Spatiotemporal imaging of 2D polariton wavepacket dynamics using free electrons

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Coherent optical excitations in 2D materials – 2D polaritons – create a plethora of possibilities for unique optical phenomena that arise from extraordinary dispersion relations which do not exist in regular materials. However, to date, all *dynamical phenomena* of 2D polaritons have remained out of reach – as they require simultaneous spatial & temporal imaging capabilities. These capabilities could reveal unknown coherent optical phenomena in 2D materials, where the extraordinary dispersion promise exotic wavepacket dynamics, such as multi-branch evolution and splitting. Here we present the first spatiotemporal measurement of 2D wavepacket dynamics, from its formation to its decay. We use an ultrafast transmission electron microscope driven by femtosecond mid-infrared pulses to coherently-excite phonon-polariton wavepackets and probe their evolution in a non-destructive manner. Our approach reveals intriguing dispersion-dependent dynamics that includes splitting of multi-branch wavepackets, and unexpectedly, wavepacket deceleration and acceleration. Accessing the full spatiotemporal dynamics of 2D wavepackets can shed light on puzzles in topological polaritons and discover novel nonlinear optical phenomena in 2D materials.

Over the past decade, research on propagating optical polaritons in 2D materials progressed from a promising concept (*1*, *2*) to a platform for demonstrating rich physical phenomena (*3–7*), now showing an impact on emerging opto-electronics (*8*, *9*) and nanophotonic technologies (*10*). These polaritons exhibit relatively low loss and long propagation distances, simultaneous with extreme confinement factors (*5*, *11–14*), facilitating their unique light–matter interactions (*2*, *3*, *15–19*).

Strong motivation exists to utilize the novel properties of 2D polaritons and integrate them into ultrafast optical technologies that rely on the spatiotemporal control of light. Conventional areas of ultrafast optics achieve such control using pulse-shaping (*20–22*) and dispersion engineering (*23–25*), which are instrumental, for example, in photonic waveguides (*24*, *25*). The attainment of similar control with 2D polaritons could promote the integration of 2D polaritonic materials in mature areas of science and technology and contribute to their fundamental understanding. However, the spatiotemporal control of 2D polariton wavepackets has remained out of reach for exactly the same reasons that make their potential applications exciting: they have extremely small wavelengths and are strongly confined inside the material. New capabilities are necessary for accessing the spatiotemporal dynamics of 2D polaritons and their wavepackets, with nanometric spatial resolution and femtosecond temporal resolution.

In this regard, it is particularly interesting to consider wavepackets in materials exhibiting hyperbolic dispersion (*26*, *27*). Owing to this unique dispersion, polaritons in hyperbolic materials show rich physical behavior, ranging from negative refraction (*28*) and subdiffraction imaging (*26*, *29*, *30*) to effective Hawking radiation (*31*). While this is most famously seen in metamaterials, phonon polariton (PhP) excitations in 2D materials also exhibit hyperbolic dispersion (*4*, *32–34*). There, the phononic resonance creates a dispersion relation that contains multiple branches (see Fig. 1(b)), which were shown to be tunable by the 2D material geometry, thickness, and surrounding environment (*4*, *10*, *15*, *30*, *34*), reaching high confinement with relatively low losses, even in room temperature (*11*, *13*). These advances exposed the intriguing spatial behavior of hyperbolic polaritons, and yet, their *rich temporal dynamics* – creating *hyperbolic wavepackets* – has remained unexplored.

The novel physics and surprising dynamics of *hyperbolic wavepackets* can be seen by revisiting the basic concept of the group velocity: the derivative of the dispersion, $\partial\omega/\partial k$, approaches zero in an hyperbolic medium, since the medium supports excitations with (in principle) arbitrarily large momenta. In practicality, the group velocity of PhPs is well defined, given an excitation of a finite bandwidth exciting a specific branch. However, in 2D hyperbolic materials, any coherent excitation is expected to simultaneously stimulate *multiple* PhP

branches, each having different dynamics. Moreover, even a small variation in the excitation's bandwidth/frequency results in a large change of the polariton group velocity and the entire wavepacket propagation dynamics. These prospects are especially intriguing in 2D hyperbolic materials such as thin flakes of hexagonal boron nitride (hBN), where the group velocity of polaritons was shown be as low as c/500 over a relatively wide bandwidth (*35*). To explore these prospects of hyperbolic wavepackets and reveal their novel physics, we need access to the field comprising the wavepacket *during* its evolution inside the 2D material, which necessitates hitherto nonexistent microscopy capabilities.

In this study, we present the first observation of coherent wavepacket dynamics in 2D materials. Specifically, our approach measures the spatiotemporal dynamics of hyperbolic PhP wavepackets inside isotopically pure hBN (^{11}B) flakes (*11*). Our measurement is made possible by exploiting a fundamental interaction: between free electrons and PhP wavepackets. The temporal dynamics is obtained using a pump-probe technique with a mid-infrared (IR) laser pump and a free electron probe in an ultrafast transmission electron microscope (UTEM) *(36–50)*, illustrated in Fig. 1(a). The pulsed free electron penetrates the sample and consequently changes its energy spectrum according to the integrated electric field along its path (inset of Fig. 1(c)). By energy filtering of the post-interaction electron, we reconstruct the image of the PhP wavepacket. The use of laser-driven energy-filtered transmission electron microscopy (EFTEM) was first demonstrated in photon-induced nearfield electron microscopy (PINEM) (*36*, *38*, *40*, *44*). Our approach takes PINEM to the mid-IR range and combines this emerging field with 2D materials for the first time.

We record the PhP wavepacket creation and propagation (Fig. 1(d), and Movies S1 and S2), revealing unforeseen physical behaviors, such as multi-branch wavepacket splitting, acceleration and deceleration. The measured acceleration and deceleration dynamics are especially surprising, as wavepackets conventionally have a *fixed* group velocity. In certain cases, as in the thin hyperbolic hBN flakes in our case, the group velocity is expected to be very slow – indeed, we observed group velocities from c/45 to c/850 – and still, each wavepacket is naively expected to propagate with a fixed group velocity. In contrast with this expectation, we show that the dispersive nature of PhPs (i.e., their momenta change rapidly in frequency) facilitates acceleration and deceleration dynamics. This result serves as a key example for the rich physical phenomena that can be found when probing non-destructively the spatiotemporal dynamics of 2D polaritons using the unique combination of femtosecond temporal and nanometer spatial resolution of the UTEM.

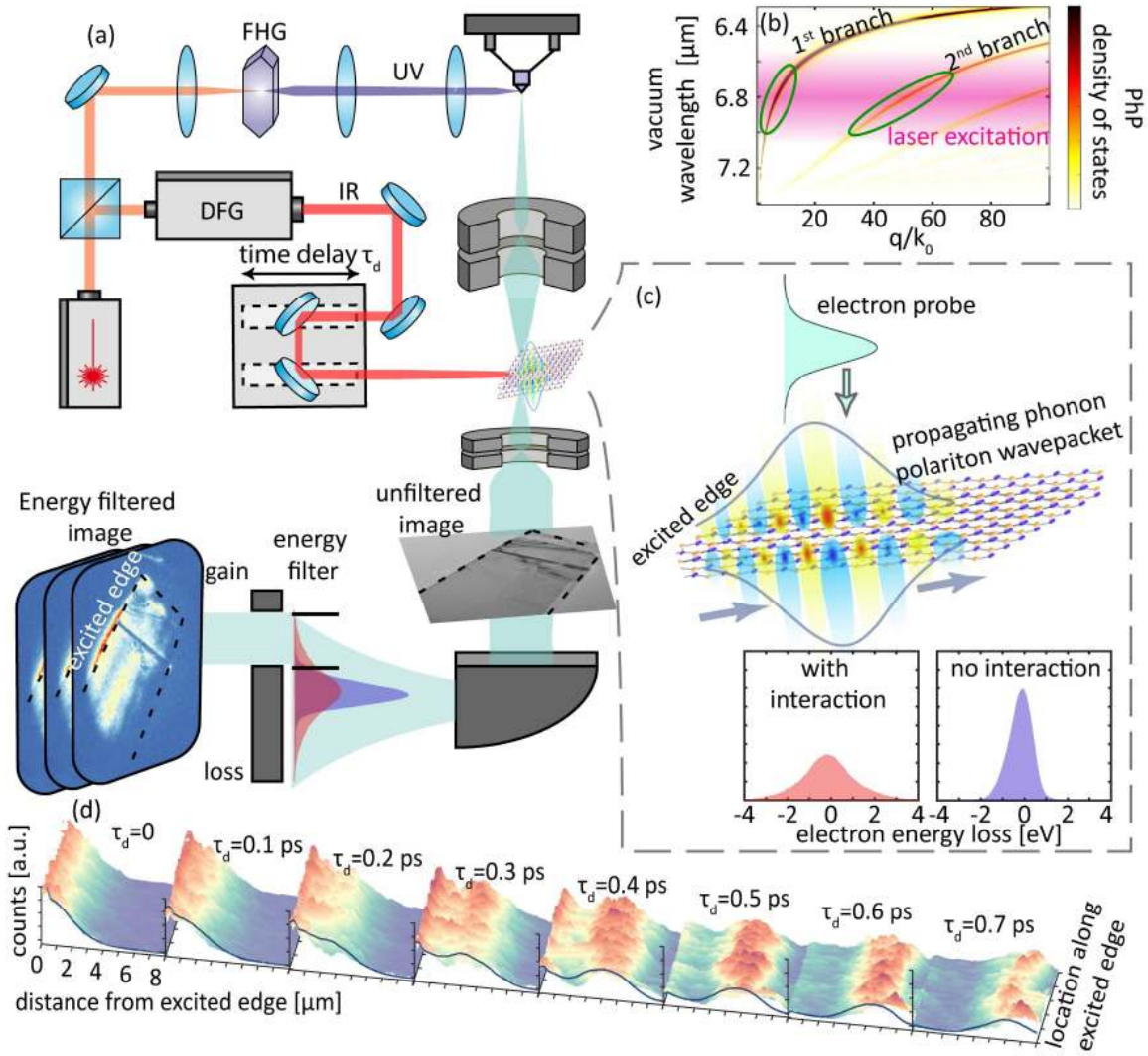

Fig. 1. Direct observation of 2D polariton wavepackets using ultrafast transmission electron microscopy (UTEM). (a) Experimental setup. A femtosecond laser (orange) splits into two branches. The bottom branch is converted into a mid-infrared (IR; red) pulse using difference frequency generation (DFG) and excites the phonon-polariton (PhP) wavepacket in the isotopically pure hBN (^{11}B) sample. The top branch is converted into an ultraviolet (UV; purple) pulse using fourth harmonic generation (FHG) and excites photo-electrically the electron pulse (cyan). The electron images the hBN sample when counting electrons at all energies (unfiltered image) and images the PhP wavepacket when counting only electrons that gained energy (filtered image). **(b)** Dispersion relation of a 55 nm thick isotopically pure hBN (^{11}B) flake on a 20 nm thick Si_3N_4 membrane (for sample-preparation, see Supplementary Materials, SM, section S.2). The hyperbolic nature of hBN creates multiple dispersion branches in each frequency, each creating a different propagating wavepacket. The spectral bandwidth of the IR pulse (pink) excites a range of polariton modes (circled in green). **(c)** Free electron probing the (TM polarized) propagating PhP wavepacket inside the hBN. Insets: electron energy loss spectra (EELS) with the laser on (left) and off (right). **(d)** Measurement of the energy-filtered electrons for different time delays τ_d between the laser pulse and the electron probe, showing the propagation dynamics of the PhP wavepacket (shown in top-view in Fig. S1, and in Movie S1). Note that the definition of τ_d is up to arbitrary shifts in all figures and movies.

Among the various experimental techniques used in the field of 2D polaritons (*51*), the scanning nearfield optical microscopy (SNOM) and its unique variants have had the most impact so far on the direct nearfield imaging of 2D polaritons (*7*, *11*, *12*, *14*, *30*, *32*, *33*, *52*). Recent advances in time-resolved SNOM also allowed the polariton's group velocity to be extracted from the interference of scattered polaritons with different time delays (*35*, *53*, *54*). However, this interferometric technique cannot image the wavepacket dynamics, as it does not provide the spectral phase, i.e., the phase difference between photons of different wavelengths. Other important experimental approaches, such as photo-emission electron microscopy (PEEM) (*55*), are also used for nearfield imaging in plasmonics; these approaches thus far did not access the mid- and far-IR region. We discuss the different experimental approaches in the Supplementary materials (SM), section S.5. Importantly, techniques based on transmission electron microscopy stand out from all the above, since the electron penetrates through the sample and becomes sensitive also to the buried field rather than only to the field on the surface (*44*), an advantage for probing the highly confined 2D polaritons.

Our approach for the observation of PhP wavepacket dynamics contributes to the expanding toolbox of electron-beam spectroscopy and microscopy (*56*). Of particular importance for our approach are the advances in the imaging of polaritons using electron energy loss spectroscopy (EELS) (*57*, *58*), which reached the ability to measure IR excitations in vibrational electron spectroscopy (*59*). EELS enabled the measurement of purely vibrational modes (phonons) in bulk media and on surfaces (*60*, *61*) and the extraction of their dispersion relations using electron imaging and diffraction (*62*, *63*). In recent years, the improvements in the energy resolution of EELS (*59*) enabled the imaging of hBN PhP resonances (*64*) and recently the extraction of the PhP dispersion in extremely thin samples (*65*). Such experiments translated methodologies in electron microscopy, once applied to plasmons in the visible range (e.g., Refs. (*66*, *67*)), to phonons in the mid-IR range. Similar methodologies are key to understanding the nanoscale behavior of mixed photon-matter excitations in different strongly coupled systems (*68*, *69*).

In all these EELS experiments, one obtains static, time-independent information on the polaritonic modes and other excitations of the sample, all of which are triggered by the free electron. In contrast, PINEM-based techniques such as ours use the electron only as a time-dependent probe (and not as a trigger of the excitation); thus, PINEM allows the extraction of time-dependent information on the temporal dynamics of the polaritons that are excited by a separate laser pulse.

Results

Fig. 1(d) and Movie S1 present an example of our experimental results: measurements of the wavepacket during its creation and propagation inside the flake. The video is created by repeating the measurement for a range of time delays between the laser pump and the electron probe. Such measurements of wavepacket dynamics rely on stimulated free-electron–PhP interactions. For the wavepacket, **the electron is a non-destructive probe**: the interaction alters the wavepacket in a *negligible* manner and hence **does not interfere with the wavepacket evolution dynamics**. Thus, the wavepacket propagates across the sample uninterrupted, starting from a single edge (chosen by optimizing the laser coupling – SM section S.3). At each time delay, the wavepacket profile is reconstructed from the electron energy distribution: at points where the PhP's out-of-plane electric field is stronger, there is a larger probability for the probing electron to gain energy and pass an energy filter. The energy filter is chosen to maximize the signal (see Fig. S4); it creates a threshold for the detectable PhP field and thus reduces the signal-to-noise ratio. Consequently, as we describe in the theory below, the connection between the number of counts and the electric field is non-linear.

To model the free-electron–PhP interaction, we find it essential to generalize the single-frequency theory of conventional PINEM (*37*, *70*) that was used to describe most PINEM experiments to date. The need to go beyond the successful PINEM theory lies in the finite bandwidth of the excitation laser (necessary for creating the pulsed PhP wavepacket) that excites the highly dispersive hBN PhPs. To capture the spectral bandwidth, we describe the free-electron–PhP coupling through a generalized coupling function $g(x,y,\omega)$ (*71*). This coupling function g quantifies the strength of the interaction for each in-plane coordinate (x,y) and each frequency ω. According to this continuous-PINEM theory (*71*),

$$g(x,y,\omega)=\frac{e}{\hbar\omega}\int_{-\infty}^{\infty}dz\,E_z(x,y,z,\omega)e^{-i\frac{\omega}{v}z}, \tag{1}$$

where e and v are the electron charge and velocity, respectively, and $\hbar$ is the reduced Planck's constant. The integral is performed along the electron propagation direction z, on the z component of the electric field phasor $E_z(\omega)=\int E_z(t)e^{i\omega t}dt$, which includes all the PhPs modes due to their TM polarization.

The PhP wavepacket is imprinted on the electron as a time-dependent phase modulation:

$$\exp\left(2i\int_0^{\infty}d\omega\,|g(x,y,\omega)|\sin\big(\omega t-\arg\big(g(x,y,\omega)\big)\big)\right). \tag{2}$$

This phase modulation multiplies the initial electron wavefunction with a time delay (τ_d) relative to the PhP wavepacket excitation; τ_d is shifted for recording a video of the dynamics. Our theory predicts the measured electron energy spectra as the Fourier transform (time→energy) of the resulting electron wavefunction. Eq. (2) shows how larger g values imply stronger modulation in the phase of the free-electron wavefunction, equivalent to the electron gaining and losing more energy (see SM section S.4). The energy required for a detectable signal is related to the incoherent energy width of the pre-interaction electron (also called zero-loss peak). Because the width (0.9 eV in our system, Fig. 1(c), right inset) is larger than the energy of a single PhP quanta, the post-interaction EELS (Fig. 1(c), left inset) does not have discrete peaks as in PINEM experiments in the visible or near-IR range (*43*, *47*). Nevertheless, the change in the electron's energy is sufficient for probing the PhP wavepacket: the electron image in the *x*-*y* plane is filtered by energy for different time delays τ_d to extract the PhP spatiotemporal dynamics.

In the analysis of the measured PhP wavepacket dynamics, we first extract the field profile along the direction of propagation (Fig. 2(a)). When averaging the signal along the sample's excited edge, we reduce the signal-to-noise ratio (described in SM section S.3) and find that a Gaussian fitting describes the measured wavepacket quite accurately. This analysis reveals the formation of the wavepacket during the arrival of the excitation pulse. Fig. 2(b) shows an intriguing phenomenon: the wavepacket appears to remain stuck at the edge for a certain time duration and does not immediately propagate away from the boundary. Instead, the wavepacket's width and amplitude gradually increase. Thus, the gradually forming wavepacket increases in amplitude while remaining near the edge. Only toward the end of the excitation pulse (when its tail arrives) does the wavepacket start to move away from the edge more quickly, exhibiting phenomena of acceleration and deceleration that vary between samples and excitation wavelengths. Once the excitation pulse is ended, we can extract the stable group velocities reported below.

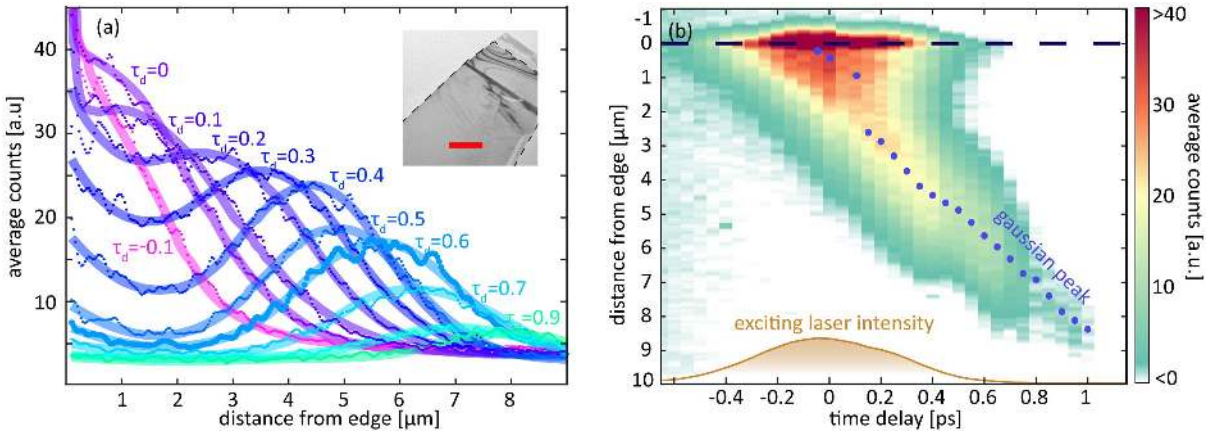

Fig. 2. Direct observation of the phonon-polariton (PhP) wavepacket's spatiotemporal dynamics. (a) Measured signal when averaged along the edge direction (dots) with the fit of a Gaussian profile for each measurement (blue-green curves). Inset: unfiltered image of the hBN flake; the scale bar denotes 5 μm. The times are in units of ps. **(b)** Map presenting the measured wavepacket as a function of time and distance from the edge; blue represents the Gaussian wavepacket peak and gold the laser excitation intensity. At short times, while the laser is still on, the group velocity undergoes changes due to different spectral components arriving at different delays (due to a chirp excitation). In this figure, the time delay $\tau_d = 0$ is related to the peak of the excitation intensity. This measurement uses a 55 nm thick hBN flake, excited by a 6470 nm laser with a bandwidth of 175 nm.

To corroborate these effects of wavepacket dynamics, we present in Fig. 3 the wavepacket properties during its formation, propagation, and gradual decay. Fig. 3 (a-c) summarizes the wavepacket dynamics in three different samples and a range of excitation pulses. As expected, the group velocities become smaller as the sample thickness decreases. The lowest measured group velocity (bright blue in (a)) is 0.35 μm/ps, which is 860 times lower than the speed of light in vacuum. In a thicker sample, the fastest recorded group velocity is 6.7 μm/ps, which is 45 times lower than the speed of light in vacuum, but still sufficiently low for our free-electron probing technique to record the dynamics. An additional notable measurement includes the propagation over a duration of more than 2.5 ps in a 7.5 nm thick sample and propagation lengths over distances of more than 12 μm for a 55 nm thick sample, crossing the entire length of the sample. These extensive propagation distances and durations are a merit of the isotopically pure hBN (^{11}B) (*72*), which encounters smaller losses than normal hBN flakes (*11*).

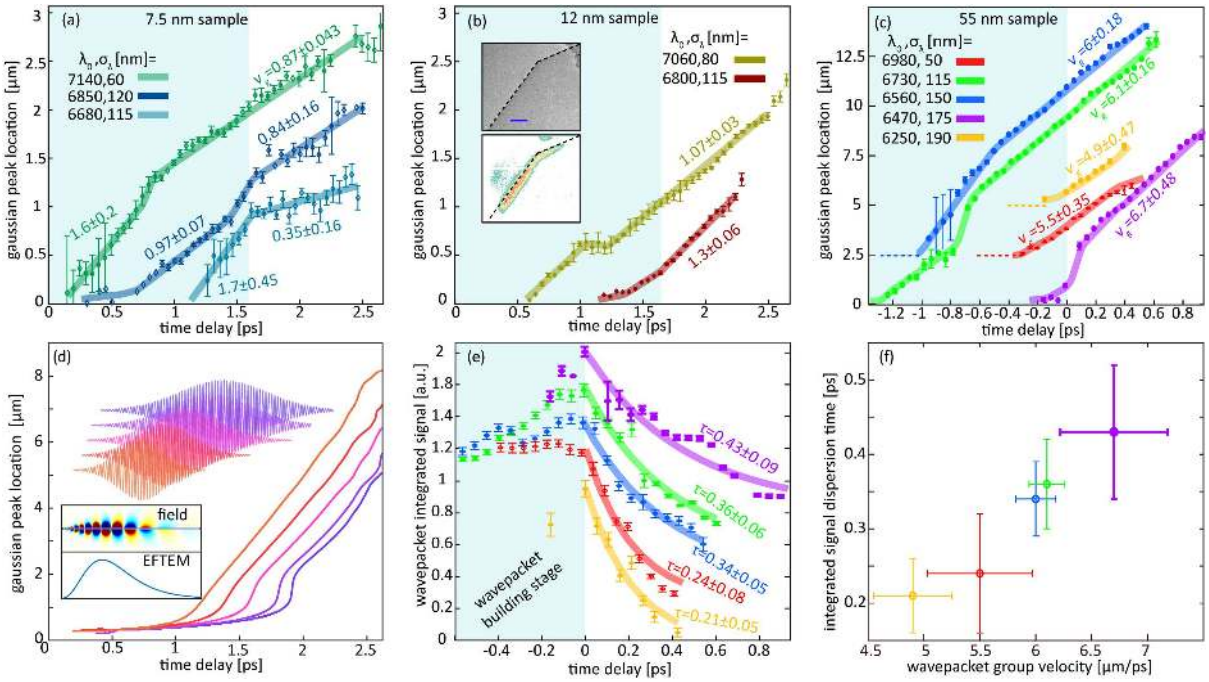

Fig. 3. Analysis of the PhP wavepacket formation, propagation, and decay - extracting the group velocities and wavepacket behavior. (a-c) The fitted Gaussian peak locations as a function of time with the extracted group velocities in units of μm/ps. We compare three $h^{11}BN$ samples having a thickness of **(a)** 7.5 nm, **(b)** 12 nm, and **(c)** 55 nm. The colored background represents the times at which the wavepacket is still being pumped. For clarity, the measurements are shifted in time from one another; also, the dashed horizontal lines in (c) represents that the blue and red curves are shifted in space by 2.5 μm and the yellow curve by 5 μm. Top inset in (b): unfiltered image of the 12 nm sample (dashed lines represent sample edges); scale bar is 5 μm. Bottom inset in (b): an electron energy loss filtered image showing the group at a specific time. **(d)** Simulation results of the wavepacket peak location as a function of time in a 55 nm $h^{11}BN$ sample, comparing different levels of chirp (the excitations' temporal profiles are brought above the curves). The simulations show the acceleration and deceleration observed experimentally. Top inset: the simulated field. Bottom inset: the energy-filtered electron signal calculated using the field from the top inset, showing that the PINEM technique indeed extracts the wavepacket profile. Further simulations of the velocity change can be seen in Fig. S5 and movies S3 and S4. **(e)** Wavepacket integrated signal (derivation in the SM section S.3), which helps identify the transition from a formation stage, in which the pump overcomes the dispersion and intrinsic PhP losses, to the eventual decay (the effective timescales are denoted in ps). **(f)** There is a clear correlation between the dispersion rate and the wavepacket's group velocity, as expected by theory: wavepackets with higher group velocities are less dispersive.

The data show a first demonstration of a dramatic change in the group velocities of PhP wavepackets during their propagation, for which we use the terminology wavepacket acceleration and deceleration. We observed this effect in all sample thicknesses (Fig. 3(a-c)). For example, in the 7.5 nm sample, the group velocity decreased by a factor of 5 (Fig. 3(a)).

This effect is surprising, because the PhP dispersion is expected to cause the slower modes to decay faster, which would result in acceleration rather than deceleration.

We find that this effect reveals a more general S-shaped trajectory for the PhP wavepackets: during the pulse excitation (bright colored background in the panels of Fig. 3), the wavepacket first remains near the edge of the sample (extraordinarily slow group velocity, as explained above), then experiences fast propagation, and finally decelerates to reach its final steady propagation velocity. The first two regimes are related to the chirp of the excitation pulse, which pumps the PhP with different spectral components at different times. The measured phenomena of wavepacket deceleration and acceleration are consistent with the continuous-PINEM analysis of a set of finite-difference time-domain (FDTD) simulations, as shown in Fig. 3(d), Fig. S5, and Movies S3 and S4. The simulations show that when the pulse is longer, and/or when the chirp is stronger, the change in velocity becomes more dominant, in agreement with our measurements.

Our experiment identifies intriguing features of the PhP wavepackets during the wavepacket formation and free propagation. We integrate over the entire observable signal at each time delay to analyze the competition between the laser pumping to the dispersion and decay. We identify two intriguing features in the PhP wavepacket dynamics: (1) We measure the gradual buildup of the wavepacket when the pump overcomes the PhP wavepacket dispersion and intrinsic losses (shown as bright background in Fig. 3(e)). Remarkably, we identify cases for which the integrated signal continues to grow even when the wavepacket peak is already 10 μm from the edge and is propagating at a stable group velocity (green curves). (2) We show that the measured wavepackets disperse and decay at different rates (Fig. 3(e-f)), quantified by a dispersion time τ (Fig. 3(e)). As expected from theory, shorter dispersion times (i.e., larger dispersion) occur for slower group velocities.

The decay in the integrated signal is caused mostly by the wavepacket dispersion (sub-ps timescale) and not by intrinsic loss (few ps timescale). The dispersion-driven broadening reduces the portion of the wavepacket that has a sufficiently large electric field, above the threshold field needed for the electron to pass the energy filter. This measurement threshold (see SM section S.1) improves our signal-to-noise ratio. Our measurement approach allows us to isolate the competition of wavepacket dispersion broadening and decay, which occur simultaneously with the laser pumping.

The efficient electron–polariton interaction enables measurement of the propagation of multi-branch wavepackets that split over time into distinguishable Gaussian-like wavepackets of different group velocities (Fig. 4 and Movie S2). The multi-branch wavepackets are created because the excitation at each wavelength can couple into more than a single branch in the PhP dispersion (Fig. 1(b)). Fig. 4(a) shows the propagation of a multi-branch PhP wavepacket that splits into two single-branch wavepackets, propagating as a double Gaussian (Fig. 4(b)). From the location of the double Gaussian peaks (shown in Fig. 4(c)), we extract two different group velocities for the first- and second-branch wavepackets (6 and 1.1 μm/ps, respectively). We enhanced the observation of this effect by changing the electron energy slit to be sensitive to a smaller threshold electric field. As confirmed by the FDTD simulations in Fig. 4(d-g), at short times the two wavepackets completely overlap. Then, at longer times the wavepackets gradually split from one another. Interestingly, as also confirmed by the FDTD simulation, the PINEM-type measurement shows a clear spatial separation between the wavepackets while their fields still appear to overlap. It is the electron's sensitivity to the field inside the hBN that enables one to distinguish the individual profiles of the two partially-overlapping wavepackets.

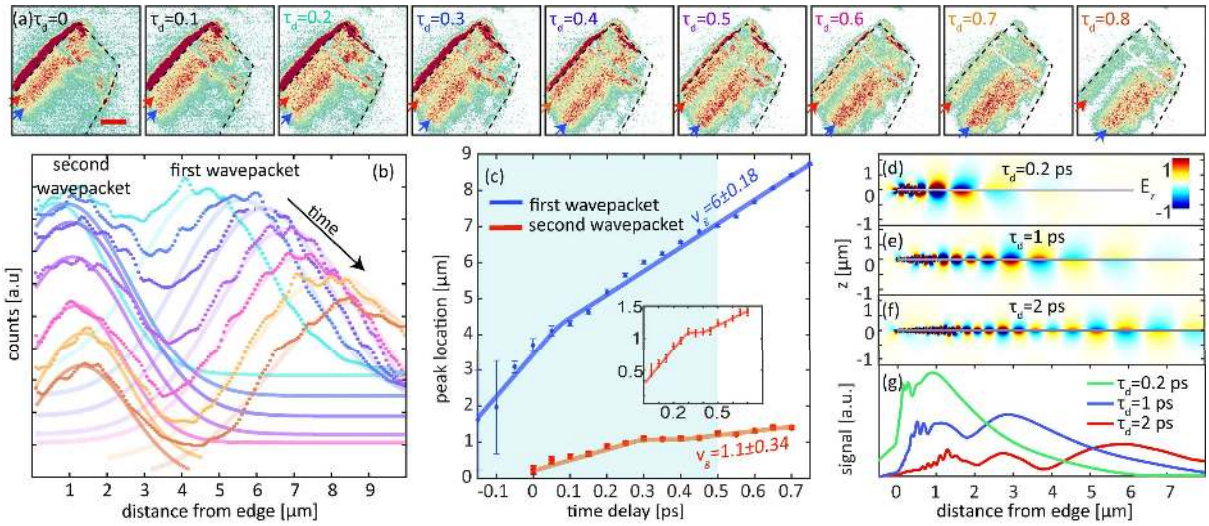

Figure 4: Observation of a multi-branch PhP wavepacket that splits into two distinct wavepackets of different branches and different group velocities. (a) Snapshots at different times of the two wavepackets propagating through the sample, with small blue and red arrows marking the peaks of each wavepacket. **(b)** Measured signal when averaged along the edge (dotted curves) with the double-Gaussian fit for each measurement (solid curves). The data show two distinct wavepackets with different group velocities. The time steps between the curves are 0.1 ps, starting at $\tau_d = 0.2$ ps. **(c)** Locations of the two wavepackets as a function of time, extracting the group velocities in units of μm/ps. The colored background represents times at which the wavepacket is still being pumped, as the excitation pulse has not ended. **(d-f)** Simulated z-component of the electric field at specific times τ_d, showing an example of wavepacket evolution as it splits into multiple individual wavepackets of different orders. **(g)** The energy-filtered electron signal, calculated using the fields from (d-f) and thus extracting

the wavepacket profiles using PINEM. The PINEM signal shows a clear distinction between the wavepacket of the first mode, second mode, and higher modes, similar to the experimental results. Noticeably, the PINEM technique remains sensitive to the higher-order branches, demonstrating its potential for probing polaritons of extreme confinement.

We found that the electron–polariton PINEM interaction remains efficient for polariton wavepackets at higher-order branches. This feature is seen in the experimental data: the first- and second-order PhP branches provide a signal of a similar magnitude (Fig. 4(b)). Our numerical simulations confirmed this surprising result: despite the second-branch having an overall smaller energy (due to less efficient coupling), the PINEM signal is of comparable strength. This result arises from the nature of the interaction, whereby the electron integrates along its trajectory and thus includes the field inside the hBN, which is larger as the field is more confined. Higher-branch modes have larger confinement and thus higher field amplitudes and yet they decay faster along the z direction; thus, the integrated signal remains comparable. Most nearfield imaging techniques probe the surface of the material and are thus essentially less efficient when the goal is to image wavepackets in higher-order branches, since they decay more rapidly along the z direction (the inefficient light out-coupling of the higher-branches reduces the signal further). By using the penetration of free electrons, PINEM-type techniques such as ours bypass these limits, becoming especially advantageous for imaging higher-branch polaritonic modes and highly confined polaritons in general.

Summary and Outlook

Our measurements provided a first observation of the spatiotemporal dynamics of a coherent excitation in a 2D material. By virtue of the direct access to the wavepacket dynamics, we extract several unique phenomena that can be further explored. Our experiments rely on PINEM in the mid-IR range and successfully resolve the PhP wavepackets. The success of the measurement is due to the extremely slow group velocities of PhPs, tens-to-hundreds of times slower than the speed of light, which enables relatively small spatial extents, where the entire wavepacket extends over a few microns along the direction of propagation.

Our work builds on key advances over the past decade in the areas of PINEM, ultrafast electron microscopy, and ultrafast electron diffraction (*39*, *73*). To date, PINEM techniques examined the temporal dynamics of optical excitations by interference patterns of plasmon polaritons (*47*, *48*) and decay of photonic cavity modes (*49*, *50*). In contrast, our experiments resolve the dynamics of the entire optical wavepacket due to the slower group velocities and shorter wavepacket extents of PhPs. The slow group velocity causes the wavepacket envelope

to remain almost static within the duration of the electron interaction (the wavepacket moves only a fraction of a micron during the electron's duration, 0.13 ps standard deviation); thus, we can record the wavepacket dynamics in a way that has not been possible so far. In this manner, our experiment is operated at frequencies that are in between the optical range and the range of mechanical vibrations (typically at GHz frequencies), where the dynamics of phonons was observed thanks to their slow oscillation relative to the duration of the electron probe (*41*, *42*). The PhPs in our experiment differ from these mechanical vibrations by being coherent optical excitations, which are in fact hybrids of the mechanical vibrations (optical phonons) and photons in the IR region. Consequently, the imaging of polaritons in 2D materials utilize advantages from both plasmon imaging (*47*, *48*) and phonon imaging (*41*, *42*).

We envision future experiments in which free electron probes are used for record-high spatial resolution in nearfield optical microscopy, reaching single-nm resolutions and below (considered beyond the reach of conventional nearfield imaging tips used in SNOMs). Single-nm resolutions are of great importance for imaging polaritons of the highest confinement (e.g., Ref. (*65*)), where new physics can emerge, such as the effects of optical nonlocality. The features in the PhP wavepacket in our experiment were not sufficiently small to test this limit. A disadvantage of the current PINEM approach is that the pulsed free electron does not sense the PhP phase since it is averaged-out over the electron pulse duration (~300 fs). To measure the propagating wavepacket phase as in SNOM, one could consider interference between two polaritons(*47*), shorter electron pulse durations, or pre-bunched electrons, which were already shown to reach attosecond timescales in electron microscopes (*45*, *46*). Using attosecond electron probes would open the possibility to measure the dynamics of plasmon polariton wavepackets in the visible range.

Looking forward, the unique optical properties of 2D polaritons can enable many novel phenomena concealed in their dynamics. For example, we could explore diffractionless polariton wavepackets (*7*) or polariton focusing and continuous wavepacket deceleration in cases where the polariton propagates in a flake with a gradually reducing thickness (*74*). The current challenge is to improve the in-coupling of the external laser excitation into the polaritonic mode, which can be overcome by using metallic nano-antennas (*75*) or nanoparticles (*76*) instead of only the sample edge, as in our study. Improved coupling efficiency would also enable the investigation of optical nonlinearities in 2D materials (*77*). A Kerr-like nonlinearity, as found in hBN, incorporates a potential for the observation of spatiotemporal soliton-wavepackets of 2D polaritons and novel forms of 2D shockwaves and light bullets. Spatial optical solitons in Moiré lattices of 2D materials (*78*, *79*) have also recently

become a topic of great interest. The observation of the dynamics of polaritons in such materials can unveil their intrinsic topological nature, such as the one-way dynamics of polaritons that propagate only along the supercell edges. Looking further ahead, the spatial and temporal resolution of the approach we developed, combined with its flexibility in mixing excitation wavelengths, could promote the observation of out-of-equilibrium polaritons and their topological properties (*80*, *81*).

As future free-electron–PhP research avenues, the free electrons can be brought to interact with propagating polaritons in a phase-matched manner by aligning the electron to propagate parallel to the surface (*82*). In such ("aloof") configurations, we expect exceptionally strong interactions and the emergence of the yet unobserved Cherenkov-type phenomena in 2D materials (*83*), potentially reaching nonlocal ultrastrong coupling between polaritons and electrons (*17*).

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