OFFICE OF STRATEGIC INTELLIGENCE & ANALYSIS (OSI&A)
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S&T Global Highlights

FEATURED ARTICLES

The world's first nuclear clock (Pg. 2)

Scientists in Austria have successfully combined a high-precision atomic optical clock with a high-energy laser system and coupled it with a crystal containing thorium atomic nuclei, creating the world's first nuclear clock. This technology not only enables more precise time measurements but also has the potential to improve the measurement of other physical quantities.

Electrically modulated light antenna points the way to faster computer chip (Pg. 3)

Researchers from Germany and Denmark made a breakthrough in modulating light antennas by changing the surface properties of a gold nanorod resonator. Based on their results, it is now possible to design antennas and exclude or amplify individual quantum effects leading to ultra-fast computer chips and efficient optical modulators.

Miniaturized brain-machine interface processes neural signals in real time (Pg. 4)

Researchers from Switzerland have developed a miniaturized brain-machine interface that enables direct brain-to-text communication on tiny silicon chips. It has the potential to significantly improve the quality of life for individuals with severe motor impairments and spinal cord injuries.

ABOUT

S&T Global Highlights

This newsletter features recent publications in science and technology research directly relevant to the DoD's Critical Technology Areas or adjacent to those fields and potentially of interest to the broader OUSD(R&E) Enterprise. S&T Global Highlights is intended to provide insights into global research efforts, and intentionally limits the inclusion of U.S.-based research and excludes DoD research efforts.

Inclusion of a research article or summary is in no way an endorsement by the DoD or OUSD(R&E), and does not constitute validation of the research findings. Articles may have been abbreviated, synopsized, or excerpted.

Questions, feedback, or suggestions?

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The world's first nuclear clock

From: Vienna University of Technology (Austria)
4 September 2024 | Press Release | DOI

For many years, scientists around the world have been working towards this technology goal, now things are moving quickly. It was only in April that a team led by Prof. Thorsten Schumm announced a major success. For the first time, an atomic nucleus had been switched from one state to another using a laser – an effect that can be used for high-precision measurements. Now, just a few weeks later, this thorium transition was successfully applied in practice: Vienna University of Technology (TU Wien) and the Joint Institute for Laboratory Astrophysics/National Institute of Standards and Technology (JILA/NIST) succeeded in combining a high-precision optical atomic clock with a high-energy laser system and successfully coupled it with a crystal containing thorium atomic nuclei. The thorium atomic nuclei can now be used as a time keeping device, making the clock even more precise – it is the world's first nuclear clock.

It does not yet deliver greater precision than an ordinary atomic clock, but that was not the aim in this first step. "With this first prototype, we have proven: Thorium can be used as a timekeeper for ultra-high-precision measurements. All that is left to do is technical development work, with no more major obstacles to be expected," says Schumm. The first nuclear clock has now been presented in the journal *Nature.*

The ticking of a laser beam

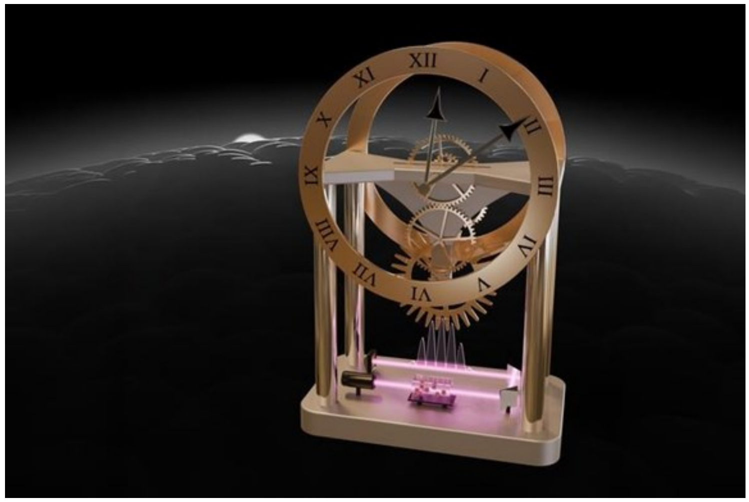
Every clock needs a timekeeper – for example the regular swinging motion of the pendulum in a pendulum clock. Today, high precision clocks use the oscillation of electromagnetic waves for this purpose; the oscillations of a laser beam are counted to measure time intervals. However, the frequency of a laser can change slightly over time, and so its frequency has to be to be readjusted.

"That's why, in addition to the laser, you need a quantum system that reacts extremely selectively to a very specific laser frequency," explains Schumm (TU Wien). This could be cesium or strontium atoms, for example. When they are hit with laser light of a very specific frequency, the electrons of these atoms switch back and forth between two quantum states, and this can be measured. If the laser frequency changes, it no longer matches the natural frequency of the atoms exactly and the atoms are no longer excited as efficiently. In that case, the laser has to be readjusted. This technique makes it possible to keep the laser frequency extremely stable – this is the basic principle of an atomic clock.

From the atomic clock to the nuclear clock

However, an intriguing idea has been around for decades: if this trick could be performed not with an atom, but with an atomic nucleus, even greater precision would be possible. Atomic nuclei are much smaller than atoms and react much less strongly to disturbances, such as electromagnetic fields from outside. The only problem was that switching atomic nuclei back and forth between two states normally requires at least a thousand times more energy than the photons of a laser have.

The only known exception is thorium: "Thorium nuclei have two states of very similar energy, so you can switch them with lasers," says Schumm. "But for this to work, you have to know the energy difference between these two states very precisely. For many years, research teams around the world had been searching for the exact value of this energy difference in order to be able to switch thorium nuclei in a targeted manner – we were the first to succeeded, this is the result we published in April."



Atomic nuclei as timekeepers: a new technology that will be even more accurate than atomic clocks . Credit: Vienna University of Technology

An "optical gearbox" and the frequency comb

The atomic clock at JILA (a research institute of NIST and the University of Boulder, USA) has now been successfully coupled with thorium atomic nuclei. This required a few physical tricks: "The atomic clock works with laser light in the infrared range, which is used to excite strontium atoms. However, our thorium atomic nuclei need radiation in the UV range," explains Schumm. "We therefore need a way to turn infrared frequencies to UV frequencies, similar to a mechanical transmission that turns a slow rotational frequency into a faster rotation using suitable gears."

Ultra-short infrared laser pulses consisting of a series of different infrared frequencies were used for this purpose. The distance between two neighboring frequencies is always the same, just like the distance between neighboring teeth of a comb, which is why this is also referred to as a "frequency comb". This frequency comb of infrared light hits xenon gas, the xenon atoms then react to the infrared light by producing UV light in a very precisely predictable way. This UV light is then transmitted to a tiny crystal containing thorium nuclei. "This crystal is the central element of the experiment," Schumm explains. "It was produced at TU Wien, in Vienna, and several years of development work were required to develop the necessary expertise."

The coupling of these elements worked well – the result is the world's first nuclear clock. This first prototype does not yet deliver an increase in precision, but that had never been intended. "Our aim was to develop a new technology. Once it's there, the increase in quality comes naturally, that has always been the case. The first cars weren't any faster than carriages. It was all about introducing a new concept. And that's exactly what we've now achieved with the nuclear clock."

Record precision

This also made it possible to measure the energy of the thorium states with extreme precision, orders of magnitude higher than before. "When we excited the transition for the first time, we were able to determine the frequency to within a few gigahertz. That was already more than a factor of a thousand better than anything known before. Now, however, we have precision in the kilohertz range – which is again a million times better. That way, we expect to overtake the best atomic clocks in 2-3 years" says Schumm.

This technology should not only enable significantly more precise time measurements than previous clocks, but other physical quantities should also be able to be measured more precisely in the future.

Electrically modulated light antenna points the way to faster computer chip

From: Julius-Maximilians University Wurzburg (Germany), University of Southern Denmark (Denmark)

6 September 2024 | Press Release | DOI

Today's computers reach their physical limits when it comes to speed. Semiconductor components usually operate at a maximum usable frequency of a few gigahertz—which corresponds to several billion computing operations per second.

As a result, modern systems rely on several chips to divide up the computing tasks because the speed of the individual chips cannot be increased any further. However, if light (photons) were used instead of electricity (electrons) in computer chips, they could be up to 1,000 times faster.

Plasmonic resonators, also known as antennas for light, are a promising way of achieving this leap in speed. These are nanometer-sized metal structures in which light and electrons interact. Depending on their geometry, they can interact with different light frequencies.

"The challenge is that plasmonic resonators cannot yet be effectively modulated, as is the case with transistors in conventional electronics. This hinders the development of fast light-based switches," says Dr. Thorsten Feichtner, physicist at Julius-Maximilians-University (JMU) Würzburg in Bavaria, Germany.

Charged optical antennas: Breaking new ground

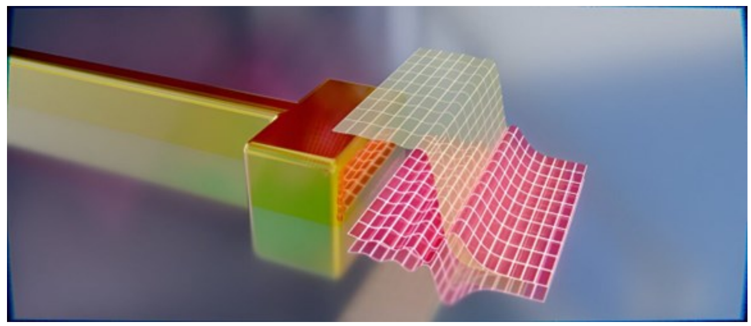
A JMU research team in collaboration with the Southern Denmark University (SDU) in Odense has now taken a significant step forward in the modulation of light antennas.

It has succeeded in achieving electrically controlled modulation that points the way to ultra-fast active plasmonics and thus to significantly faster computer chips. The experiments have been published in the journal Science Advances.

Instead of trying to change the entire resonator, the team focused on changing its surface properties. This breakthrough was achieved by electrically contacting a single resonator, a nanorod made of gold—an idea that is conceptually simple, but could only be realized with the help of sophisticated nanofabrication based on helium ion beams and gold nanocrystals.

This unique fabrication method has been established at the JMU Chair of Experimental Physics (Biophysics) under the direction of Professor Bert Hecht. Sophisticated measurement techniques with a lock-in amplifier were crucial for detecting the small but significant effects on the surface of the resonator.

Study leader Dr. Feichtner explains, "The effect we are making use of is comparable to the principle of the Faraday cage. Just as the electrons in a car struck by lightning collect on the outside and the occupants inside are safe, additional electrons on the surface influence the optical properties of the resonators."



Artist's impression of an electrically contacted optical antenna (left) and the quantum mechanical distribution of its surface electrons. The normal distribution is shown in yellow, while the change induced by an applied voltage is shown in red. Credit: Julius-Maximilians University Wurzburg

Surprising quantum effects

Until now, optical antennas could almost always be described classically: the electrons of the metal simply stop at the edge of the nanoparticle, like water at a harbor wall. However, the measurements taken by the Würzburg scientists revealed changes in the resonance that can no longer be explained in classical terms: The electrons smear across the boundary between metal and air, resulting in a soft, graduated transition, similar to a sandy beach met by the sea.

To explain these quantum effects, theorists at SDU Odense developed a semi-classical model. It incorporates the quantum properties into a surface parameter so that the calculations can be carried out using classical methods.

"By perturbing the response functions of the surface, we combine classical and quantum effects, creating a unified framework that advances our understanding of surface effects," explains JMU physicist Luka Zurak, first author of the study.

New field of research with great potential

The new model can reproduce the experiments, but exactly which of the many quantum effects are involved at the metal surface is not clear at the moment. "But with this study, it is now possible for the first time to specifically design new antennas and exclude or amplify individual quantum effects," says Dr. Feichtner.

In the long term, the researchers envisage even more applications: Smaller resonators promise optical modulators with high efficiency, which could be used technologically. In addition, the influence of surface electrons in catalytic processes can also be investigated with the system presented. This would provide new insights into energy conversion and energy storage technologies.

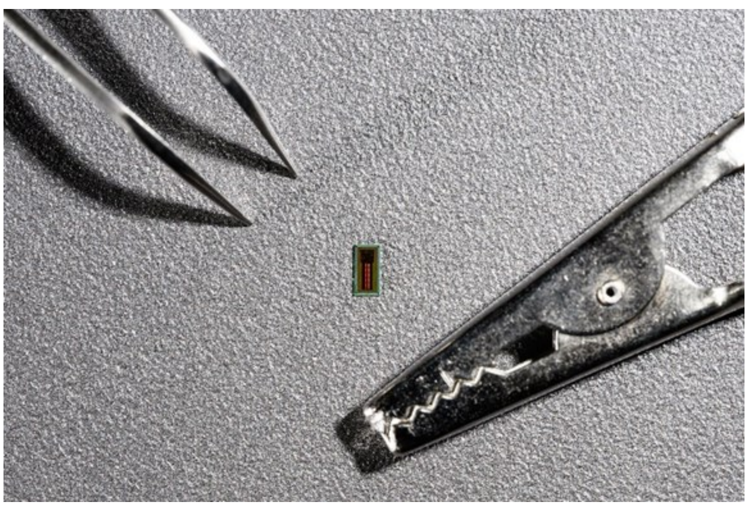
Miniaturized brain-machine interface processes neural signals in real time

From: École Polytechnique Fédérale de Lausanne (Switzerland)
23 Aug 2024 | Press Release | DOI

Researchers from École Polytechnique Fédérale de Lausanne (EPFL) have developed a next-generation miniaturized brain-machine interface capable of direct brain-to-text communication on tiny silicon chips.

Brain-machine interfaces (BMIs) have emerged as a promising solution for restoring communication and control to individuals with severe motor impairments. Traditionally, these systems have been bulky, power-intensive, and limited in their practical applications.

Researchers at EPFL have developed the first high-performance, Miniaturized Brain-Machine Interface (MiBMI), offering an extremely small, low-power, highly accurate, and versatile solution.



Miniaturized Brain-Machine Interface (MiBMI). Credit: EPFL

Published in the latest issue of the *IEEE Journal of Solid-State Circuits* and presented at the International Solid-State Circuits Conference, the MiBMI not only enhances the efficiency and scalability of brain-machine interfaces but also paves the way for practical, fully implantable devices.

This technology holds the potential to significantly improve the quality of life for patients with conditions such as amyotrophic lateral sclerosis (ALS) and spinal cord injuries.

The MiBMI's small size and low power are key features, making the system suitable for implantable applications, and its minimal invasiveness ensures safety and practicality for use in clinical and real-life settings.

It is also a fully integrated system, meaning that the recording and processing are done on two extremely small chips with a total area of 8mm2. This is the latest in a new class of low-power BMI devices developed at Mahsa Shoaran's Integrated Neurotechnologies Laboratory (INL) at EPFL's IEM and Neuro X institutes.

"MiBMI allows us to convert intricate neural activity into readable text with high accuracy and low power consumption. This advancement brings us closer to practical, implantable solutions that can significantly enhance communication abilities for individuals with severe motor impairments," says Shoaran.

Brain-to-text conversion involves decoding the neural signals generated when a person imagines writing letters or words. In this process, electrodes implanted in the brain record neural activity associated with the motor actions of handwriting.

The MiBMI chipset then processes these signals in real time, translating the brain's intended hand movements into corresponding digital text. This technology allows individuals, especially those with locked-in syndrome and other severe motor impairments, to communicate by simply thinking about writing, with the interface converting their thoughts into readable text on a screen.

"While the chip has not yet been integrated into a working BMI, it has processed data from previous live recordings, such as those from the Shenoy lab at Stanford, converting handwriting activity into text with an impressive 91% accuracy," says lead author Mohammed Ali Shaeri.

The chip can currently decode up to 31 different characters, an achievement unmatched by any other integrated systems. "We are confident that we can decode up to 100 characters, but a handwriting dataset with more characters is not yet available," adds Shaeri.

Current BMIs record the data from electrodes implanted in the brain and then send these signals to a separate computer to do the decoding. The MiBMI chip records the data but also processes the information in real time—integrating a 192-channel neural recording system with a 512-channel neural decoder.

This neurotechnological breakthrough is a feat of extreme miniaturization that combines expertise in integrated circuits, neural engineering, and artificial intelligence. This innovation is particularly exciting in the emerging era of neurotech startups in the BMI domain, where integration and miniaturization are key focuses. EPFL's MiBMI offers promising insights and potential for the future of the field.

To be able to process the massive amount of information picked up by the electrodes on the miniaturized BMI, the researchers had to take a completely different approach to data analysis. They discovered that the brain activity for each letter, when the patient imagines writing it by hand, contains very specific markers, which the researchers have named distinctive neural codes (DNCs).

Instead of processing thousands of bytes of data for each letter, the microchip only needs to process the DNCs, which are around a hundred bytes. This makes the system fast and accurate, with low power consumption. This breakthrough also allows for faster training times, making learning how to use the BMI easier and more accessible. Collaborations with other teams promise to create the next generation of integrated BMI systems. The team is exploring various applications for the MiBMI system beyond handwriting recognition.

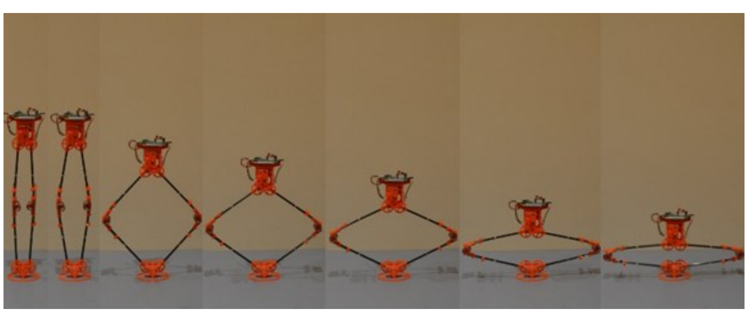
"We are collaborating with other research groups to test the system in different contexts, such as speech decoding and movement control. Our goal is to develop a versatile BMI that can be tailored to various neurological disorders, providing a broader range of solutions for patients," says Shoaran.

ARTICLE SUMMARIES

Engineers unlock design for record-breaking robot that could jump twice the height of Big Ben

From: University of Manchester (United Kingdom)
1 September 2024 | Press Release | DOI

Engineers at the University of Manchester have developed a robot capable of jumping vertically 120 meters, higher than any other jumping robot to date, by removing movement inefficiencies. Through a combination of mathematics, computer simulations, and laboratory experiments, the researchers have determined the optimal size, shape, and arrangement of the robot's parts to enable it to clear obstacles many times its own size. The current highest-jumping robot can reach up to 33 meters, while the newly designed robot could jump more than 120 meters in the air or 200 meters on the moon. The researchers found that traditional jumping robots often waste energy by not fully releasing their stored spring energy and by moving side to side or rotating instead of moving straight up. The new designs focus on removing these inefficiencies while maintaining structural strength and stiffness. The researchers' next goal is to control the direction of the jumps and harness the kinetic energy from landing to improve the number of jumps the robot can perform in a single charge. They also plan to explore more compact designs for space missions to enhance transportability and deployment on the moon. This advancement has applications such as planetary exploration, disaster rescue, and surveillance of hazardous or inaccessible spaces.

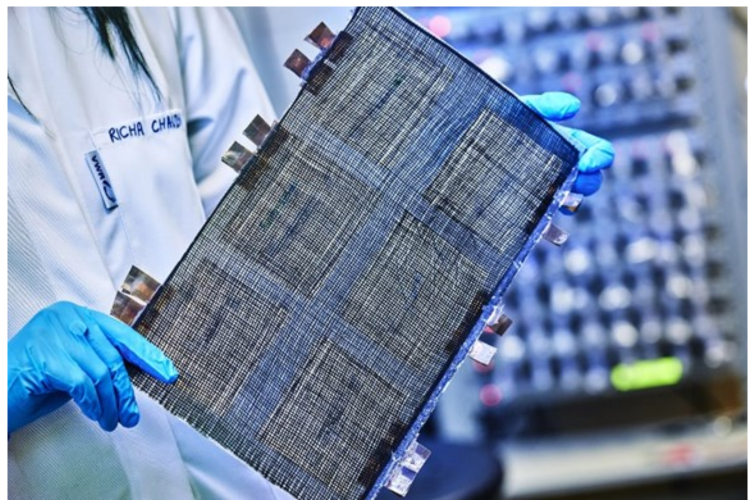


Robot springs into action. Credit: University of Manchester

Carbon fiber structural battery paves way for light, energy-efficient vehicles

From: Chalmers University of Technology (Sweden)
10 September 2024 | Press Release | DOI

Researchers at Chalmers University of Technology have developed a structural battery by using a carbon fiber composite, which functions as both a battery and a load-bearing structure. This innovation could significantly reduce the weight and energy consumption of devices and vehicles. The battery, as stiff as aluminum and energy-dense enough for commercial use, could halve the weight of laptops, make mobile phones as thin as credit cards, and increase the driving range of electric cars by up to 70% on a single charge. The research has evolved since 2018, achieving an energy density of 30 watt hours per kilogram and a stiffness of 70 gigapascals. This multifunctional battery material reduces the need for additional structural components, thereby lowering overall weight and energy requirements. The technology is moving towards commercialization, although further engineering work is needed for large-scale production. The research has garnered interest from the automotive and aerospace industries due to its potential to revolutionize energy-efficient design.

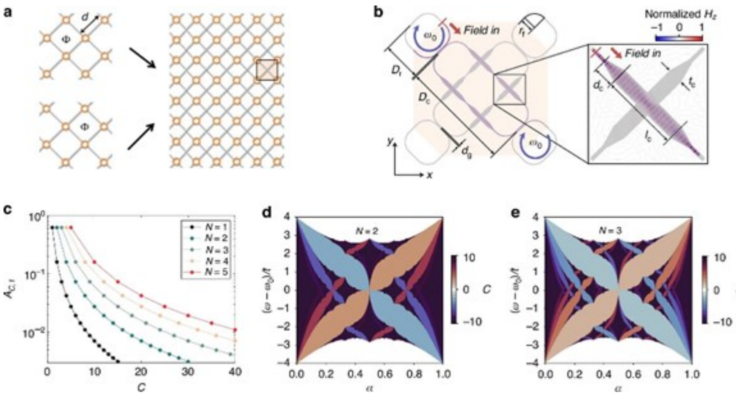


Researchers at Chalmers University of Technology have succeeded in creating a battery made of carbon fiber composite that is as stiff as aluminum and energy-dense enough to be used commercially. Credit: Chalmers University of Technology

Long-range-interacting topological photonic lattices breaking channel-bandwidth limit

From: Seoul National University (South Korea)
2 September 2024 | Press Release | DOI

Researchers at Seoul National University have developed a technique to overcome signal processing bandwidth limitations by tailoring long-range interactions in topological photonic lattices. In photonic integrated circuits, efforts have focused on implementing noise-resistant signal processing using topologically protected light states. However, a major challenge is overcoming bandwidth limitations due to a trade-off between the number of signal channels and channel bandwidth. Unlike conventional systems relying on nearest-neighbor interactions, their approach employs substantial long-range interactions, enabling effective overlap of lattice structures within a two-dimensional plane. This lattice overlap technique tailors topological invariants, such as Chern numbers, while preserving the bandgap, thus breaking the trade-off between signal channels and bandwidth. Using the Hofstadter model and Tidy3D software, the researchers demonstrated a multichannel wave splitter robust to various disorders, enhancing information capacity. This breakthrough enables robust, high-capacity signal processing in photonic integrated circuits with implications for artificial intelligence accelerators and quantum computing, and the potential for models of higher-dimensional physics on a two-dimensional (2D) plane.



Overlapped Hofstadter lattices for long-range connectivity. Credit: Seoul National University

New quantum error correction method uses 'many hypercube codes' while exhibiting beautiful geometry

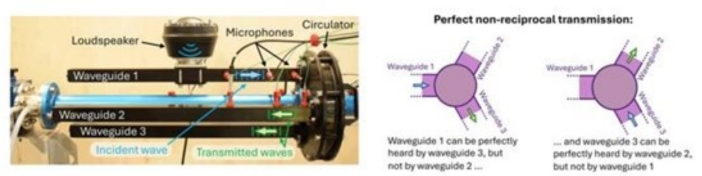
From: RIKEN Center for Quantum Computing (Japan)
4 September 2024 | Press Release | DOI

Researchers from the RIKEN Center for Quantum Computing have introduced a new quantum error correction method called "many-hypercube codes, by using a geometric structure to enhance error correction efficiency and support highly parallel fault-tolerant quantum computing. Traditional quantum error correction methods, which encode a single logical qubit onto many entangled physical qubits, face scalability issues due to the high number of physical qubits required. This method, based on high-rate concatenated quantum codes, visualizes logical qubits as forming hypercubes, simplifying the complex structures of high-rate quantum codes. A novel dedicated decoder using level-by-level minimum distance decoding was developed to interpret results from physical qubits, enabling parallel processing of logical gates. This innovation achieves an encoding rate of up to 30%, the highest for fault-tolerant quantum computing, with performance comparable to conventional low-rate codes. The research indicates this code could be implemented with physical qubit systems like laser-trapped neutral-atom qubits.

One-way street for sound waves

From: Federal Institute of Technology Zurich (Switzerland)
28 August 2024 | Press Release | DOI

Researchers at the Federal Institute of Technology Zurich have developed a method to prevent sound waves from traveling backward without affecting their forward propagation by using harmless, self-sustaining aero-acoustic oscillations. This method creates a one-way street for sound waves and relies on self-oscillations, where a dynamic system periodically repeats its behavior. The lead researcher based this approach on a previous study of self-sustaining thermo-acoustic oscillations in aircraft engines. The circulator, a disk-shaped cavity with swirling air generates a whistling sound from a spinning wave. The team added three acoustic waveguides to the circulator, arranged in a triangular shape. Sound waves entering through the first waveguide can exit through the second but not the third. The researchers successfully demonstrated this loss-compensation approach by sending an 800 hertz sound wave through the first waveguide, which emerged stronger from the second waveguide. This concept of loss-compensated non-reciprocal wave propagation could be applied to metamaterials for electromagnetic waves, improving microwave guidance in radar systems and enabling topological circuits for future communication systems.

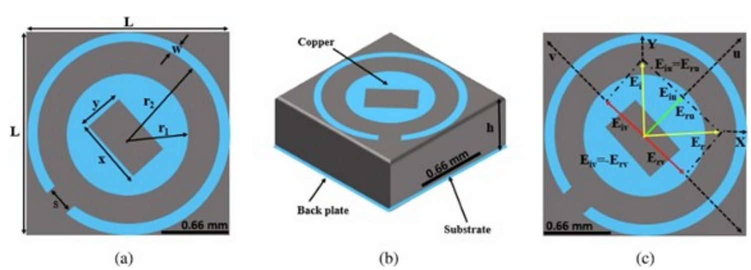


Schematics of the experimental set-up (left) and wave propagation (right). Credit: Federal Institute of Technology Zurich

New 2D metamaterial enhances satellite communication for 6G networks

From: University of Glasgow (United Kingdom)
8 September 2024 | Press Release | DOI

Researchers from the University of Glasgow have developed an ultrathin 2D metamaterial surface by using geometrically patterned copper on a commercial circuit board. The surface converts linearly polarized electromagnetic waves into circular polarization. This promises to improve signal quality and reliability. Circular polarization is resistant to atmospheric effects and eliminates the need for precise antenna alignment, doubling channel capacity and simplifying antenna design for small satellites. The metamaterial operates across a wide range of frequencies (12 gigahertz to 40 gigahertz) commonly used in satellite applications. Lab tests confirmed its high performance even at angles up to 45 degrees. The device can be mass-produced affordably using conventional printed circuit board techniques, making it a promising addition to future satellite systems. This breakthrough could lead to better phone signals, more stable data connections, and improved Earth observation capabilities.



Ultrathin 2D metasurface structural unit cell design (a. front view, b, perspective view, c. UV diagram). Credit: University of Glasgow

Discovery of a new convective instability in complex fluids, 140 years after Lord Rayleigh

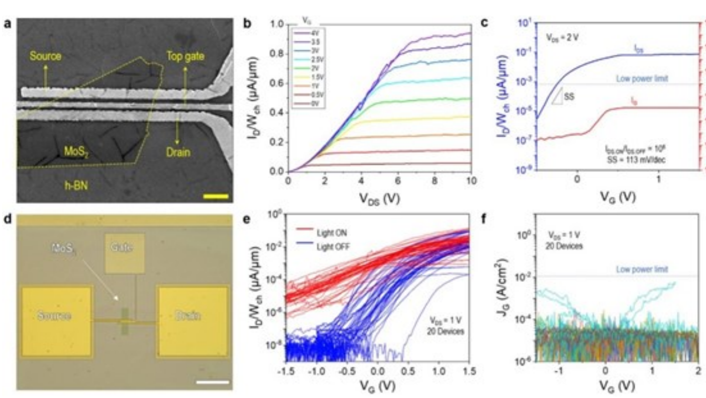
From: University of Milan (Italy)
3 September 2024 | Press Release | DOI

Researchers from the University of Milan discovered a new convective instability by adding silica nanoparticles into a system where the heavier liquid (glycerol) sits at the bottom and a lighter one (water) on top. The well-known Rayleigh-Taylor instability occurs when a lighter fluid moves upward into a denser fluid, as seen in volcanic eruptions and nuclear explosions. Adding silica nanoparticles, which move upward to minimize interfacial energy through diffusiophoresis, creates locally denser regions in the water-rich layers. These regions are pushed back by gravity, triggering a hydrodynamic instability. This instability manifests as a peak in the structure factor when the sample is irradiated with light, forming a pattern of colloid-poor regions surrounded by colloid-rich arms. The pattern formation ends with phase separation over time. This new effect, different from Rayleigh-Taylor and Rayleigh-Benard instabilities, has been mathematically modeled using coupled diffusion equations. The discovery has potential applications in technology and environmental protection, such as creating new microscopically structured materials, separating fluid mixtures, and removing colloidal contaminants like microplastics.

Researchers develop approach to fabricate highly performing transistors based on 2D semiconductors of the future

From: King Abdullah University of Science and Technology (Saudi Arabia), Soochow University (China)
26 August 2024 | Press Release | DOI

Researchers from King Abdullah University of Science and Technology and Soochow University have developed a method to improve the performance of transistors by using two-dimensional (2D) semiconductors as channel materials. Their approach involves using hexagonal boron nitride (h-BN) dielectrics and high cohesive energy metal gate electrodes like platinum (Pt) and tungsten (W). This combination significantly reduces interfacial traps and enhances transistor performance. The team found that Pt/h-BN gate stacks exhibit 500-times lower current leakage and a high dielectric strength of at least 25 millivolts per centimeter compared to gold/h-BN stacks. The team also discovered that h-BN is most compatible with high cohesive energy metals. The clean van der Waals interface between molybdenum disulfide and h-BN in their transistors minimizes defects and enhances gate control. Their findings suggest that using high cohesive energy metals makes chemical vapor deposition h-BN an effective gate dielectric in 2D transistors, potentially facilitating the development of reliable solid-state microelectronic circuits.

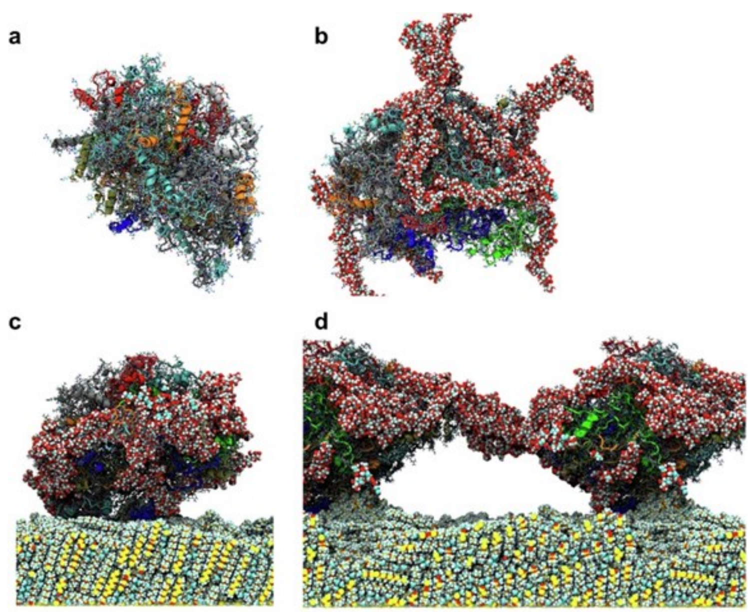


Morphology and electrical characteristics of MoS2 transistors. Credit: King Abdullah University of Science and Technology

Plant proteins could be radical alternative to oil-based super lubricants

From: University of Leeds (United Kingdom)
3 September 2024 | Press Release | DOI

Researchers from the University of Leeds have developed an oil-free super-lubricant by mimicking the actions of synovial fluids. This material, made from potato proteins, achieves super lubricity similar to the synovial fluids found in human joints. The interdisciplinary team used eco-friendly building blocks, such as potato protein. Potato proteins can be naturally sourced and have a lower carbon footprint. The material has potential applications in engineering and biomedical fields, including artificial synovial fluid and low-calorie foods. The study demonstrates the potential for sustainable, plant-based aqueous lubricant materials.



Molecular dynamics simulations of the interaction in an aqueous dispersion and in contact with a polydimethylsiloxane surface. Credit: University of Leeds