Enhanced Photoluminescence of Cesium Lead Halide Perovskites by Quasi-3D Photonic Crystals

José Mendoza Carreño, Nicolás Passarelli, Clara Otero-Martínez, Lakshminarayana Polavarapu, Luis A. Pérez, Juan Sebastián Reparaz, María Isabel Alonso, and Agustín Mihi*

Cesium lead halide perovskite nanocrystals have emerged as one of the most promising candidates for manufacturing portable lasers and light sources. In order to harness and exploit their photoluminescence more effectively, the nanocrystals are often accompanied by a photonic scheme that improves light emission. In this work, one introduces a quasi-3D photonic crystal composed of a 2D-grating on top of a distributed Bragg reflector (DBR) that provides a greater photoluminescence enhancement than the isolated architectures alone. The quasi-3D photonic crystals support both Rayleigh-Wood anomalies and guided modes that populate the photonic bandgap of the Bragg mirror, all of them capable of enhancing the outcoupling of light from the emitting layer. In order to demonstrate the benefits of the quasi-3D system, one prepares 2D-gratings, DBRs, and quasi-3D photonic crystals covered with metal halide perovskite nanocrystals and studies the photoluminescence enhancement produced in each case. Interestingly, the quasi-3D structure exhibits a photoluminescence enhancement of 16 times and an increase in spontaneous emission rate, greatly exceeding the values observed for the separate components.

1. Introduction

The abundance of novel optical sources has stimulated their implementation in a variety of instruments useful for material processing, industrial applications, imaging, and medical therapy, among others. The newly developed devices are relatively cheap, extremely lightweight and compact, and are pretty rugged with a long usable life span. Besides, these solid-state sources generate less heat and require less power compared with more traditional light sources. Among these new materials, cesium lead halide (CsPbX3) perovskite nanocrystals (NCs) are excellent candidates for emerging optoelectronic devices [1–4] due to their low cost, scalable synthesis, high photoluminescence (PL) quantum yield, and tunability along all the visible range varying their composition and size [5–7]. Inorganic perovskite NCs present narrow emission bands and good stability to environmental conditions. Moreover, these NCs are pretty versatile, and they can be embedded within organic and inorganic matrices, such as polymethyl methacrylate [7] or silica [8], for improved stability [9].

In order to harness and control the emission from the cesium lead halide (CsPbX3) nanocrystals, they are often accompanied by a light managing scheme that enhances the PL [9,10] or provides emission directionality [11]. It is also possible to directly shape the perovskite NCs themselves into photonic architectures such as thin films [12], 2D gratings [13], microdisks [14], nanowires [15,16], 3D photonic crystals [17,18], or 1 microhemispheres [19], among others. Even though this material is suitable for many optoelectronic devices, its toxicity and instability against oxidation and humidity limit their potential into potentially commercial applications. The encapsulation of these NCs into transparent oxides has proved to be a solution to improve their photonic stability as well as to reduce the metal halide toxicity, leaving the luminescent properties reasonably unmodified. Different strategies of encapsulation have been recently reported, such as the in situ growth of the NCs within the precursor glass by thermal treatment [20], the incorporation of perovskite thin layers or powder heating the transparent oxide above glass its transition [21] or by femtosecond laser-assisted crystallization induced by a nonlinear localized network glass destruction and giving chance to perovskite crystallization [22].

Many optoelectronic devices feature light-trapping schemes that improve their performance by facilitating the light absorption in the active layer (as in solar cells and photodetectors) or provide pathways to enhance the light emission from light sources. Among the different strategies employed, diffraction
gratings are among the best methods to provide the additional momentum to couple light in or out of thin films.\textsuperscript{[23,24]} Similarly, photonic crystals (PhC) can control the flow of light in a medium by modifying the dispersion relations. PhCs are materials with a periodic arrangement in the refractive index that inhibits light propagation for those wavelengths in a forbidden interval (the photonic bandgap).\textsuperscript{[25,26]} The simplest case of a photonic crystal is a multilayered 1D structure, known as distributed Bragg reflector (DBR), constituted by the alternate stacking of layers of different materials.\textsuperscript{[27]} DBRs are frequently used in optics as dielectric lossless mirrors, as they reflect light falling within their forbidden interval of wavelengths with high efficiency. The photonic bandgap from DBRs has been used for enhanced light absorption in solar cells\textsuperscript{[28]} or photoluminescence enhancement (PLE).\textsuperscript{[29,30]} for instance.

Both photonic structures, diffraction gratings and Bragg mirrors, are widely known for their ability to help manage light propagation in various devices. However, it is the combination of the two that has provided the highest absorption enhancements in Si-based solar cells\textsuperscript{[31,32]} thanks to increasing the light optical path inside the absorbing semiconductor layer by a combination of back-reflection and diffraction of the incoming radiation. The 2D-grating-DBR system has been recently used for in-coupling normal incident light into in-plane waveguided modes\textsuperscript{[33]} and produced highly sensitive biosensors.\textsuperscript{[34]} These applications are based on the loss of symmetry induced by the 2D grating on top of the DBR, which provides a way to couple light within the quasi-3D photonic crystal, thus creating allowed optical states within the photonic bandgap.\textsuperscript{[35]}

In this work, we explore the optical response of the photonic architecture constituted by a 2D-grating onto a DBR. The fabricated quasi-3D PhC facilitates the in-coupling and out-coupling of EM radiation, boosting the performance of quantum emitters placed on top. This can be accomplished by the combination of resonant excitation, emission with resonant modes, but also with the capacity to drive emitted photons out of the photonic crystal effectively.\textsuperscript{[36]} Herein we achieve a 16 times enhancement of the photoluminescence (PL) and a life-time reduction from CsPbBr\textsubscript{1/2}I\textsubscript{2} perovskite NCs deposited on top of the 3D PhC. In addition, these quasi-3D PhCs result from a simple and scalable fabrication using soft nanoimprinting lithography of a resist on top of an e-beam evaporated DBR, facilitating the implementation of this system in a variety of emitters that can be simply placed on top.

### 2. Results and Discussion

The fabrication of our quasi-3D photonic crystals is summarized in Figure 1 and detailed in the Experimental section. In brief, the first step is the fabrication of the DBR by the alternate deposition of silica (105 nm) and titania (57 nm) layers on a glass slide by electron beam evaporation. Next, we deposit a 140 nm photoresist thin layer (SU-8 2000.5 from Microchem) by spin-coating and then create a 2D array of pillars by using soft nanoimprinting lithography (NIL) while heating the resist. Finally, the structure is decorated with CsPbBr\textsubscript{1/2}I\textsubscript{2} nanocrystals by spin-casting them from the solution directly onto the surface of the quasi-3D PhC.

CsPbBr\textsubscript{1/2}I\textsubscript{2} perovskite NCs were chosen as emitters because of their reported high luminescence quantum yield and tunable emission (see the Supporting Information for preparation of CsPbBrI\textsubscript{2} NCs).\textsuperscript{[6,37]} Their versatility enabled the overlapping of the wavelength of excitation and the photoluminescence with resonances of the quasi 3D structures thus maximizing the photonic effect on the system. In this case, the photoluminescence maximum of the NCs in solution is located at 640 nm, as shown in Figure 1b. The TEM image in Figure 1c shows the cubic-shaped NCs with a size range of 10–12 nm.\textsuperscript{[9]} The photographs of the 3D PhC sample before and after the coating (Figure 1d,e) illustrate the change toward the reddish color of the samples once coated with CsPbBr\textsubscript{1/2}I\textsubscript{2} NCs. Top-view SEM images before and after NC coating are shown in Figure 1f,g, where the 500 nm pitch square array of 240 nm wide pillars can be seen surrounded by the perovskite nanocrystals (seen as brighter spots). The SEM cross-section image (Figure 1h) shows the quasi-3D PhC composed of the 2D-grating on top of the TiO\textsubscript{2}/SiO\textsubscript{2} DBR structure containing five and four layers of 57 and 105 nm thickness, respectively. A set of reference samples was also fabricated, including a SU-8 resist flat film, SU-8 resist 2D-gratings on glass, and thin-film SU-8 coated DBR mirrors.

All photonic architectures were fabricated in the epoxy resist material under different topologies. The optical characterization, reflectance, and transmittance, from a 2D-grating, a DBR and a quasi-3D photonic crystal under normal incidence are summarized in Figure 2 (see Figure S1, Supporting Information for the angular dependence). Figure 2a shows the response of a 2D-grating, a square array of pillars with lattice parameter $L = 500$ nm made of SU-8 on a glass substrate. Here, two features appear in transmittance (seen as changes in slope) corresponding to the Rayleigh-Wood (RW) anomalies in air and SU-8, respectively. These features can be predicted using the square grating equation under normal illumination, at $\lambda = nL/\sqrt{1 + m^2}$; where $n$ is the corresponding refractive index ($n_{SU-8} = 1.6$), $L$ is the lattice parameter and, $l$ and $m$ are integers standing for the orders of diffraction. In this case $m = 0$ and $l = \pm 1$ or vice-versa, here called [0,1] for simplicity. In Figure 2b, the characteristic broad high reflectance peak (minimum in transmittance) corresponding to the photonic bandgap structure of a 1D photonic crystal can be clearly identified. Since no photonic states are available within the photonic bandgap, light is reflected back, acting as a dielectric mirror with no light transmission detected within this wavelength range. However, when this DBR is coupled with the 500 nm lattice parameter 2D grating constituting the quasi-3D photonic crystal, several dips appear within the reflectance peak maximum (Figure 2c). The number and position of these resonances do not match the two RW anomalies seen in the 2D grating. Instead, these minima in the reflectance broad maximum indicate that the 2D-grating enables light propagation within the DBR at wavelengths lying within the forbidden interval.\textsuperscript{[31–33]} Three different main modes appear at wavelengths: 525, 593, and 640 nm under unpolarized white light (see Figure S2, Supporting Information for quasi-3D PhCs with 2D gratings made of lattice parameters 400 and 600 nm). These features...
are not found in the transmittance spectrum, and since the quasi-3D photonic crystal is composed of lossless dielectric materials, we must assume that the light traveling through the crystal is deflected and escapes the light cone defined by the 0.10 numerical aperture of the 4x objective used in transmission mode (see Figure S3, Supporting Information for total transmittance measurements).

As described in a recent publication,[38] an improvement in the resonance linewidth can be obtained by inspecting the photonic structure under coherent light. This is also the case when we inspect three different quasi-3D PhCs using a supercontinuum white light source (Figure 3). Indeed, sharp resonances can be clearly observed in the three structures, all of them composed of the same DBR but changing the lattice parameter (L) of the grating on top to 400, 500, and 600 nm. Now, in the quasi-3D crystal with 500 nm lattice parameter (Figure 3b) we can distinguish signals that match the expected wavelength for the [0.1]th diffractive order in air (λ = 500 nm), and the [0.1]th (λ = 800 nm) and [1.1]th (λ = 560 nm) diffraction orders in the SU-8 resist. In addition to these modes, we can find several additional resonances corresponding to guided modes in the DBR.

We employed finite-differences in time domain (FDTD, Lumerical inc.) to reproduce the optical measurements. Details and fitting values can be found in the experimental section and supporting information (Tables S1 and S2, Supporting Information). Some design guidelines of these quasi 3D structures such as the dependence of the optical properties with the pillar radius, height of the 2D-grating and SU-8 residual layer thickness are presented in Figure S4 (Supporting Information).

Since the spin-coated perovskite nanocrystals constitute an incoherent light source, we used FDTD to reproduce the reflectance spectrum observed under the tungsten lamp (Figure 2). The refractive indexes for simulation were obtained through ellipsometry measurements using the Cauchy model with excellent agreement between simulated and experimental values (Figure 4a), except for the narrow resonances that could not be

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*Figure 1.* a) Schematic fabrication process of metal halide nanocrystal decorated quasi-3D photonic crystals. b) Absorption (black) and photoluminescence spectra (red) of CsPbBrI₂ nanocubes in hexane. c) TEM Image of CsPbBrI₂ perovskite nanocubes. Photograph of the 1 cm² quasi-3D crystal under white light illumination d) before and e) after perovskite deposition. Top-view SEM image from the quasi-3D crystal f) before and g) after perovskite deposition. White bright dots around the pillars correspond to perovskite nanocrystals. h) Cross-section SEM image taken from the sample before perovskite deposition with SU-8 pillars on top of a distributed Bragg reflector (DBR) multilayered structure composed of TiO₂ (bright) and SiO₂ (dark).
seen under incoherent light. From the simulations, we extracted the near field spatial distribution along the XZ plane (x-polarized incidence) from the three main resonances observed in Figure 4 at \( \lambda_A = 532 \text{ nm} \) (Mode A in Figure 4b), \( \lambda_B = 585 \text{ nm} \) (Mode B in Figure 4c) and \( \lambda_C = 651 \text{ nm} \) (Mode C in Figure 4d). We also include a 2D plot of the simulated reflectance versus wavelength by varying the lattice parameter \( L \), shown in Figure 4e. In this last panel, the linear dependence of the RW anomalies with \( L \) can be seen, suggesting a diffractive character. Instead, the broad resonances that do not depend linearly with \( L \) are assigned to guided modes within the DBR, as illustrated by the spatial distribution of the electric field in modes A (Figure 4b), B (Figure 4c), and C (Figure 4d). Interestingly, mode C is close to the emission peak of the NCs (640 nm) and it has field profile on the surface where the emitters will be placed. The frequency and number of these modes are dependent on the number of unit cells of the DBR as reported elsewhere\cite{33,39} and further illustrated for our system in Figure S5 (Supporting Information).

Next, we compared the performance of the quasi-3D PhCs with that of a 2D-grating and a bare DBR for PL enhancement by decorating the surface of all the photonic structures with CsPbBrI_2 perovskite NCs by spin coating. The PL measurements presented in Figure 5a (see Experimental section) were performed using a pulsed laser as the excitation source (532 nm laser Crylas FDSS 532-150 with pulse duration of 1.1 ns and mean power of 0.2 mW with a repetition rate of 100 Hz) with a TE polarized electric field oriented along one of the directions of the 2D lattice (sketch of the PL setup in Figure 5a). The laser impinged at an angle of 50° on the sample, matching a resonance in the quasi-3D crystals (see Figure S6, Supporting Information for the reflectance of the quasi-3D PhC at 50°). In each case, the photoluminescence enhancement (PLE) is calculated as the ratio between the PL from each photonic structure and

Figure 2. Optical characterization of reflectance (black) and transmittance (red) for different photonic architectures. a) A 2D-grating (lattice parameter \( L = 500 \text{ nm} \)) on a glass substrate. b) Distributed Bragg reflector on glass with a photonic bandgap from 500 to 750 nm. c) A 2D-grating (\( L = 500 \text{ nm} \)) onto a DBR on glass exhibiting several peaks within the photonic bandgap in its reflectance spectrum (black curve). The insets illustrate the type of photonic architecture measured in each case.

Figure 3. Optical characterization of transmittance (black) and reflectance (colored line) from quasi-3D PhCs for three different pitches. a) 400 nm, b) 500 nm and c) 600 nm under supercontinuum white light illumination.
Figure 4. a) Simulation (red) versus experimental (black) reflectance of a quasi-3D PhC (2D lattice parameter of 500 nm) under incoherent white light. b–d) Spatial distribution of the electric field (XZ plane) for b) $\lambda = 532$ nm (Mode A), c) 585 nm (Mode B) and d) 651 nm (Mode C). e) Simulated dependence of the reflectivity with the lattice parameter $L$ of the 2D-grating upon a fixed DBR system.

Figure 5. Reflectance or transmittance spectra at normal incidence (black curve, left axis) of the different photonic architectures measured after CsPbBr$_3$I$_2$ NCs deposition versus photoluminescence enhancement (right axis, red curve). a) Sketch of the photoluminescence setup used to pump (green beam) and collect the signal (red beam) normal to the surface. b) Transmittance spectrum (left axis) and PLE spectrum (right axis) of a SU-8 2D-grating on glass. c) Reflectance and PLE spectra of a SU-8 thin film on a DBR. d–f) Reflectance and PLE spectra from three different quasi-3D PhCs with the same DBR and varying the pitch of the 2D-grating: d) 400 nm, e) 500 nm, and f) 600 nm.
the PL from a thin film of NCs on a flat resist film on glass to ensure that, in all cases, the nanocrystals were in contact with the same material, SU-8.

The PL measurements were taken immediately after the NCs film preparation, as due to the ionic nature of the perovskite NCs, they are especially sensitive to polar solvents. It was demonstrated that humidity and light are the main degradation factors of any halide composition. However, this effect is especially significant in the case of iodide perovskites. The presence of bromide anions in the NCs composition leads to a decrease in the degradation ratio. This was confirmed by control tests where a pair of NCs films was stored under inert conditions and atmospheric conditions (relative humidity ≈52.5%). The film exposed to normal conditions shows after one week a blue shift due to the iodide expulsion induced by the atmospheric influence. On the other hand, the film stored under an inert atmosphere keeps the initial optical properties after the same time. The signs of degradation were analyzed by TEM and summarized in Figure S7 (Supporting Information) before and after one week storage under ambient or nitrogen conditions. The iodide expulsion process is shown in the morphology change of the NCs as a decrease in their size. The difference in the halide size (I⁻ >> Br⁻) leads to a decrease in the cell edge and, as a consequence, a decrease in the crystal size after the expulsion of iodide.

The PLE values and reflectance spectrum (at normal incidence) from each structure are shown in Figure 5 (PL intensity values can be found in Figure S8, Supporting Information). The 2D-grating on glass substrate shows a PLE with a double peak coinciding with the RW anomalies with a twofold enhancement of PL in good agreement with previous reports. Similarly, the 140 nm SU-8 layer coated DBR exhibited a PLE of 4.5 for frequencies within the photonic bandgap. This significant enhancement in the PL is originated by the thin film of SU-8 on top of the DBR which breaks the periodicity of the structure, creating a planar defect, as seen in the modified reflectance spectra in Figure 5c, leading to an enhancement at the wavelength of this specific defect state.

In the case of the quasi-3D PhC, we studied samples with three different 2D-gratings (400, 500, and 600 nm pitch) on top of the same DBR mirror (Figure 5d–f). For the 400 nm lattice parameter (Figure 5d), the NCs emission is enhanced a 6.5-fold for two resonance modes within the photonic bandgap at 615 and 653 nm. In the case of a 500 nm lattice parameter 3D quasi PhC (Figure 5e), the resonance labeled before as mode C (651 nm in Figure 4d), enhances the PL emission up to 16 times compared to the reference sample. Finally, for a 600 nm lattice parameter 3D PhC (Figure 5f), two enhanced emission peaks are observed at 600 and 655 nm, matching the modes seen in the reflectance spectrum. Both modes result in up to a 10 and 12-fold enhancement of the PL emission, respectively. These results illustrate the great potential of the quasi-3D PhC to boost the PL from emitters placed on its surface beyond current photonic alternatives, benefitting from an increased electric field at those wavelengths, as seen in the simulated field profiles.

It is worth mentioning that the inherent NCs instability against standard atmospheric conditions is completely independent of the all-dielectric proposed structure. The materials that compose the quasi-3D PhC (SiO2, TiO2, and SU-8) do not suffer from oxidation nor degradation, presenting great robustness over time. Moreover, the proposed structure offers the opportunity to produce amplification on any emitting material whose absorption/PL matches the photonic resonances of the system. We illustrate this possibility in Figure S9 (Supporting Information) for an organic dye. In Figure S9 (Supporting Information), a Rhodamine-B doped SU-8 quasi-3D PhC greatly enhances the emission from the dye and severely modulates the PL band of the emitter, illustrating the potential of our system for organic dyes.

We also studied the angular dependence of the PLE and its reflectance from the quasi-3D PhC. To do so, we measured the reflectance from the samples using an ellipsometer, adjusting both incoming and outgoing directions from 12° up to 30°. In the case of the PL, the sample was placed on a rotating stage and the PL data were obtained varying the collection angle from 0° to 30°. A schematic setup is shown in Figure 6a, where θem stands for the emission angle. Figure 6b shows the correlation between the measured PLE (photoluminescence enhancement) and the reflectance for the different angles. The largest PLE is achieved for the normal direction, corresponding to the PLE value shown in Figure 5e. As the collecting angle increases, the PLE decreases and redshifts following a minimum seen in reflectance. By increasing the angle of collection, we observe a decrease in the PLE from 16 down to a value of 10 times, indicating that the system produces its highest enhancement in PL at normal incidence when the emission peak is coupled with the guided mode (Mode C), and this peak value decreases as the mode moves towards the edges of the bandgap where the photonic bandgap starts to disappear.

Finally, in order to further evaluate how the quasi-3D PhC affects the emission characteristics of the CsPbBrI₂ NCs, we measured the lifetime of the NCs on each different photonic structure. The time-resolved photoluminescence (TRPL) data collected at 647 nm is presented in Figure 7 for the different photonic systems studied herein under pulsed excitation with 470 nm (see Experimental section for details). The TRPL data was obtained through time-correlated single-photon counting.
of \( \tau_1 \) was obtained from fitting the TRPL data measured from the flat film, with a value of \( \tau_1 = 1.80 \) ns. The rest of the parameters obtained and their tolerance interval for the fitted curves are summarized in Table 1. As expected, the 2D-grating does not significantly alter the decay rates with respect to the values obtained in the flat sample (\( \tau_2 = 6.1 \pm 6.2 \) ns in both cases). \[^{[11]}\]

In the case of the NCs on top of the DBR, the intrinsic decay rate \( \tau_2 \) decreases to 5.9 ns, still within the experimental dispersion of 0.3 ns measured among different samples (see Figure S10 and Table S3, Supporting Information). However, a clearly faster decay rate is observed for the quasi-3D PhC. In this case, the core radiative component is further reduced to a lifetime of \( \tau_2 \approx 5.6 \) ns, i.e., 500 ps faster as compared to the NCs on flat SU-8 on glass substrate. The effect of the quasi-3D structure is more evident if we consider the averaged lifetimes, where we see a reduction from \( \langle \tau \rangle = 4 \) ns from the flat NCs case until the \( \langle \tau \rangle = 3.1 \) ns found for the NCs deposited on the quasi-3D system.

We consider the origin of the considerable PLE observed in our 3D quasi PhCs to be a convolution of the following phenomena: First, the 532 nm laser excitation at 50° falls within a resonance of the quasi 3D system (Figure S11, Supporting Information). In the field profile calculated under these conditions, an enhanced field intensity can be found at the location of the NCs, thus making the pumping more efficient (Figure S11, Supporting Information). Second, the PL of the perovskite NCs coincides within the 650 nm resonance of the quasi-3D PhCs whose field profile is depicted in Figure 4d. Matching the PL with the resonance improves light extraction (see an estimation in the Figure S11, Supporting Information) and also modifies the angular distribution of the PL \[^{[13]}\] as seen in Figure 6. Finally, the grating leads to the appearance of photonic modes within the photonic bandgap of the DBR. These modes within the photonic bandgap can contribute to accelerate the lifetime of the nanocrystals as observed in other works. \[^{[41]}\] In sum, the capability of the quasi-3D PhC to sustain several photonic modes matching both the absorption and the emission of the emitter renders the quasi-3D PhCs ideal to improve the performance of current light sources.

3. Conclusions

We propose a simple and efficient strategy to amplify the emission of CsPbBr\(_3\)I\(_2\) perovskite nanocrystals using quasi-3D photonic crystals. The quasi-3D PhC is a straightforward architecture obtained by placing a 2D-grating on a DBR mirror, however, the final optical performance of the coupled system surpasses that of each individual component. The quasi-3D PhC possesses a series of resonances within the bandgap of

![Figure 7. Time-resolved PL for different samples. Experimental data are fitted (yellow) with a biexponential decay with \( \tau_1 \) (shell effective radiative recombination) and \( \tau_2 \) (core intrinsic radiative recombination). CsPbBr\(_3\)I\(_2\) NCs on unpatterned SU-8 on glass (black) and on patterned SU-8 on glass (red) show similar core radiative decays of \( \tau = 6.1 \) ns. NCs on unpatterned SU-8 on DBR substrate (blue) show a slightly faster decay \( \tau_2 \approx 5.9 \) ns. NCs on patterned SU-8 on the DBR substrate (green) exhibit the fastest decay of \( \tau_2 = 5.6 \) ns.](https://www.advancedsciencenews.com/file?doi=10.1002/adom.202101324)
the photonic crystal corresponding to Rayleigh-Wood anomalies and guided modes within the DBR. These abundant resonant modes can be used to amplify the emission of the perovskite nanocrystals placed on top beyond what can be achieved with gratings of DBRs, by facilitating matching both the excitation and the emission of the nanocrystals with resonant modes of the quasi-3D structure. This strategy enabled reaching a PLE at the surface normal direction of 16 times accompanied by an increase in the spontaneous emission rate. Since these quasi-3D systems can be seamlessly fabricated, for instance, by solution processing of the DBR[27] and soft lithography of the 2D-grating, we believe this photonic architecture will provide an excellent playground for tuning the optical properties of emerging light sources beyond traditional gratings and photonic crystals.

4. Experimental Section

**Distributed Bragg Reflector (DBR) deposition:** A multilayered thin film structure composed of 57 nm of titanium oxide (TiO$_2$) and 105 nm of silicon oxide (SiO$_2$) was obtained by electron beam (e-beam) deposition (ATC-8E Orion from AJA International Inc. with up to 10 kV HV source) on glass microscope slides (SLU-005-050 26x76mm Lab Box).

**Polymeric Solution:** The material chosen as the grating structure was SU-8 2000.5 from Micro Chem with an initial weight concentration of 14%. Due to the required thickness for the nanoimprinting lithography process, the initial solution was dissolved to 6% in weight using a commercial SU-8 2000 Thinner from Micro Chem.

**Cesium Halide Perovskites:** The CsPbBr$_3$ NCs were synthesized by the ultrasonication method. In a typical synthesis, 0.345 g of Cs$_2$CO$_3$ (1 mmol), 1.101 g of PbBr$_2$ (3 mmol), octadecene (15 mL), oleic acid (4 mL), and oleylamine (4 mL) were combined in a 50 mL sample vial. The resulting mixture was subjected to tip-sonication at a power of 30 W for 30 min. During the course of the reaction, the color change of the reaction mixture can be seen clearly, indicating the formation of perovskite NCs. (Further details in the Supporting Information)

**Cesium Halide Perovskites Washing:** 5 mL of CsPbBr$_3$ NCs were centrifuged for an hour at 14 000 rpm to remove the excess of oleic acid and other remaining synthesis products. The NCs were resuspended in 1 mL of toluene, achieving an approximate concentration of 100 mg mL$^{-1}$.

**Nanoimprinting Lithography (NIL):** The resist SU-8 2000.5 (Micro Chem 14% wt) was diluted to 6% wt using the SU-8 2000 Thinner. PDMS molds with prepatterned areas of 1 cm$^2$ were pressed onto the SU-8 layers at 90 °C, above the glass transition temperature of the photoresist for 20 s. After this time, the SU-8 had adopted the negative shape of the mold, and the whole structure had a residual layer around 10–30 nm thickness.

**Optical Characterization—FTIR:** A Fourier-transform infrared (FTIR) spectrometer (Bruker Hyperion) was used for optical reflectance and transmittance measurements, using a silver mirror as a reference for reflectance measurements. Reflectance measurements are collected through a 2x objective (NA 0.05). For transmittance measurements, a 4x NA 0.10 objective was used to focus light on the sample.

**Optical Characterization—Coherent Source:** A supercontinuum laser source (Fianium SC400) was used for coherent reflectance measurements. Reflectance values were measured as the ratio of the photocurrent intensity (ThorLabs 50 mW 200–1100 nm) obtained with the sample normalized to that of a silver mirror, acting as a reference.

**Optical Characterization—Ellipsometer:** A GESSE ellipsometer from SOPRALAB was used to characterize the thickness and optical properties of the thin films and the DBR by ellipsometry. Variable-angle reflectance of the samples was obtained by normalizing the measured spectra at different angles with the incident beam intensity of a 75 W Xe arc lamp attenuated by neutral density filters.

**Photoluminescence Measurement—Optical Bench:** The photoluminescence (PL) was collected with a homemade setup on an optical bench consisting of a laser source, optical components for alignment, and signal collection and measurement. The laser source is a pulsed Cylas FDSS 532-150 of 532 nm wavelength vertically polarized (TE) impinging at oblique incidence for resonant excitation, with a pulse duration of 1.1 ns and mean power of 0.2 mW with a repetition rate of 100 Hz. An f = 100 mm biconvex lens was used to focus the laser source upon the sample. The laser source was filtered, and only the light emitted by the NCs was collected with the second lens of optical power f = 100 mm that collimated the signal onto a lens coupled to a commercial optical fiber (Ocean Insight) connected to a spectrometer (QPRO Ocean Optics). The detection setup was placed on a rotational stage to change the collection emission direction. The power measurements for the laser source were done by a photodetector (Thor Labs 400–1100 nm 500 mW).

**Time-Resolved Photoluminescence:** A 470 nm pulsed diode laser (Taiko PDL M1) was used as the excitation source. Pulses of 12 µJ were sent at a repetition rate of 5 MHz to ensure the relaxation of the luminescent nanoparticles. A (647 ± 10) nm bandpass filter was placed in front of an optical fiber coupled to a single photon counting module (PMA Hybrid PicoQuant) for time-resolved photon counting.

**Numerical Simulations—FDTD:** All simulations were performed with the Finite Difference Time Domain (FDTD) commercial software (FDTD-Solutions, Lumerical). Periodic boundary conditions were imposed at the grating plane and perfect-matched layer in the normal axis (set for steep angles matching). The refractive index of the substrate was taken as n = 1.5 (glass). The rest of the dielectric materials were modeled using the Cauchy model with the values obtained from ellipsometry. The fitted parameters and thickness values of the DBR are detailed in Tables S1 and S2 (Supporting Information), whereas parameters for SU-8 were taken from ref. [43].

For the angular incidence, the incoming light was simulated with the Broadband Fixed Angle Source Technique; for the sake of stability, the constant part of the refractive index was fixed to 1.4848 for SiO$_2$, 2.2044 for TiO$_2$, and 1.6 for SU-8. In all cases, the polarization of the impinging wave was transverse electric and oriented along one direction of the 2D-grating. The experimental reflection spectra were fitted with the built-in particle swarm optimization algorithm.

**Supporting Information**

Supporting Information is available from the Wiley Online Library or from the author.

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**Conflict of Interest**

The authors declare no conflict of interest.
The data that support the findings of this study are available from the corresponding author upon reasonable request.

Keywords
light emission, perovskites, photonic crystals, photonics