Exciton-polaritons in multilayer WSe$_2$ in a planar microcavity

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Due to high binding energy and oscillator strength, excitons in thin flakes of transition metal dichalcogenides constitute a perfect foundation for realizing a strongly coupled light-matter system. In this paper we investigate mono- and few-layer WSe$_2$ flakes either deposited on or fully encapsulated in hexagonal boron nitride and incorporated into a planar dielectric cavity. We use an open cavity design which provides tunability of the cavity mode energy by as much as 150 meV. We observe a strong coupling regime between the cavity photons and the neutral excitons in direct-bandgap monolayer WSe$_2$, as well as in few-layer WSe$_2$ flakes exhibiting indirect bandgap. We discuss the dependence of the exciton’s oscillator strength and resonance linewidth on the number of layers and predict the exciton-photon coupling strength.

I. INTRODUCTION

The possibility to engineer multilayered structures using two-dimensional (2D) van der Waals materials allows to construct new artificial crystals of designed functionalities [1] with strong application potential in photonics and opto-electronics [2], including, especially, the areas of photo-detectors, ultrathin-film photovoltaic devices, light emitting diodes and lasers [3–7].

Optical properties of monolayer (ML) transition metal dichalcogenides (TMDs) are widely explored as they are dominated by particularly strong exciton resonances stable up to room temperatures [8, 9]. This is a consequence of their direct bandgap in contrast to few-layer and bulk form that exhibit indirect optical transitions [10–12]. These properties make ML TMDs interesting for coherent light sources [13–16] and light-matter interactions which demand narrow-resonance oscillators [17, 18].

For ML, the lowest energy transition occurs between the band-edge states at $K^\pm$ points of the Brillouin zone, which are mostly composed of the transition metal atom orbitals: $d_{x^2-y^2}$ or $d_{xy}$ orbitals in the valence band (VB) and $d_z^2$ orbitals in the conduction band (CB). Starting from the bilayer, an indirect transition between the band-edge states at the $\Gamma$ point in the VB and the Q point in the CB appears, as those states are partially composed of $p_z$ orbitals of chalcogen atoms, which overlap significantly between the layers [19–21].

For a long time the indirect bandgap of multilayer TMDs was considered as a drawback in construction of opto-electronic devices due to low emission rate and poor quantum efficiency. However, compared to ML, multilayers of TMDs have also several advantages as they possess larger optical density of states and exhibit higher absorbance as well as longer exciton lifetimes [22]. It is also possible to tune the bandgap and carrier type in FET devices through control over thickness [23].

In this work, we explore high optical absorbance of multilayer TMDs and demonstrate strong light-matter coupling between the cavity photons and neutral excitons in multilayer WSe$_2$ placed in a tunable, planar optical resonator. Multiple works have already demonstrated the strong coupling regime for excitons in TMD monolayers incorporated into various types of planar optical cavities [24]: dielectric [25], tunable [26, 27], metallic [28], semiconductor–metallic [29], but all of them were entirely focused on direct-bandgap ML flakes or MLs separated by thin hexagonal boron nitride (hBN) flakes [30]. Here we report on the observation of strong coupling regime between photons confined in a planar cavity and neutral excitons in ML as well as in few-layer-thick WSe$_2$ flakes. Starting from the bilayer WSe$_2$ the bandgap becomes indirect, but the absorption at direct excitonic resonance is efficient enough to allow for creation of strongly coupled light–matter states. The exciton–photon coupling strength reaches even higher values for multilayers than for a ML due to increased thickness of TMD material. Our findings are well reproduced by calculations done within the framework of a transfer matrix method, where parameters of the excitonic resonances in WSe$_2$ are determined based on the analysis of reflectance spectra of the flakes deposited directly onto the bottom distributed Bragg reflector (DBR).

II. RESULTS

We investigated 1ML- to 4ML-thick WSe$_2$ flakes embedded in an open, tunable dielectric cavity schematically shown in Fig.1(a). The cavity consists of two dielectric distributed Bragg reflectors (DBRs), each made of 5 pairs of SiO$_2$/TiO$_2$ layers with maximum reflectance at 723 nm (1.715 eV), chosen specifically to match the energy of the A exciton in monolayer WSe$_2$ encapsulated in

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FIG. 1. (a) Scheme of a tunable cavity with few-layer flakes of WSe$_2$ encapsulated in hBN. (b) Microscopic image of investigated WSe$_2$/hBN and hBN/WSe$_2$/hBN heterostructures deposited onto a distributed Bragg reflector (DBR). (c) Amplitude image obtained with the help of an atomic force microscope operated in the tapping mode, revealing the difference in surface roughness between the DBR and hBN. (d–f) Angle-resolved reflectance spectra of hBN/WSe$_2$/hBN heterostructures with 1ML- to 4ML-thick WSe$_2$ flakes shown in (b) embedded in a dielectric cavity. White dashed lines mark fitted upper and lower polariton dispersion relations given by a coupled oscillators model with energies of the uncoupled excitonic and photonic modes drawn with purple dashed lines.

WSe$_2$ flakes were mechanically exfoliated from a nominally undoped bulk crystal purchased from HQ Graphene. Selected flakes of 1 to 4ML thickness were then transferred onto approx. 183nm thick (see Fig.S1 Supplementary Materials) hBN flakes previously deposited on top of the bottom DBR. Thickness of the bottom hBN flakes was chosen to obtain the local maximum of electric field standing wave inside the final full cavity at the position of the WSe$_2$ flakes to assure most efficient exciton-photon coupling conditions (see Supplementary Materials for details). The hBN capping layer covering WSe$_2$ was much thinner, approx. 10nm. Fig.1(b) presents the image of the investigated WSe$_2$ flakes under an optical microscope. hBN encapsulation allows to significantly reduce inhomogeneous broadening leading to linewidths approaching radiative decay limit [32, 33]. It also allowed for the demonstration on number of excitonic complexes in WSe$_2$ and the observation of excited exciton complexes [34] or identification of charged biexciton complexes [35–38]. Overall, the influence of the encapsulation is still under investigation [39], but hBN provides isolation of the electrostatic disorder at the SiO$_2$ interfaces. hBN acts also as an atomically flat substrate for the flakes. Comparison of surface roughness of the DBR and the hBN flake deposited on DBR measured by atomic force microscopy is shown in the inset of Fig.1(c).

The full cavity, presented in Fig.1(a), is formed by covering the structure with another DBR. We performed angle-resolved reflectance measurements at 5K revealing strong coupling regime between cavity photons and excitons in all 1 to 4 ML thick WSe$_2$ layers, as presented in Fig.1(d–f). In an angle-resolved experiment the cavity photon energy (Ph) depends quadratically on in-plane wavevector, which is proportional to the emission angle. Strong coupling regime of the cavity mode with exciton
resonances in thin WSe$_2$ layers ($X_i$) is revealed by the appearance of two anticrossing lower and upper polariton branches (LP and UP), with dispersion relations well described by a two coupled oscillators model [dashed white lines in Fig. 1(d–f)].

The energy of photon confined in the cavity was tuned by smooth change of the distance between the mirrors [40]. Experimentally, it was realized by placing one of the mirrors on a piezoelectric stage and applying an external bias. Reflectance spectra at normal incidence for variable electrical bias applied to the piezoelectric chip taken at the position of WSe$_2$ flake are presented in Fig. 2. By applying the voltage the distance between the DBRs decreases, which results in the increase of the cavity photon energy. When the mode approaches the energy of excitonic resonance in a given WSe$_2$ flake, a clear anticrossing behaviour can be observed. The minimal energy separation between the modes is equal to the coupling strength $\Omega$, also referred as vacuum field Rabi splitting. Observed coupling strength increases with number of the WSe$_2$ layers, as shown in Fig. 3.

The coupling strength between photonic mode of a planar cavity incorporating an active layer with excitonic resonances can be in general well approximated by [41, 42]:

$$\Omega = 2\sqrt{\frac{fd}{L n_c^2}} - \frac{1}{4} (\gamma_{ph} - \gamma_X)^2,$$  \hspace{1cm} (1)

where $L$ is the effective cavity length, $n_c$ is cavity refractive index and $f$ is proportional to the exciton oscillator strength in a layer of a thickness $d$. The coupling strength given by eq. (1) can provide an upper limit for Rabi splitting. For $\gamma_X = \gamma_{ph} = 0$ one can expect an increase of the coupling strength proportional to the square root of the active layer thickness, as plotted by a solid line in Fig. 3. In our experiment we observed slower increase of the coupling strength with number of WSe$_2$ layers than are given by described here upper limit, derived for monolayer. According to the equation (1) such behaviour can be caused by two factors: change of the exciton resonance width or decrease of the exciton oscillator strength for multilayer WSe$_2$ in comparison to the monolayer.

To evaluate the influence of both of these factors we performed reflectance contrast (RC) and photoluminescence (PL) measurements without the top DBR. RC spectra were taken for each WSe$_2$ flake and are presented in Fig. 4. The spectra are dominated by a dip around 1.71 eV, corresponding to the absorption of a neutral free exciton formed at the $K^\pm$ valleys, i.e. so-called A exciton [9]. For a monolayer, this excitonic transition is also observable in PL spectra, which furthermore is dominated by a broad band attributed to the so-called localised excitons [43–46]. With the increase of WSe$_2$ layer thickness the energy of the excitonic resonance observed in RC slightly decreases and broadens, with the most significant difference occurring between monolayer and bilayer. For WSe$_2$ thicker than the monolayer, as the bandgap changes from direct to indirect, the transitions related to the A excitons are not observed in the PL spectra. For

FIG. 2. Reflectance spectra at normal incidence for the cavity mode energy tuned by voltage applied to the piezoelement for: (a) 1 ML, (b) 2 ML, (c) 3 ML, (d) 4 ML WSe$_2$ flakes encapsulated in hBN.
2 MLs, the observed emission occurring at around 1.53 eV is related to the indirect bandgap transitions [43].

The high optical quality of hBN encapsulated flakes allow to observe in RC the first excited exciton states, i.e. 2s [34, 47–49], shown in the insets in Fig.4(a). Their energy separation from the main absorption line significantly decreases with a number of layers, due to the expected decrease of the binding energy of the neutral exciton [47].

To extract both exciton oscillator strength and exciton resonance linewidth, RC spectra were fitted using transfer matrix method. RC was calculated based on simulated reflectance of the DBR and the DBR with a corresponding WSe₂ layer encapsulated in hBN. The exciton resonance was introduced as a dielectric function of the WSe₂ layer given by a Lorentz model in a form given by:

$$\varepsilon_{WSe_2}(E) = \varepsilon_0 - \sum_i \frac{f_i}{E_i^2 - E^2 - i\gamma_i E}, \quad (2)$$

where i describes the excitonic ground state and the first excited 2s state. Dielectric constant away from the resonances was taken as $\varepsilon_0 = 16$ [50]. Depending on a number of monolayers, WSe₂ thickness was taken as a multiplication of the width of single layer equal to 0.65 nm [51]. Transfer matrix model was fitted directly to the experimental RC spectra with $f_i$, $E_i$ and $\gamma_i$ as a fitting parameters. Fitted curves are presented by color lines in Fig.4. All fitting parameters are also summarised in Tab.1. Fig.4(b) presents energies of excitonic resonances for different thickness of WSe₂ encapsulated in hBN. The ground state energy is almost independent of the layer thickness, whereas the energy of the excited exciton state significantly decreases. For the monolayer the 2s state is 130 meV above the ground state and for the tetra-layer such energy difference decreases to 61 meV. Also the exciton oscillator strength [see Fig.4(c)] for the ground state decreases slightly with a number of layers. For the excited exciton states the oscillator strength is 19 to 14 times smaller than for the corresponding ground state with no evident dependence on the number of layers.

It is worth to mention that due to the low oscillator strength of the excited 2s exciton state, we do not observe a strong coupling regime at this transition, as shown in Fig.S8, although coupling with excited exciton states are recently of interest due to high optical nonlinearities [52, 53]. The 2s exciton-polariton is expected to occur with $\Omega = 3.2$ meV in our structures (see Fig.S9), which is much lower than the linewidth of the 2s resonance [see Fig.4(c)].

The exciton resonance linewidth determines the optical quality of the layers and is usually affected by homogeneous and inhomogeneous contributions. For both, the ground state and the excited 2s state, the spectrally narrowest transition occurs in monolayer. For bilayer the linewidth increases over two times, and then is almost constant for 3 and 4 ML thick layers. Starting from the 3 ML thick flakes, the excitonic resonances reveal a double structure. Appearance of such fine structure can be explained by the hybridisation of the valence and conduction bands in TMD layers (>1 ML), as has already been observed for multilayers of WS₂ deposited on Si/SiO₂ substrate [12] and of MoS₂ encapsulated in hBN [54, 55].

Exciton properties obtained from the RC measurements of the WSe₂ layers deposited on the DBRs were used to simulate their behaviour inside a full cavity structure, as presented in Fig.5. We used transfer matrix (TM) method to simulate reflectance at normal incidence from a whole structure consisted of two DBRs with WSe₂ encapsulated in hBN for variable spacing between the mirrors. Calculations well reproduce the experimental reflectance maps from Fig.2. The exciton–photon coupling strength was extracted from the reflectance maps as a minimum energy distance between the two polaritonic branches, and is included in Fig.3. The TM simulations slightly underestimate the coupling strength, but properly reconstruct the trend of increasing coupling strength with thickness of WSe₂.

Observed here increase of the coupling strength should not be confused with similar trend in plasmonic cavities [56–58]. In that case, resonant electric field is polarised perpendicularly to the flakes plane, which leads to ineffective coupling with excitons in thin TMDCs layers with in-plane oriented dipole moment [59].

III. SUMMARY

In summary, we demonstrated strong coupling regime in a planar optical cavity with excitons in multilayer WSe₂. We investigated flakes encapsulated in hBN as well as unprotected ones. The strong coupling is observed regardless the crossover from direct to indirect
FIG. 4. (a) Reflectance contrast (RC) and photoluminescence (PL) spectra of WSe$_2$ multilayers without a cavity at 5 K. Experimental RC spectra are marked with gray lines, whereas color lines represent the fitted TM model. Fitting parameters of ground and first excited exciton resonances in multilayer WSe$_2$: (b) energy positions, (c) oscillator strength and (d) linewidth.

FIG. 5. Transfer matrix simulations for variable distance between the DBR mirrors with (e) 1 ML, (f) 2 ML, (g) 3 ML, (h) 4 ML WSe$_2$.

bandgap occurring for transition from a monolayer to thicker flakes of WSe$_2$. Observed coupling strength increased with thickness of an active WSe$_2$ layer despite the decrease of excitons oscillator strength at the $K$ points for multilayer WSe$_2$, which proves that multilayers can be well adopted to operate in the strong light-matter coupling regime with strong absorption at polariton modes. By changing the number of WSe$_2$ layers and controlling the distance between Bragg mirrors we were able to tune energies of crystal’s eigenstates: exciton-polaritons. Re-
TABLE I. RC fitting parameters for WSe$_2$ deposited on the DBR encapsulated in hBN with modeled exciton-photon coupling strength in dielectric cavity (abbrev. model) compared with the values obtained experimentally (abbrev. exp.).

| Layer (ML) | $E_{1s}$ (eV) | $f_{1s}$ (eV$^2$) | $\gamma_{1s}$ (meV) | $\Omega_{1s}^{\text{model}}$ (meV) | $\Omega_{1s}^{\uparrow\downarrow}$ (meV) | $E_{2s}$ (eV) | $f_{2s}$ (eV$^2$) | $\gamma_{2s}$ (meV) |
|-----------|--------------|-----------------|-------------------|-------------------------------|---------------------------------|------------|----------------|-------------------|
| 1 ML      | 1.7128       | 1.23            | 7.2               | 21.9                          | 24.5                            | 1.8426     | 0.065          | 4.8               |
| 2 ML      | 1.7059       | 1.30            | 20.0              | 28.7                          | 30.5                            | 1.8122     | 0.090          | 20.8              |
| 3 ML      | 1.7055       | 1.07            | 16.7              | 33.0                          | 35.0                            | 1.7713     | 0.068          | 15.2              |
| 4 ML      | 1.7036       | 1.03            | 19.5              | 36.9                          | 36.1                            | 1.7632     | 0.072          | 19.4              |

Recently, it was demonstrated that excitons polaritons can be coupled to the emission of a semiconductor quantum well [29, 60], or organic dye [27] forming hybrid TMDs-semiconductor-light states. Although indirect transitions presented in this paper would decrease efficiency of such emission, it shows potential route towards engineering of hybrid TMDs eigenstates.

METHODS

All optical measurements were performed with samples placed in a cryostat at the temperature of 5 K. PL signal was excited nonresonantly with 514.5 nm (2.41 eV) laser beam. The excitation power, measured before the entrance of microscope objective, was equal to 100 µW and focused in approx. 1 µm spot. For reflectance and RC measurements a broadband halogen lamp was used with a spot size of approx. 5 µm.

Investigations of the cavity structures were performed with angular resolution, which was executed by imaging of the Fourier space of high numerical aperture ($NA = 0.55$) microscope objective. Data shown in Fig. 2 corresponds to reflectance at normal incidence, selected from angle-resolved spectra.

Strong light-matter coupling regime and formation of exciton-polariton modes from 1 to 6 ML thick WSe$_2$ flakes, which weren’t hBN encapsulated, can be found in supplementary material.

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Supplementary information for Exciton-polaritons in multilayer WSe$_2$ in a planar microcavity

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I. hBN CHARACTERISATION

To ensure the most effective light–matter coupling the WSe$_2$ layer should be positioned at the antinode of the standing wave of the electromagnetic field inside the cavity. For cavity without hBN such requirement can be fulfilled when DBRs are ending with lower refractive index material: SiO$_2$. Using the same DBRs for encapsulated WSe$_2$, lower hBN layer should have optical thickness of $\lambda_0/2$. For the excitonic transition in monolayer WSe$_2$ at approx. 710 nm and hBN refractive index of 2.1 [1], this corresponds to approx. 170 nm.

The exfoliated hBN flakes with comparative thickness were transferred to the DBRs. Images of the transferred hBN with the corresponding height profiles measured by AFM are presented in Fig. S1.

II. EMPTY CAVITY

Reflectance from a tunable cavity without active WSe$_2$ flakes is presented in Fig. S2. Measurements were taken from the position of 183nm thick hBN layer. All of the measurements of the cavity structures were angle-resolved. Fig. S2(a) shows reflectance maps obtained at two different electric biases applied to the piezoelectric chip, which was used to tune the distance between the mirror. Full tunability range for voltages 0–150 V is shown in Fig. S2(a), which presents reflectance at normal incidence. Data for incidence perpendicular to the cavity plane was selected from the angle-resolved maps. The cavity mode resonance energy shifts over 150 meV linearly with voltage.

In Fig. S2(c) the experimental position and linewidth of the cavity mode is compared with transfer matrix simulations. The air-gap thickness taken for simulations were extracted from the experimental energy position of the cavity mode. Reflectance deep linewidth, at the order of 5 meV, is almost constant up to 110 V, and slightly increases for thinner cavity. This behaviour is consistent with transfer matrix simulations marked by blue line in Fig. S2(c), but the calculated linewidths are slightly lower than is observed experimentally. Such broadening of experimental results can be explained when the mirrors forming the cavity are not perfectly parallel. Measuring reflectance with a 5 µm Gaussian spot we average over such area. This averaging can be taken into account in transfer matrix simulations with assumption, that the distance between the mirrors doesn’t have a finite value, but rather is a random variable. Calculations performed for the intermirror distance described by a normal distribution with a small dispersion $\sigma$ equal to only 1 nm, shows better agreement between linewidth observed in the experiment and the model [purple line in Fig. S2(c)].

Fig. S2(d)] presents reflectance spectra given by such modified for broadening model for different values of the dispersion of the normal distribution.

III. CAVITY WITH WSe$_2$ FLAKES: COMPARISON WITH THE MODEL

Fig. S3 shows side by side comparison between experimental and the transfer matrix model. Optical parameters of multilayer WSe$_2$ flakes were obtained by fitting to the reflectance contrast spectra, as described in the main text.

IV. WSe$_2$ FLAKES WITHOUT hBN ENCAPSULATION

As a reference we prepared another sample with WSe$_2$ flakes without hBN encapsulation. Those 1 to 6 ML thick flakes were deposited directly onto a surface of a identical DBR, as described in the main text. Performed reflectance contrast (RC) and photoluminescence (PL) measurements of the on top mirror are presented in Fig. S5(a).

For the WSe$_2$ monolayer the RC spectrum measured in the vicinity of the optical bandgap, consists of a single narrow deep at 1.753 eV, corresponding to the absorption of a neutral free exciton (so-called A exciton) [2]. For the bilayer, the absorption transition is observed at lower energies and significantly broadens. Starting from the 3 ML thick flakes, the related resonances reveal a doubled structure. Appearance of such fine structure can be

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explained by the hybridisation of the valence and conduction bands in TMD layers (>1 ML), as has already been observed for multilayers of WS\textsubscript{2} deposited on Si/SiO\textsubscript{2} substrate [3] and of MoS\textsubscript{2} encapsulated in hBN [4, 5].

For monolayer, the PL spectrum is dominated by a broad band attributed to the so-called localised excitons [6–8]. The inset in Fig. S5(a) shows a weaker peak at higher energies, which is associated with the emission of free neutral A excitons. Its energy coincides with the energy of the corresponding A resonance apparent in the RC spectrum. The emission energy and intensity decrease significantly for thicker WSe\textsubscript{2} flakes, as the bandgap change from direct one for the ML to indirect one in multilayers. For the 2 and 3MLs, the observed emission occurring correspondingly at around 1.55 eV and 1.42 eV is related to the indirect band gap [6].

V. FLAKES DEPOSITED ON hBN WITHOUT CAPPING LAYER

We investigated also two additional monolayer and a bilayer WSe\textsubscript{2} flakes isolated from the DBR by hBN, but without the thin covering hBN flake. Photoluminescence and reflectance contrast spectra without the top mirror are shown in Fig. S8 for monolayer and in Fig. S9 for bilayer. Optical properties of those flakes, like linewidth and emission intensity, are similar to the fully encapsulated WSe\textsubscript{2}. The excitonic transition energies are in between dielectric-screened encapsulated flakes and the deposited directly on the DBR. 2s excited exciton transitions are not observed in the reflectance measurement.

VI. COUPLING WITH 2s EXCITON STATE

Tuning the cavity mode to the 2s exciton resonance energy visible on reflectance contrast spectra for encapsulated monolayer flake does not reveal any sign of coupling due to low value of oscillator strength of this transition. For the cavity mode energy crossing the 2s exciton resonance energy no sign of anticrossing or mode linewidth broadening is observed, as shown in Fig. S10. No sign of coupling can be seen also at angle resolved spectra shown in Fig. S10(a,b).

Such observation is consistent with the transfer matrix simulations. Fig. S11(a) shows calculated reflectance spectra for zero detuning between the cavity mode and a 2s exciton state for different values of oscillator strength. For the value determined by the fitting to the reflectance contrast measurement, simulated reflectance spectra can be well described by a sum of two Lorentz functions, but with the distance between them lower than their widths.

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FIG. S1. Characterization of hBN layers. (a) Microscopic image of DBR surface with deposited exfoliated hBN. Marked regions were investigated using AFM and are presented in (b). (c) Height profiles along straight lines marked in (b).

FIG. S1. Characterization of hBN layers. (a) Microscopic image of DBR surface with deposited exfoliated hBN. Marked regions were investigated using AFM and are presented in (b). (c) Height profiles along straight lines marked in (b).
FIG. S2. Tunable cavity with 183 nm thick hBN layer. (a) Angle-resolved reflectance spectra at two different voltages applied to the piezoelectric actuator. (b) Tuability of the cavity at normal incidence [range between the dashed lines in (a)]. (c) Experimental values of cavity mode energy and reflection deep linewidth change with bias applied to the piezoelectric chip (points) compared with transfer matrix simulations for decreasing air gap thickness (lines). Blue line shows linewidth for a perfectly parallel mirrors. Purple line marks simulation with assumption that the distance between the mirror is a random variable described by normal distribution with a dispersion $\sigma = 1$ nm. (d) Simulations of normal incidence reflectance from the cavity where the distance between the mirrors is given by normal distribution with mean value of 300 and given dispersion $\sigma$. 
FIG. S3. hBN-encapsulated WSe$_2$ few-layer flakes in tunable cavity. Experimental reflectance maps for normal incidence for tuning the cavity with voltage applied to the piezoelement with: (a) 1ML, (b) 2ML, (c) 3ML, (d) 4ML WSe$_2$ encapsulated in hBN. All of the measurements were performed at 5K. Transfer matrix method simulations for variable distance between the DBR mirrors: (e) 1ML, (f) 2ML, (g) 3ML, (h) 4ML.
FIG. S4. Transfer matrix simulations for WSe$_2$ layer with $f = 1.23$ and encapsulated in hBN. (a) Rabi energy dependence on (b) WSe$_2$ layer thickness (c) exciton resonance linewidth.
FIG. S5. (a) Reflectance contrast (RC) and photoluminescence (PL) spectra of WSe$_2$ multilayers deposited on top of a DBR measured at 5 K. Experimental RC spectra are marked with gray lines, whereas color lines represent the fitted transfer matrix model. Fitting parameters of ground and first excited exciton resonances in multilayer WSe$_2$: (b) energy positions, (c) oscillator strength and (d) linewidth. △ mark the fine structure components of higher energy and ▽ of the lower one.

TABLE I. RC fitting parameters for WSe$_2$ deposited on the DBR with modeled exciton-photon coupling strength in dielectric cavity (abbrev. model) compared with the values obtained experimentally (abbrev. exp).

| Number of monolayers | $E_{1s}$ (eV) | $f_{1s}$ (eV$^2$) | $\gamma_{1s}$ (meV) | $\Omega^\text{model}_{1s}$ (meV) | $\Omega^\text{exp}_{1s}$ (meV) |
|---------------------|---------------|-------------------|---------------------|-------------------------------|-------------------------------|
| 1 ML                | 1.7532        | 1.63              | 13.8                | 19.4                          | 23.9                          |
| 2 ML                | 1.7258        | 1.45              | 31.4                | 20.8                          | 23.2                          |
| 3 ML                | 1.7103        | 0.72              | 28.5                | 29.1                          | 30.2                          |
| 4 ML                | 1.7257        | 0.54              | 24.5                | 31.3                          | 37.5                          |
| 5 ML                | 1.7026        | 0.52              | 24.5                | 31.3                          | 37.5                          |
| 6 ML                | 1.7196        | 0.54              | 28.5                | 33.6                          | 36.8                          |
|                     | 1.7002        | 0.47              | 23.5                | 33.6                          | 36.8                          |
|                     | 1.7182        | 0.59              | 35.4                | 33.2                          | 40.7                          |
|                     | 1.7041        | 0.37              | 20.3                | 33.2                          | 40.7                          |
|                     | 1.7228        | 0.55              | 38.6                | 33.2                          | 40.7                          |

FIG. S6. Experimental coupling strength of multilayer WSe$_2$ flakes. Modeled values of coupling strength based on reflectance spectra calculated with transfer matrix method are marked with crosses.
FIG. S7. WSe$_2$ few-layer flakes in tunable cavity. Reflectance map for normal incidence for tuning the cavity with voltage applied to the piezoelement with: (a) 1 ML, (b) 2 ML, (c) 3 ML, (d) 4 ML, (e) 5 ML and (f) 6 ML WSe$_2$ flakes without encapsulation. All of the measurements were performed at 5 K. Transfer matrix method simulations for variable distance between the DBR mirrors: (g) 1 ML, (h) 2 ML, (i) 3 ML, (j) 4 ML, (k) 5 ML, (l) 6 ML.
FIG. S8. WSe$_2$ monolayer deposited on hBN. (a) Photoluminescence (red) and reflectance contrast spectra (gray). Blue line presents fitted reflectance spectra. (b) Reflectance at normal incidence for variable cavity length. (c) Modeled reflectance map based on the fitting the blue curve in (a).

FIG. S9. WSe$_2$ bilayer deposited on hBN. (a) Photoluminescence (red) and reflectance contrast spectra (gray). Blue line presents fitted reflectance spectra. (b) Modeled reflectance map based on the fitting the blue curve in (a).

TABLE II. Fitting parameters for WSe$_2$ deposited on hBN with modelled coupling strength in dielectric cavity compared with the values obtained experimentally.

|      | $E_{1s}$ (eV) | $f_{1s}$ (eV$^2$) | $\gamma_{1s}$ (meV) | $\Omega_{1s}^{\text{model}}$ (meV) | $\Omega_{1s}^{\text{exp}}$ (meV) |
|------|---------------|-------------------|----------------------|-----------------------------------|----------------------------------|
| 1 ML | 1.7366        | 1.10              | 7.6                  | 21.7                              | 24.5                             |
| 2 ML | 1.7132        | 1.03              | 20.5                 | 27.6                              |                                  |
FIG. S10. Cavity resonant with 2s exciton transition in monolayer WSe$_2$. (a) Reflectance at normal incidence with cavity mode crossing 2s exciton energy. Angle-resolved reflectance spectra at (b) 75 V and (c) 100 V applied to the piezoelectric chip. No sign of coupling at 2s state energy is visible.

FIG. S11. Simulations for cavity resonant with 2s exciton transition in monolayer WSe$_2$. (a) Reflectance at normal incidence calculated for various oscillator strength of 2s exciton $f_{2s}$. (b) Cross section through (a) for experimental value of $f_{2s}$. Sum of two Lorentz functions was fitted to the spectra giving distance between two modes of 3.2 meV, which is lower than linewidth of 4.5 meV.