NANYANG TECHNOLOGICAL UNIVERSITY SINGAPORE

EEE RESEARCH NEWS

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Developing technologies for future megacities

Materials, Transports and Communications Innovation

School of Electrical and Electronic Engineering

Contents

Innovative solutions, enhance the quality of life for people

The School of Electrical and Electronic Engineering (EEE) has grown from strength to strength since it was established as one of Nanyang Technological University's (NTU) three founding schools. Today, our research and academic prowess has contributed NTU the ranking of 4th best university in the world in engineering and technology by faculty, according to the latest QS World University Rankings, and we also attract about S$90 million in research funds annually.

Just this year, we launched Singapore's 7th satellite into space from the International Space Station, partnered with world-leading automotive semiconductor supplier NXP Semiconductors to launch Singapore's first Smart Mobility Consortium, and joined forces with the Schaeffler Group, a global powerhouse in automotive and industrial components, to create a joint laboratory for smart mobility devices.

With these and other new partnerships and work, EEE will continue to push the boundaries of technologies and research in the Internet of Things, photonics, satellite engineering, power electronics, cyber security, biomedical engineering, semiconductor technology and even more fields. Our innovations will also contribute to Singapore's ongoing plan to become a Smart Nation that deploys technology in service of its people.

As one of the largest electrical and electronic engineering schools in the world, we now have more than 140 full-time faculty members renowned for their research and professional expertise. Their calibre is also matched by a well-developed teaching and research infrastructure, comprising 12 comprehensive and sophisticated constellations of research centres, 50 laboratories and 4 corporate laboratories set up with industry partners.

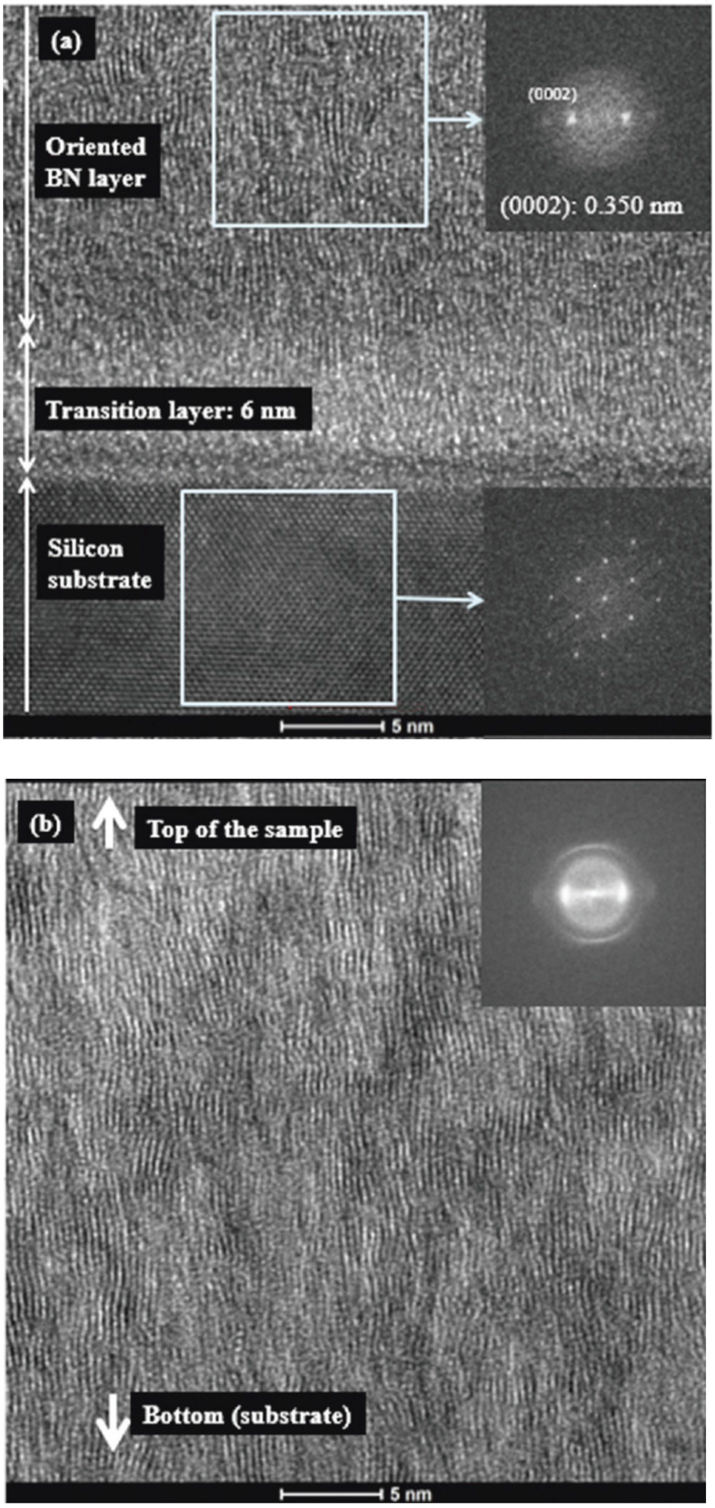
We've highlighted some of our recent research and technological breakthroughs in this edition of EEE Research News, and we hope you will enjoy learning more about them. Going forward, we will continue to do even better by taking our research centres to the next level, improving our value propositions, sharpening our strategic vision and growing in both size and international stature.

Keeping your electronics cool

Electronic devices that are dense with components can overheat and fail leading to poor performances and system failures. This is especially pertinent when heat from hot components is spread laterally to its surrounding devices causing a cascading effect.

Now, scientists at Nanyang Technological University's School of Electrical and Electronic Engineering (EEE), Silicon Technologies, Centre of Excellence (*Si-COE*) have developed a way to 'grow' thick boron nitride (BN) thin films that discharge most of their heat vertically rather than laterally.

These vertically-oriented nanocrystalline boron nitride thin films could be used to minimise the risk of electronic devices becoming too hot internally.



The researchers used high power impulse magnetron sputtering for the controlled growth of these films. Since boron nitride is electrically insulative, a lanthanum hexaboride target was used instead and reactively sputtered in nitrogen gas to grow the films.

The surface roughness of the films was below 1 nm RMS, which makes it usable for electronic devices, and the low lanthanum content in the film does not change the material's insulative properties.

Unlike other high thermally conductive dielectric materials, such as diamond and cubic boron nitride, the EEE films can be deposited at room temperature. The scientists also created films with thicknesses beyond 1.5 micrometres without any film dislocation at the interface between the silicon substrate and the film.

The EEE films have considerably high thermal conductivity, comparable to nanocrystalline graphite grown at 300 degrees Celsius, and four times higher than that of amorphous silicon dioxide, which is used in high-power electronics.

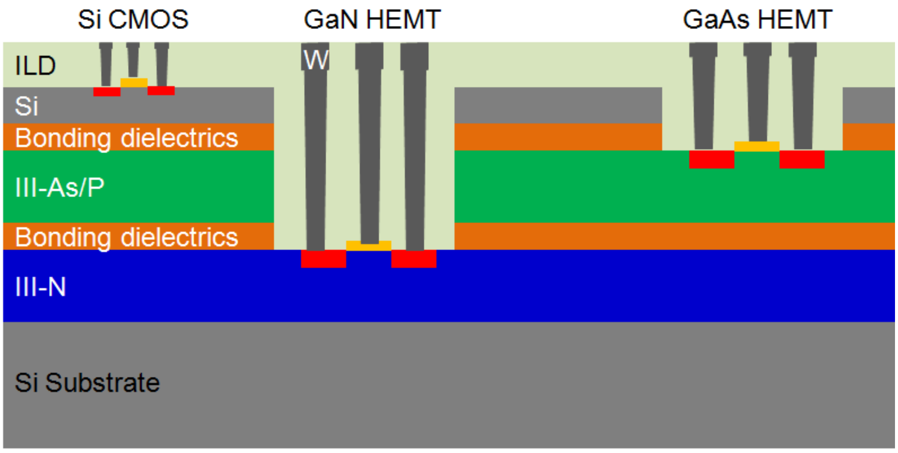
"Our films' favourable thermal conductivity is useful for heat dissipation from active regions of electronic devices if they are used to replace silicon dioxide as the gate dielectrics," said Professor Edwin Teo Hang Tong from EEE.

"They could be an alternative to silicon dioxide in high-power electronics where the dielectric layer is always the thermal bottleneck due to its poor thermal conductivity," he said.

A more powerful device

Semiconductor companies have long relied on the shrinking of silicon complementary metal-oxide-semiconductor (CMOS) devices to improve electronic products' performance, reduce their power consumption and decrease transistors' cost.

However, such scaling is now reaching fundamental and economic bottlenecks. The further shrinking of CMOS devices is expected to lead to unreliable, variation-prone and more expensive electronics.



Now, scientists at Nanyang Technological University's School of Electrical and Electronic Engineering (EEE), Centre for Micro-/Nano-electronics (*NOVITAS*), led by Professor Tan Chuan Seng have integrated silicon, gallium arsenide and gallium nitride on a single, 200 millimetre silicon platform.

By combining the materials, which have different functionalities, on a single piece of wafer, their innovation could lead to smaller electronic devices that have more functionalities and capabilities.

For example, silicon, gallium arsenide and gallium nitride are suitable for the fabrication of digital control circuitry, high-frequency, high-electron-mobility transistor devices and high-power devices such as power amplifiers, respectively.

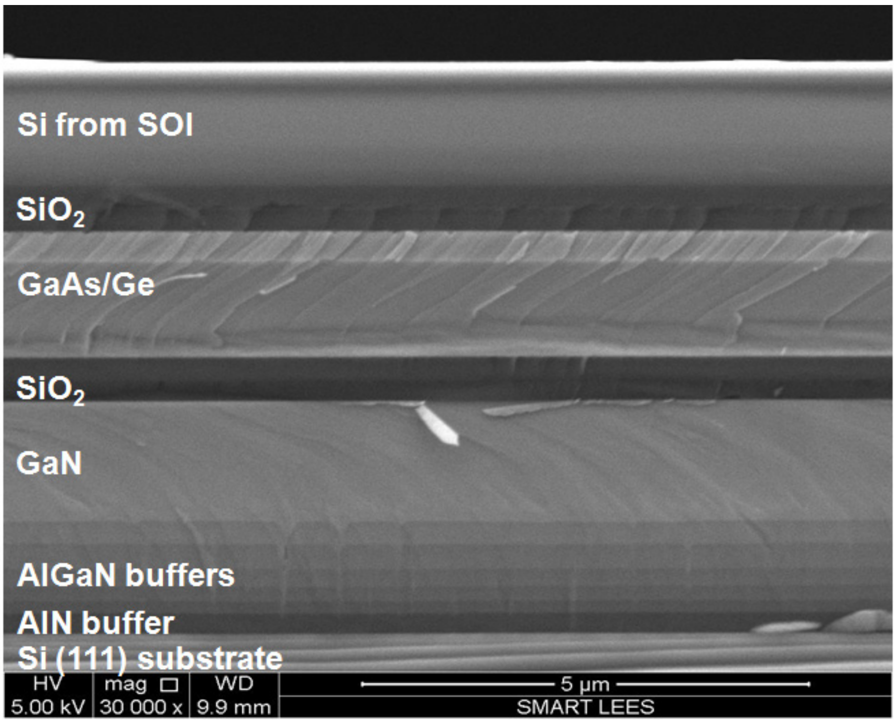
"Using our method, we can combine the circuitry, transistor devices and power amplifiers on a single platform to further reduce the package size at the system level," said Professor Tan.

The researchers used a triple layer transfer process to integrate the silicon, gallium arsenide and gallium nitride on a single common silicon platform. They used plasma-activated fusion bonding partly because it can be carried out at room temperature and atmospheric pressure which is manufacturable.

They added that their success means that it is possible, in principle, to use their method to combine other III-V compounds and group IV materials on a single silicon platform.

Hybrid devices made out of silicon and III-V compounds, for instance, could compensate for silicon's poor ability to emit light, and lead to new circuit capabilities and applications beyond communications, such as sensing and optical computation.

Professor Tan said: "The monolithic integration of inexpensive, high-density silicon digital control circuitry with application-specific III-V electronic and optical devices can open up new circuit applications and capabilities."



A photonics breakthrough

Photonic devices that can create, manipulate or detect light have long been used in products such as photo-detector and LED.

Now, researchers are attempting to extend photonics' operational wavelengths to the mid-infrared range, due to the potential applications in a wide range of fields, including next-generation communications and environmental monitoring.

Scientists at Nanyang Technological University's School of Electrical and Electronic Engineering (EEE), Centre for Micro-/Nano-electronics (*NOVITAS*) have created a breakthrough in photonics with their new germanium-on-silicon nitride waveguides for mid-infrared integrated photonics.

These photonics could be used in next-generation, compact sensors with mid-infrared sensing capabilities, such as advanced biochemical sensors.

The researchers led by Professor Tan Chuan Seng noted that many other platforms have been tried and evaluated, including silicon-on-sapphire and silicon-on-nitride. Since germanium has a wide transparency and unique optical properties, many germanium-based platforms have also been studied.

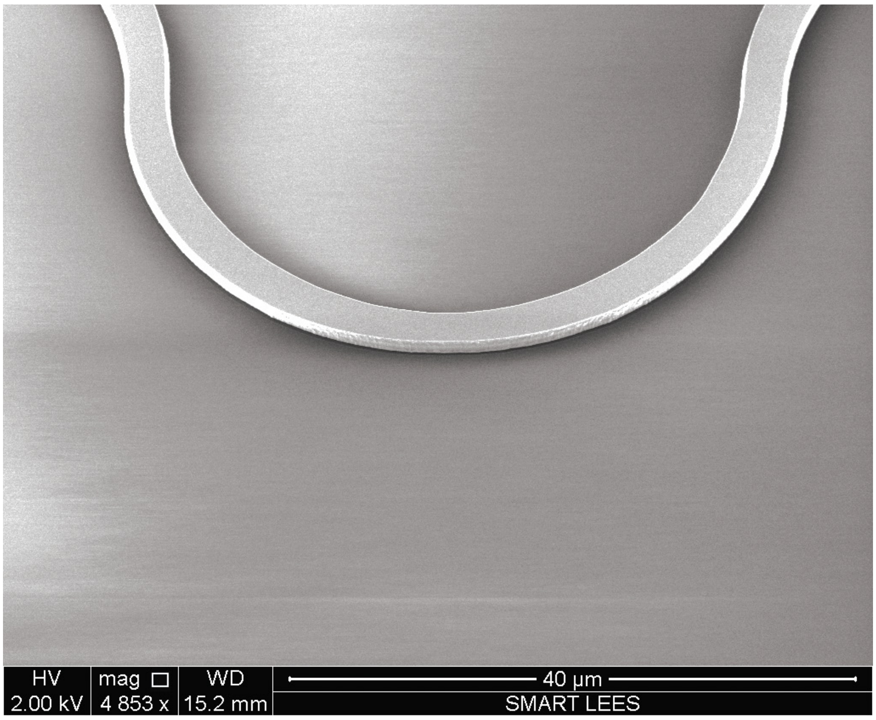
"Germanium-on-silicon-on-insulator has been reported to have electrical advantages, and many impressive achievements have also been made with germanium-on-silicon," said Professor Tan.

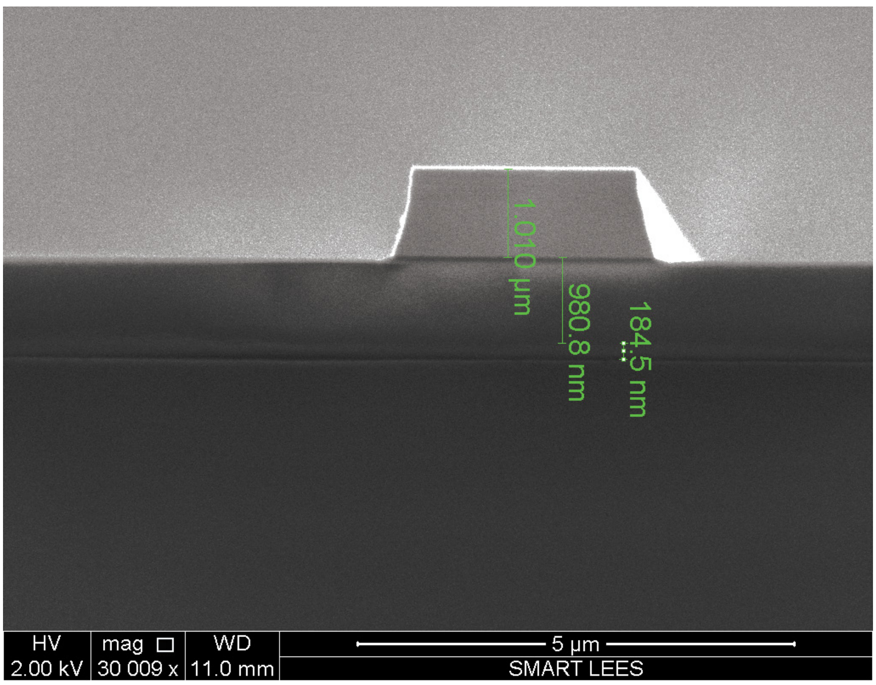
"However, what is desired is a better, alternative germanium-based waveguide platform that will provide a larger core-clad index contrast than germanium-on-silicon, as well as a useful transparency range and smaller channel-bend radii. That is why we proposed and realised germanium-on-silicon nitride," he said.

The researchers developed a feasible and scalable wafer bonding and layer transfer technique to create germanium-on-silicon-nitride.

This involves first bonding a silicon-nitride-deposited germanium-on-silicon donor wafer onto a silicon substrate wafer, and then using a layer transfer approach to obtain the germanium-on-silicon nitride.

Professor Tan said: "Our germanium-on-silicon-nitride platform could be used to make many small and passive photonic devices, such as photonic-integrated Mach-Zehnder interferometers and micro-ring resonators. These would be useful for compact sensor devices for mid-infrared sensing applications, as well as active devices such as micro-ring modulators."





Spearheading laser ceramics research

High-power, solid-state lasers are widely used in fields such as industrial material processing, medical surgery, scientific research and the military.

While conventional solid-state lasers use single crystal hosts, doped with rare earth or transition metal active ions, as their gain medium, researchers have long advocated the use of ceramics instead as these have advantages such as lower costs.

At Nanyang Technological University's School of Electrical and Electronic Engineering (EEE), Centre for OptoElectronics and Biophotonics (*OPTIMUS*) scientists have been conducting research on laser ceramics fabrication for a decade.

The EEE team led by Professor Tang Ding Yuan is now one of the few groups in the world that can routinely fabricate high-quality yttrium aluminium garnet (YAG) and lutetium aluminium garnet (LuAG)-based laser ceramics, among many other accomplishments.

It is the first group in the world to successfully manufacture ytterbium-doped LuAG laser ceramics, a milestone that was highlighted in the international magazine "Laser Focus World".

Using its own ytterbium-doped, erbium-doped and thulium-doped YAG laser ceramics, the team has also demonstrated high power laser emissions at 1 micrometre, 1.6 micrometre and 2 micrometre with high lasing efficiency.

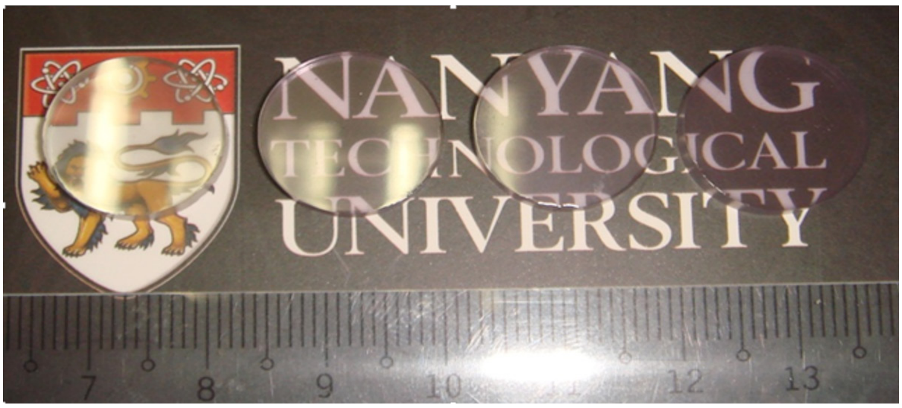
"With our holmium-doped YAG laser ceramics, we have also demonstrated 21 watt continuous wave laser emissions at 2.1 micrometre. This is still the highest output power of ceramic lasers at that wavelength," said Professor Tang Dingyuan from the EEE.

The researchers also recently successfully fabricated lasing quality erbium-doped yttrium oxide and ytterbium-doped lutetium oxide laser ceramics.

Professor Tang said that the goal of the EEE research is to develop technological know-how on laser ceramics fabrication, and to use the fabricated laser ceramics to develop novel ceramic lasers.

The scientists are now focusing on the development of rare earth ions-doped sesquioxide laser ceramics and Spinel ceramic armours.

"We are also going to further develop the transition metal-doped, iron-doped zinc selenide laser ceramics for 4 micrometre ceramic lasers, and fluoride-based laser ceramics for visible ceramic lasers," said Professor Tang.



Improving stealth technology

The field of stealth technology has gotten a boost from new research by scientists at Nanyang Technological University (NTU).

Scientists at the School of Electrical and Electronic Engineering (EEE), Centre for Bio Devices and Signal Analysis (*VALENS*), led by Professor Liu Ai Qun have developed a new liquid-metal-based metasurface absorption material with broadband tunability and wide-angle features. The material could improve terahertz wave shielding and stealth technology.

While scientists elsewhere have created other terahertz metasurface absorption materials, most of these suffer from a limited tuning range and narrow incident angle.

Even when much effort has been devoted to making wide-angle absorption materials, these have been effective only within a restricted frequency range.

The EEE researchers' proof-of-principle material uses a liquid-metal pillar array that can be continuously controlled in the vertical direction using microfluidic technology. A U-shaped resonator is filled with liquid metal, in this case mercury, to form the liquid-metal pillars.

By applying different air pressures to the resonator, the pillars' height can be increased or decreased to between 0 and 100 micrometres.

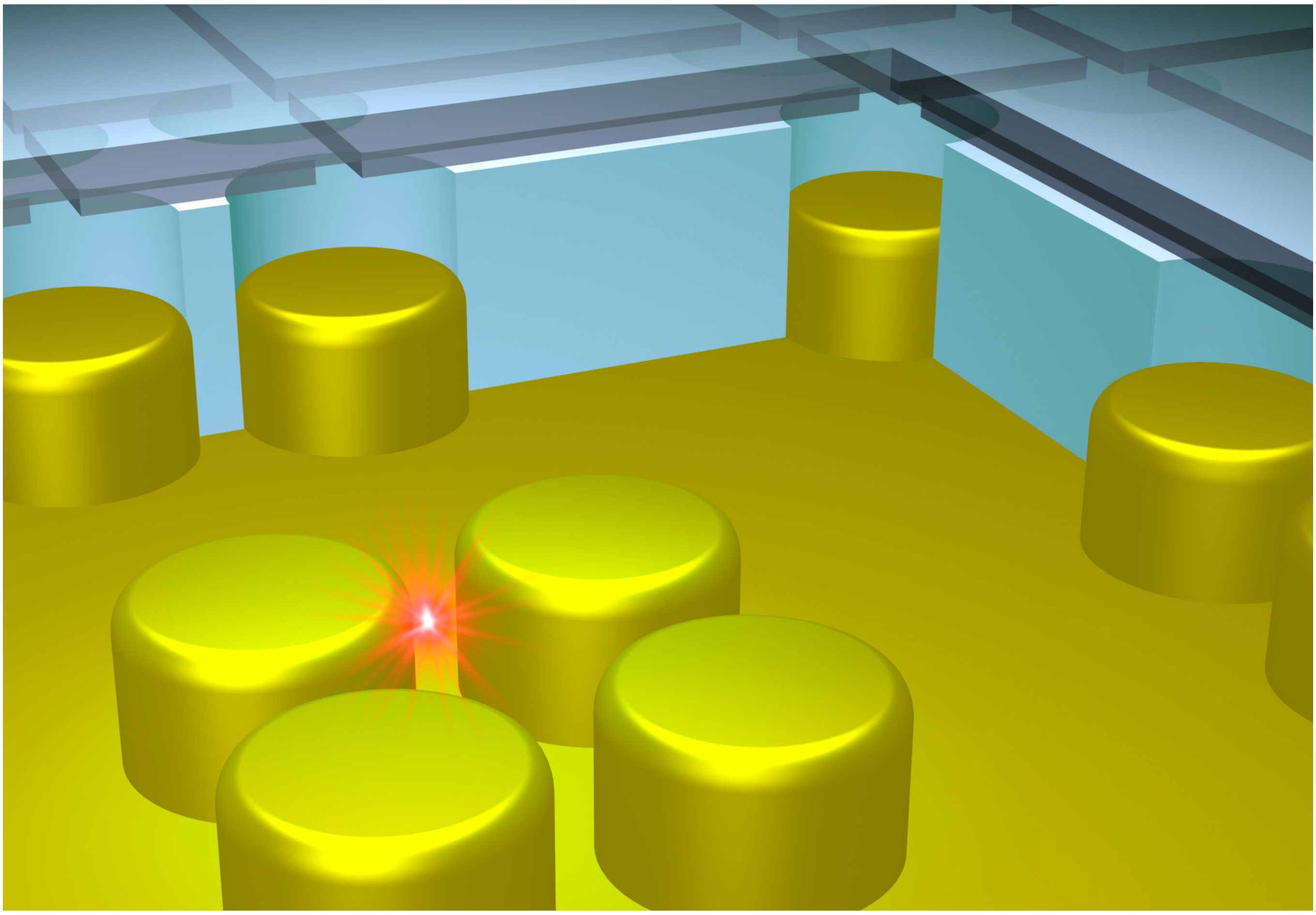
For their experiments, the EEE team used four of the pillars sandwiched between two polydimethylsiloxane layers as one element. This element was then patterned periodically into a square array.

By controlling the height of the pillars, the absorption frequency of the metasurface can be tuned from 0.246 terahertz to 0.415 terahertz with a tuning range of central frequency 51.1 percent and absorbance of more than 90 percent.

When the incident angle is increased from 0 degrees to 60 degrees, the tuning range of central frequency of the absorption peak covers 27.6 percent from 0.25 terahertz to 0.33 terahertz, with absorbance of more than 90 percent.

While the researchers used mercury, the liquid metal can be replaced by other such metals, including galinstan and liquid phase conducting polymers.

"Our frequency-agile and wide-angle terahertz absorption material has potential applications in terahertz wave shielding, stealth technology and more," said Professor Liu.

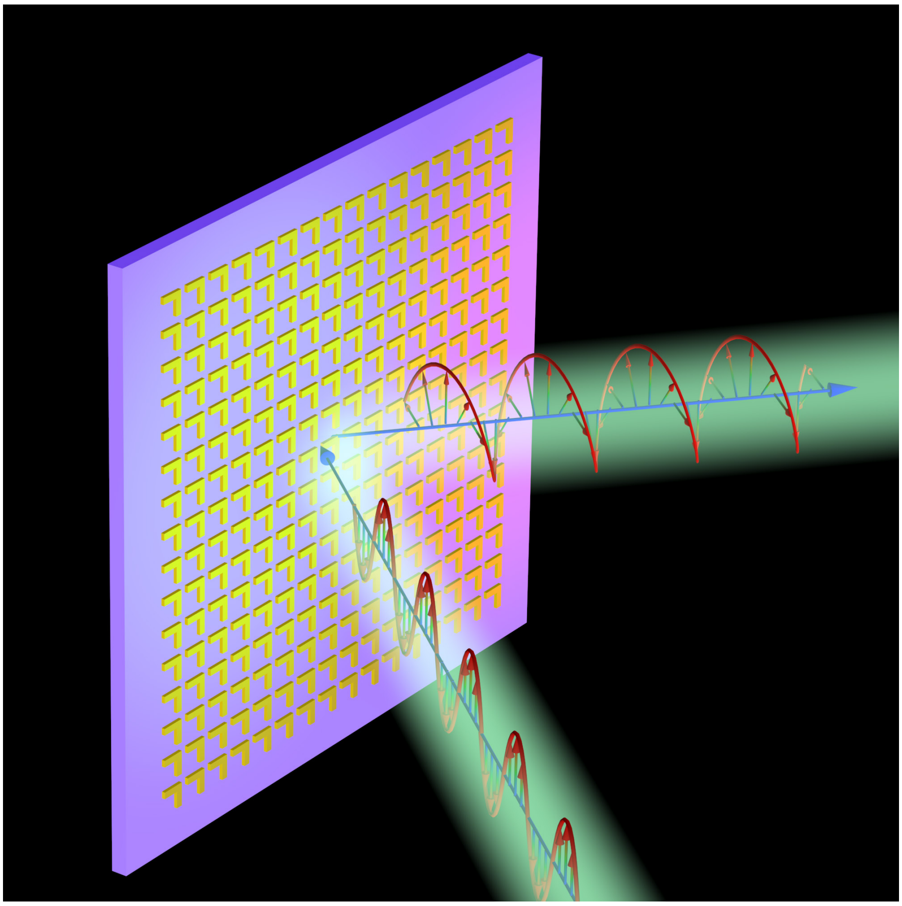


Making waves

Smart radar, stealth technology and quantum communication are just some of the fields that rely on the manipulation of electromagnetic waves.

Now, researchers at Nanyang Technological University's School of Electrical and Electronic Engineering (EEE), Centre for Bio Devices and Signal Analysis (*VALENS*), led by Professor Liu Ai Qun have developed the first-ever broadband wide-angle multifunctional polarization converter.

It can be tuned to convert electromagnetic waves to different polarisation states. This could be used for a wide range of applications, including to "cloak" items and make them invisible to radar.



While metasurfaces – which are flat, ultra-thin optical components – have been used as polarisation converters, they can only convert electromagnetic waves from one specified state to another specified state.

Some researchers have proposed using micro-electromechanical systems (MEMS) to control a metasurface's elements. This would allow users to change the metasurface continuously so that it can convert electromagnetic waves to different polarisation states.

As a metasurface's size grows, however, it would require more and more complex MEMS, eventually affecting its performance.

The EEE researchers sidestepped this limitation by developing a liquid metal-based metasurface.

Their invention consists of L-shaped resonators and microfluidic channels with one inlet and two outlets. Each resonator has two arms that are filled with galinstan, a highly conductive and non-toxic liquid metal, and hydrochloric acid vapour.

By increasing or decreasing the amount of vapour in each resonator, the length of galinstan in its arms can be tuned from 0.6 mm to 5 mm. This enables the metasurface to act as a multifunctional polarisation converter.

In experiments, the EEE researchers showed that their invention has a broad working bandwidth larger than 60 percent of central frequency and a large angular tolerance of 45 degrees. It also has broadband reflection and optical attenuation functionalities.

"Our converter provides prospects for various applications, such as smart radar, stealth technology and quantum technology," Professor Liu said.

Breakthroughs in plasmonics

When light hits a metal, it generates electromagnetic waves that travel along the surface of the metal. These waves, called surface plasmon polaritons (SPPs), can be harnessed to make powerful sensors and ultra-compact devices that relay data almost instantaneously.

One major obstacle in developing plasmonic devices, however, is dissipative loss. SPPs decay as they travel along the metal due to the conversion of optical energy to heat. These losses severely limit the performance of metal-based plasmonic devices at optical frequencies.

To overcome this problem, some scientists have proposed using waveguides – structures that confine and convey waves – that are made of only dielectric materials. These could enable modal-dispersion-induced effective SPPs that do not suffer dissipative losses.

Now, scientists at Nanyang Technological University's School of Electrical and Electronic Engineering (EEE) have achieved the first experimental realisation of modal-dispersion-induced effective surface plasmon polariton (ESPP) propagation in an all-dielectric waveguide.

The EEE team is led by Professor Luo Yu. A schematic of their design is shown in the figures. Their work could improve the performance of plasmon-based optical devices, and help realise many other plasmonic capabilities, such as sub-wavelength focusing, super-resolution imaging and plasmonic cloaking.

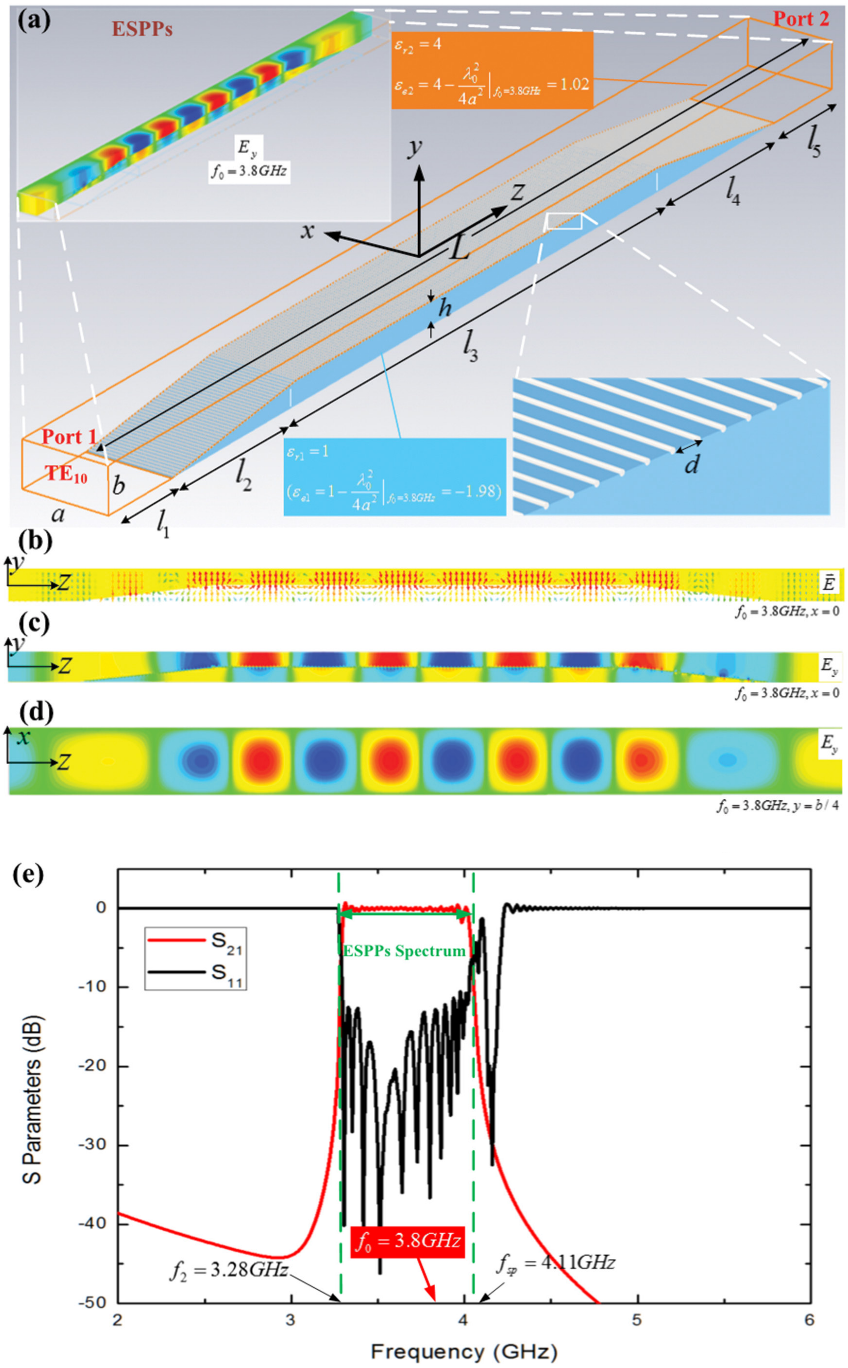
Before the EEE team's work, the existence of modal-dispersion-induced ESPPs had not been verified through experiments.

The team provided further theoretical insights into, and experimental verification of, the ESPPs by engineering transverse-electric modes in conventional rectangular waveguides.

They also derived the ESPPs' complete field distributions, dispersion relations and asymptotic frequencies analytically, and designed wave-port excitations and smooth bridges for the mode conversion between propagating modes in rectangular waveguides and the ESPPs.

Their all-dielectric waveguide makes use of the structured transverse-electric mode in a conventional rectangular waveguide, and has the advantages of simple design and large propagation length.

Professor Luo added that their work opens up avenues for low-frequency designer surface plasmons, and could lead to compact filters, resonators and sensors of ESPPs in the microwave and terahertz frequencies.



The future of personal transport

Going home from the train station in the future could be as easy as hopping onto an electric kickboard equipped with a smart, self-navigating unit.

Singapore's Nanyang Technological University (NTU) has set up a joint research laboratory with Germany's automotive system manufacturer Schaeffler Group to develop advanced personal mobility devices that are safe and efficient.

The laboratory, which will have $5 million in funding over three years, will also study personal urban mobility and intelligent transport systems for megacities of the future.

The joint laboratory, housed in NTU's School of Electrical and Electronic Engineering (EEE), led by Professor Guan Yong Liang, is part of the Schaeffler Hub for Advanced Research (Share) at NTU, and is Schaeffler's first Share lab outside of Europe.

For their work, NTU and Schaeffler will use an industry standard vehicle-to-everything wireless communications technology and analyse personal mobility device users' behaviour in Singapore. They will also tap on the NTU-NXP Smart Mobility Test Bed comprising 50 vehicles with smart units and 35 roadside units with cameras across NTU's campus.

Professor Lam Khin Yong, NTU's Vice President (Research) and Chief of Staff, said that the collaboration will help address Singapore's transportation challenges within the context of the country's Smart Nation vision.

"NTU has deep expertise in smart mobility technologies and a strong track record of industry collaborations. Together with Schaeffler, we will develop innovative solutions that support Singapore's drive towards a car-lite society," he said.

Professor Yoon Soon Fatt, Chair of the EEE, added: "NTU is already a living lab for advanced mobility concepts and technologies. Coupled with our world-class engineering faculty, the campus becomes the perfect place to develop next-generation mobility devices."

Revving up smart mobility

Imagine a car that can alert you in advance to tolls, road works and traffic jams, display the number of parking lots available when it approaches a car park, and keep track of other vehicles and pedestrians nearby to avoid traffic accidents.

Such an intelligent car could be created and tested under a new partnership in Singapore.

Singapore's Nanyang Technological University (NTU) and the Netherlands-based NXP Semiconductors have launched Singapore's first Smart Mobility Consortium to develop and test smart mobility technologies.

The consortium's 12 industry partners include Japanese electronics giant Panasonic, American software multinational Red Hat and German automotive systems manufacturer Schaeffler Group.

The partners will pool their expertise in different areas, such as wireless communication design, data analytics and network security. NXP itself is a world-leading automotive semiconductor supplier for secure connected cars.

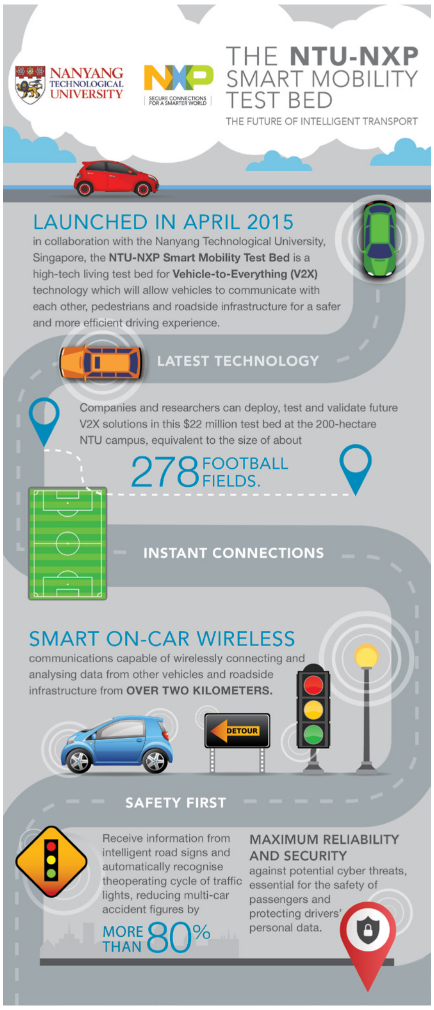
To develop their innovations, the consortium will harness an international wireless standard for vehicular use known as vehicle-to-everything communication technology.

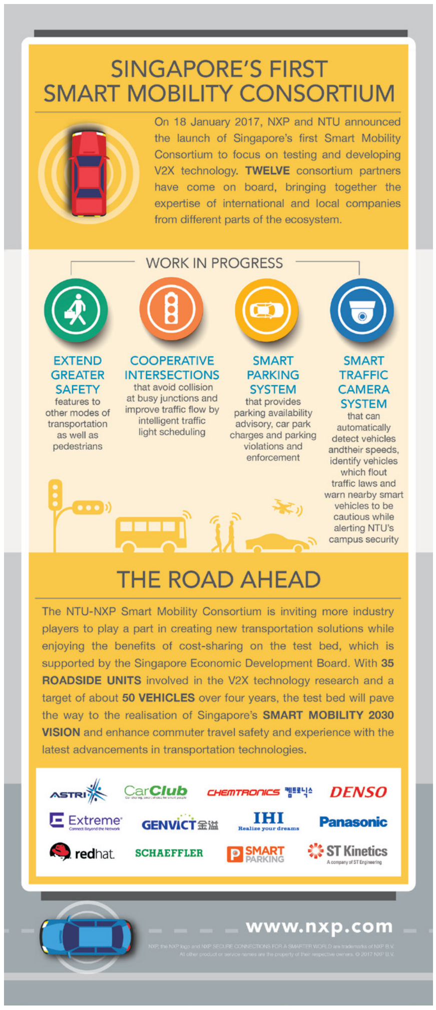
The industry partners will also test and validate their inventions on the NTU campus, which has already been converted into a living test bed for such technologies under an ongoing project called the NTU-NXP Smart Mobility Test Bed.

Mr Wang Hai, NXP's Senior Vice President, Global Technology Innovation, said: "The launch of the consortium is an important step in realising Singapore's vision of a sustainable transport system that includes driverless vehicles."

Professor Yoon Soon Fatt, Chair of NTU's School of Electrical and Electronic Engineering, added: "Our researchers have developed novel ideas and technological solutions that are in line with Singapore's Smart Nation vision and highly relevant for industry.

"This new consortium will help turn such innovations into actual products, which can then be adapted to other big cities facing similar smart mobility challenges."





Helping autonomous vehicles go off-road

Off-road environments can be challenging for autonomous vehicles when there are heavy shadows, steep inclines or muddy water puddles.

Researchers led by Professor Justin Dauwels at Nanyang Technological University's School of Electrical and Electronic Engineering (EEE), Centre for System Intelligence and Efficiency (*EXQUISITUS*) have created a two-stage semantic segmentation system to help autonomous vehicles "see" off-road routes more clearly.

The system can not only differentiate between dirt roads and their surroundings, such as vegetation and sky, but also identify water puddles, which can look like dirt roads.

The invention will help autonomous vehicles to navigate off-road routes more easily and safely. An unmanned ground vehicle without the EEE system may get stick in water puddles on the road, for example, requiring costly human intervention such as towing.

To "see" the off-road route and identify water puddles, the EEE system relies on images from cameras and data from a 3D Lidar (light detection and ranging) rig.

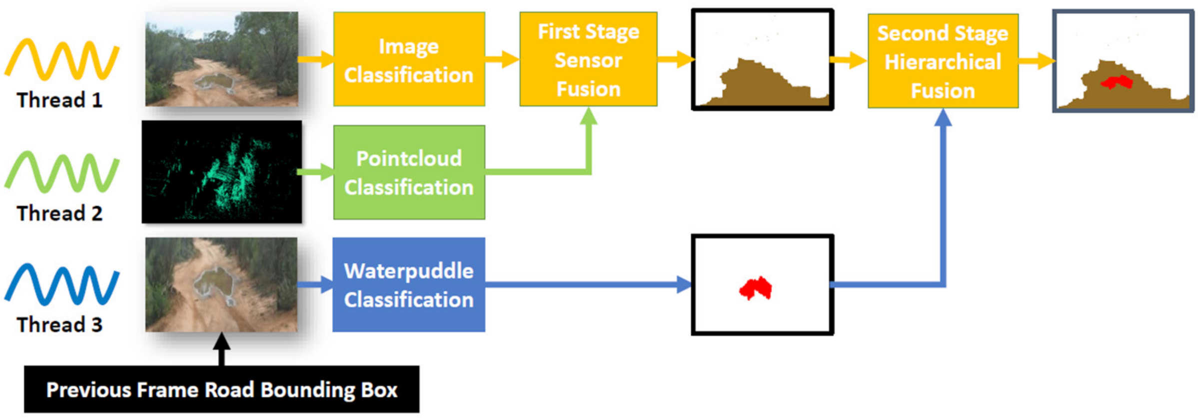
It first uses the information to classify the environment in front of the autonomous vehicle into road and non-road segments. This helps the car to "see" the dirt road.

It then uses a specialised water puddle classifier, trained by the EEE researchers, to analyse the road segments and distinguish between water puddles and the road. This allows the car to "see" the puddles on the road and avoid them.

Dividing the process into two stages reduces the amount of work for the specialised classifier, since it need only examine the dirt road and identify water puddles on it. This improves its speed and accuracy.

The EEE researchers tested their system on eight videos containing 1,023 annotated frames. It achieved an F1 score of about 93 per cent for road detection and 80 per cent for water puddle segmentation in more than 10 hertz.

Professor Dauwels added that their system can be used in urban environments as well, for example to enable autonomous vehicles to distinguish lane markers from road regions.



Power, wirelessly

Batteries and inconvenient electricity wires may soon be a thing of the past for some devices, with a new wireless power transfer system developed by researchers at Nanyang Technological University (NTU).

Scientists at the NTU Electromagnetic Effects Research Laboratory (*EMERL*), led by Professor See Kye Yak have developed a far field directional-radiation-based wireless power transfer system that can transmit power at a distance, eliminating the need for electrical wiring and regular battery replacement.

With the system, unmanned aerial vehicles could be charged while they are in the air.

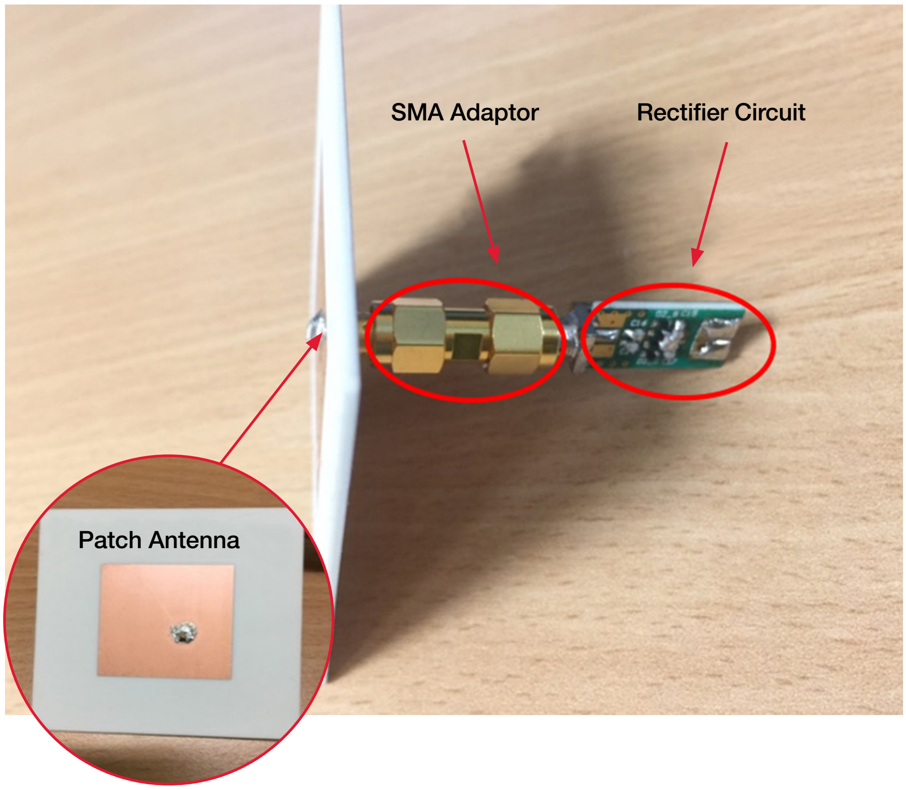
The wireless power transfer system consists of an antenna, a rectifier circuit and a power management circuit.

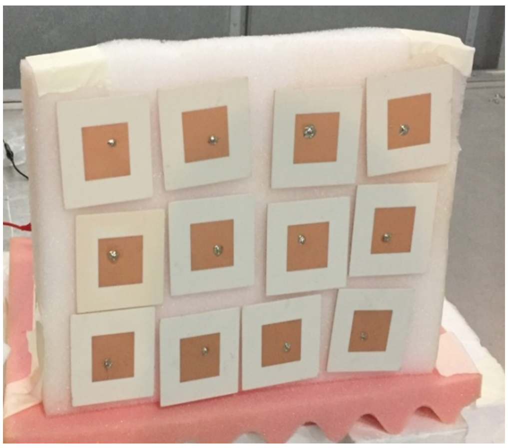
The antenna and rectifier circuit are combined into a “rectenna”. The antenna captures incoming radio frequency electromagnetic wave and passes it to the rectifier circuit which converts it into direct current power.

The researchers chose to use 2.45 gigahertz (GHz) as their system’s frequency as high-efficiency microwave components, such as rectifiers, are already readily available for it. Its propagation loss is also lower compared to other bands such as 5.8 GHz and 9.3 GHz.

After analysing the performance of the rectenna module, the researchers decided that a 3 by 4 rectenna array and a selected power management circuit would form the final rectenna module for high-power wireless power transfer applications, such as charging for unmanned aerial vehicles.

They also determined that a 2 by 2 array formed using the same module would be optimal for low-power wireless power transfer applications, such as powering a sensor tag.





Try these invisible headphones

In the near future, you'll be able to watch videos on your smartphone or tablet in the bus or train without needing earphones and without disturbing others.

Researchers from Nanyang Technological University's School of Electrical and Electronic Engineering (EEE), *VIRTUS*, IC Design Centre of Excellence have developed "invisible earphones" – a way of transmitting sounds to just one person without the need for earphones.

The research team led by Dr Ge Tong said "Their invention could simplify the listening of audio from devices such as smartphones and tablets, and reduce noise pollution from them to other people."

The EEE team's system is based on a parametric and directional speaker which emits a highly directional amplitude modulated ultrasonic signal beam.

This beam is automatically demodulated in the air so that it generates an endfire-like virtual loudspeaker array which outputs a highly directional audio beam.

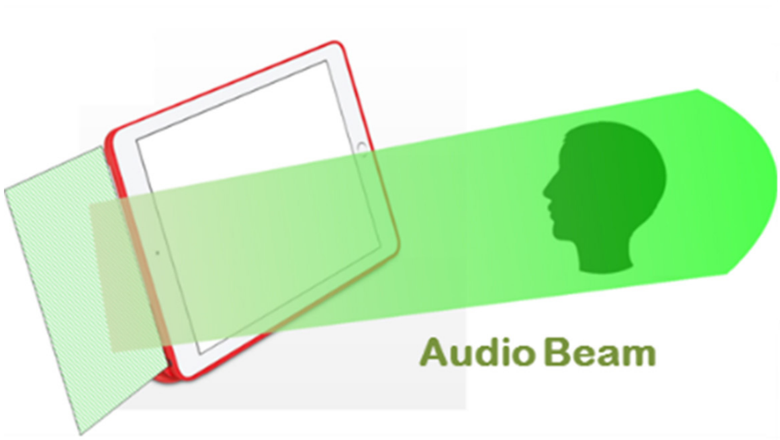
Compared to other parametric and directional loudspeakers that have been reported, the EEE invention has several unprecedented advantages.

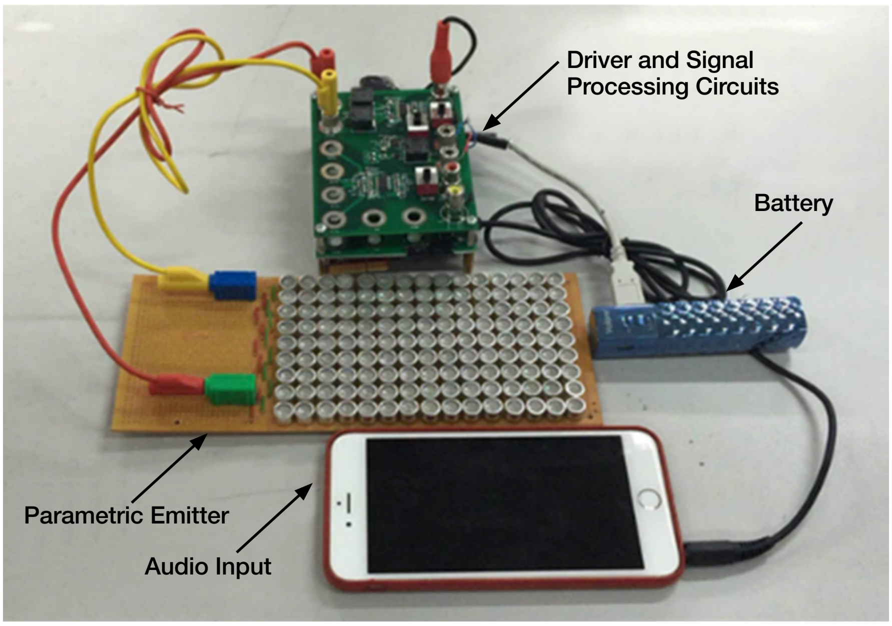
By using a novel and patent-pending low-cost fully-additive printing technology that they developed, the EEE researchers estimate that the cost of their system can be reduced from hundreds of dollars to tens of dollars – significantly lower than the reported counterparts.

The researchers also created an ultra-high power-efficiency Class D amplifier – which is also patent-pending – so their invention has much lower power dissipation and can be battery-powered.

The project is currently funded by an innovation grant from the Singapore-Massachusetts Institute of Technology Alliance for Research and Technology (SMART), and a start-up company is being planned.

Dr Ge said "Our invention is a demonstration of 'science magic', or how multidisciplinary research – in this case, a unique combination of complex mathematics, signal processing, electronics hardware and printed electronics – can yield devices that were previously thought to be impossible."





Making a mark in space

Singapore has taken another step in its space ambitions with the launch of Nanyang Technological University's (NTU) latest satellite.

The NTU School of Electrical and Electronic Engineering (EEE), Satellite Research Centre (*SaRC*) has launched the AOBA VELOX-III, its seventh satellite and the first Singapore one to be launched from the International Space Station (ISS).

The 2kg satellite will test several technologies during its orbit, including a new wireless communication system and a unique made-in-NTU micro-thruster that will enable it to remain in space for twice as long as it otherwise would.

The nano-satellite was a joint project between EEE and Japan's Kyushu Institute of Technology (Kyutech), a leading university for satellite research and engineering.

The national Japan Aerospace Exploration Agency delivered the satellite to the ISS. Orbiting at 400 kilometres above sea level, the AOBA VELOX-III will also conduct experiments to evaluate the durability of off-the-shelf microprocessors in space.

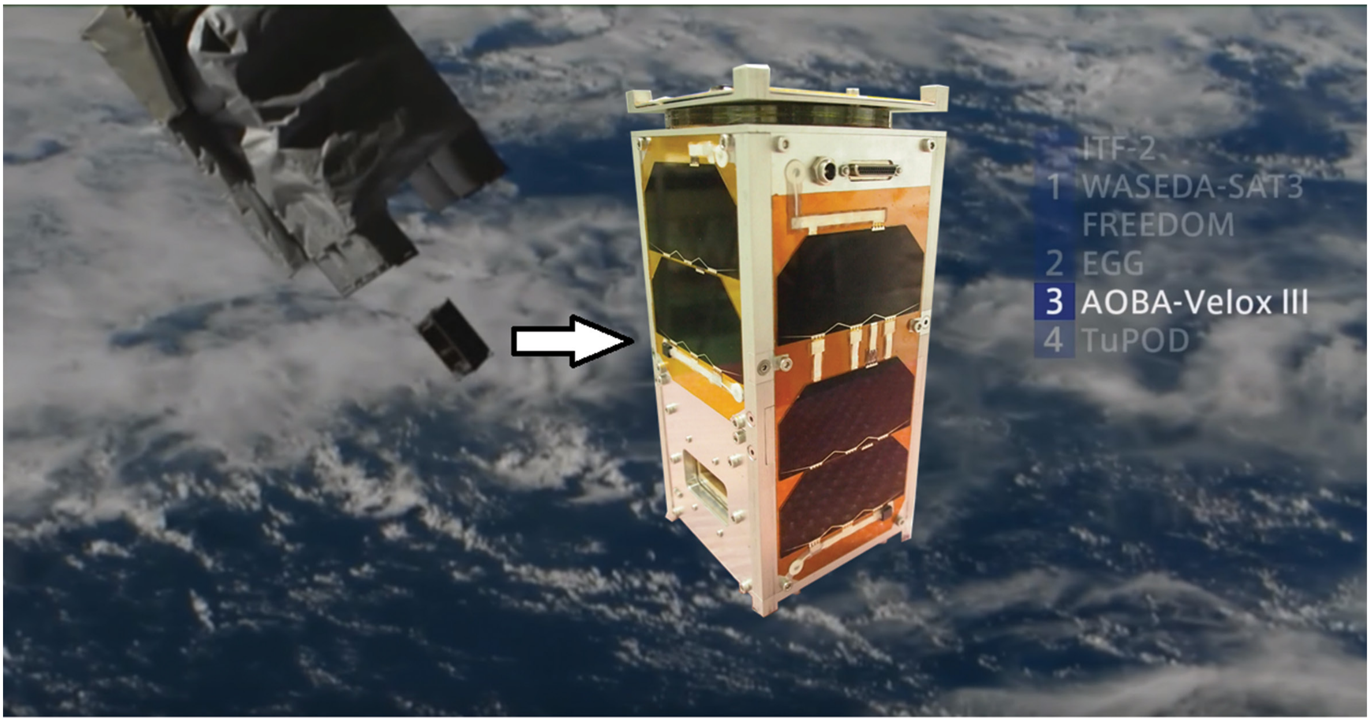
The NTU micro-thruster system uses pulsed plasma, which could lift the satellite 200 metres for each hour of flight. The thrusters will also help the satellite to extend its flight lifespan to six months from the usual three months before it loses altitude.

Professor Cho Mengu, director of Kyutech's Laboratory of Spacecraft Environment Interaction Engineering, said that the launch of AOBA VELOX-III is a significant milestone in Japan-Singapore inter-university space exploration.

"We look forward to another joint satellite that is under development and scheduled to be launched in 2018. The long-term goal of the Kyutech-NTU joint space programme is a lunar mission using the technologies demonstrated by these two satellites," he said.

Professor Yoon Soon Fatt, Chair of the EEE, added that such real satellite missions are crucial to training local talents for Singapore's future satellite industry.

"By designing, building and operating real satellites in space, our students get a huge boost in their learning journey and unparalleled experience should they seek careers in the space industry," he said.



The ISS new JEM Small Satellite Orbital Deployer is on the upper left, which is seen launching out the AOBA-VELOX III using springs. Credit: JAXA

A hub for trailblazing research

Centre for Infocomm Technology *(INFINITUS)*

In the Centre for Infocomm Technology, our researchers and engineers are working together on translational projects for the Singapore Smart Nation Programme. The centre combines our in-depth research in the areas of digital data processing, communication, data analytic, and internet-of-thing (IoT), with our engineering expertise in turning research outcomes into tangible solutions for the government agencies and deployment in the real world. Together with our industry partners, we are pushing ahead with several new IoT initiatives that will help to propel the education and R&D activities in NTU.

www.infinitus.eee.ntu.edu.sg

Centre for Bio Devices and Signal Analysis *(VALENS)*

Striving to uncover the human body's workings and improve people's health, *VALENS* has four research priorities: lab-on-a-chip; bio-imaging; e-Health, which includes wearable devices to monitor health; and neurotechnology, where scientists develop methods to detect and predict neurological disorders. A recent collaboration with Massachusetts General Hospital and Harvard Medical School, for instance, resulted in a computer program to help doctors quickly diagnose epilepsy. *VALENS* also works with many Singaporean hospitals and international institutions.

www.valens.eee.ntu.edu.sg

Centre for Micro-/Nano -electronics *(NOVITAS)*

NOVITAS, Centre for Micro-/Nano-electronics, conducts research and development in micro/nanoelectronics. Its 34 faculty members, 42 researchers and more than 69 PhD students' research interests cover electronic material syntheses and characterizations, micro-/ nano-electronic device design and fabrication, device performance evaluation, simulation and physical mechanism study, etc. *NOVITAS* collaborates extensively with local and global academic and industrial partners and it holds 58 on-going research projects with a total fund of S$34 million.

www.novitas.eee.ntu.edu.sg

Centre for OptoElectronics and Biophotonics *(OPTIMUS)*

The science of light, and how to control it for various uses, is at the heart of *OPTIMUS*. Its research areas include optoelectronics which studies of electronics and light converge through semiconductor technologies, and biophotonics which uses light to image, detect and manipulate biological materials. Integrated optics at various wavelengths and biomedical imaging are among the key research directions in *OPTIMUS*, apart from the development of high performance semiconductor, fiber, solid-state, and ceramic lasers. *OPTIMUS* has partnered with many top institutions such as Harvard, MIT, Imperial College London, A*STAR, and various companies.

www.optimus.eee.ntu.edu.sg

LUMINOUS! Centre of Excellence for Semiconductor Lighting and Displays

LUMINOUS! developed and demonstrated full capability for the epitaxial growth of III-N for high-efficiency and high-quality solid-state lighting, displays and other optoelectronic applications. The new advanced knowledge, proprietary know-how and technologies developed under this center enabled superior performance for packaged LED chips while also changing their cost structure. *LUMINOUS!* flagship program on energy-saving quality lighting has been attracting a high level of interest for the technology transfer of different modules in the LED growth and fabrication in the international arena. *LUMINOUS!* scientific research work, together with strong innovation in LED material and device design, has generated a strong IP portfolio at NTU and is in the commercialization phase. *LUMINOUS!* semiconductor optoelectronic solutions strengthen the national capabilities in Singapore and international industries in the region.

www.luminous.eee.ntu.edu.sg

VIRTUS, IC Design Centre of Excellence

An integrated circuit (IC, 'microchips') usually embodies millions of transistors and functions as the 'brain' of the myriad of electrical and electronic devices in our modern society – the major driver in humanity's third wave of invention and economic disruption. Research at the *VIRTUS* - IC Design Centre of Excellence encompasses most areas in IC design, ranging from contemporary areas to emerging areas, including organic/ printed electronics on flexible substrates, the Internet-of-Things, Terahertz circuitsand-systems, satellite electronics, III/Von-CMOS, Point-of-Care devices, etc. *VIRTUS* collaborates with major research universities, including MIT, Caltech, Cornell, etc., and with major industry players, including NXP, Infineon, Huawei, Mediatek, etc.

www.virtus.eee.ntu.sg

Centre for System Intelligence and Efficiency *(EXQUISITUS)*

EXQUISITUS develops core technologies to make complex engineering systems smarter and improve their performances. Main research areas in the centre include control and optimization, machine learning, data analytics, autonomous systems, intelligent systems and robotics, power systems and power electronics, smart grid technologies, smart building technologies, and smart manufacturing technologies, etc. Over the years, *EXQUISITUS* has worked with many universities and organisations including MIT, UC Berkeley, Cambridge University, Technological University of Munich, Rolls-Royce, Singapore Power, ST Engineering, Delta Electronics, Building and Construction Authority of Singapore, and Land Transportation Authority of Singapore, etc.

www.exquisitus.eee.ntu.edu.sg

Centre for Optical Fibre Technology *(COFT)*

The Centre for Optical Fibre Technology (*COFT*) gathers fibre-based technology and applications in Singapore under one roof hosted by the school of EEE, NTU. Being equipped with state-of-the-art facilities, the centre is well-placed to fabricate optical fibres - both standard as well as specialty fibres. The centre aims to become a centre of excellence in the advanced research of optical fibres and their related technologies, developing core capabilities and technologies for specialty optical fibre fabrication and characterisation. *COFT* has also partnered the overseas universities and research groups to develop ways to manufacture special optical fibres and related technologies. *COFT*'s goal is to become a hub for optical fibre fabrication and fibre-based devices research.

www.coft.eee.ntu.edu.sg

Electromagnetic Effects Research Laboratory *(EMERL)*

Though invisible to the naked eye, electromagnetic fields are all around us and can interfere with electronic devices. *EMERL* – short for the Electromagnetics Effects Research Laboratory – researches and measures electromagnetic effects on military and commercial electronic systems. Spearheaded by NTU and Singapore's defence organisation DSO National Laboratories, *EMERL*'s goal is to achieve the safe and innovative use of electromagnetic fields in new technologies. Its research could lead to increasingly compact electronic systems with high immunity to electromagnetic fields.

www.emerl.eee.ntu.edu.sg

Satellite Research Centre *(SaRC)*

The Satellite Research Centre or *SaRC*'s high-flying research includes putting into space Singapore's first locally-built satellite, the X-SAT, in 2011. Since then, it has developed and deployed six more satellites. Its researchers are also pushing the frontiers of satellite technology with innovations such as a fault-tolerant electronic system, precision navigation hardware, sensors, advanced control and electric propulsion system etc. In 2009, it started training students in various fields including advanced payload and satellite development from pico- to micro-satellites. Its goal is to become a centre of excellence in small satellite technology.

www.sarc.eee.ntu.edu.sg

Rapid-Rich Object Search Lab *(ROSE)*

In Internet searches, a picture could be worth a thousand words. The Rapid-Rich Object Search or *ROSE* Laboratory is a collaboration between NTU and China's Peking University to boost the efficiency and effectiveness of visual search from mobile devices or over the Internet. In particular, the lab is focusing on the classification, recognition, retrieval, and tracking of visual objects in images and videos. The *ROSE* Lab is working with Internet giants (e.g. Tencent) and industry leaders (e.g. Accenture, NVIDIA, and OMRON) in social media, e-commerce, digital advertising, image forensics, and surveillance to commercialise its research.

rose.ntu.edu.sg

Silicon Technologies, Centre of Excellence *(Si-COE)*

Silicon is found in virtually all electronics and has transformed every aspect of our economy, including information technology, transportation, energy production, and national security. The Silicon Technologies, Centre of Excellence or *Si-COE* aims to find new uses for it in sectors from multi-purpose healthcare wearables to energy efficient sensors for Internet of Things. Its four research focuses are the use of silicon in advanced sensors and non-volatile memories, new silicon chips intermixed with compound semiconductors, advanced packaging, and innovative solutions to dissipate heat in microchips. It has established research partnership with multinational corporations like GLOBALFOUNDRIES, Infineon, Hewlett Packard as well as Institute of Microelectronics in Singapore.

www.sicoe.ntu.edu.sg

School of Electrical and Electronic Engineering
50 Nanyang Avenue, Block S1, Singapore 639798
Tel: (65) 6592 5402 | Fax: (65) 6791 2687
www.eee.ntu.edu.sg