The emergence of spatial and temporal coherence of light emitted from solid-state systems is a fundamental phenomenon intrinsically aligned with the control of light-matter coupling. It is canonical for laser oscillation, emerges in the superradiance of collective emitters, and has been investigated in bosonic condensates of thermalized light, as well as exciton-polaritons. Our room temperature experiments show the strong light-matter coupling between microcavity photons and excitons in atomically thin WSe₂. We evidence the density-dependent expansion of spatial and temporal coherence of the emitted light from the spatially confined system ground-state, which is accompanied by a threshold-like response of the emitted light intensity. Additionally, valley-physics is manifested in the presence of an external magnetic field, which allows us to manipulate K and K' polaritons via the valley-Zeeman-effect. Our findings validate the potential of atomically thin crystals as versatile components of coherent light-sources, and in valleytronic applications at room temperature.
Atomically thin transition metal dichalcogenide crystals (TMDCs) have emerged as a highly interesting material class in opto-electronic\cite{1,2} and nanophotonic\cite{3} applications because of their giant light-matter coupling strength. They are profusely investigated to provide efficient light-to-current converters of great flexibility\cite{4,5}, and are considered as gain-material in micro-and nanolasers\cite{6,7}. However, the strong Coulomb-interactions, which dominate the optical response up to room temperature in those materials, and which make them particularly promising for fundamental studies of many-particle and quantum correlated phenomena, hinders efficient population inversion and compose a serious issue to achieve lasing in the standard (non-excitonic) picture at moderate particle densities\cite{8}.

Fortunately, when embedded in high-quality factor microcavities, the coupling of strongly absorbing and emissive excitonic media can yield the formation of exciton-polaritons, which are composite bosons emerging from strong light-matter coupling conditions\cite{9}. As opposed to uncoupled cavity photons, cavity polaritons do interact efficiently with their environment, and the bosonic final state stimulation of their scattering has been identified as an efficient mechanism for the formation of spatially and temporally coherent states without the stringent requirement of population inversion\cite{9}.

While at thermal equilibrium, such a phenomenon is commonly described in the framework of a Bose-Einstein condensate\cite{10,11}, the kinetic nature of polariton quantum liquids, arising from rapid particle tunnelling out of the microcavity puts the bare formation of coherent states in the polariton laser class\cite{12}. Such devices, thus far, were realised in GaAs and II-VI microcavities at cryogenic temperatures\cite{12,13} and under electrical injection\cite{14}, and realized in GaN\cite{15}, and later in organic\cite{16} and perovskite\cite{17} microcavities at ambient conditions.

Our work tackles the crucial question, whether exciton-polaritons, which are created in an atomically thin crystal sheet of WSe2\cite{18-21} coupled to an optical microcavity, can emit coherent light at room temperature. Indeed, utilizing atomically thin transition metal dichalcogenides in polariton light sources and condensates\cite{22} can pave the way towards a multiplicity of interesting applications and experiments. The locking of spin and valley in those materials profoundly changes optical selection rules, and the resulting chirality can be harnessed in topological nanophotonic applications\cite{23,24}. The possibility of hosting excitons and free carriers of substantial density in one, or multiple monolayers holds big promise towards the study of high-density Bose-Fermi mixtures in polaritonics. Finally, the possibility to expand towards multiple, even rotationally aligned monolayers holds big promise towards the study of high-density quantum correlated phenomena, hinders efficient population inversion and compose a serious issue to achieve lasing in the standard (non-excitonic) picture at moderate particle densities\cite{8}.

In our experiment, we scrutinize density-dependent phenomena in the radiation from exciton–polaritons based on a single WSe2 crystal in a microcavity. While we capture signatures of a polaritonic threshold already at modest pump-powers, the interacting nature of polaritons becomes particularly evident at high pumping conditions where a frequency blueshift depending on the free carrier density in the monolayer is observed. The valley character of our polaritons is evident in magneto-optical measurements, revealing a substantial valley-Zeeman effect. Most importantly, we find a clear onset of spatial coherence in our confined polariton modes, which is retained for a characteristic timescale of 4.5 ps.

Results

Sample and polariton dispersion relation. Figure 1a shows a scheme of the sample structure. The bottom distributed Bragg reflector (DBR) is composed of 10 pairs of SiO2/TiO2 films, and its central Bragg wavelength is 750 nm. The embedded heterostructure consists of a WSe2 monolayer covered by a hexagonal-boron nitride (h-BN) layer, this set is assembled via the deterministic dry-transfer method. The top DBR is deposited via a carefully adapted evaporation routine\cite{25} and consists of 9 pairs of SiO2/TiO2 (see Fig. 1a). We measure a quality factor of 4300 ± 400 (see Fig. S11).

Similar to previous studies on analogous devices, which are detailed in Ref. 27, the WSe2 monolayer under study in this work has a finite size of approximately 10 × 7 µm² (see a dashed area in Fig. 1b). The monolayer flake is surrounded by few-layer areas as well as empty cavity regions that can act as a trap. The geometry of the monolayer area defines the size of the polariton trap.

Throughout this work, we study the sample under ambient conditions with a standard confocal setup, and utilize a continuous wave green laser (setup details are described in the Methods section), focused to a spot of 3 µm diameter.

The angle-resolved photoluminescence (PL) spectrum of our sample is shown in Fig. 1c. The spectrum is recorded under ambient temperature with a standard confocal setup, and utilize a continuous wave green laser (setup details are described in the Methods section), focused to a spot of 3 µm diameter. The angle-resolved photoluminescence (PL) spectrum of our sample is shown in Fig. 1c. The spectrum is recorded under ambient temperature with a standard confocal setup, and utilize a continuous wave green laser (setup details are described in the Methods section), focused to a spot of 3 µm diameter.
To gain a deeper understanding of the mode dispersion, in Fig. 1d, we calculate the dispersion relation of exciton-polaritons by solving the Schrödinger equation for exciton-polaritons in a trap based on realistic system parameters: The energy of the WSe₂ monolayer exciton was experimentally determined to be 1.67 eV, and the energy of the cavity photon is 1.612 eV, as confirmed by transfer matrix calculations. The free parameter of our model, thus, is the Rabi-energy, which we extract from the fit to the experimental data as ~30 meV. The size of the optical trap is 10 × 7 μm², yielding the discretised ground state. By utilizing these parameters, our theory reproduces all experimental features of the ladder-like polariton dispersion and allows us to conclude on the potential depth of ~15 meV (see supplementary material section S1 for further details on the calculation of the polariton dispersion relation). Similar results on polariton trap formation in TMDCs, due to the strong valley dependence and the spectrally resolved DOCP is reproduced in recent publications²⁴⁻²⁸⁻³⁰.

**Magnetic response of room temperature polaritons.** Excitons in WSe₂ monolayers can be formed in the two energetically degenerate K and K' valleys which are locked to opposite spins. In the presence of an externally applied magnetic field, the valley degeneracy is lifted via the valley-Zeeman effect³¹⁻³⁵ resulting in two circularly polarized optical transitions. Consequently, exciton-polaritons formed by valley excitons display an analogous Zeeman energy-splitting under a magnetic field³², which clearly distinguishes them from cavity photons, and which provides a unique control knob in Valley Polaritonics³⁶.

In Fig. 2a,b, the top panels represent the PL intensity distribution map at room temperature under a magnetic field of -8/+8 T, respectively. The corresponding degree of circular polarization (DOCP) is presented in the bottom panels. The confined polariton mode (see dashed grey rectangle) shows a strong valley dependence and the spectrally resolved DOCP is inverted as the magnetic field changes from negative to positive (additional data is shown in Figs. S13 and, S14 in the Supplementary Material, no DOCP is observed at zero magnetic field). Analysing the trapped state within the grey box, in Fig. 2c we present the normalized PL intensities of σ⁺ and σ⁻ emission at -8 T (top) and 8 T (bottom panel), respectively. They clearly show an energy splitting between σ⁺ and σ⁻ emission.

This Zeeman splitting in the trapped state is systematically studied as a function of the applied magnetic field in Fig. 2d. A line with a slope of 0.081 ± 0.004 meV/T fits the experimental data points. From this result, the Zeeman energy splitting can be linked to the polariton g-factor (gpol), following the relation $E_{\sigma^+} - E_{\sigma^-} = g_{\text{pol}}\mu_B B$, where $\mu_B$ is the Bohr magneton and $B$ is the magnetic field strength. Provided the fitted slope of Zeeman splitting vs. magnetic field reported in Fig. 2d, we obtain $g_{\text{pol}} = 1.40 ± 0.07$.

**Density dependent properties of room temperature polaritons.** To assess the fundamental features of our sample throughout the regimes from low to high quasiparticle densities, we study the angle-resolved PL emitted from the lowest energy (trapped) mode as a function of the pump power. In Fig. 3a-c we represent three exemplary dispersion relations at 0.7, 5, and 90 µW, respectively, in three different points of the polariton input-output curve (the acquisition time is 180 s for each pump power). Following the counts in the false-color scale, we observe an increase of polariton PL, predominantly emitting from the trapped state at ~1.61 eV. We integrate the counts around this energy state and we represent its averaged intensity versus pump power in Fig. 3d: the red arrows in this panel indicate the corresponding dispersion relations plotted in panels a-c. The input-output curve clearly displays deviations from the linear trend and features a kink at a pump power of ~1 µW, as well as the reduction of the slope towards larger pump densities, resembling the soft shape of an S. Since our device is operated under strong coupling conditions, the population of the trapped mode needs to be treated in a kinetic model based on the Boltzmann equations, where we consider phonon- and polariton-polariton scattering channels (see Supplementary Material section S2 for further details on the model), as well as the experimentally extracted parameters of our sample. The result of this model is plotted alongside the experimental data, shown as the solid line in Fig. 3d. It corroborates our findings of a smooth S-curve induced by quasiparticle scattering to the final state. We thus attribute this input-output line shape to a signature of the polariton condensation threshold.
Simultaneously, in Fig. 3e we investigate the blueshift (blue, left axis) and linewidth (orange, right axis) of the trapped state versus pump power. The blueshift increases slowly up to a pump power of 40 µW, while a stronger increase up to 0.4 meV is observed in the high-density regime. We argue that the dominant contribution of this blueshift arises from a fermionic screening of excitons by free carriers, which consequently quenches the Rabi-splitting in our system. The accumulation of free carriers in TMDC monolayers subject to optical pumping is a well-documented phenomenon, both at cryogenic and ambient conditions. It occurs over multiple minutes and hours, and hence during the full measurement of the input-output curve. We emphasize, that the resulting energy renormalization, arising from the screening effect, is a clear sign of strong coupling conditions, which cannot be explained for a cavity in the weak coupling regime. Interestingly, we confirm the nature of the charge-induced blueshift by repeating the input-output experiment via reducing the pump power, yielding an ‘inverted’ blueshift of the mode (see supplementary section S3, Fig. S1). The linewidth of the trapped state, which is an indicator for temporal coherence of the system, only features a mild decrease within the measurement accuracy, which calls for a deeper analysis utilizing more sensitive interferometric tools, as we provide later in this work.

In Fig. 3f,g we investigate the linear polarization properties of the trapped state versus pump power. For this study, we place a half-waveplate and a linear polarizer in the collection path, providing the linear polarization dependence of the trapped state as a function of the half-waveplate angle. Figure 3f shows the average intensity of the trapped state (the studied area is indicated in a dashed box in panel c) analyzing its linear polarization, for three pump powers, 5, 30, and 85 µW. The full rotation of the half-waveplate results in four periods of intensity oscillation, evidencing the presence of linearly polarized emission from the trapped state. We extract the corresponding visibility of the oscillations, retrieving the degree of linear polarization (DOLP) for the three different pump powers: 9 ± 2%, 12 ± 2%, 17 ± 1%. Overall, we find a clear enhancement of the DOLP as a function of pump power. This linear polarization predominance in the trapped state is expected from the polariton macroscopic occupation state under strong excitation. The trapped state presents two orthogonally-polarized modes, \( H \) and \( V \). Figure 3g represents the spectra of these modes, revealing a fine structure splitting of 0.40 ± 0.03 meV.

Coherence of room temperature polaritons. In this section, we present the build-up of macroscopic phase coherence in the polariton emission. The degree of spatial and temporal coherence is investigated via interferometric experiments, where the first-order correlation function \( G^{(1)}(r_1, t) \) is experimentally extracted.
Due to the cavity mode emission at higher energies (see dispersion relation in Fig. 1c, cavity modes present at ~1.64 and ~1.66 eV), and the energy discretized polariton modes, we focus our coherence analysis in a one-dimensional slice centered in the sample (see dashed white arrow in Fig. 1b). The polariton emission is interfered with a retroreflected version of itself in a Michelson interferometer. We image the real-space distribution of the interference and we spectrally resolve the marked slice in the spectrometer. In this way, we investigate the energy-resolved coherence of the polariton emission in a one-dimensional slice of the real space emission.

A representative set of images from the interferometric measurement is displayed in Fig. 4b–d. They correspond to the reference arm, the interference at zero temporal delay, and the resulting Fourier-extracted $G^{(1)}$ map, respectively, encoded in a false-color scale (see Methods and Supplementary Material for further details on the interference measurements). The pump power used in this measurement is 90 μW. The PL from the reference arm shows a set of three dominant modes: the polariton ground state (~1.610 eV), a second discrete mode around ~1.62 eV, we detect weak emission features that we attribute to high energy trapped states. One of the interference arm images (region I) is localised in the lowest energy mode, reaching a value of ~0.25.

For a pump power of 90 μW, the $G^{(1)}$ map is localised in the lowest energy mode, reaching a value of ~0.25. Next, we investigate the temporal coherence length of the polariton emission at this same pump power (90 μW). This measurement is done by displacing the delay arm of the interferometer, and recording the resulting interferences for different relative delays between the two interferometric arms. In our analysis, we focus on two different regions I and II indicated with dashed boxes in Fig. 4d. We average the $G^{(1)}$ values in these two regions, yielding the $\langle G^{(1)} \rangle$ dependence in each region versus delay, see Fig. 4e. From a Gaussian fit to the experimental data points, we extract a coherence time of 4.5 (3.6) ps FWHM in the region I (II), which reflects the monochromatic nature of the modes of interest in our study.

Lastly, we investigate the coherence buildup as a function of the pump power in the region I. We fix the interferometer delay at zero and we study the $\langle G^{(1)} \rangle$ values for different pump powers of excitation (see Supplementary Materials for the full maps of interference and $G^{(1)}$ as a function of pump power). In both regions I and II we observe an increase and saturation of $\langle G^{(1)} \rangle$ at high pump power excitation, demonstrating the phase-locking of a collective polariton state at room temperature. This feature clearly distinguishes the polariton condensate from incoherent polaritons in the linear regime. In Fig. 4g we study the coherence length $\lambda_c$ as a function of pump power in the region I. We fit a Gaussian function to the spatial profile of $G^{(1)}$ in the trapped state (region I), and we associate the corresponding coherence length to the standard deviation $\sigma$ of the fit: $\lambda_c = (2\pi)^{1/2}\sigma$. It is interesting to see that at low pump powers, $\lambda_c$ is comparable to the laser spot diameter, and at high pump powers, it reaches...
approximately the size of the polaron trap (see Fig. S9 for further details on the coherence length analysis of the different states in Fig. 4d).

**Discussion**

We have presented the experimental evidence of phase coherence and the Zeeman-splitting of room temperature TMDC polaritons. These two experiments unambiguously prove the polaronic origin of the emission: solely excitonic emission hardly can display extended phase coherence over many micrometres, and purely photonic emission cannot display the Zeeman-splitting. Our density-dependent study of monolayer exciton-polaritons at ambient conditions allows us to conclude that the observed input-output characteristics of the studied structure strongly hint at the formation of a bosonic condensate of exciton-polaritons. The experimental data are in full agreement with a Boltzmann model, which accounts for stimulated photon- and polariton-polariton scattering to the system ground state, which are the two essential prerequisites to obtain a macroscopic population in the polaronic ground state.

Our data suggest that the overall energy renormalization of the trapped polaronic mode is dominated by free-carrier screening, which clearly reflects the polaronic nature of our system. Furthermore, this effect is highly promising for future experiments to scrutinize the complex interplay of bosons and fermions in macroscopic coherent states. The characteristic features of polaron lasing, such as the built-up of linear polarization, and in particular the spatial and temporal coherence induced by the increase of quasi-particle densities are all observed in our system. We highlight, that our room temperature polaron condensates display clear features associated with the intricate valley physics provided by the TMDC monolayer. In our particular case, we scrutinize the valley Zeeman-effect, which enables to tune the polarization and energy structure of our TMDC polaritons, and highlights the promise of coherent polaronic TMDC systems in nanophotonic valleytronic devices.

Our observations certify the realization of the first generation of room temperature polaronic coherent light emitters based on atomically thin crystals. We recently became aware of similar results to the ones reported in this paper, based on WS$_2$-based excitons.**

**Methods**

**Sample fabrication details.** The bottom DBR is composed of 10 pairs of SiO$_2$/TiO$_2$ layers (terminated in a SiO$_2$ layer), purchased from Laseroptics GmbH, with a central reflectivity wavelength at 750 nm. On top of this DBR, and via a deterministic dry-transfer method, we place a monolayer of WS$_2$ (0.8 nm thick), encapsulated with a multilayer of h-BN (5 nm thick). Following the technique described in Ref. 50, the top DBR is deposited via evaporation, consisting on 9 layers of SiO$_2$/TiO$_2$ pairs: the first SiO$_2$ layer (in contact with the h-BN) is 105 nm thick, the next SiO$_2$/TiO$_2$ pairs are 129 and 83 nm thick, respectively, see Ref. 29 for further details. The polaron trap is formed from the reduced dimensions (\(10 \times 7 \mu m^2\)) of the entire area of the exfoliated and deposited WS$_2$ monolayer flake. It is surrounded by areas that are fully unloaded (only hBN) and areas where more than one monolayer is loaded in the cavity (substantially shifting the eigen-energies of the modes, and thus creating a deep trap in the monolayer area).

**Experimental setup details.** The excitation path contains two different light sources: a 532 nm CW laser, and a white light source (Thorlabs SLS301). The sample is mounted on a motorized XYZ stage, model AttocubeECSxy5050/Al/NUM/RT and ECSz5050/Al/NUM/RT. The magnification of the real space imaging is x110 (the first lens on top of the objective). It is surrounded by areas that are fully unloaded (only hBN) and areas where more than one monolayer is loaded in the cavity (substantially shifting the eigen-energies of the modes, and thus creating a deep trap in the monolayer area).

The experimental data are in full agreement with a Boltzmann model, which accounts for stimulated photon- and polariton-polariton scattering to the system ground state, which are the two essential prerequisites to obtain a macroscopic population in the polaronic ground state.

Our data suggest that the overall energy renormalization of the trapped polaronic mode is dominated by free-carrier screening, which clearly reflects the polaronic nature of our system. Furthermore, this effect is highly promising for future experiments to scrutinize the complex interplay of bosons and fermions in macroscopic coherent states. The characteristic features of polaron lasing, such as the built-up of linear polarization, and in particular the spatial and temporal coherence induced by the increase of quasi-particle densities are all observed in our system. We highlight, that our room temperature polaron condensates display clear features associated with the intricate valley physics provided by the TMDC monolayer. In our particular case, we scrutinize the valley Zeeman-effect, which enables to tune the polarization and energy structure of our TMDC polaritons, and highlights the promise of coherent polaronic TMDC systems in nanophotonic valleytronic devices.

Our observations certify the realization of the first generation of room temperature polaronic coherent light emitters based on atomically thin crystals. We recently became aware of similar results to the ones reported in this paper, based on WS$_2$-based excitons.

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Author contributions

The experimental effort was initialized and guided by C.S. and C.A.-S. The experiments were conducted by H.S., L.L., B.H., N.K., M.E. and C.A.-S. The magnetic field measurements were conducted by H.S., J.B. and C.A.-S., and supervised by S.K. and S.H. The data analysis was conducted by H.S., C.S., M.E. and C.A.-S. The TMDC [h-BN] crystals were produced by K.Y. and S.T. [K.W. and T.T.]. The sample was assembled by C.R. and further processed by H.K. and F.E. The theory and simulations were done by E.S., under the supervision of A.V.K. The manuscript was written by H.S., C.S., and C.A.-S., with input from all the co-authors.

Competing interests

The authors declare no competing interests.

Additional information

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