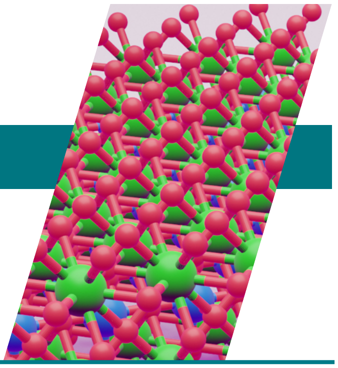
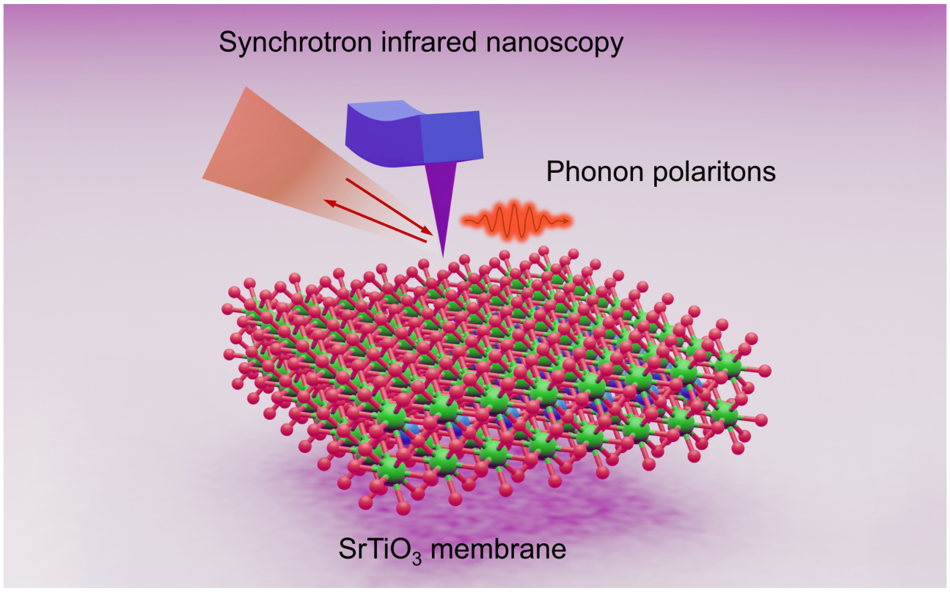
ADVANCED LIGHT SOURCE

MATERIALS SCIENCES

A New Way to "Squeeze" Infrared Wavelengths Down to Size





In this experiment, an atomic force microscope tip focuses broadband synchrotron infrared light onto the surface of a strontium titanate ($SrTiO_3$) membrane, just 100 nm thick. The infrared light excites phonon polaritons—quasiparticles that arise when light strongly interacts with dipole oscillations in the material's lattice. Spectroscopic analysis of the scattered light enabled researchers to determine the properties of phonon polaritons on the material surface.

Scientific Achievement

Using the Advanced Light Source (ALS), researchers demonstrated a new way to confine, or "squeeze," infrared light—far better than the bulk crystals typically used for this purpose—by coupling photons with phonons (lattice vibrations) within a certain type of thin film.

Significance and Impact

The work heralds a new class of optical materials for controlling infrared light, with potential applications in photonics, sensors, and microelectronic heat management.

A light squeeze

Researchers have demonstrated that thin films of strontium titanate ($SrTiO_3$, or STO) can confine, or "squeeze," infrared light 10 times more than its bulk form can—a finding that holds promise for next-generation microelectronic and photonic devices. While this unusual behavior had been theoretically predicted for STO membranes, it had not yet been experimentally observed.

The researchers took advantage of advances in the synthesis of freestanding, large-scale crystalline oxide membranes, then used a combination of infrared micro- and nanospectroscopy to observe how infrared light couples to lattice vibrations in the membranes. They found that the coupling produced hybrid vibrational and electromagnetic waves (phonon polaritons) in the material, with different modes characterized by highly compressed wavelengths or greatly enhanced fields inside the sample.

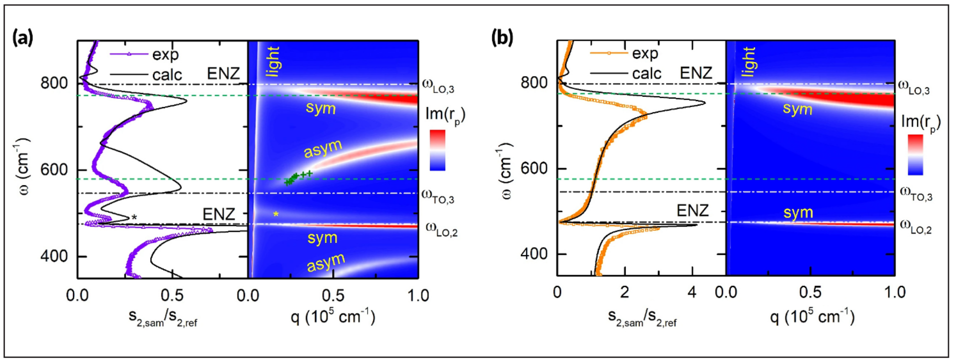
Transferable membranes

Theoretical studies have suggested that ultrathin STO and other perovskite membranes can host highly confined surface phonon polaritons (SPhPs) with good propagation quality. Other compounds may have higher figures of merit, but because they are typically manually exfoliated, their lateral size is constrained to the micrometer range, which limits their potential for large-scale device fabrication.

For this work, the researchers prepared single-crystal membranes of STO, grown on a substrate with a water-soluble buffer layer. When the buffer layer is dissolved, a millimeter-scale STO film just 100 nm thick is released and can be transferred onto arbitrary materials. This approach avoids the problem of lattice mismatches, which can lower membrane quality in heterostructures that are epitaxially grown. Here, the STO membrane was transferred onto a SiO_2/Si substrate partially coated with gold, which allowed direct comparison of SPhP properties on metals versus insulators.

Symmetric-antisymmetric splitting

Using lab-based Fourier-transform infrared (FTIR) spectroscopy, the researchers were able to associate absorption peaks with what's known as a Berreman mode, in which the normal component of the electric field inside the sample is strongly enhanced.



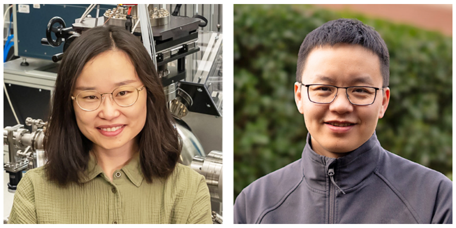
(a) Left panel: SINS spectra (purple symbols) for STO membrane on SiO_2/Si, compared to a model calculation (solid black line). Right panel: Corresponding (calculated) dispersion map showing symmetric and antisymmetric SPhP modes corresponding to the SINS peaks. Green crosses represent experimental data extracted from SINS imaging. (b) Same analyses as in (a), but for the STO membrane on gold.

For further insights, the researchers used synchrotron infrared nanospectroscopy (SINS) at ALS Beamline 2.4 to probe the SPhPs with nanoscale resolution across a wide frequency range. The data revealed a splitting of the SPhP modes into symmetric and antisymmetric branches. These branches result from interactions between SPhPs at the top and bottom surfaces as the membrane thickness decreases. In the symmetric branch, the normal component of the electric field is greatly enhanced. In the antisymmetric branch, propagating SPhPs are highly confined (by a factor of 10 compared to the corresponding bulk mode). Notably, the antisymmetric mode is fully suppressed on the metallic substrate—an important observation for theory and applications. Theoretical modeling fully corroborates the experimental results.

A broader palette of properties

Finally, SINS scans across a sample edge allowed the researchers to extract from the data important SPhP parameters such as momentum, confinement factor, propagation length, and quality factor.

In general, the results open up a broad new class of complex oxide materials that, as transferable membranes, can be easily integrated with other photonic materials to generate SPhPs for light manipulation. The work expands scientists' options for controlling infrared-wavelength light and establishes the enormous potential of transition-metal oxide membranes as building blocks for future long-wavelength nanophotonics.



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