ENGINEERING AND TECHNOLOGY EANDTMAGAZINE.COM

E&T

VOLUME 13 ISSUE 9 OCTOBER 2018

Engineering & Technology | volume 13 issue 9 | October 2018

IET The Institution of Engineering and Technology

LIGHT BULBS
LI-FI NETWORKS
SATCOMS
URBAN FARMS
HUMAN-CENTRIC LIGHTING
LIGHT AND BUILDINGS

LIGHT

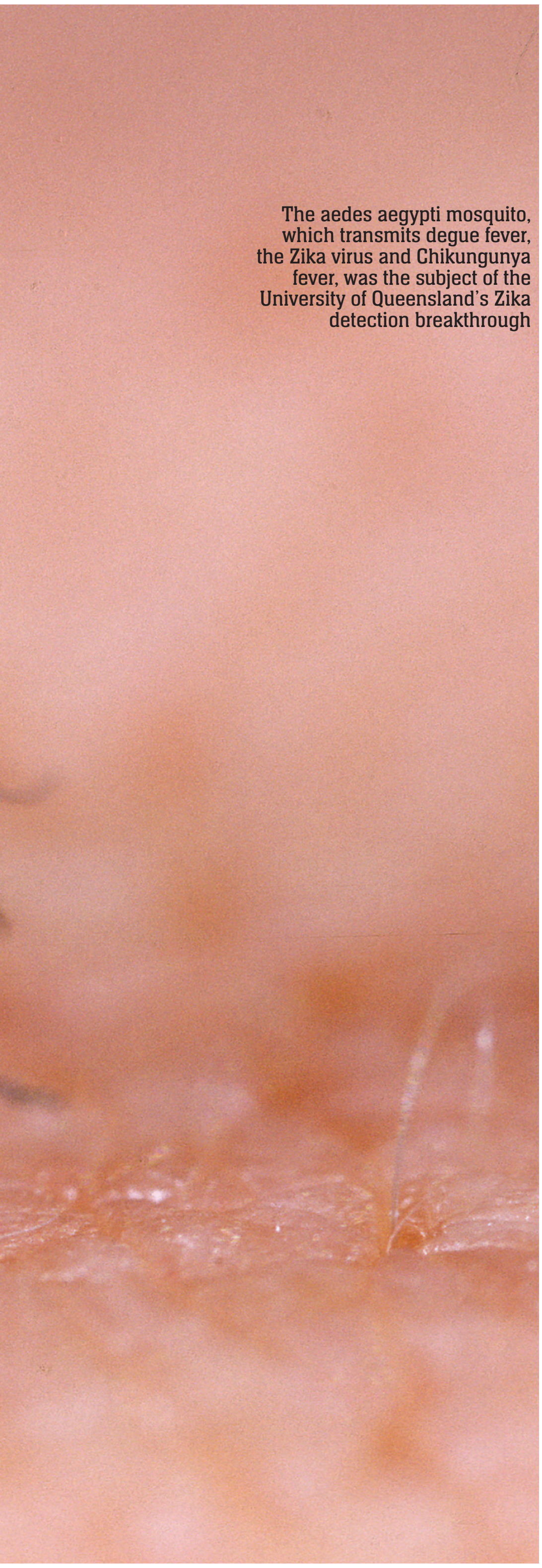
Much of human development is tied to our ability to create and use light. Advances in the 19th century brought electric lighting to the world in the form of the incandescent bulb (p54), which is now being superseded by the LED as it inspires a new generation of designers (p40) and opens up control possibilities in the form of 'human-centric lighting' (p36). It is even spurring advances in horticulture (p50). Researchers are also turning to optical technologies to tackle mosquito-borne diseases (p30). Photonics continues to advance too, bringing the prospect of much higher data rates both in satellite links (p34) and within buildings (p44).

DREAMSTIME, BRYDEGAAR

LIGHT OF LIFE

Mosquito-borne viruses can ravage nations, but researchers hope to stop the next Zika-like outbreak with lasers

By **Rebecca Pool**



The aedes aegypti mosquito, which transmits degue fever, the Zika virus and Chikungunya fever, was the subject of the University of Queensland's Zika detection breakthrough

SUMMER IS MOSQUITO TIME, and for more than a billion people across the world every year, this means debilitating pain, blindness, brain damage or possibly death. Well-known mosquito-transmitted diseases include dengue fever, malaria, the West Nile virus, yellow fever and, following the horrific outbreak of 2015 and 2016, Zika.

Yet as mosquito populations relentlessly rise, physicists, entomologists and mosquito-borne disease researchers are stepping in with a host of optics-based technologies to improve surveillance and eradicate outbreaks.

In May this year, Dr Maggy Sikulu-Lord, from the University of Queensland, Australia, and colleagues revealed they had used infrared light to detect the Zika virus in mosquitos, 18 times faster and 110 times more cheaply than today's painstakingly slow and expensive standard – quantitative reverse transcription polymerase chain reaction (RT-qPCR).

She says: "We just use a benchtop spectrometer with external probes and direct the light beam at the mosquito... we can tell if it is infected in 10 seconds."

Near-infrared spectroscopy (NIRS) has been used for decades in agriculture, pharmaceuticals and medicine to classify biological samples based on type and concentration of chemical compounds in the sample. However, prompted by the rise in mosquito-borne diseases, Sikulu-Lord as well as researchers at the renowned Ifakara Health Insitute, Tanzania, and UK-based Institute of Biodiversity, Animal Health & Comparative Medicine, Glasgow University, have been investigating the method to characterise mosquito species.

Sikulu-Lord's latest Zika detection breakthrough promises to be a lifesaver. Having reared Aedes aegypti mosquitos in their laboratory, the entomologist and her colleagues fed half with Zika-infected rabbit blood and the other half with virus-free blood.

Four, seven and ten days later, mosquitos were killed and then scanned, using NIRS, with distinctly different spectra generated. Sikulu-Lord says her method has been shown to be between 94 and 99 per cent accurate compared to RT-qPCR, and is now searching for Zika-infected insects in Korea, so she can test her method on 'true' specimens.

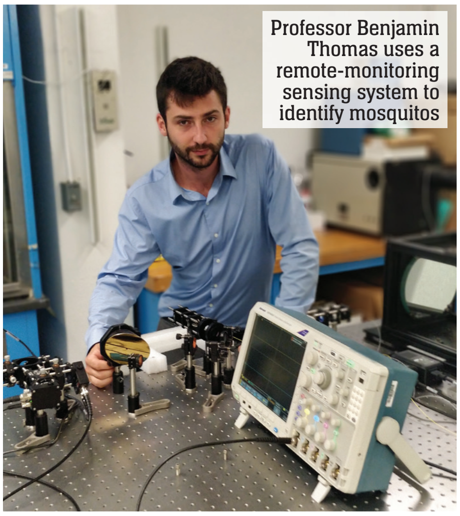
Interrogating the insects

She also has high hopes the method will be adopted by the World Health Organisation for surveillance in countries where Zika is endemic and is assessing the effectiveness of NIRS on mosquitos carrying dengue and malaria.

"Our main goal is to find the virus hot-spots quickly and more effectively," she says. "In the future we want to develop smaller handheld spectrometers that can be used to scan mosquitos in the field and I would also like funding bodies to set up centres to process NIRS data sent in from countries with budget restrictions."

Yet you don't necessarily have to get close to a mosquito to analyse it. As early as the 1970s, researchers have been using lidar – pulsed laser-based detection which works on the principle of radar – to measure atmospheric processes. Here, a laser is transmitted into the atmosphere with detected backscattered light providing information on, say, aerosol distribution, greenhouse gas concentrations, cloud base heights and more.

Then, in the last decade, a handful of physicists adapted the optical remote-sensing system to measure the wing beat frequency, body and wing size of large insects, including moths, dragonflies and honey bees, to distinguish different species. So-called entomological lidar typically uses at least one infrared, continuous laser to interrogate insects, with one or more telescopes collecting the backscattered light. The wing beat frequency can then be retrieved by applying, for example, a Fourier transform on the recorded signal.



Professor Benjamin Thomas uses a remote-monitoring sensing system to identify mosquitos

Fast-forward to the last couple of years, and several laser-based systems have been applied to mosquitos to discriminate these flying menaces not only on species but also gender: so very important as only females can transmit disease. Indeed, Professor Benjamin Thomas from New Jersey Institute of Technology, USA, recently used his continuous-wave infrared optical remote-sensing system, in a controlled laboratory environment, to reliably distinguish male and female mosquitos in species that transmit yellow fever, dengue fever, Chikungunya fever and the Zika virus.

"Female mosquitos have a very different wing-beat frequency to the males, so you can identify females very specifically – our system has retrieved gender with 96.5 per cent accuracy," says Thomas. "We're now also improving the accuracy at which we can identify different species – we've reached more than 75 per cent in the lab – and will be retrieving even more optical properties in the next couple of months."

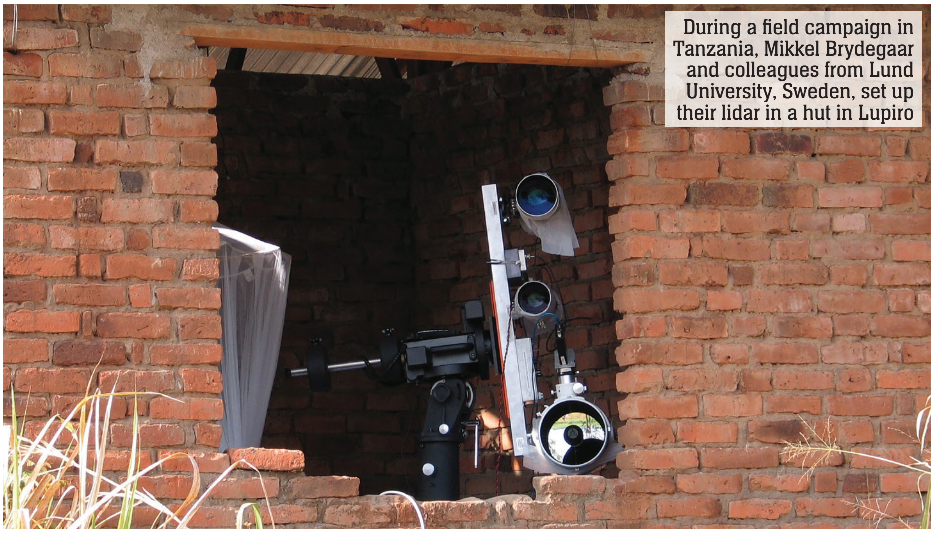
Thomas is certain his laboratory-based system can be reliably used in the field to analyse mosquitos within a 100m range by increasing the size of the collecting optics, using, say, a Newtonian telescope with a large primary mirror. Importantly, such systems provide a speedy and easy alternative to the mosquito traps used to monitor insect populations.

While almost 100 per cent accurate, these traps rely on pheromones, food or carbon dioxide as bait and are tedious to set up with extensive coverage being overwhelmingly labour-intensive. What's more, the trapped mosquitos then have to be individually counted and identified in a laboratory, a painstakingly slow procedure.

"These laser approaches may be less accurate now, but you can monitor a much larger number of mosquitos in real time, and get more data that provides good statistics on the ecosystem you are looking at," says Thomas. "Every time a mosquito transits through the laser beam, you can identify it, and out on the field we can potentially analyse around 100 insects an hour."

In the field

Mikkel Brydegaard from the Lund Laser Centre, Lund University, Sweden, is a long-standing pioneer of entomological lidar and has devoted his career to developing >



During a field campaign in Tanzania, Mikkel Brydegaar and colleagues from Lund University, Sweden, set up their lidar in a hut in Lupiro

Brydegaar's lidar in Tanzania, where a mosquito can be seen crossing the beam

< systems to characterise biological lidar targets such as plankton, migrating birds and flying insects, including mosquitos. In his words: "It is a challenge to estimate wing-beat frequency in a robust way."

However, he and colleagues have forged ahead with multi-band modulation spectroscopy methods and a novel lidar based on a 19th-century photography concept devised by Captain Theodor Scheimpflug.

To correct perception distortion in aerial photographs, the Austrian army captain invented a novel camera set-up, in which the lens plane did not lie parallel to the image plane. One century later, and as part of a lidar system, Brydegaard and colleagues combined this principle with continuous wave infrared lasers and CMOS detector arrays to implement remote modulation spectroscopy with high sensitivity and resolution in space and time, in principle faster than the round-trip of light.

"We've been making high-resolution Scheimpflug and other systems with ranges up to a couple of kilometres that have time- and space-resolution way beyond anything you see from other atmospheric lidars," he says. "For example, we have lidar that is sensitive enough to pick up molecular backscatter from the atmosphere itself."

Crucially for mosquito management, the lidar system can sample tens of thousands of flying insects an hour, so Brydegaard and collaborating biologists have been using the systems to understand insect flight activity, and importantly, determine the sex and species of mosquitos in flight.

"[Discriminating] between mosquito sex has been easier than species," he says. "We can look at body size, wing size, melanisation and have been [considering] if we could differentiate the females with and without bloodmeal."

Key insect species

As part of this research a Lund University spin-off company, Denmark-based Fauna Photonics, has been busy carrying out several field campaign assignments and developing software for Brydegaard's flavour of lidar, in a bid to monitor mosquitos and other pests in real time for public health and agricultural markets.

Indeed, in recent field studies in Tanzania, Brydegaard, fellow researchers and Fauna Photonics colleagues used a 1km-range lidar to profile the activity of Anopheles mosquitos – which can carry malaria – measuring the size and wing-beat frequency of these insects.

As Michael Stanley Pedersen, chief executive of Fauna Photonics, points out: "This was a ground-breaking way of studying the behaviour of these mosquitos. We looked at how these insects swarmed as well as the interactions between males and females, which is normally so very difficult.

"People seem to think our systems are science-fiction; shining light over an open area to measure wing-beat frequency, insect glossiness, number of legs and so on," he adds. "The data analysis behind the hardware is very complex... but this isn't science fiction, we can do this, and we're now seeing a lot of traction with this technology."

Where next for the rapidly developing world of mosquito-borne disease detection? The New Jersey Institute of Technology's Thomas, for one, believes optical systems such as his and lidar-based set-ups could be used in tandem with traditional mosquito traps, and even Zika-detecting NIRS such as Dr Sikulu-Lord's, from the University of Queensland. As he points out, systems such as his cannot yet detect if a mosquito is carrying an infectious disease, but these methods can. So combine the two systems and you have an accurate means of monitoring and pinpointing potentially deadly mosquitos.

For Thomas, such a move can't happen soon enough. As he points out, climate change is altering the global distribution of insects, and researchers are struggling to keep up. "Look at Zika; that virus was always one step ahead of us, we only knew where the mosquitos were from the clinical reports of the sick, and we had no idea how far north it had reached," he says.

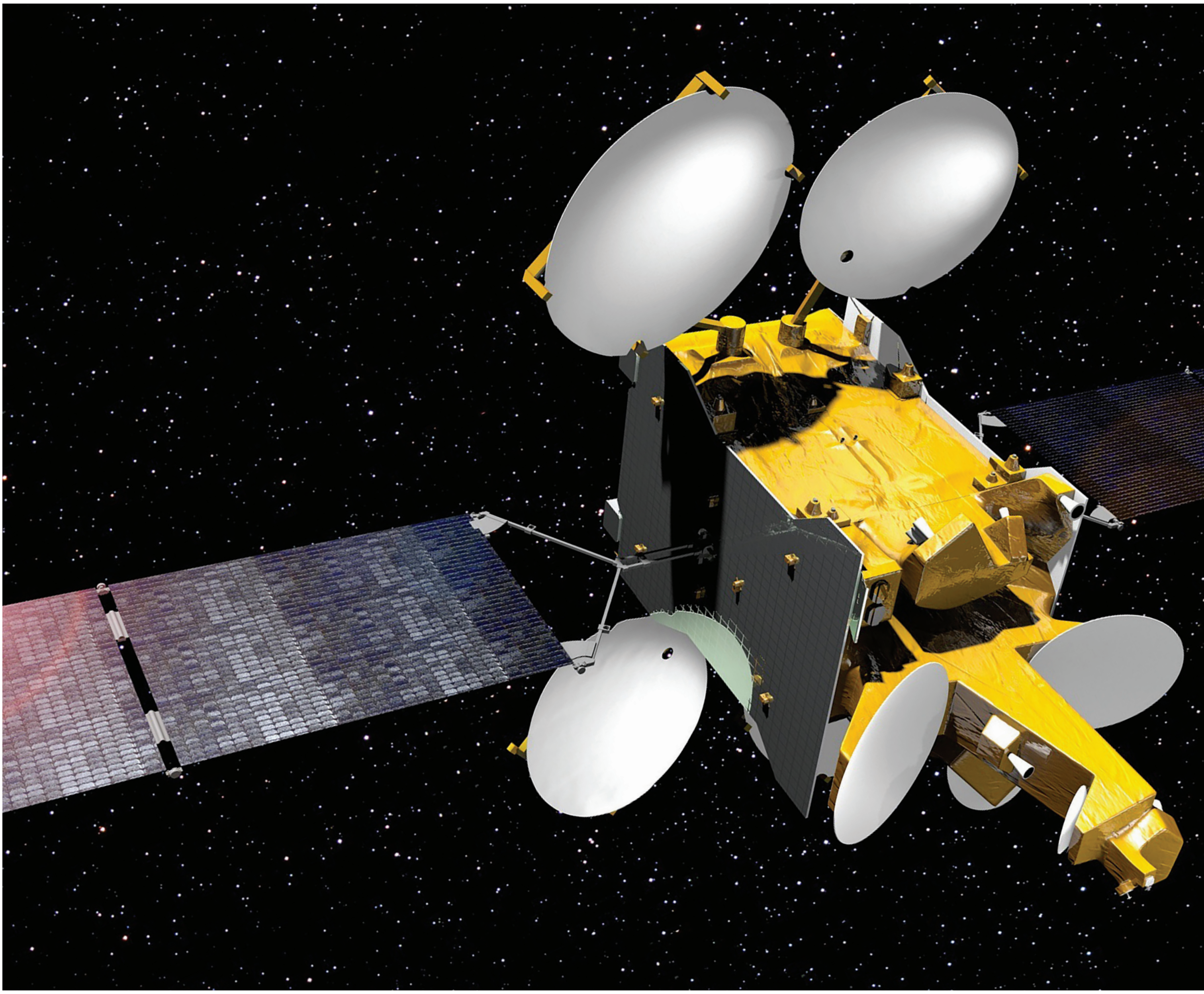
"Yet data from these remote optical-monitoring systems will allow us to precisely monitor the distribution of key species," he adds. "Today aerosol lidars are used in every city to monitor so many activities, and my goal is to demonstrate that our instruments can be used by, say, mosquito-control associations to do the same."

Fauna Photonics' Pedersen has similar aspirations. His company is "in dialogue" with key public health players including Switzerland-based Vestergaard and the Bill Gates Foundation, and hopes to form industrial partnerships to take the company's lidar technologies further.

"Eventually I would like to see thousands of instruments taking measurements and sharing data to inform local authorities of a potential disease outbreak," he says. "We could map this data, work out how disease migrates around the world, how resistance builds up and provide better interventions for the benefit of mankind." *

> 'The data analysis behind the hardware in particular is very complex... but this isn't science fiction, we can do this.'
> **Michael Stanley Pedersen** Fauna Photonics


uk.rs-online.com



AIRBUS

JUST LAST YEAR, France-based Thales Alenia Space revealed that its cutting-edge communications payload for satellite flight would use high-speed serial links with fibre-optic interconnects instead of coaxial cables. The development may not have stirred, let alone shaken, the world, but out in space, the ramifications are set to be huge and exciting.

"This is the first time fibre-optical interconnects will be employed on a massive scale in a commercial satellite," says Nikos Karafolas, technical officer at the European Space Agency. "Once these are introduced the technology will be here to stay."

Why are such photonics technologies so crucial to future telecommunications satellites? In short: size, weight and power.

Today's high-throughput communications satellites (comsats) generate narrow beams to transmit data, exploiting frequency re-use schemes and raising overall satellite capacity and data rates to some 100Gbit/s. Yet come the early 2020s, the 100Gbit/s capacity will need to shift upwards by an order of magnitude to a mighty 1Tbit/s to meet operators' rising bandwidth demands.

Even if today's microwave and radio-frequency technologies could hit the terabit data-rate target for a next-generation satellite, components and systems would struggle to meet the power consumption, size and weight limits of space flight.

Enter photonics. Already the norm in telecommunications, the race has been on since the turn of the century to transfer lightweight, compact, high-performance technologies from the ground to satellite payloads and space.

Photonics in space

In 2005, France-based navigation and positioning device pioneer IXBlue qualified its Fibre Optic Gyroscope for flight on the Planck scientific satellite. The gyroscope uses optical waves propagating in a fibre-optic coil to accurately measure a rotation rate and, crucially, is resilient to temperature changes, magnetic perturbations, extreme shock and vibrations.

In 2009, two ESA satellites – Soil Moisture Ocean Salinity (SMOS) and PRoject OnBoard Autonomy (Proba-2) – were launched aboard a Russian Rockot launch vehicle. Karafolas says: "SMOS was critically dependent on tens of fibre-optic communications links and was the first operational use of fibre-optics communications in an institutional satellite."

Proba-2 also contained a fibre sensor-system to monitor temperature and tank pressure within the satellite propulsion system, marking the first full fibre-optic sensor network in space. "We had demonstrated we could use fibre optics with confidence and nine years later the systems are still working fine... a defining moment for photonics in space," says Karafolas.

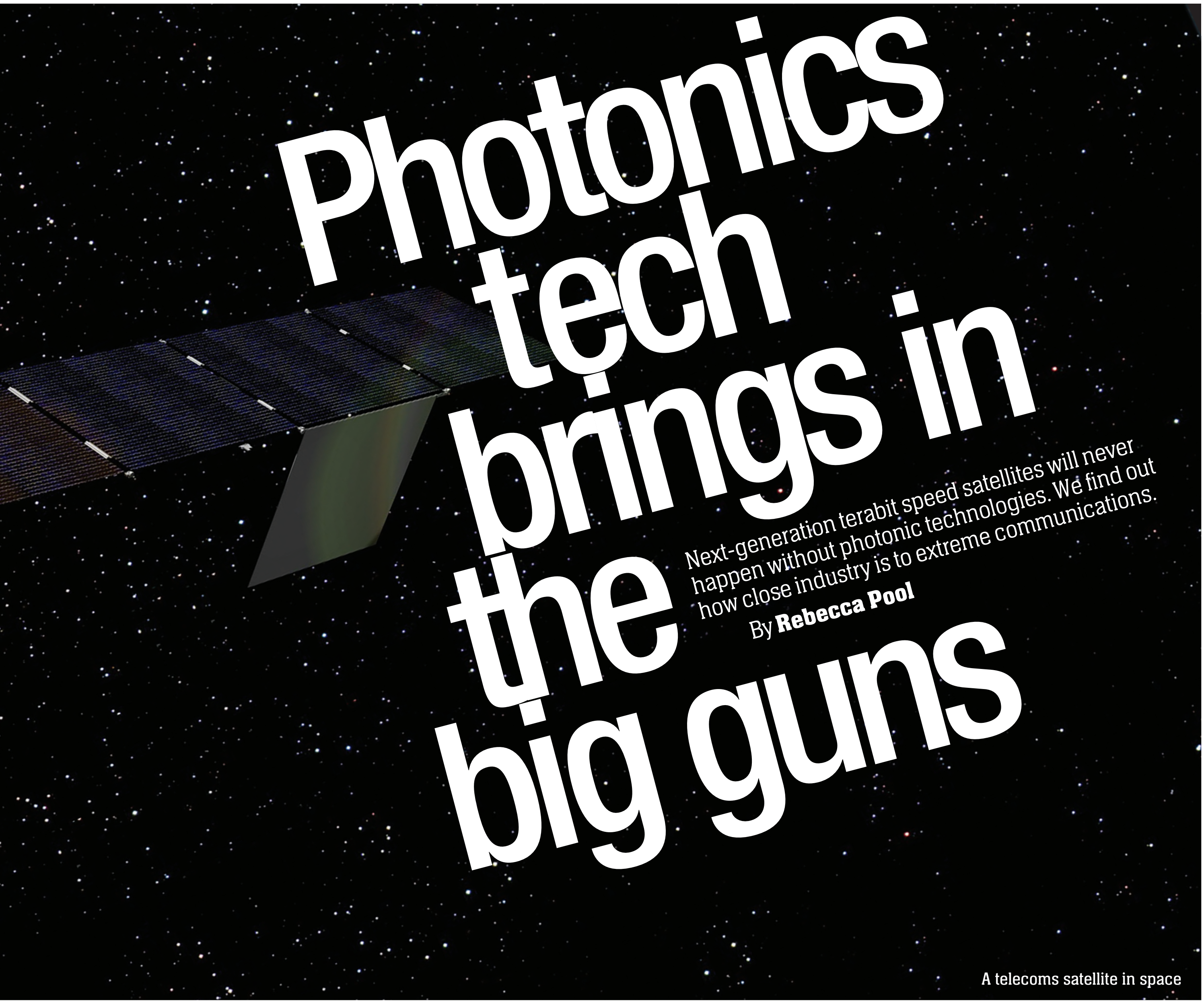
Since this time, worldwide space agencies and partners have also been working on the use of fibre-optic cables, instead of coaxial cables, within comsat payloads.

ESA has delivered its SpaceWire and SpaceFibre standards for high-speed communications, with VTT Technical Research Centre of Finland, France-based Radiall and Reflex Photonics from Canada also developing high-frequency, fibre-optic transceiver modules. Meanwhile, Norway-based T&G Elektro has been devising a flexible routing assembly that will one day route hundreds, even thousands, of optical fibres.

Then, of course, came Thales Alenia Space's 'digital transparent processor', dubbed SpaceFlex. Karafolas says: "What we have been developing for years could fly in 2019... and the [payload] mass is going to be massively reduced."

Cabling and beyond

However, fibre-optic digital interconnections is just the beginning for photonics in satellite communications. Aerospace companies have



A telecoms satellite in space

also been developing systems that can perform microwave functions in analogue satcom payloads. And again, results are edging closer to commercial exploitation.

In a key ESA collaboration, Thales Alenia Space demonstrated a lightweight satcom repeater based on microwave photonic technologies to frequency-convert and cross-connect the growing number of channels in future satellites. Key partners on this development were DAS Photonics of Spain, Sercalo, Switzerland, and France-based Vectrawave.

In parallel, Airbus Defence and Space has been collaborating with DAS Photonics, Cordon Electronics, IMEC, UK firm Polatis and France-based Sodern on a project called OPTIMA, which will deliver a test photonic payload demonstrator for communications satellites.

According to Airbus project manager Javad Anzalchi, the demonstrator is the first step towards maturing this technology for space applications. What's more, the project has been focusing efforts of European photonics and space players, from both industry and academia, on proving the validity of the photonic payload concept.

"Key challenges include the low interest of large companies to qualify a small number of recurrent items for space... while some

A microwave photonic wideband repeater demonstrator built by Thales Alenia Space, France, under an ESA ARTES contract

photonic devices and technologies for terrestrial applications are not capable of sustaining flight [or withstanding] a space environment," he says.

Importantly, Anzalchi reckons the photonic equipment Airbus has developed for OPTIMA and other projects will reduce payload mass by at least 25 per cent compared to conventional payload technology. "Most of this comes from replacing coaxial cables with fibre-optic cables," he says. "We also use wavelength division multiplexing in our payload architecture which, in most cases, reduces the equipment required."

Anzalchi reckons Airbus will perform an in-orbit technology demonstration after 2021, with ESA's Karafolas also expecting systems from Thales and Airbus to be offered to satellite operators within five years. Yet as years of dogged research reaches fruition, perhaps the most ambitious developments are yet to come.

Microphotonics

ESA has also spent over a decade working on microphotonics – miniaturised photonics components on a chip – for use in satellites. Collaborating with the likes of DAS Photonics, Lionix from the Netherlands, Antwerp Space, the University of Ghent and IMEC from Belgium, EPFL and CSEM from Switzerland, the organisation has already demonstrated how the comsat payload microwave functions of frequency generation, frequency conversion, beam-forming and RF filtering can be performed by microphotonic circuits.

ESA and partners will spend the next five to ten years looking at developing and maturing microphotonics for photonic payloads. Karafolas says: "This is going to be a real challenge. Ten years in space is a very short time, and once you put your spacecraft into a rocket you cannot access it for its entire lifetime, which is up to 20 years. This means we really have to take extra care with all developments and qualification." *

SIGNIFY, STEELCASE, DREAMSTIME

HCL can give your brain the benefits of natural light

LIGHTING UP YOUR *life*

Human-centric lighting (HCL) has been around for a few years, but has only recently become a buzzword in the technology community. So what's it all about? And could it become commonplace in our homes and places of work?

By **Rebecca Northfield**

YOU'RE FLYING like a bird. Slicing through clouds, flapping your arms, feeling the brisk wind on your face. You're having the most wonderful dream. Relishing the blissful moment. Suddenly, a crow appears out of nowhere, squawking directly into your ear. And it won't stop. Then you're ripped from the ethereal sky and land in your bed, jolted awake by the morning alarm.

Waking up in this unnatural way can often leave you bleary-eyed and sleepily hunting for coffee. When you finally get to work after the exhausting commute, you're left feeling dishevelled and not fully awake all day, no matter how much caffeine you chug.

That is where the apparent power of human-centric lighting (HCL) comes in. According to the LightingEurope industry association, HCL supports health, wellbeing and performance of humans by combining visual, biological and emotional benefits of light. The use of LEDs means this kind of lighting can be energy-efficient and simple to control with smart, connected systems.

As well as letting us see, light evokes a physiological response in humans depending on its characteristics, such as colour spectrum, intensity and timing. Therefore, if we spend a lot of time indoors, it affects our circadian rhythm – the body's master clock that helps determine our sleep pattern. HCL is supposed to aid our rhythm to improve health and wellbeing.

Dr Russell Foster, British professor of circadian neuroscience, is credited with >


Our mood can be influenced by light colour temperature – warm white is calming and neutral white is more stimulating

< discovering light-sensitive ganglion cells – which influence the body's biological clock and are the basis of HCL – in the retina of the eye. The cells respond most sensitively to visible blue light, synchronising our bodies with the external cycle of day and night.

However, Foster says we're not ready for HCL and it's too early to implement it. Speaking at the Light & Building 2018 exhibition in Frankfurt, he said: "We can't develop human-centric lighting until we know what impact light has upon human biology across the day and night cycle."

According to Foster, there is no standard 'recipe' that manufacturers can use, as people are either 'larks' or 'owls' – lighting affects each group differently.

Regulating and synchronising

So what does the industry think? Mark King, product line manager of lighting at power management company Eaton, says: "General understanding around the impact that lighting has on the body – from its influence on the circadian rhythm to affecting moods and general wellbeing – has greatly improved. Yet the idea of human-centric lighting still has a way to go."

Health and wellbeing is often linked to a good sleep and wake cycle; a disrupted rhythm impacts on how we function and our long-term health. Tiredness leads to stress, memory problems, lack of creativity, drug and stimulant use, obesity, lower immunity and even cancer.

Bianca van der Zande, scientist at Signify (formerly Philips Lighting), says the positive influence of light on our sleep-wake cycles has been studied in depth. "Production of melatonin, the hormone that helps to induce sleepiness and regulates our sleep-wake cycle, is impacted by natural and artificial light. In darkness, the body gets a signal to start production of melatonin; subsequently, if there is enough light, the body gets a signal to stop production of melatonin to become more alert."

She adds that our natural body clock runs for between 15 and 30 minutes longer than our artificial 24-hour clocks. "Unless reset, this will make us want to go to bed later, causing us to be more dependent on our morning alarm. Correct quality light and timing can reset the half-hour lag and resynchronise our body clock with our artificial 24-hour clocks." Morning light is very powerful in adjusting our sleep-wake cycle; artificial light that mimics bright daylight is said to be highly effective at regulating and synchronising, contributing to our overall health.

How does it work?

Our mood can be influenced by light colour temperature – warm white is calming and neutral white is more stimulating. The colour rendering index Ra measures what colour display is the closest rendition to daylight. In offices, for instance, Ra greater or equal to 80 is needed.

Light distribution and direction influences visual performance and comfort. Osram Lighting Solutions says optimum HCL in an office requires a wide area with indirect lighting and high, vertical "illuminances" to create an "artificial sky", with dynamic white colour temperatures and light control, and highly reflective surfaces.

For relaxation, the lighting must be warm with an elevated red component. Higher blue components/colour temperature influences our brain and body clock, increasing alertness, concentration and attention. Osram says the biological effect is strongest when light is emitted from a wide-area source and from above, as with sunlight.

Van der Zande claims there are already examples of the positive and tangible influence of HCL. "In Prague, we installed lighting in the Czech headquarters of energy company Innogy this year. It is tuned to support workers' circadian sleep-wake cycles and stimulate energy levels at set times in the day.

"Employees enjoy a comfortable bright light, similar to natural daylight, to start their day and after lunch. This helps stimulate energy levels and enhance workplace comfort and vision." She adds that the stimulus from the HCL fixtures is likened to a strong cup of coffee, which could be music to the ears of many workers who rely on mild stimulants to get through the day.

Yet Dawn Hollingsworth, principal of Darkhorse Lightworks, says the industry needs more funding for research. "There are roadblocks to implementation such as different priorities, costs and control systems that suppress demand," she adds.

Eaton's King explains that while many understand the idea on a granular level, i.e. mood versus lighting colour, one could argue that the idea has yet to be understood across the industry – and that lack of awareness is reflected in product development.

LIGHTING

BENEFITS OF HCL

Education

- In the early morning hours, correct light can help students to wake up with less sleepiness.
- Improved light environment can aid alertness and concentration.
- At the correct time, higher-intensity lighting systems and colour temperature can improve learning quality and sleep.

Healthcare

For residents:

- It can prevent mood swings and depression.
- Stabilises human circadian rhythm. Wellbeing improves due to better-quality rest and sleep-inducing drugs are reduced.

For staff:

- Counteracts insomnia.
- Improves employee wellbeing.
- Under less pressure as residents experience correct activity and resting phases.

Office

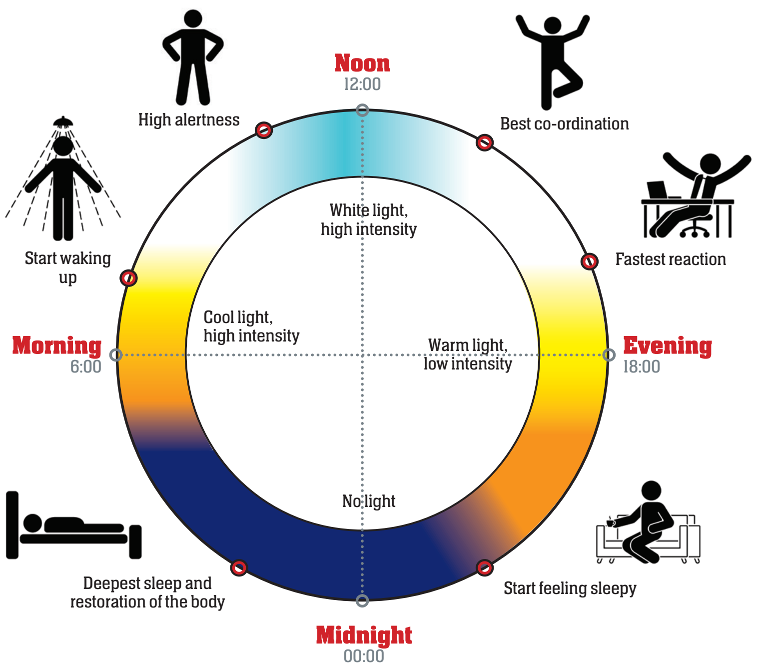
- More intense and circadian light exposure can help employee alertness during the day and sleep at night.
- Individual lighting control, which varies from person to person, may increase job satisfaction.

Industry

- Intense lighting installations and tuneable white light may help production, fatigue and errors – effects are more apparent with repetitive tasks.
- Shift workers may benefit from phase-shift lighting to ease into night work.

THE EFFECTS OF LIGHT

THE HUMAN BODY CLOCK



THE BENEFITS OF HUMAN-CENTRIC LIGHTING, EE PUBLISHERS

More intense and circadian light exposure can help you stay alert at work during the day and sleep better at night

He adds that "in order to move forward, key concepts surrounding HCL must be understood by electrical contractors and installers. A deeper understanding of issues surrounding HCL on their part would provide added value for manufacturers, installers, and especially the end user," such as workers in an office or factory, children in a school, residents in a care home or hospital, or you at home.

Hollingsworth says the lighting industry is great at talking to itself, but more needs to be done to educate the general public and those with the money to build projects.

"When people demand better lighting, the benefits will be evident, but until there is demand, HCL will continue to be a target for cost reductions and widespread adoption will be slow."

King agrees that while it may be some time before we see HCL implemented on a regular basis, having a basic understanding of it will prepare contractors for when it's time to move to this next level. "In the meantime, it's important that installers choose the right luminaire to light every space in the best possible way," he says. "This will not only maximise staff productivity, but it will deliver the best results overall."

Alex Gifford, UK brand communications manager at Steelcase, says details like lighting, materiality, informal spaces and natural elements are powerful influences on behaviour and communicate company brand and culture. "It's important to ensure the technology available is easy-to-use and accessible; frustration can build when there is discord between humans and technology."

Signify's Van der Zande adds: "Given that we as a species now spend much of our day indoors, as well as the advancements in our understanding of health, I expect the role of lighting in our physical and mental wellbeing to become increasingly commonplace in our daily lives." *

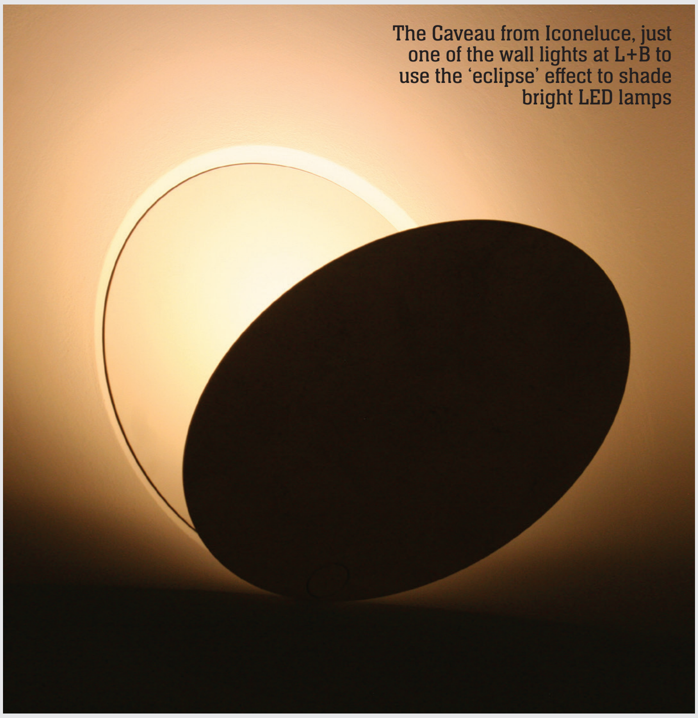
THE GALLERY

LIGHT BRIGADE

LED dominance is opening up new possibilities for lighting designers. **Dickon Ross** found a variety of innovative ideas at this year's Light + Building trade fair in Frankfurt.

Nyta's Pong is a portable lamp that can be slung over a rafter, tree or anywhere with the cable that connects the lamp to its battery

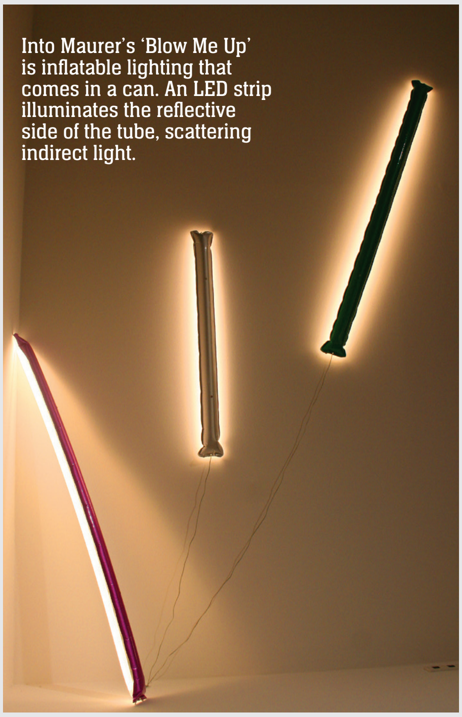
Anke Meumann of Lichtpapier weaves fibre optics into paper and lights them with LEDs to create bright new materials for interiors



The Caveau from Iconeluce, just one of the wall lights at L+B to use the 'eclipse' effect to shade bright LED lamps

The Orb, from Copenhagen start-up Shade, is a tunable uplighter and downlighter in a lamp just 13cm across. See it in action on the *E&T* app.

Light touch: Front's Hoop holds a globe-shaped diffuser resting in a metal frame containing hidden wires to power it



Into Maurer's 'Blow Me Up' is inflatable lighting that comes in a can. An LED strip illuminates the reflective side of the tube, scattering indirect light.

LEDs are small and bright enough to be arranged on the inside, outside or edge of suspended hoops. Adding crystals sets them on fire.

The Bird desklamp by Bernhard Ossan could never be this slim without LED technology

The simplest of shapes inspired these Phenomena glass pendant lights from Czech design company Boomba


Compact LEDs allow more space in the luminaire for other elements, like plants in this terrarium light


The shape of the plant pot echoes the light in Palma, a clever combination design by Vibia


Num Lighting designs sculptured LED-illuminated polycarbonate tiles that be easily joined together to create custom panel installations


Does today's LED technology spell the end of ridiculously huge, over-the-top chandelier bling? Er, no it doesn't.

The elegantly simple Above light designed by Mads Odgård for Louis Poulsen takes LED technology into timeless design

If you have LED lights you are on the way to getting faster internet. But switching to light from radio for communications may be a bigger problem than it looks.

By **Chris Edwards**

LET THERE BE LIGHT

NASA, DREAMSTIME

RADIO FREQUENCY communication has a problem: it's running out of headroom. Traditionally, its most valuable property when delivering data from one user to another is you do not have to aim the device in the right direction. Mobile users can move around as much as they want and they will still receive signals from a basestation just as long as they are in range. But that comes at the cost of increasing the interference when more than one user wants to use the same part of the RF spectrum.

Researchers have come up with increasingly sophisticated ways to code data so that it makes the most of each available RF band but they have butted up against the theoretical limit. To deal with the problem, designers of cellular communications decided to reduce the size of each cell and so cut the amount of interference that eats into the available bandwidth even though it is more expensive to achieve: the number of basestations you need spirals upward.

Another way to get more data over the airwaves is to move up in frequency. Telecom operators plan to make use of millimetre-wave transmissions, where the signals are much more directional: active antennas are needed to steer them, which tends to cut mutual interference. The bands are also able to squeeze in much more data than those in the conventional sub-3GHz space. Although the military snaffled the best slots in the mm-wave region, there is a lot more available spectrum between 10GHz and 100GHz. But go even further up the frequency range, into the infrared and visible-light range, even higher data rates are available and you do not have to ask anyone to use it.

Fraunhofer's Heinrich Hertz Institute is investigating Li-Fi use in industrial areas, one of its most promising applications

The idea of using light is nothing new, though not at the data rates Professor Harald Haas of the University of Edinburgh proposed in 2011 when he coined the name Li-Fi as a nod towards the still-dominant Wi-Fi RF networking standard. Haas alludes to an invention of Alexander Graham Bell's that preceded the telephone, the photophone, which encoded the vibrations of a speaker's voice onto light using a mirror. Bell successfully demonstrated that it could work over distances up to a kilometre.

Aside from its limited data rate, Li-Fi is quite similar to the TV remote control, the most pervasive example of digital light-based communication we have today. Like the remote control, Li-Fi does not need an unbroken line of sight – light bouncing off a wall can still work, though this might lead to more errors in the signal picked up by the receiver. As a result, Li-Fi systems will need to trade off error correction against speed. If they do not have a direct line of sight and suffer from flashes coming from other light sources that impinge on the detector, the effective data rate will drop.

Visible-light or infrared wireless links have also been used to take care of high-speed communications across wide rivers and between tall buildings scattered across a campus. The IEEE 802.11 wireless-networking standards committee, which looks after the Wi-Fi standard, has decided to include this kind of wireless backhaul as a use-case for the Li-Fi standardisation effort it kicked off earlier this summer.

Among the systems looking to exploit this use of light-based communication is one developed by Fraunhofer's Heinrich Hertz Institute (HHI) together with Japanese telecom company Sangikyo. They designed the system to be able to support communications across a shopfloor or through subways without laying cables, with a peak data rate of 750Mbit/s to provide a balance between speed and robustness.

As with Wi-Fi, the IEEE 802.11bb task force has volume markets in the home and offices as its main focus. It proposes a system that, at minimum, supports data rates of 10Mbit/s but, through advanced coding schemes analogous to those used in the latest RF modems, scale to a peak of 5Gbit/s: almost ten times faster than the current maximum on Wi-Fi. In many cases, Li-Fi would operate alongside Wi-Fi, acting not just as a faster channel for anyone in sight of a light that can support it but a more secure one. The return channel would also be light-based but use a smaller emitter operating in the infrared region so that it does not interfere with the downstream signal or distract the user.

Rolling out Li-Fi in the home

Volker Jungnickel, head of the metro, access and inhouse systems group at Fraunhofer HHI, says: "Standardisation is a prerequisite required to scale [Li-Fi] technology to larger volumes. However, behind successful standards such as Wi-Fi and 3GPP there is usually, in addition, a mass market and an ecosystem. Thus, besides standardisation we have to establish the market for Li-Fi and the ecosystem likewise."

Finding applications for mass-market Li-Fi may be trickier than it looks even though Haas sees a willing ally in the lighting industry. That industry is faced with a shrinking market because the renewal rate for LED-based lamps is much lower than the difference in price they can charge for each unit. Light bulbs that can double up as routers for data lets them potentially increase the value of their product. And the core lighting technology barely needs to change at all. LEDs respond very rapidly to changes in current they receive from the electronic controllers in the bulb's circuit board. All that is needed is a more complex controller that balances the demands of light generation and encoding data. But there are other obstacles.

One early concern was that of flicker. In practice the changes in light intensity are so small and fast, the human eye does not appear to notice them. However, Joël Thomé, general manager and senior research and innovation consultant at PISEO, points out that modulating the light to send data tends >

PICTURE CREDITS

< to shift the colour balance of the lighting slightly.

A bigger problem lies in getting data to and from the light fitting. Few homes are cabled for Ethernet and, where they are, the sockets are at plug height. Homeowners would need to run Ethernet cables into their ceilings to get to the Li-Fi bulbs. Would they want to incur the cost and inconvenience, or stick with Wi-Fi? Thomé says Li-Fi needs to show a strong advantage over existing RF communication systems to be deployed in the home: "For homes, Wi-Fi currently does the job very well. Why should we add the burden of additional cables? One might think about wireless communication between the LAN connection and the bulbs. But again, what is the competitive advantage over Wi-Fi?

"At the moment we do not really see any good reason why Li-Fi should be massively integrated in the consumer lighting market, especially in the short term," Thomé adds.

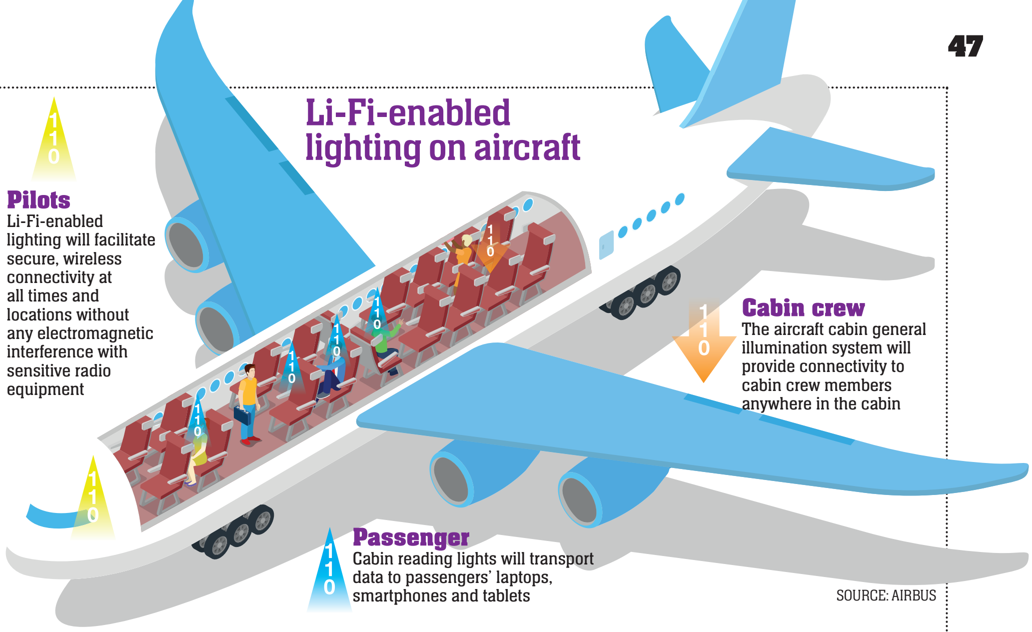
Office-based Li-Fi

The office environment provides maybe more fertile ground for Li-Fi. Lighting suppliers are already looking to building maintenance as a way of helping to keep them in business. Rather than sell lights and maintenance, the lighting supplier can provide a set of services delivered through the light sockets. A number of lighting specialists have already started to work on incorporating Bluetooth into their products so that the lighting grid can act as a feeder network for IoT sensors. They avoid new wiring by taking advantage of mesh networking in Bluetooth version 5.0.

Mesh networking lets Bluetooth messages hop from node to node until they reach their destination, possibly across an entire building. As a result, it needs no new wiring. But building owners might choose to take advantage of ability to use Ethernet cables to transfer power as well as data. The Power over Ethernet (PoE) standard was developed as a way of providing electricity to network devices so that they do not need a separate mains connection. Most offices already have cabling running close to the lighting grid that could support PoE and, with it, data delivering to Li-Fi-enabled bulbs.

But Bluetooth overlaps with potential Li-Fi services in other ways. The RF standard, for example, has the concept of the beacon: a device that provides location services, such as the ability to tell devices in range where they are and what services are available to them. Li-Fi proponents want to do the same.

Bought by Philips in 2016, French specialist Luciom came up with the Li-Fi Tag – using a relatively low-speed code imprinted on the light to act as an indoor guide and asset tracker. One of the first applications Philips found for light-based communications was in a trial for the French supermarket chain Carrefour. Codes picked up from the light fittings overhead by a smartphone's camera would tell an app where the user is in a store and provide a map to where they would find items on offer or something they want to buy. >



SECURITY

CONE OF PROTECTION

When the IEEE started work on what would go into a standard for Li-Fi communications, the task force looked at reasons why people might swap from RF to light. One is security.

Professor Harald Haas of the University of Edinburgh, a keen proponent of light-based communication, maintains the technology has a high degree of innate security for a couple of key reasons. One is that light is easy to block: if you are on the wrong side of a wall, you will have no way to pick up on transmissions. Wi-Fi signals, on the other hand, readily leak through many solid objects although the higher-frequency bands are easier to block.

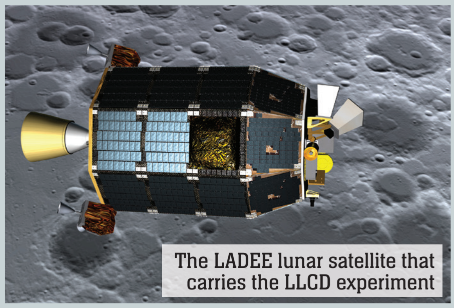
A further reason for Haas's confidence in the higher security of Li-Fi is that even if you are in the room, interception is still tricky to pull off. At a seminar organised by the Universidad Internacional Menéndez Pelayo (UIMP) in Santander, northern Spain, in late June, Haas argued that practical interception of encrypted Wi-Fi transmissions demands the attacker not just be able to see the downstream transmissions from a Li-Fi-enabled light bulb, but that of the return transmitter aimed at it. "The eavesdropper will need to be very close to you," he argued.

The light cone itself could be very small. One of the IEEE's proposed use-cases at home is a Li-Fi desk lamp with the user's computer sitting directly underneath. However, as this requires a wired connection to the lamp, there remains the question of why not take that cable all the way to the device itself?

APPLICATIONS

SPACE IS THE PLACE


The Nasa team inspects the Laser Communications Relay Demonstration modem


The LADEE lunar satellite that carries the LLCD experiment

Li-Fi could reach into deep space. In 2013, Nasa launched a satellite destined for lunar orbit that carried a novel way of relaying data back to the Earth. The Lunar Laser Communication Demonstration used an infrared laser working at a similar wavelength to those used in long-distance fibre-optic communication to send data back to Earth.

The 622Mbit/s link coped with clouds by switching between ground stations. The team found it was able to switch and resynchronise with each new station without having to fall back on a radio side-channel, which helps simplify the system. For space missions a shift from RF to infrared or visible light communications makes possible a hundred-fold increase in bandwidth.

The next step in the Nasa project is the Laser Communications Relay Demonstration project, which will be used to explore the feasibility of having satellites in orbit capture signals from deep-space probes and convey them to ground stations.

Visible light may prove the key to making it possible for robots operating underwater to talk to each other more easily. RF scatters so readily in water that it is hard to establish reliable communications except at very low frequencies – with equally low data rates. Water also absorbs visible light but, using Li-Fi-type modulation, blue-green lasers can send data much further than all but the highest energy electromagnetic waves. Even with blue-green lasers, scattering remains an issue but Li-Fi could be used for tens or hundreds of megabits per second communications over distances of tens of metres.

PICTURE CREDITS

Lighting on public transport and aircraft may provide a solution to giving passengers reliable connectivity

< Although office and retail could provide a sizeable market for Li-Fi in the future, the near-term applications may be in more specialised markets. Thomé points to healthcare and aviation as possible targets.

Last year, Airbus said it is experimenting with Li-Fi as it provides a way of delivering high-speed data to each passenger's seat without having to install large quantities of cabling that will add to the aircraft's weight. As each passenger has their own light above their seat, the passenger aircraft may be one of the environments best suited to Li-Fi communications.

Where Li-Fi comes into its own...

In hospitals, a big concern that prevents widespread deployment of Wi-Fi or Bluetooth is that of electromagnetic interference affecting the more sensitive instruments. Explosion-sensitive environments on oil rigs and industrial plants that handle fine powders and volatile chemicals similarly cannot make use of high-frequency RF communications and also demand stringent protection around data cables. Light-based messages are much safer. One of the use-cases explored by the IEEE 802.11bb task force is for communicating with robots sent into gas pipelines – again, because of the lower risk of explosion.

Fraunhofer HHI has focused more on industrial applications than on consumer for the near term. Jungnickel says it is hard to predict where Li-Fi will succeed. "We just believe that the original idea, to jump in one step from zero market into a mass market for consumer applications, is too high. This requires from the beginning low cost, low power-consumption and high volumes. That's why we were seeking for other use-cases and found them in the industrial area. Our biggest challenge is to find real customers and work with them to introduce the technology into real markets."

As well as working on its wireless-backhaul technology, Fraunhofer HHI put infrared Li-Fi transmitters and detectors into a manufacturing cell at car company BMW's plant in Munich in a project called Owicells supported by the German government. As a robot carried out its usual activities – welding and test parts – and it moved around the 5 x 5m^2 cell, it exchanged data with an array of infrared emitters and detectors scattered around the perimeter. The team used multiple transmitters and receivers to improve the reliability of the 100Mbit/s link, with most of the data being beamed from the robot to the cell as it welded parts together.

The Fraunhofer team found the bright flashes from the welding equipment did not affect reception and believe this was because the flashes are short compared to the time it takes to transmit each set of data symbols. The use of multiple emitters helped avoid breaks in communication as the robot's arm moved, sometimes blocking the line of sight to the nearest detector.

> 'The technology is available and is not an issue for widespread adoption of Li-Fi'
> **Joël Thomé** PISEO

Tablet with Li-Fi dongle attached

AUTOMOTIVE

MIXED MESSAGES

The IEEE now has four groups working on different aspects of optical communication, only one of which is Li-Fi. Two focus on point-to-point visible-light communications that may be useful for telecom backhaul and low-speed transactions between internet-of-things devices. The fourth is optical camera communication (OCC), which treats pixellated light sources such as screens and LED lighting arrays, including those in vehicle headlamps, as active barcodes.

A human may just see a picture on an active billboard. But subtle changes in lighting may signal to a smartphone camera aimed at it other information, such as special offers or where to buy the product.

There are technical issues with the OCC concept. It takes more compute power to identify the transmitter than it does for the more straightforward problem of decoding the changes in light intensity that take place using Li-Fi. But OCC avoids the problem of having to fit the system with additional circuitry to decode light-based signals. When it comes to smartphones, the usage model is one already exploited for static QR codes and augmented-reality apps.

The major application for OCC may be in automotive. Cars today are routinely armed with front- and rear-facing cameras and use sophisticated image processing to pull important features out of the field of view. And they need to be powered-up while the car is moving. The additional overhead of homing-in on traffic lights, headlights or brake lights to see if they are also OCC transmitters is unlikely to be high, although brake lights introduce a complication. OCC can potentially use low-level signals so that lights that appear to be off are still useful for communication – but detecting them in the field of view may be trickier.

Proponents of OCC see those lights as being conduits for information on traffic flows and near-term intentions such as "traffic light will change to green in three seconds".

The technology is moving ahead and will most likely be spread across the visible spectrum, with infrared being used in many cases because it is less distracting. However, the ability to use standard LED light fittings will avoid the need to budget as tightly for energy as with RF – because most of the power will be used for illumination. "In the end," says Thomé, "one might have different scenarios for Li-Fi deployment depending on what drivers will appear in the future.

"The technology is available and is not an issue for widespread adoption of Li-Fi," he adds. But he notes that standards and the demonstration of competitive advantages over wireless technologies that are already in place are the challenges Li-Fi needs to overcome. But, in the long-term, Li-Fi may become a necessity simply because RF has run out of space and Li-Fi and optical fibres have to come together to keep pace with the data demand. *

Green Sense Farms specialises in growing leafy green salads and herbs in its indoor 'vertical farms'

GREEN SENSE FARMS/ROBERT COLANGELO, DREAMSTIME, OSRAM

A LIGHT SALAD

With their low energy usage, reduced heat output and the ability to control the light colour they emit, LEDs are poised to revolutionise the horticulture industry.
By **Len Williams**

"IT'S A REAL luxury to eat locally grown, leafy greens in the middle of a Chicago winter," declares Robert Colangelo, founder and CEO of Green Sense Farms. Before he launched his business in 2012, the only truly feasible way to provide fresh salads and herbs during the cold Illinois winter was to truck them thousands of miles from farms in the warmer southern US states.

However, Colangelo has no ordinary farm. Inside a warehouse a few miles east of Chicago, his 'vertical farm' contains rows of tightly packed plants, stacked from floor to ceiling. Bathed in a bluey-pink LED light, the vertical farm principally grows salads, herbs and starter crops, while also constantly experimenting with new plants. Green Sense Farms, which is in the process of building new installations and selling its technology worldwide, mostly supplies a local Whole Foods Market distribution plant, as well as nearby restaurants.

Colangelo's farm offers benefits beyond producing basil in winter. He is able to intensively grow his crops within 30-35 days and constantly send these to his customers – far more regularly and dependably than growing the same crops in a field. The warehouse attracts few pests and, because the environment is entirely controlled, the company uses significantly less water than traditional farming, while avoiding the need for pesticides.

Farms like Colangelo's offer a tantalising vision for the future of farming. They allow for faster, more efficient growing, significantly less waste and the ability to produce crops near or even within cities – where most plants are now consumed. This potential revolution is, above all, powered by LEDs.

Plants need light to provide the energy that lets them create their own food: they capture this through chlorophyll, a pigment in their leaves. Until relatively recently, there have only been two commercially viable ways to provide plants with this light: using the Sun, or via high-pressure sodium lamps (HPS) installed in greenhouses.

The Sun is, of course, undependable – cloud cover can limit the light available to plants, meaning crops grow more slowly. Growing outdoors also introduces many risks – from too much or too little water, pests, and the requirement to use pesticides. You can also only grow on one level, meaning farms require a huge footprint.

HPS lamps have advantages over the Sun. When installed in a greenhouse they can provide a constant source of light – even when the Sun is behind clouds or when days are shorter. However, Simon Thaler, press officer at Osram, the German lighting manufacturer, explains their drawbacks: "HPS lamps produce over 100lm/W [lumens per watt] but over a wide wavelength range, which is not necessarily optimised to plant growth. The high power consumption and the heat radiated from HPS luminaires also require a significant distance between the light source and the plants, leaving them primarily suitable for top-lighting systems in greenhouses. To compensate for the heat development, they also often require additional hydration of the plants."

LEDs offer many advantages over these traditional light sources. They do not warm up the surrounding air in the same way as HPS luminaires do, meaning they can be placed much closer to plants in stacks – allowing for 'vertical farms' like Colangelo's. Thaler notes that LEDs last significantly longer than HPS lamps and use less electricity. They can also be turned on and off in seconds – which is more effective than HPS lamps that require up to >

Osram horticultural light fixtures installed in a greenhouse

ECONOMICS
URBAN FARMING

Move over allotments: industrial vertical farms with plants grown under LED arrays might be the future of urban farming. By growing produce close to where it's eaten, growers and supermarkets could cut their transport costs, while giving environmentally conscious consumers produce with a lower carbon footprint.

Professor Neil Mattson of Cornell University has been working with economists on a project to study the scalability of controlled urban agriculture. The research looks at the energy costs, as well as carbon and water footprint of a hypothetical urban greenhouse or warehouse farm in New York City, compared to growing and shipping the same food 3,000 miles from California.

Right now, it seems urban farming remains more expensive than traditional agriculture, with production costs roughly twice as high. Nonetheless, high-value and highly perishable plants do have the potential to be more valuable when grown close to where they're eaten, because more of the product can be consumed before it goes bad. City slickers may soon be eating Waldorf salad grown down the road.

< 30 minutes to reach capacity.

However, perhaps the most exciting thing about LED is that it gives growers control over the kind of light that the plant is exposed to. As it turns out, plant growth is especially benefited by light in the blue or red part of the spectrum. LEDs can be designed to specifically generate more of this kind of light, which is especially useful for growing plants.

Professor Neil Mattson, a horticulture researcher at Cornell University in New York, describes his lab's research into LEDs and light. "We look at plant performance when the plant is exposed to different spectra of light, and how this affects the plant's qualities. For instance, if you expose the plant to more blue light, this produces a plant with thicker leaves. It can also turn on the pathways for secondary benefits such as a plant which contains more antioxidants."

Mattson describes cutting-edge research which looks at how different light wavelengths mean you can get taller or shorter plants, earlier flowering, or impact nutritional value. His current research has found that "lighting treatments can double the amount of vitamin C found in a tomato", for instance.

Custom-designed produce

Brandon Newkirk, marketing director at smart lighting company LumiGrow, explains how his company's LEDs provide growers with this kind of cutting-edge control today. The Californian company has developed cloud-based software that connects to its lighting hardware. This allows growers to constantly monitor light levels in their greenhouses and then 'tell' the LEDs what to do according to their own automated growing strategy – whether that's exposing the plant to more LED light or reducing it on sunny days to bring down electricity costs.

He describes custom-designed treatments, or 'recipes', that expose plants to either more red or blue light. These kinds of treatments can, for example, "make for a sweeter or spicier basil leaf". LumiGrow's customers can effectively design the ideal produce that end consumers might want by exposing the plant to different light spectrums at different stages of its growth. Newkirk explains how, for example, lettuce plants could be exposed to more blue light towards the end of their growth cycle in order to give a more vibrant colour to the final product.

For the end grower, LEDs have the added benefit of giving them much more predictability – and this can save them money. Professor Marc van Iersel from the University of Georgia reports that in the US alone, around $600m is spent every year on energy used in horticultural lighting. If growers can cut that cost by using more energy-efficient LEDs, then they can boost their profit margins. What's more, he explains that "in the US, by the time a grower plants a crop in a greenhouse, it's already been sold". LED lighting means growers can confidently provide the plant with the right amount of light to ensure it will grow in time – because when growers miss deadlines they are often hit by financial penalties.

A growing technology

LEDs clearly have enormous potential. However, Mattson notes that only around 2 per cent of US greenhouses currently use LED technology, according to a recent Department of Energy study. What's stopping uptake?

Put simply, LEDs are more expensive to buy than HPS lamps or sunlight. Prices will go down – van Iersel expects the technology to keep improving while costs drop over the coming decade. And companies like Osram and LumiGrow point to the longer lifespan of their products and reduced electricity bills.

Then there's the question of return on investment (ROI). Mattson explains that for certain crops, it may take up to 10 years to achieve payback, although lighting firms assure ROI is normally achieved in less than five. Either way, growers expect ROI fast, meaning that many still have doubts about whether the investment is right for them.

And there's the final price for the plants themselves. LED lights can, in theory, be used to grow any plant. However, at present the economics doesn't make sense for anything but the highest value crops such as salads, herbs, flowers and marijuana. From apples to potatoes to wheat, many cheaper crops are already pretty much perfectly farmed in the great outdoors, meaning LEDs would offer limited value. Van Iersel describes a colleague's calculation, which estimated that, should wheat be grown under LEDs in the US, a simple loaf of bread would cost an extortionate $11.

He explains that "it's frustrating for people like us working in the field, because there are various 'visionaries' who claim that in future all produce will be grown in warehouses. But, as the example with the loaf of bread shows, that's not going to happen any time soon."

Besides the cost aspect of LEDs, Colangelo of Green Sense Farms also highlights other practical industry challenges, especially for vertical farms. There's a general lack of workers in the agricultural industry, and even fewer who know how to build and rig up LED farms. "There's no standard textbook on building a vertical farm yet."

Despite these challenges, rapid advances in LED technology suggest we will reach a tipping point soon – Mattson estimates this will be reached within 5-10 years. At this point, LEDs will be more attractive and cost-effective than HPS, and this could really revolutionise the horticultural industry.

Colangelo expects to see farming become more stratified, with different types of crop being grown in the most appropriate environment. Some plants will always be best grown under the Sun, some in greenhouses and others in vertical farms.

He adds: "People get very excited to see plants growing indoors in a very sanitary environment." If he's right, the future's bright for the sector. •

Robert Colangelo, founder and CEO of Green Sense Farms

SCIENCE

EFFECTS OF COLOUR ON PLANTS

Light is a kind of electromagnetic radiation. It is visible to the human eye at wavelengths between approximately 400 and 700nm, with different wavelengths perceived as being different colours. The human retina is most effective at picking up blue, red and green light, with different cells being sensitive to each.

Plants absorb light via pigments called chlorophyll a and chlorophyll b, which reflect green light but are effective at absorbing 'deep blue' light (450nm) and 'hyper red' light (660nm) as well as 'deep red' (730nm). Exposure to different amounts of these wavelengths can affect how the plant grows.

Blue light provides plants with a lot of energy and is used to regulate the opening of stomata – tiny openings on the surface of leaves that control water loss and uptake of carbon dioxide. Providing more blue light results in plants with smaller, thicker and darker green leaves. Hyper red light is especially effective at triggering photosynthesis, and makes plants grow tall and fast. And deep red light impacts on when a plant begins to flower. By combining different colour light in different quantities, you can change the final plant's qualities.

For instance, a plant mainly exposed to red light will grow tall and thin. But add around 10 per cent of blue light into the 'recipe' and it will grow shorter and more densely. Exposing the plant to more of one type of light or another at different stages of its growth can also affect its development.

The whole story of...

Light bulbs

PART ONE: Early developments
PART TWO: Market dominance
PART THREE: The LED revolution

With its evolution in the 19th century and its terminal decline in the 21st, the incandescent light bulb dominated both domestic and public lighting for the entire 20th century. It was a technology that changed the way we lived, worked and were entertained.

By **Nick Smith**

ALAMY

1761
Ebenezer Kinnersley demonstrates incandescence from a heated wire.

1802
Humphry Davy uses a 'battery of immense size' to create incandescent light, by passing an electrical current through a platinum filament.

BRIGHT IDEAS

PART ONE: Early developments

Without the technological and business flair of one man – Thomas Edison – the world would look a lot different today. But, back in the 19th century, the journey into light was a shadowy sequence of events.

Such was the importance of the light bulb – or lamp, as it is known to engineers – that the expression has entered into the language as a synonym for invention. Yet its road to supremacy was an untidy street fight dominated by one man – Thomas Alva Edison – who, for all his visionary prowess and business acumen, could not have predicted that a century later, his development of an idea that lit up the world would be rendered virtually obsolete by the emergence of light-emitting diode technology.

In one of the neatest twists of technological fate, the so-called 'invention' of the light bulb never had a 'light bulb moment'. As with so many critical innovations that had far-reaching effects in the commercial and cultural development of humankind, the light bulb – or more specifically here, the 'incandescent' light bulb – was the product of a series of independent and incremental breakthroughs by engineers and scientists separated by both time and geography. Although it is the great American inventor and entrepreneur Edison that is conventionally given the laurels for bringing the bulb into the world, Smithsonian Institution curator emeritus Bernard S Finn says we've been refining one of our most important discoveries ever since early humans learned that controlled fire could produce light as well as heat.

Edison's role in bringing light to the modern world was as a developer of other engineers' ideas that went before him in the 19th century. "It was Thomas Edison who came up with a commercially viable solution," says Finn. In 1879, on New Year's Eve, Edison lit up his laboratory at Menlo Park – a display visible for more than 20 miles – and the era of electric lighting was quite literally switched on. Always ready with a sound bite, Edison predicted that electric light would become "so cheap that only the rich will burn candles".

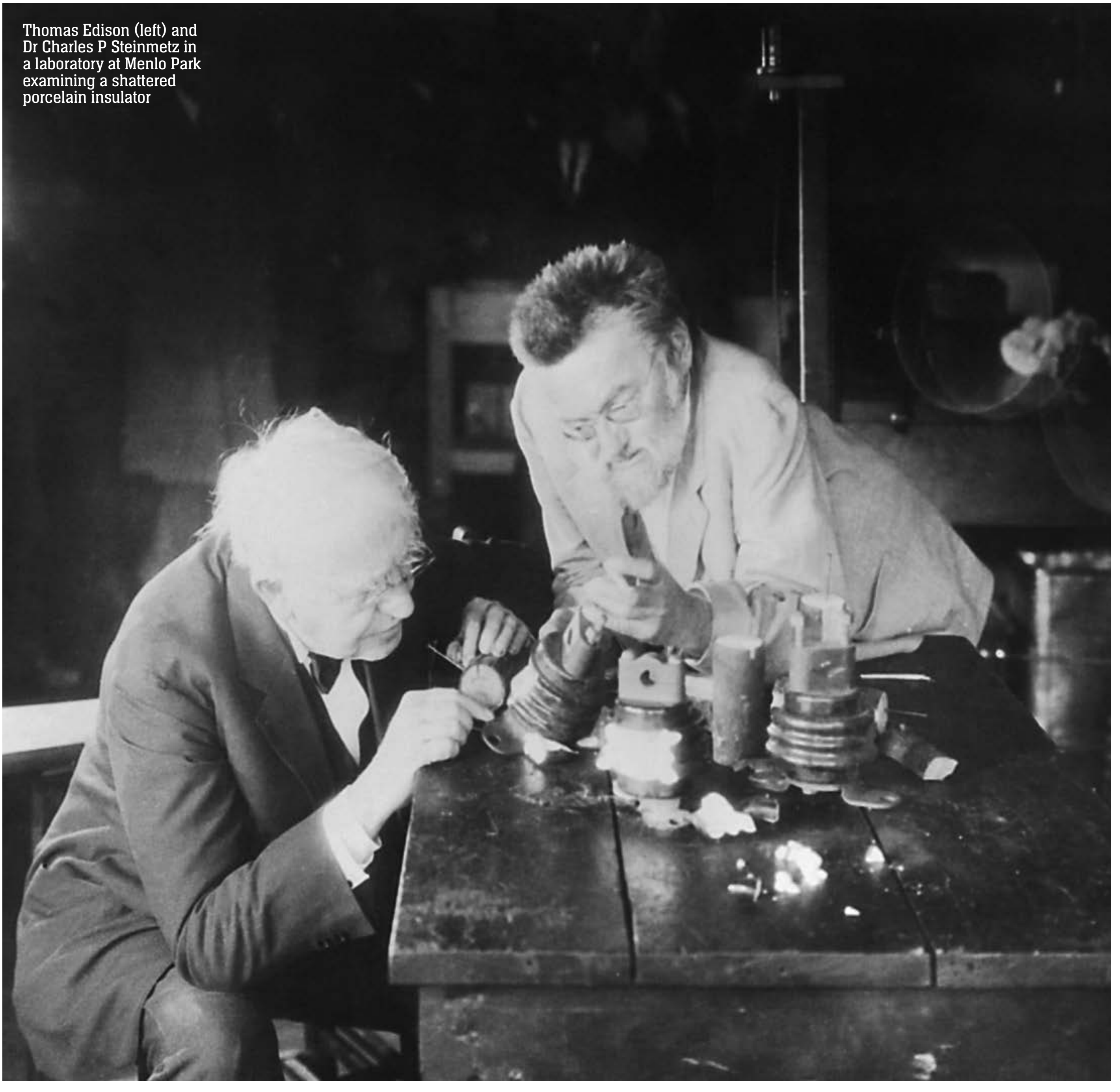
The real value of Edison's achievement was that it marked the end of a tentative phase in creating light from electricity by establishing the incandescent lamp as the front-runner technology. In 'Edison's Electric Light: The Art of Invention', historians Robert Friedel and Paul Israel cite 22 inventors of incandescents ahead of

1835
James Bowman Lindsay demonstrates constant electric light by which it was possible to "read a book at a distance of one and a half feet".

1838
Marcellin Jobard invents an incandescent light bulb with a vacuum atmosphere using a carbon filament.

1840
Warren de la Rue devises and encloses a coiled platinum filament in a vacuum tube. Development shelved due to cost of platinum.

1841
Frederick de Moleyns is granted the first patent for an incandescent lamp, a design using platinum wires contained within a vacuum bulb.



Thomas Edison (left) and Dr Charles P Steinmetz in a laboratory at Menlo Park examining a shattered porcelain insulator

Edison, and yet still place him firmly at the head of the family. This is due to the combination of three critical factors Edison got right simultaneously: the incandescent material, high vacuum levels and high resistance.

It was the last of these three that Edison really understood better than his predecessors. With high resistance, heat (and therefore light) would build up in the element instead of the feed wires coming from remote electric generators. After testing hundreds of materials, says Finn, "he settled on a thin strip – or filament – of carbon". Because the carbon filament would burn if exposed to air, the glass enclosure, or 'bulb', needed to be evacuated by a vacuum pump. Early versions of the incandescent (the word comes from the Latin '*incandescens*', meaning 'glowing') bulb have a 'tip' showing where the pump was originally connected. By 1881, there was a standard connector at the electrical end, where the bulb could now be screwed into a socket and could be switched on and off.

It was by standing on the shoulders of those who went before him that Edison could see so far into the electric light future. He relentlessly refined innovations of other scientists such as Humphry Davy, James Bowman Lindsay, Moses G Farmer, William E Sawyer, Joseph Swan and Heinrich Göbel, whose ideas were commercially impractical. Realising that platinum was too expensive a commodity to be used in electric lighting, he pursued the avenue of a carbon-coated bamboo filament (anecdotally, he had the idea of using bamboo from observing his fishing rod while on a field trip to watch an eclipse).

But he also wheeled and dealed, scooping up patents of other engineers, while forming strategic alliances, especially with his British competitor, Joseph Swan (who, in many ways, was a player of equal importance, whose house was the first to be lit by a light bulb). Edison secured substantial financial backing from both the Vanderbilt family – the richest in America, having made their money in shipping and the railway – as well as the corporate financier J P Morgan. Yet it was mostly by sheer visionary ingenuity that the man with more than a thousand patents to his name became the driving force behind lighting up the 20th century.

1845
John W Starr acquires patent for his incandescent light bulb involving the use of carbon filaments.

1851
Jean Eugène Robert-Houdin publicly demonstrates incandescent light bulbs on his estate in Blois, France.

1859
Moses G Farmer builds an incandescent bulb with platinum filament. Thomas Edison purchases Farmer's later light bulb patent.

LET THERE BE LIGHT: A CENTURY OF INCANDESCENCE

PART TWO: Market dominance

For much of the 20th century it seemed the incandescent light bulb had no serious challenger. Yet with growing pressure to improve energy efficiency, in the closing decades the writing was on the wall.

Way back in 1835, Scottish inventor James Bowman Lindsay demonstrated his early version of constant electric light with the claim that by using such technology he was able to "read a book at a distance of one-and-a-half feet". He could hardly have expected that, within a century, the incandescent light bulb to which he had contributed so much would be turning night into day. It would illuminate our lives, extend office hours and make football stadiums glow in the dark. It would provide security and illumination for public buildings and searchlights to guide wartime anti-aircraft weaponry. Roads would be lit to accommodate the relentless rise of the automobile and night-ready airports would revolutionise international freight.

With the dawn of the 20th century came an unprecedented opportunity for developers of the newly established incandescent light bulb. Applications were limitless, ranging from the extremely modest (such as bicycle headlamps) to national infrastructure (such as road lighting). The field was open and the market was soon awash with manufacturers hoping to cash in on the gold rush in artificial lighting.

Yet, by Christmas 1924, household names such as Osram, Philips and General Electric were becoming nervous. This was because the market, while booming, was becoming unpredictable. After seeing his sales tumble from 63 million units in 1922-23 by more than half in the following year, the head of Osram William Meinhardt proposed that he met with his competitors to agree on trading principles that would safeguard their future. While Christmas tree lights festooned the Swiss city of Geneva, on 23 December 1924 the top brass of the global incandescent manufacturing community colluded to form the Phoebus Cartel to establish quotas and territories, share knowledge and agree on standards (such as the Edison screw-in connector).

Yet the hidden agenda was revenue protection in a market where manufacturers were becoming victims of their own success. Even back in the third decade of the 20th century, light-bulb manufacturing was so advanced that units had an operational life of 2,500 hours, meaning that it was years before units needed replacing. One of the major (and yet lesser-broadcast) outcomes of the 'Convention for the Development and Progress of the International Incandescent Electric Lamp Industry' was that life expectancy was to be reined in to 1,000 hours. To ensure companies complied with the new obsolescence regulations, they were obliged to send their products for independent testing in Switzerland. If the products displayed unwanted longevity, manufacturers faced heavy fines.

Despite the cartel deliberately stagnating technological development, the incandescent bulb gained traction as one of the great innovations of the time. By the end of the First World War, with cost of electricity plummeting, it was also presenting a serious alternative to gas lighting.

Edison had not been wrong when he said only the rich would burn candles. According to research data published by Fouquet and Pearson, the cost of artificial light had fallen over the centuries from thousands of pounds per lumen hour to fractions of a penny as we evolved from the use of handmade candles to mass-produced light bulbs. This fall in cost led to consumption of artificial light in the 20th century being 100,000 times more than it was in the 18th century.

Energy and light was so abundant the market could afford to, and did, become complacent. The tungsten filament could absorb the hit from emergent fluorescent 'strip-light' technology that appeared in factories and offices. The cost of powering artificial light was such that there was no real pressure to change the status quo until the oil crisis of the mid 1970s. This triggered the emergence of the compact fluorescent light bulb (CFL), which, with energy efficiency five times greater than the incandescent technology, made it a serious challenger. With Philips and Osram bringing them to market by the early 1980s, the first cracks in incandescent supremacy appeared.

Efficiency became the buzzword. New technologies were queuing up to be the next big thing. The unthinkable was starting to happen: governments were passing legislation to phase out the incandescent light bulb.

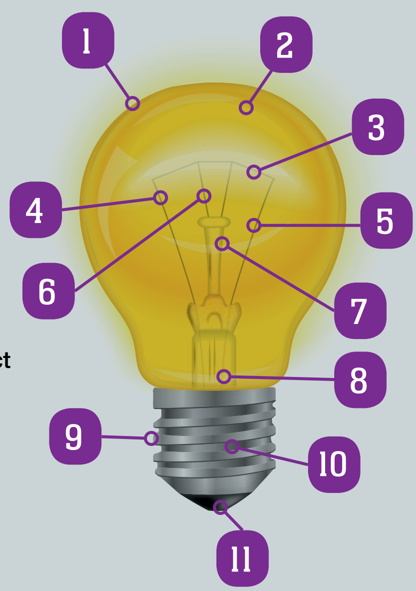
LIGHTING

ANATOMY OF AN INCANDESCENT LAMP

Despite its 19th-century birthing pains, the incandescent light bulb was to evolve into a masterpiece of engineering simplicity that was both cheap to mass produce and inexpensive for the consumer to procure. The boilerplate design was to eventually settle on that of a glass enclosure containing a tungsten filament with an electric current passing through it, heating the filament to a temperature that produces light. The bulb contained a stem or glass mount attached to its base that allowed electrical current to run through a circuit in a vacuum or surrounded by inert gas, protecting the filament from combusting. Despite the ubiquity of the design, the incandescent bulb had a huge flaw, which was energy loss. As much as 95 per cent of the energy required to create light was lost as unwanted heat.

General arrangement of the major parts of a 20th-century incandescent light bulb

1. Glass bulb
2. Inert gas
3. Tungsten filament
4. Contact wire (goes to foot)
5. Contact wire (goes to base)
6. Support wires
7. Glass mount/support
8. Base contact wire
9. Screw threads
10. Insulation
11. Electrical foot contact



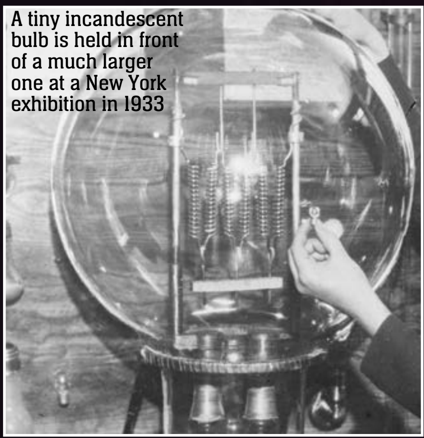
1872
Russian Alexander Lodygin invents an incandescent light bulb using nitrogen in the glass enclosure and obtains a Russian patent in 1874.

1874
Canadian patent is filed by Henry Woodward and Mathew Evans for a lamp consisting of carbon rods mounted in a nitrogen-filled glass cylinder. Patent later sold to Edison.

1878
Thomas Edison begins serious research into developing a practical incandescent lamp.

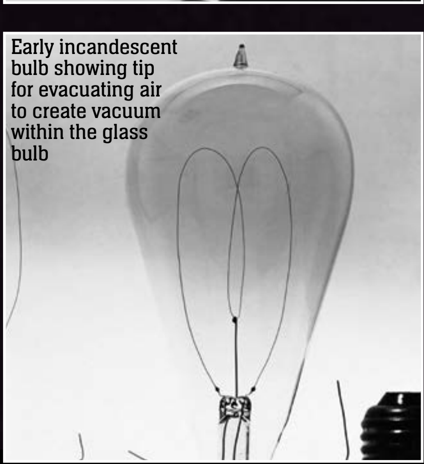
1879
Joseph Swan gives working demonstration of his carbon rod arc lamp. Mosley Street in Newcastle upon Tyne becomes the first highway in the world to be lit by an incandescent bulb.

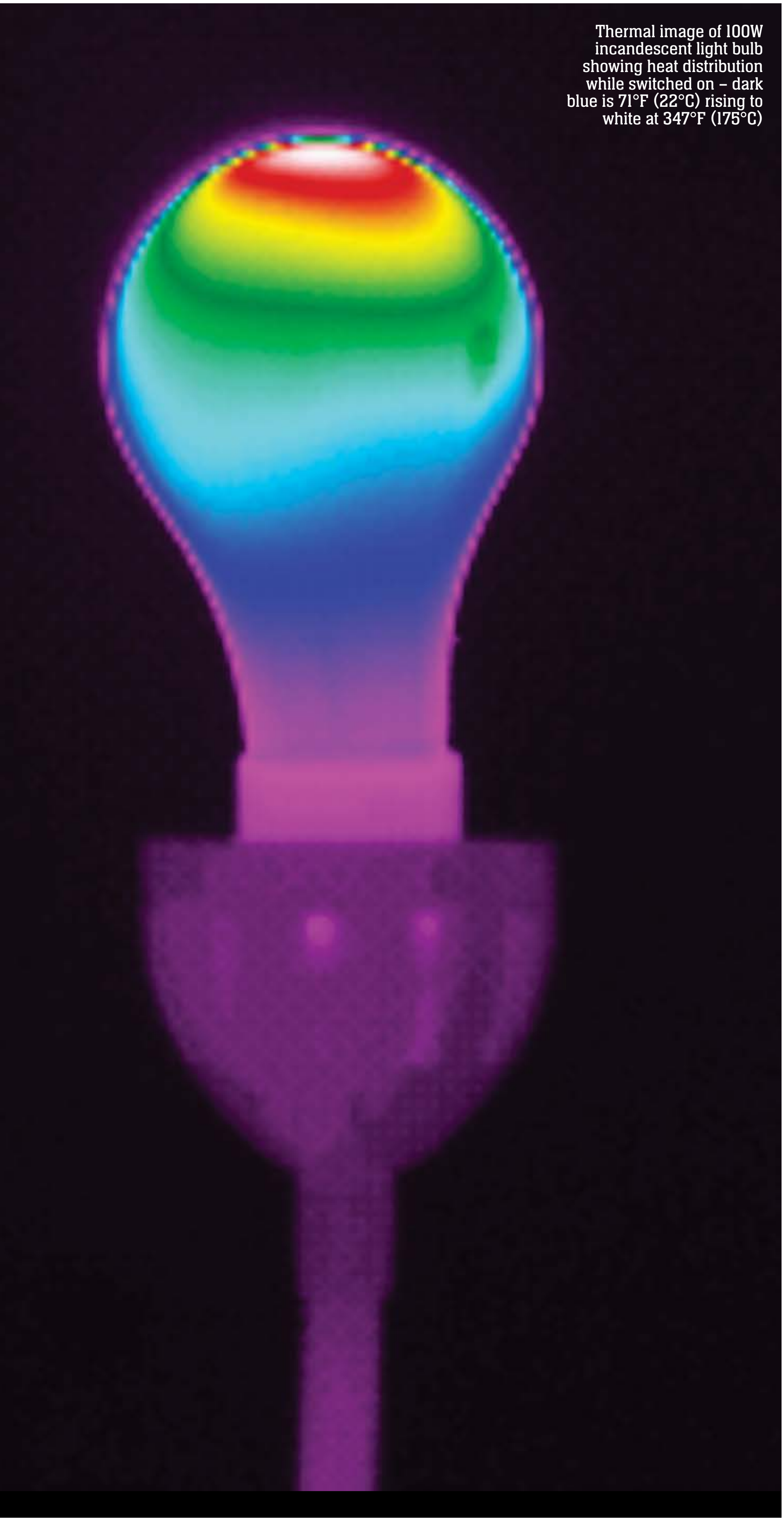
1879
Edison files US patent for an electric lamp using "a carbon filament or strip coiled and connected to platina contact wires".


A tiny incandescent bulb is held in front of a much larger one at a New York exhibition in 1933


Early publicity shot of GE incandescent light bulb


1950s publicity shot of large incandescent light bulb


Early incandescent bulb showing tip for evacuating air to create vacuum within the glass bulb


Thermal image of 100W incandescent light bulb showing heat distribution while switched on – dark blue is 71°F (22°C) rising to white at 347°F (175°C)

IET Events
The Institution of Engineering and Technology

Engineering Live

A Story of Unseen Engineering: Digital TV Compression - The IET President's Address

11 October 2018, 18:00, IET London: Savoy Place

Organised by the IET

EMT 3.2: Electromagnetic Tools, Techniques and Tricks

19 October 2018, IET Birmingham: Austin Court

Organised by the IET Electromagnetics Network

Engineering Safety into Medicine: the IET Annual Healthcare Lecture

31 October 2018, 18:00, IET London: Savoy Place

Organised by the IET Healthcare Technologies Network

Distributed Generation 2018

6-8 November 2018, University of Strathclyde, Glasgow, UK

This November the IET is running its 4th annual course on Distributed Generation in Glasgow covering the principles, practices and fundamentals that will enable practitioners to really hit the ground running with what they've learnt when they get back to work. The course will run over 3 days and include two tailored off-site technical visits – one to the Power Network Demonstration Centre (PNDC) and the other to Whitelee Windfarm.

www.theiet.org/disgen

Key:

IET.TV:
- Live Streamed on IET.tv
- On Demand at IET.tv

Sector:
- Built Environment
- Energy
- Design and Production
- Information and Communications
- Transport

Engineering Diversity and Inclusion

8-9 November 2018, InterContinental London - the O2

Valuing every member of your team as an individual is a guaranteed way to recruit the best people and maximise your company's performance. Our new Engineering Diversity and Inclusion conference is the place to meet engineering managers and recruiters who have already gone the extra mile in their inclusion strategy, learn how you can reap the full benefits of a diverse workforce and grow your talent pool.

www.theiet.org/diversity

IET Achievement Awards

14 November 2018, The Brewery, London

These awards recognise some of the world's most outstanding engineers and technologists and acknowledge the talents of exceptional apprentices, students and young professionals. Join us at this year's ceremony in central London to find out who the winners are. It's free to attend and open to members and non-members, but spaces are limited so secure yours today.

www.theiet.org/achievement

Living in the Internet of Things (IoT) 2019: Call for Papers

Deadline: 1 December 2018

An IET and PETRAS two-day call for papers conference and exhibition focusing on realising the socioeconomic benefits of an interconnected world. The conference will provide insight into how society can benefit from the power of interconnected devices (the IoT) while remaining safe, secure and resilient.

www.theiet.org/living-iot

Cyber Security in transport

6 December 2018, 09:30-16:00, IET Birmingham: Austin Court

Organised by the IET ARTS, Aerospace and Railway TPNs

IET.tv highlights

The IET President's Address: Digital TV Compression

Access to hundreds of high resolution live TV channels and millions of YouTube videos is now the norm. Do you ever hit 'pause' to wonder how this came about? This Presidential address will overview the highlights and evolution of video compression engineering, starting with the relative simple schemes of the late 1970's through to latest sophisticated techniques in common use today. Watch live on October 11th on IET.tv

https://tv.theiet.org/?videoid=12402

EngTalks: AI and Human digitisation: when seeing is not believing?

Is the next generation inspired to push the boundaries in the future? Are they given a chance to show their creativity and bring engineering and the arts together? From the latest smartphones to advances in supercomputing, the visual effects technology behind today's digital age is rapidly changing. Watch Dr Li discuss all topics live on IET.tv September 17th.

https://tv.theiet.org/?videoid=12401

Bringing Innovation to the NHS

On the day of the event, the IET spoke to three healthcare experts about why technology providers often find it hard getting their product into the NHS. In this video, Dr Guy Gross, Dr Peter Bannister and Ian Sharp explain how the structure of the NHS and its approach to innovation continues to create challenges for the sector, while also outlining what industry need to do to give the NHS what it wants from new tech.

https://tv.theiet.org/?videoid=12412

For a complete list of events from the IET please visit:

www.theiet.org/events

1889
US judge rules that Edison's patent for "a filament of carbon of high resistance" is valid.

1896
Arturo Malignani patents method of mass production of light bulbs. Patent bought by Edison in 1898.

NEW LIGHT ON AN EFFICIENT FUTURE

PART THREE: The LED revolution

With the incandescent light bulb now effectively a dinosaur and all eyes on emergent LED technology as an environmental panacea, the next evolutionary phase of lighting is all about efficiency and legislation.

According to light bulb manufacturer Philips, today lighting accounts for 19 per cent of the world's electricity consumption globally. Given that incandescent light bulbs effectively waste as much as 95 per cent of their energy producing heat rather than light, there is massive potential for energy-saving in a world where alleviating demand on resources is increasingly legislated. Looking at the US light bulb market in 2010 – around the time when phase-out legislation of incandescents was drafted around the world – there were eight billion lamps sold, of which half were incandescents, with barely 10 per cent LEDs.

At the time, consumers appeared to be unprepared for the LED revolution despite research coming out of the University of Cambridge predicting potential energy savings for switching to LEDs to be "huge". Iterating the base-line energy-saving figures, the research paper, entitled 'Lighting for the 21st century', says that in the UK, lighting consumes over a fifth of all the electricity generated at power stations, and LEDs have potential to reduce this figure by at least 50 per cent. Statistics from the US Department of Energy agree, estimating that by 2025, "solid state lighting such as LEDs could reduce the global amount of electricity used for lighting by 50 per cent and could eliminate 258 million metric tonnes of carbon emission, alleviate the need for 133 new power stations, and result in cumulative financial savings of over a hundred billion dollars".

With universal agreement that there are massive energy savings to be gained, the world seems set for spontaneous change in how we illuminate it. Yet that predicted market revolution has been slow and reluctant, causing governments to step in to accelerate the change in our manufacturing and consumption patterns. The EU has progressively banned various incandescent product types over the past decade, with this September seeing the phase-out of halogen and compact fluorescent lamps (CFLs) – effectively the end of the incandescent light bulb as we know it.

The Energy Saving Trust uses more measured tones, saying that while historically we might have had "little concern" over the fact that "light bulbs were only 10 per cent efficient… a very different attitude to lighting has emerged in the past few years". In its white paper 'The Right Light', the Trust says that this new attitude is only partly driven by legislation, with goodwill from the "growing public appreciation of the role good lighting can play in the improvement of their homes" supplying the remainder of the market shift.

The reality is that industrial and domestic are only now seriously beginning to undergo a step change, driven by the desire to phase in energy-efficient emerging technologies such as LEDs at the expense of incandescents and, now, halogen and compact fluoresecents too.

Today, despite its prolonged arm-wrestle over Brexit negotiations, Britain is still a member of the European Union and we are facing what the media has chosen to describe as a 'bulb ban', with the more excitable daily newspapers routinely reporting on the (largely non-existent) public stockpiling of incandescent bulbs as a safeguard against a future lit by LEDs. The objection to it is unclear, apart from a vague feeling that LED lighting is not as 'warm' as incandescent. This 'bulb ban' is actually a set of draft European regulations over efficiency that will see the removal of tungsten halogen and CFLs as light sources by 2020.

As part of its review of its Ecodesign laws, the EU has published the necessity for replacement light sources to have minimum efficiency requirement of 85 lumens per watt and a maximum standby power of 0.5W. Ecodesign requirements are mandatory for all standard bulbs, fluorescent lamps and spotlights sold in the EU. These regulations set energy-efficiency requirements and other factors such as bulb lifetime, warm-up time and energy labelling. According to the EU, "with energy-efficient lighting, household electricity bills could fall by €25 per year. By substituting a halogen lamp with an LED, you could save up to €100 over the product's lifetime of around 20 years. Energy-efficient lighting could save enough energy to power 11 million households for one year and avoid the emission of 12 million tonnes of CO_2 in Europe."

Yet not everybody is quite as enthusiastic about the benefits of LED replacement technology or the Ecodesign requirements, with the entertainment industry saying the EU directive will sound the death knell for dramatic lighting. The CEO of German stage lighting company GLP, Udo Künzler, is predicting "extinction for theatres, concert venues and other sections of the performing arts, since no tungsten fixtures and many LED-based entertainment fixtures don't appear to meet these requirements".

In order to protect the professional stage lighting industry he is hoping to "succeed in convincing the European Commission to ratify an exception for our industry. There is no time to lose. We need to act as a united industry to prevent these proposals from becoming enshrined in law." *