Reaching New Hertz: Developing Novel Photodetector Technology

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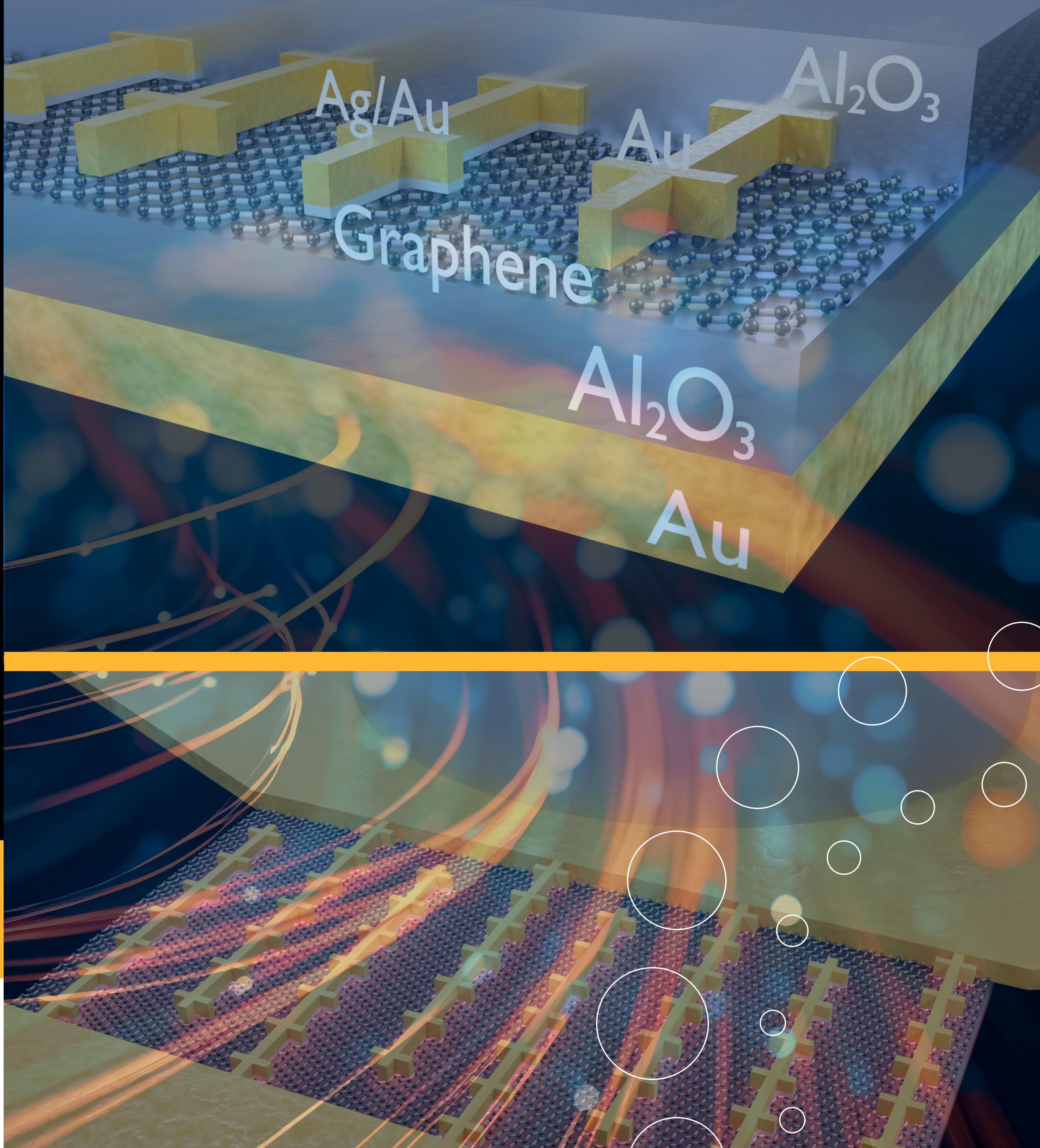

Reaching New Hertz: Developing Novel Photodetector Technology

Photodetectors, or sensors which detect light and send information about the light via an electronic signal, are an essential piece of technology in modern optical science. Dr Stefan Koepfli from the Institute of Electromagnetic Fields, ETH Zurich in Switzerland, works with colleagues on the development and creation of these detectors. They look at how materials such as graphene can be used in these devices to improve the range of wavelengths that they can detect and also the speed at which they can transfer information.

Using Graphene in New Photodetector Technology

Being able to detect light and find out information such as its power, is key in applications across optics – from sensing through communication. Photodetectors allow this to be achieved by detecting the photons (wave packets of light) which are incident on the sensor. These wave packets of light have a certain amount of energy, which then excites the negatively charged electrons in the photodetector. This creates a flow of electrons, or a current, which is proportional to the power of the input light. By measuring this current, we can gain information about this light.

To convert the to-be-detected wave packets into measurable excited charge carriers, an appropriate material needs to be found. Graphene (like graphite, which we find every day in the lead of pencils) is made up of carbon atoms arranged in a honeycomb structure. Unlike graphite, it has a unique set of properties due to its atomic thickness, including being responsive to a wide range of different wavelengths, or colours, of light and allowing particles which carry charge, such as electrons, to move quickly through the material when an electric field is applied. Properties like this make it an exciting candidate to be used in photodetectors.

To make a photodetector, the interaction of light with the extremely thin layer of graphene has to take place. One way is to sandwich a layer of graphene beneath nobel metal structures, and on top of a silicon photonics chip. Light can be passed through the silicon chip, using a waveguide to direct the light around the chip, and the electric field associated with this light couples with the graphene. In more recent plasmonic photodetectors, the light also interacts with the nearby nobel metals, thereby resonantly enhancing the absorptivity and efficiency of detectors. As a results of the absorption of light in graphene assisted by the plasmonic enhancement, one may see a difference in the current when a voltage is applied to the detector. This can be used to find out more about the light in the waveguide.

Improving the Wavelength Operation and Speed of Photodetection

With the ever-growing demand for faster internet and improved connectivity, an important property of photodetectors is their bandwidth – defined as the speed at which they can respond to a light pulse. At ETH Zurich in Switzerland, Dr Stefan Koepfli, Professor Juerg Leuthold, and colleagues in the Institute of Electromagnetic Fields, have achieved a bandwidth of over 500 gigahertz (GHz) for their graphene-based photodetector – making it the world's fastest photodetector. This bandwidth allows for high-speed operation, achieving an astonishing rate of data transfer of 132 gigabits per second.

To develop this photodetector, Dr Koepfli and his colleagues create a device where a layer of graphene sits on top of a gold backplane and a layer of aluminium oxide to reflect light towards the graphene (see Figure 1). On top of the graphene, they place gold structures called dipole resonators combined with alternating gold and silver electrical contact lines. This creates structures that act as tiny dipole antennae, enhancing the absorption in graphene. The length of these antennae can be altered to resonate at a particular wavelength. By using these antennae and the reflecting backplate, Dr Koepfli and the team at the Institute of Electromagnetic Fields can allow for almost all the light of the chosen wavelength to be absorbed by the photodetector. These photodetectors are also compatible with complementary metal

oxide semiconductor, or CMOS, manufacturing techniques, which are commonly used to make chips – like those in our phones and computers. By being able to be integrated with these processes, these detectors could be readily manufactured and would offer a low cost solution in comparison to existing technologies.

As part of the development process, the Institute of Electromagnetic Fields researchers led by Professor Leuthold characterise many different properties of the device, including looking at the range of wavelengths the photodetector can detect and varying the power of the incident light. To test the capability of the detector for data communication, they carry out an on-off keying experiment, where the presence or absence of light is detected as a 0 or a 1, allowing for binary data to be transferred bit-by-bit, finding that its data rate is 132 gigabits per second. The bandwidth is tested by using multiple lasers and measuring the radio frequency power from the device – the photodetector gives a response from 2 GHz up to the limit of the test set-up, 500 GHz. The large bandwidth and range of operating wavelengths give this photodetector powerful potential in sensing and communication applications.

Controlling Photocurrents in Photodetectors

The unique properties of graphene allow for it to be used in different ways within photodetectors. Dr Koepfli and his colleagues have also investigated how photothermoelectric directional currents can be generated in plasmonic graphene photodetectors. The photothermoelectric effect occurs when there is a temperature difference between two parts of an electrically conductive material, and it leads to energy transfer in the electrical circuit. The temperature difference here is caused by light being absorbed on a thermoelectric material, which here is the graphene at specific operating conditions.

To use this effect, the researchers design asymmetric resonators, shaped like an inverted 'T' in this photodetector. This asymmetry leads to 'hot spots' in the plasmonic resonators, which then leads to a current being induced in the channel that connects the resonators. Dr Koepfli and his team simulate how the design of these asymmetric resonators can affect detection, for example, considering the rotation of the T shape, or the length of the two lines that make up the T. By simulating these, they show how they can choose the resonator such that they can understand how polarisation affects the response of the photodetector and pick an orientation such that the polarisation does not change the absorption in the graphene.

Dr Koepfli and his colleagues test these devices, showing that they have a bandwidth of over 400GHz – something very uncommon for usually slow thermal detectors. They also show how multiple detectors can be used within one area – for example, using different asymmetric resonator designs with different orientations opens up the possibility of detecting different wavelengths or polarisations in the input light. To show this, they fabricate four resonators, with two resonators operating at a higher wavelength and two operating at a lower wavelength. Each pair of resonators also has a different orientation to measure different polarisations. Using this, they successfully detect when different wavelengths are incident on the sensor, and when different polarisations are input. This allows for multiple channels to operate at the same time within a small detector area and adds to the potential for these devices.

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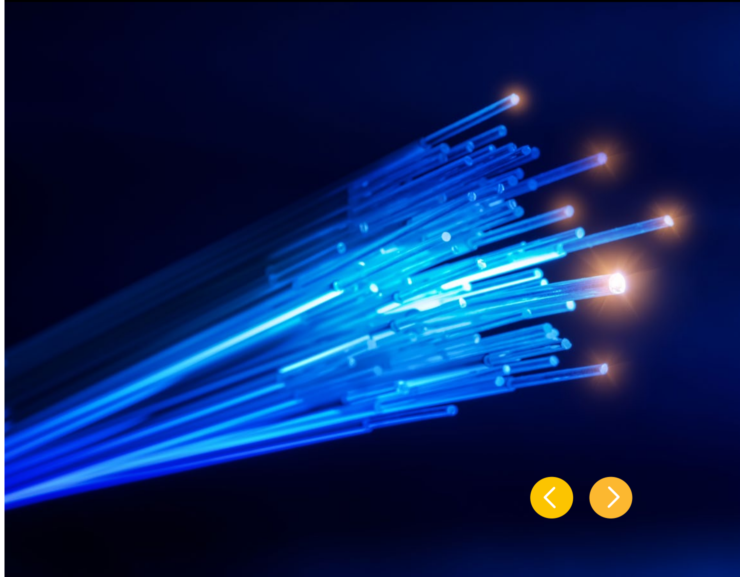
V Optical fibre.



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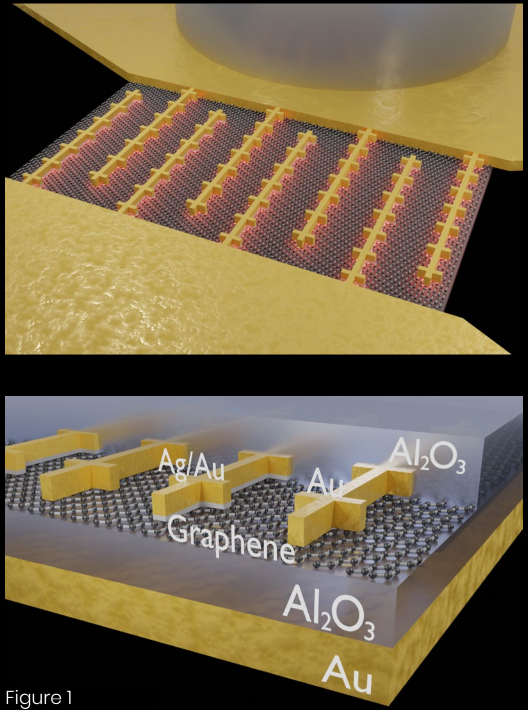

Figure 1

Operating Photodetectors at Cryogenic Temperatures

Whilst the aforementioned photodetectors have been demonstrated at room temperature, Dr Koepfli and his team are also looking at how the photodetectors can be used at cryogenic temperatures of 4 Kelvin (around -269°C). Being able to have photodetectors operating at these extremely low temperatures could be useful for future superconducting or quantum computers. These computing devices have to be operated at cryogenic temperatures, and to connect them to room temperature instruments, researchers use coaxial cables to send radio frequency signals between the two. These cables are good electric conductors but also are inherently good thermal conductors, which leads to heat being transferred from the environment and beginning to increase the temperature of the cryostat system. This can be a limiting factor as these systems grow in size, as more cooling power is then needed to keep the cryostat cold. One way of overcoming this problem is by replacing them with optical interconnects, such as sending light through optical glass fibres, which conduct very little heat. However, to enable this, one needs to have photodetectors that are able to operate at these very low temperatures.

The high-speed graphene based photodetectors developed by the team of Professor Leuthold could be an advantageous solution for the cryogenic signal generation. Their device can be operated without needing any additional electric lines as it doesn't need a voltage to operate. To test the performance of their sensor, they have a light source outside of the cryostat, which sends a signal to the photodetector through an optical fibre. The output signal from the photodetector is then sent via a coaxial cable to be analysed.

At cryogenic temperatures, the researchers achieve a 110 GHz bandwidth for their device, which may be the fastest-operated photodetector at these temperatures. This could potentially be useful in communication systems as well, as Dr Koepfli and his team test how this could be used as a cryogenic data link. To do this, they encode a bit sequence, or a series of 0s and 1s, into their optical input, send this to the photodetector in the cryostat and then detect the signal, seeing both how quickly this data was transmitted and how many errors occurred, for example, if a 0 was received in place of a 1. The team achieve rates up to 112 gigabits per second, showcasing the successful high-speed signal transfer into a cryostat by means of an optical fibre.

Overall, the group of Professor Leutholdat the Institute of Electromagnetic Fields is working on many aspects of improving graphene photodetector devices. From designing the way they are illuminated, resonators to maximise absorption of light, and improving the bandwidth through to considering thermal effects and designing asymmetric resonators to utilise this, they have developed some of the fastest graphene-based photodetectors to date. These developed photodetectors are also faster than any other available technology. These high-speed detectors could be useful in optical communication networks or beyond, and by considering the different environments these may operate in (such as at cryogenic temperatures), the team demonstrate how useful these devices could be for future quantum and superconducting computers. The design flexibility and choice of wavelength could also make them important in future sensing applications, highlighting how important these devices could be for our future technologies across various fields.

MEET THE RESEARCHER

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Dr Stefan Koepfli gained his BSc in Mechanical and Process Engineering at ETH Zurich in Switzerland in 2016, followed by his MSc in Process Engineering in 2018, where his research focused on the fabrication and optical characterisation of plasmonic structures for controlling light. He obtained his PhD from ETH Zurich in 2023, receiving a prize for the best thesis in electrical engineering in Switzerland. Dr Koepfli's work focuses on electro-optics and photodetector technology, and how these devices are developed, fabricated in cleanrooms, and characterised. Dr Koepfli now works as a Postdoctoral Researcher within the Institute of Electromagnetic Fields at ETH Zürich, continuing his work on photodetection as the subgroup leader of this research. Dr Koepfli has published numerous papers, including publishing on the world's fastest photodetector to date, and has given many conference presentations, including two presentations in the prestigious post-deadline session at the European Conference on Optical Communication.

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FURTHER READING

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