Ultrasensitive molecular sensing with synthesize complex-frequency waves

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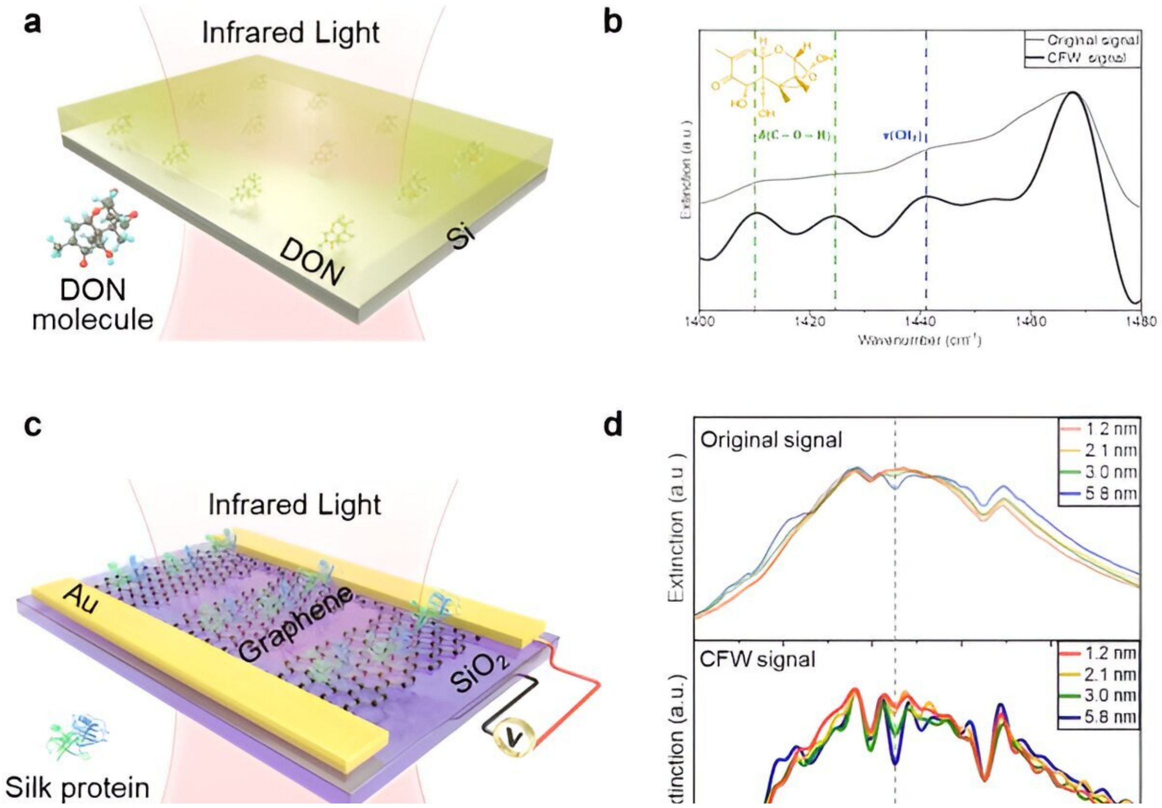

(a-b) Direct detection of multiple vibration modes. (c-d) The detection of silk protein molecular layer based on graphene-based SEIRA sensor; (e-f) The detection of BSA protein solution based on graphene-based SEIRA sensor. Credit: *eLight* (2024). DOI: 10.1186/s43593-023-00058-y

Sensors are essential tools for detecting and analyzing trace molecules in a variety of fields, including environmental monitoring, food safety, and public health. However, developing sensors with high enough sensitivity to detect these tiny amounts of molecules remains a challenge.

One promising approach is surface-enhanced infrared absorption (SEIRA), which uses plasmonic nanostructures to amplify the infrared signals of molecules adsorbed on their surface. Graphene is a particularly promising material for SEIRA because of its high sensitivity and tunability. However, the interaction between graphene and molecules is weakened by intrinsic molecular damping.

In a new paper published in *eLight*, researchers from multiple institutions demonstrated a new approach to improve the sensitivity of SEIRA. This approach employs synthesized complex-frequency waves (CFW) to amplify the molecular signals detected by graphene-based sensors by at least an order of magnitude. It also applies to molecular sensing in different phases.

SEIRA was first demonstrated using Ag and Au thin films. Still, the advancement of nanofabrication and the development of new plasmonic materials have led to plasmonic nanostructures capable of much greater enhancement of biomolecule signals. Compared to metal-based SEIRA, strong field confinement supported by two-dimensional (2D) Dirac fermion electronic states enables graphene-based SEIRA with excellent performance in molecular characterization for gas and solid phase sensing. Graphene can also enhance molecular IR absorption in aqueous solution.

Notably, the active tunability of graphene plasmons broadens their detection frequency range for different molecular vibrational modes by changing the doping level via gate voltage. These advantages make graphene-based SEIRA a unique platform for molecular monolayer detection.

However, intrinsic molecular damping significantly reduces the interaction between the vibrational modes and plasmons. As a result, at very low concentrations, the spectra of plasmon-enhanced molecular signals become very weak and broad, ultimately overshadowed by noise.

One way to compensate for molecular damping is to add optical gain materials. However, this requires a complex setup which may not be compatible with the detection system. In addition, gain materials usually increase instability and noise.

Another possibility is to use complex-frequency waves (CFW); theoretical studies have proved that CFW with temporal attenuation can restore information loss due to material losses. However, producing CFW in real optical systems remains a challenging task.

The researchers propose a new method for synthesizing CFW by combining multiple real-frequency waves. This method has been successfully applied to improve the spatial resolution of superlenses.

The researchers demonstrate that synthesized CFWs can dramatically enhance the molecular vibrational fingerprints in graphene-based SEIRA. They successfully apply synthesized CFWs to improve the molecular signals in the mid-IR extinction spectrum for biomolecules under different conditions, including direct measurement of multiple vibrational modes of deoxynivalenol (DON) molecules and graphene-based SEIRA of proteins in both solid phase and aqueous solution.

This new approach to SEIRA using synthesized CFWs is highly scalable to various SEIRA technologies and can generally increase the detection sensitivity of traditional SEIRA technologies. It could be used to develop ultrasensitive sensors for a wide range of applications, such as early disease diagnosis, personalized medicine, and rapid detection of toxic agents. This approach has the potential to revolutionize the field of molecular sensing, enabling the detection of trace molecules that are currently undetectable.

More information: Kebo Zeng et al, Synthesized complex-frequency excitation for ultrasensitive molecular sensing, *eLight* (2024). DOI: 10.1186/s43593-023-00058-y

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