Atomically-smooth Gold Crystals Help to Compress Light for Nanophotonic Applications

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Highly compressed mid-infrared optical waves in a thin dielectric crystal on monocrystalline gold substrate investigated for the first time using a high-resolution scattering-type scanning near-field optical microscope.

KAIST researchers and their collaborators at home and abroad have successfully demonstrated a new platform for guiding the compressed light waves in very thin van der Waals crystals. Their method to guide the mid-infrared light with minimal loss will provide a breakthrough for the practical applications of ultra-thin dielectric crystals in next-generation optoelectronic devices based on strong light-matter interactions at the nanoscale.

Phonon-polaritons are collective oscillations of ions in polar dielectrics coupled to electromagnetic waves of light, whose electromagnetic field is much more compressed compared to the light wavelength. Recently, it was demonstrated that the phonon-polaritons in thin van der Waals crystals can be compressed even further when the material is placed on top of a highly conductive metal. In such a configuration, charges in the polaritonic crystal are "reflected" in the metal, and their coupling with light results in a new type of polariton waves called the image phonon-polaritons. Highly compressed image modes provide strong light-matter interactions, but are very sensitive to the substrate roughness, which hinders their practical application.

Challenged by these limitations, four research groups combined their efforts to develop a unique experimental platform using advanced fabrication and measurement methods. Their findings were published in Science Advances on July 13.

A KAIST research team led by Professor Min Seok Jang from the School of Electrical Engineering used a highly sensitive scanning near-field optical microscope (SNOM) to directly measure the optical fields of the hyperbolic image phonon-polaritons (HIP) propagating in a 63 nm-thick slab of hexagonal boron nitride (h-BN) on a monocrystalline gold substrate, showing the mid-infrared light waves in dielectric crystal compressed by a hundred times.

Professor Jang and a research professor in his group, Sergey Menabde, successfully obtained direct images of HIP waves propagating for many wavelengths, and detected a signal from the ultra-compressed high-order HIP in a regular h-BN crystals for the first time. They showed that the phonon-polaritons in van der Waals crystals can be significantly more compressed without sacrificing their lifetime.

This became possible due to the atomically-smooth surfaces of the home-grown gold crystals used as a substrate for the h-BN. Practically zero surface scattering and extremely small ohmic loss in gold at mid-infrared frequencies provide a low-loss environment for the HIP propagation. The HIP mode probed by the researchers was 2.4 times more compressed and yet exhibited a similar lifetime compared to the phonon-polaritons with a low-loss dielectric substrate, resulting in a twice higher figure of merit in terms of the normalized propagation length.

The ultra-smooth monocrystalline gold flakes used in the experiment were chemically grown by the team of Professor N. Asger Mortensen from the Center for Nano Optics at the University of Southern Denmark.

Mid-infrared spectrum is particularly important for sensing applications since many important organic molecules have absorption lines in the mid-infrared. However, a large number of molecules is required by the conventional detection methods for successful operation, whereas the ultra-compressed phonon-polariton fields can provide strong light-matter interactions at the microscopic level, thus significantly improving the detection limit down to a single molecule. The long lifetime of the HIP on monocrystalline gold will further improve the detection performance.

Furthermore, the study conducted by Professor Jang and the team demonstrated the striking similarity between the HIP and the image graphene plasmons. Both image modes possess significantly more confined electromagnetic field, yet their lifetime remains unaffected by the shorter polariton wavelength. This observation provides a broader perspective on image polaritons in general, and highlights their superiority in terms of the nanolight waveguiding compared to the conventional low-dimensional polaritons in van der Waals crystals on a dielectric substrate.

Professor Jang said, “Our research demonstrated the advantages of image polaritons, and especially the image phonon-polaritons. These optical modes can be used in the future optoelectronic devices where both the low-loss propagation and the strong light-matter interaction are necessary. I hope that our results will pave the way for the realization of more efficient nanophotonic devices such as metasurfaces, optical switches, sensors, and other applications operating at infrared frequencies.”

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Figure. Nano-tip is used for the ultra-high-resolution imaging of the image phonon-polaritons in hBN launched by the gold crystal edge.

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