wealth of information on cardiovascular health, such as pulse rates and blood oxygen levels.

Health trackers use LEDs to shine light through skin and tissues, optical detectors and digital signal processors to capture and analyze the reflected light, and optical filters to reduce the noise from the ambient light. The use of multiple light wavelengths that interact differently with different types of tissue addresses variables such as shifting of the skin, differences in skin tones, and health of veins. Analyzing structured scattered light in the form of speckle patterns also helps to filter out motion-induced artifacts.

Courtesy of Integrated Device Technology

In addition to the hardware requirements, high-quality algorithms also constitute a key to overall accuracy of these sensors. Packaging is likewise crucial to success. Large arrays of photodiodes and integrated compensation circuits can now be packed onto ICs less than one millimeter square; once again, these advances in micro-packaging have come from the integration of optical sensors into displays for smartphones and smart watches.

Sensors can be embedded into displays with minimal trade-offs in performance. Vertical connectivity using "through-silicon via" (TSV) technology has enabled the smallest products on the market. Consumer products nowadays feature multichannel solutions in a 1×1×0.26-mm package—a dimension difficult to see with the human eye. Thus, optical sensors can be integrated into clothing, watches, headsets and glasses, or even applied directly to the skin, with minimum real estate required.

With high-volume consumer platforms adopting optical solutions, as they did with motion sensors, a new wave of optical innovation has become available. Ultimately, consumer needs are what drive the wearables market—so the outlook for innovative products has never been as bright as it is today.

David Simpson, Integrated Device Technology (IDT.com)

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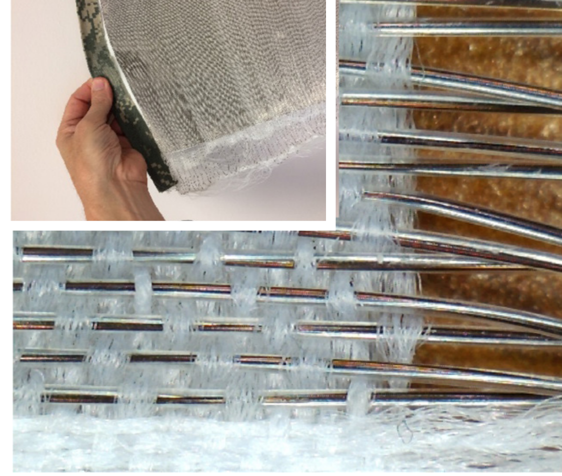
Solar Energy and Storage



In third-generation solar fabric, photovoltaic wires are woven into a fabric composed of standard polymer fibers.

Courtesy of D. Erb, R. Gaudiana, R. Childers and M. Lee / University of Maine Advanced Structures and Composites Center

The first generation of solar power has involved installing panels semi-permanently on rooftops or trackers for residential, commercial and industrial markets. Typical 3×5-foot solar modules have efficiencies reaching 20 percent, can produce 270 W in bright sunlight and are built in some cases to withstand the impact of golf-ball-sized hail at over 100 mph. These modules are heavy, weighing some 20 kg (including metal frames and glass covers), and have power-to-weight ratios around 13 W/kg.

Lightweight, flexible, inexpensive solar modules are in high demand for exploring the wilderness or for generating power in developing countries with limited infrastructure. Portable solar lamps and chargers for small electronics already make a significant impact on the lives of people in off-grid households worldwide. A 6×6-cm solar panel can generate enough power in a day to run a small lamp for as much as 100 hours or to charge devices such as smartphones or fitness trackers.

Multi-day military missions, and other operations in which one "lives off the land" and carries multiple electronic devices, require higher-power solar modules—and those modules are useful only if they weigh less than the battery weight they replace, and if just a few hours' sunlight can provide useful charging. One rechargeable battery can weigh 1.4 kg, and warfighters can carry 20 pounds of back-up batteries on multi-day missions. Although expensive backpack-mounted arrays of solar cells already exist, they can take more than a day to charge a 150 W-hour battery.

Second-generation "solar blankets"—which use thin, low-density polymer backing material, fabric packaging and flexible contacts, and can be carried in a backpack—can already be purchased by credit card. These modules generate about 100 W and weigh 2 to 2.5 kg, having power-to-weight ratios of some 47 W/kg, much higher than for traditional rooftop solar panels.

Wearable solar power, integrated into clothing and taking advantage of the roughly 1.5-m^2 surface area of the human body, requires development of very lightweight solar cells. Various substrates and form factors currently explored include flexible thin glass films and textile-compatible photovoltaic wires or fibers. The third generation of solar blankets will be very lightweight and easily portable, with power-to-weight ratios above 70 W/kg; such technologies will rely on a sparse array of fibers or films to reduce weight, while efficiently harvesting sunlight through advanced optical techniques.

Solar energy is never completely reliable, and often batteries cannot be fully charged during a cloudy or rainy day. These factors require complementary textile-based energy storage solutions that are safe, conformal and washable. Fiber-based batteries and supercapacitors have been demonstrated in laboratory experiments, although many do not scale well to large sizes; knitting garments can require more than a kilometer of yarn. Because of the stringent demands of wearable textiles, it seems possible that non-wearable textiles will be one of the earlier beneficiaries of new solar power storage technologies.

Future fibers and fabrics will incorporate new materials with higher solar conversion efficiencies, new form factors and new weaving patterns to enhance solar power harvesting and storage in wearable and portable textiles, creating this third generation. Electronic devices carried on the body may become ubiquitous, fueling further demand for wearable power sources.

Richard Osgood III, Warfighter Directorate, U.S. Army Natick Soldier Research, Development, and Engineering Center, Natick, Mass., USA.

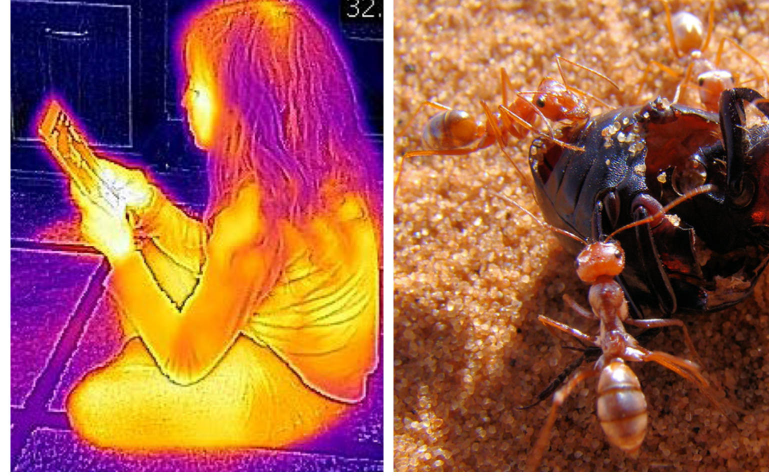
Wearable solar power, integrated into clothing and taking advantage of the roughly 1.5-m^2 surface area of the human body, requires development of very lightweight solar cells.

Passive Wearable Technologies

Humans have used passive optical solutions for centuries. Frequency-selective light absorption in pigments allows a rainbow of colors in garments and other wearables. White fabrics reflect light across the entire visible spectrum, protecting people from overheating under direct sunlight. Commercial technologies developed in the last century that use reflective, fluorescent or phosphorescent pigments to achieve "glow-in-the dark effect" in applications ranging from safety reflective patches on active wear and children's clothing to glow-in-the-dark apparel beloved by children and adults alike. These technologies are largely safe, after long trial and error. (The early users of glow-in-the dark phosphorus developed painful, slow-healing skin burns; the infamous Hound of the Baskervilles would have met the same tragic fate.)

Nature has also developed passive solutions for reflection and structural color, via light scattering by nano- and micro-scale features. The color of insects has been studied for more than a century, but only recently has technology matured enough to mimic it in creating wearables. Today, a structurally colored fiber, Morphotex, mimics the microscopic structure of the Morpho butterfly's wings to make otherwise colorless garments appear shimmery cobalt blue under reflected light.

While reflection and color formation are important for communications and protection, the sun and human bodies also generate photon emissions outside of the visible spectrum. About half of solar energy reaching Earth's surface comes in infrared and ultraviolet photons. Ultraviolet light is very harmful; infrared solar radiation can cause overheating. Existing wearable optical solutions enable frequency-selective light scattering and absorption by nanoparticles embedded into fabrics or spread directly on the skin in the form of sunblock lotions. It is now possible to stay cool in the sun while wearing colored or even black clothes.



As an infrared image shows (left), the human body can shed much energy via thermal radiation, which is blocked by conventional fabrics. Infrared-transparent fabrics allow for passive cooling, mimicking the survival mechanism of Saharan silver ants (right).

S. Boriskina (left); B.C. Tørrissen / Wikimedia (right)

"Cool black" fabrics and leather paints that reflect the near-infrared solar radiation can reduce the temperature of the wearer by several degrees.

Infrared-reflective patches on clothes and wearables, viewed through night-vision equipment, can also help distinguish friend from foe in military and security situations. Infrared reflective emergency blankets that block thermal radiation from the human body have been used for years on patients by doctors and first responders. This technology has recently found its way into winter sports apparel, in the form of little silver dots or thin fibers covering the inside of the garments to reflect body heat.

Fabrics can also achieve an opposite "cooling" effect by letting thermal radiation from the body pass through without being absorbed or reflected. Passively cooling fabrics made of microfiber or microporous materials that are visibly opaque, yet infrared-transparent, can help reduce body temperature by several degrees. Humans, however, were not the first to invent this technology—Saharan silver ants, for example, use similar techniques to stay cool in the desert heat.

Future passive wearable optical technologies will likely combine visible color effects, invisible communications features, thermal regulation, and even self-cleaning and microbial treatment by sunlight. OPN

Svetlana V. Boriskina, Massachusetts Institute of Technology, Cambridge, Mass., USA.

Nature has developed passive solutions for reflection and structural color, via light scattering by nano- and micro-scale features.