Tunable Polymer/Air-Bragg Optical Microcavity Configurations for Controllable Light–Matter Interaction Scenarios

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Complex optical systems such as high-quality microcavities enabled by advanced lithography and processing techniques have paved the way to various light–matter interaction (LMI) studies. Sub-micrometer-precise lithographic development of a polymer photoresist allows construction of microcavity structures for various spectral regions based on the material's transparency and the geometrical sizes. On the other hand, this approach also avoids lattice-matching constraints in epitaxy, complex coating techniques, and shaky open-cavity constructions. Herein, a new approach based on 3D nanowriting in a photoresist is introduced, which can be used to achieve microscopic photonic Fabry–Pérot cavity structures with mechanically tunable resonator modes and polymer/air-Bragg mirrors, directly on a chip or device substrate. By transfer-matrix calculations and computer-assisted modeling, it is demonstrated that open microcavities with up to two “air-Bragg” reflectors comprising alternating polymer/air-mirror-pair layers enable compression-induced mode tuning that can benefit many LMI experiments, such as with 2D materials, nanoparticles, and molecules.

1. Introduction

Optical microcavities play an important role in a wide range of research areas, such as light–matter interaction (LMI).

Various high-quality microcavities have been explored for decades and enabled the hunt for ultralow-threshold nanolasers, opening up fundamental cavity quantum electrodynamics (QED) experiments and the study of Bose–Einstein-like condensation (BEC) of polaritons in solids.

Microcavities have reached popularity not only for conventional (more energy-efficient) lasers, often harnessing the weak coupling regime in suitable microcavity structures, but also for polariton physics as well as the novel field of polariton chemistry and become indispensable for optical quantum technologies. In fact, the list of abundant research directions with confined light fields cannot be projected adequately in this short summary here.

Recently, a variety of new and practical configurations of optical microresonators were used for the investigation of LMI with ultrathin van der Waals materials, such as 2D transition-metal dichalcogenides (TMDCs), colloidal quantum dots, fluorescent dyes, III–V semiconductors, and many other materials. For the investigation of LMI, be it (quantum) optoelectronic or optomechanical coupling, the most commonly used microcavities are (monolithic) planar/Fabry–Pérot (FP) microcavities, open tunable fiber-based concave mirror microcavities, (total-internal-reflecting) photonic crystal nanocavities, and plasmonic metal cavities (with possible Ohmic losses) as well as the air-gap-type microresonators. Among the various designs, those highly versatile, spectrally tunable, and relatively simple open-cavity configurations have already covered a large spectrum of applications ranging from cavity quantum electrodynamics (CQED) to (fiber-coupled) optoelectronic or optomechanical devices as well as sensors.

Many different and unique approaches have been already demonstrated to improve the confinement of the light and functionality of cavity systems. Some approaches such as photonic crystal membranes and whispering gallery modes do provide significant confinement of light in all the three spatial dimensions, whereas open-cavity configurations with an air-gapped microresonator such as fiber-based FP cavities provide intrinsic tunability in both the spectral and spatial domains as flexible light–matter interfaces. Often, a top-down nanotechnology approach is used to define precise (monolithic) resonator structures, or movable reflectors are combined to form tunable open resonators. In contrast, within our concept 3D (nano)printing offers on-demand bottom-up production of cavity configurations nearly arbitrarily on various substrates and in combination with different active materials, around quantum emitters, in combination with fluids and gases (molecules), and even providing cheap polymer structures in a disposable fashion, e.g., for
diagnostics with a one-time-use sensing device or cavity-enhanced optical probe.

The tunable nature of open (air-gap) FP microcavities is a key advantage that provides in situ control over LMI through longitudinal mode tuning, lateral mode positioning, compatibility with different (nano)materials and access to the intracavity space. However, open-microcavity configurations are typically susceptible to vibrations and unstable at relatively large cavity length. In contrast, nanoprinting of FP microcavities around a target material could open up a new path to tailor-made optical resonators. To achieve this, suitable 3D-printable micromirror structures need to be designed and developed for the incorporation of the desired active material prior to or after completion of the cavity structure, as appropriate for the given experiment. While mirror production can easily rely on metallization of surfaces, wavelength-tunable on-demand deposition of (top) mirrors can be best addressed with layered dielectric mirrors based on the distributed Bragg reflector (DBR) concept, which can conveniently be formed by polymer/air layer pairs offering considerable refractive index contrast. In case the rigidity and elasticity allow for pressure-induced thickness changes of layered polymer/air-gap structures, even mechanically tunable optical microcavities can be envisioned. Thus, research platforms for tunable Rabi splitting, BEC studies, polaron transmission, Purcell-enhanced single photon sources, and field-enhancement-benefitting nonlinear optics can arise, considering the estimated reasonably high Q factors, wavelength, or structure design flexibility, and the stability of such a printed photonic microstructure. In this work, two promising printed cavity system configurations are discussed utilizing simulations of optical properties of the microcavities with and without active materials based on the transfer matrix method (TMM). The presented simulation study for different selected layer thicknesses in the polymer/air (“air-Bragg”) microcavity, i.e., of air and the polymer material, is supported by additional stress analysis using a finite element analysis (FEA) for the examination of the mechanical stability of the designed structures. Thereby, we demonstrate the practicality and conceptual feasibility of mode-tunable strong-coupling experiments with a van der Waals semiconductor monolayer incorporated theoretically in the polymer/air microcavity. In the future, laser nanoprinting of (integrated) photonic structures directly on the chip with similar and more advanced polymer optical microreflectors and microresonators promises great flexibility for optoelectronic, optomechanic, nanophotonic, and nonlinear-optics applications.

2. The Optical Microcavity Configurations

The optical mirrors in the form of DBRs, i.e., alternating refractive index layers with thicknesses of $i\lambda_0/(4n_{mat})$, where $\lambda_0$ is the wavelength in vacuum, $n_{mat}$ is the refractive index of the material used, and $i = 1,3,5$, and so forth (odd integer numbers), solely rely on the resist material (and air) and are designed to work well with WS$_2$ monolayer excitonic resonances. In the following, $\lambda = \lambda_0/n_{mat}$.

The first configuration (Figure 1a) is composed of a conventional dielectric mirror, comprising six pairs of SiO$_2$ and Ti$_3$O$_5$, as the bottom mirror as well as substrate for the active medium, and the polymer/air-Bragg structure as the top mirror (in the following “air-Bragg” reflector). The second configuration (Figure 1b) aims at directly printing two air Braggs on top of
one another with an appropriate distance (cavity spacer) between them to form a microresonator incorporating the active medium, which needs to be (in most cases) inserted in an intermediate step. For layered materials, this is sketched in the Supporting Information. Later on, the desired tunability of cavity modes can be introduced by application of mechanical pressure on the polymer/air microstructure. If the two different air Bragg of the printed microcavity are appropriately constructed without any physical contact (see schematics in Figure 1c,d, with a stable enough configuration), one can in principle compress mirrors independently, i.e., only the underlying mirror, only the top mirror, or on demand both simultaneously. Tuning in any of these experiments would generally take place by external mechanical pressure application onto the polymer-based support structures via nanopositioning stages or any equivalent mechanical device. In the simple case, both mirrors will be addressed by an external (here vertical) pressure simultaneously. This air-Bragg-reflector cavity also allows one to have the active material placed on the bottom DBR in a contact manner, provided that the terminating layer features an adjusted thickness, or the material is incorporated in suspended form. This is a unique approach as far as spectrally tunable microcavities are concerned.

The refractive index of the IP-DIP photoresist in the visible spectral range is 1.52 at room temperature, which exhibits minor changes at low temperature. This allows one to obtain a reasonable refractive index contrast of 1.52/1 between the two materials of the dielectric mirror. The refractive index contrast is not very high, but compared to typical III/V DBRs made of GaAs/AlAs with index contrast in the range of 3.5/3, the dielectric mirror with air and a polymer still yields an improvement. Nonetheless, with a large number of mirror pairs, an overall high reflectivity is achievable.

For the TMM calculations, considering the active material to be thin-layered semiconducting materials (TMDCs), the design wavelength of the air-Bragg reflector is targeted to be in the range of 600–800 nm (for the most popular TMDCs with their A excitons in that range). Note that longer wavelengths, e.g., for a near-infrared to infrared intralayer or interlayer excitonic species in TMDC monolayers or 2D heterostructures, respectively, provide more favorable printing conditions than for the here-chosen WSe2 A-exciton resonance. For detailed explanations regarding the TMM, we refer the reader to the Supporting Information of our previous work by Wall et al..

Figure 2a–d shows the stopband of an air-Bragg reflector with different layer pair numbers, for four different layer thickness configurations, considering the design wavelength ($\lambda$) to be around 620 nm in air (2.0 eV). The air-Bragg reflector with $\lambda/4$ layer thickness exhibits a reflectivity close to 1 over a 100 nm range when composed of eight mirror pairs (of air and IP-DIP). The reflectivity as a function of the layer thickness does not change significantly, but it expectedly relies on the number of pairs in the air-Bragg reflector (Figure 2e). A large number of mirror pairs typically result in a high reflectivity, as evidenced in the calculated reflectivity spectra for all four configurations.

In a fully air-Bragg-based cavity system, the bottom reflector consists of seven or eight pairs and the top one of six pairs for better outcoupling. The air Braggs with seven and six pairs possess maximum reflectivities of 98.5% and 97%, respectively (Figure 2e).

Next, the influence of the layer thickness on the stopband width is briefly summarized. It can be clearly seen that the stopband width changes drastically as a function of the layer thickness. The stopband width for the $\lambda/4$, $3\lambda/4$, $5\lambda/4$, and $7\lambda/4$ air-Bragg reflector amounts to ≈100, 60, 40, and 25 nm, respectively (Figure 2f).

### 3. Stress Analysis of Tunable Polymer/Air-Bragg Microcavities

The crucial stress analysis based on FEA was performed on aforementioned polymer/air-Bragg reflector designs, using a computer-aided design (CAD) tool (see methods section). Here, Autodesk Inventor allows simulating the practical pressure-affected cavity configurations, which use air-Bragg reflectors toward their applications in tunable open-microresonator devices. This is possible due to material-specific mechanical properties allocated to the structure’s CAD model. The physical and mechanical properties of the photoresist IP-DIP are summarized in Table 1.

The CAD of air Braggs for various layer thickness configurations is shown in Figure 3 along with the stress analysis simulation. The air-Bragg reflectors consist of eight layers with $i = 1, 3, 5, 7$ quarter-wavelength layer thickness (Figure 3a–d, respectively) and cover each an area of $50 \times 50 \mu m^2$. The gradual increment or decrement in the applied pressure leads to the deformation of the polymer parts of the air-Bragg structures. The pressure is solely applied on the (here two opposing) side pillars/bars which mechanically support the quasi-free-standing submicrometer-thick polymer layers in the vertical microstructure. The upper surface area of each pillar is $20 \times 50 \mu m^2$.

The size of the air-Bragg structures (and resonators thereof) highly depends on the mechanical properties of the polymer and desired polymer layers thickness in air-Bragg structures. For a $7\lambda/4$ design, the “optical area” (excluding the support-pillar area) can become close to $100 \times 100 \mu m^2$ and according to stress analysis simulations will be pretty stable. But a similar thing cannot be said for $3\lambda/4$ layers. Therefore, $50 \times 50 \mu m^2$ has been chosen as an optical area to be on the safe side with good rigidity in our comparative considerations across a wide range of Bragg layer thickness designs. For rigid configurations, larger footprints are realistic, whereas a presumed minimum size of the air-Bragg area could be around $10 \times 10 \mu m^2$, which additionally makes considerations of strong lateral confinement of the optical mode necessary.

To fulfill their purpose, the deformation of these pillars causes a noticeable change in polymer layer separation, which gives the overall microresonator platform the intended functionality to tune/detune cavity modes by deforming the air-Bragg structure. The application of external pressure on such a small structure modifies the thickness of all air layers considerably while leaving the polymer layers basically unchanged. Thereby, the structural modification results in the desired shift of the reflectivity spectrum and ultimately the spectral position of the optical cavity modes in a complete microresonator. However, the tunability of the air-Bragg reflector is limited, on the one hand, by the pressure-bearing capacity (i.e., maximum compression and expansion) of the photoresist IP-DIP, and on the other hand...
by the pressure degree, at which the deformation still provides a functioning DBR based on the pressure-affected effective layer thickness ratio between air and polymer layers.

Our simulation-based mechanical analysis indicates that the $\lambda/4$ air-Bragg structure is unstable as can be evidenced by the strong bending and bunching of the photoresist layers. In addition, the air Bragg with layer thickness $3\lambda/4$ (Figure 3b), $5\lambda/4$ (Figure 3c), and $7\lambda/4$ (Figure 3d) exhibit a clearly more stable behavior under the influence of gravity and external pressure due to the improved rigidity. As can be deduced from TMM calculations based on extracted structural information, the effective deformation (in terms of thickness reduction) of the air layers in

Figure 2. Stopband and reflectivity dependencies of the polymer/air-Bragg reflector for different layer thicknesses. a–d) Calculated reflectivity spectra for $\lambda/4$ (a), $3\lambda/4$ (b), $5\lambda/4$ (c), and $7\lambda/4$ (d) material-specific (air and polymer) layer thickness. e) Maximum reflectivity given at the Bragg wavelength as a function of the mirror-pair number. Here, the calculated maximum reflectivity exceeds 99% for eight mirror pairs. f) Extracted stopband width (for eight pairs) as a function of the layer thickness. Accordingly, for a $\lambda/4$ layer thickness, the total stopband width is 100 nm, whereas for $7\lambda/4$ layers it becomes 25 nm.
Table 1. Key physical and mechanical properties of the IP-DIP resin.

| Resin  | Density (liquid) [g cm⁻³] | Density (solid) [g cm⁻³] | Young’s modulus [GPa] | Hardness [MPa] | Poisson’s ratio | Refractive index |
|--------|---------------------------|--------------------------|-----------------------|----------------|----------------|-----------------|
| IP-DIP | 1.14–1.19                 | 1.2⁹                   | 4.5                   | 152            | 0.35⁶          | 1.52            |

⁹If not indicated by *asterisks, the values are from the Nanoscribe GmbH;⁹¹ Jiang et al.;⁹² Greaves et al.

Figure 3. FEA of the polymer/air-Bragg reflector with different layer thickness configurations. FEA simulations for air Braggs with a) λ/4, b) 3λ/4, c) 5λ/4, and d) 7λ/4 layer thickness demonstrate a gradual deformation of that structure upon application of a uniform pressure of 100 MPa on the side bars of the structure (double arrows). The central arrow indicates the force of gravity applied to the overall structure. The area shaded blue experiences less induced deformation and less pressure (densification) compared to the green and particularly the red colored areas. Here, the floating layers remain unaltered. Note that the thin black lines in the background indicate the initial shape of the structure in the absence of external pressure. In fact, gravity leads to the pronounced bending of the thinnest and, thus, least rigid layers.
air-Bragg structures influences the overall stopband of the microcavity. The stopband of the individual air-Bragg reflector experiences an increasing blueshift in its spectral position when the external pressure is gradually increased as applied on the upper surface of the structure (indicated by double arrows in Figure 3).

The stress analysis method used in this work can also be utilized to study the behavior of the cavity structures upon application of mechanical pressure. To address the targeted effect of cavity-mode tunability by external pressure, two different examples of (printable) cavity configurations under a variation of the applied pressure are discussed, that are 1) the air-Bragg/DBR microcavity and 2) the air-Bragg/air-Bragg microcavity (see Figure 1a,b, respectively).

To begin with, Figure 4a shows the tunability induced by applied pressure in the range of 0–50 MPa (corresponding to a uniform force of maximally 0.1 N on the two side bars) on the \( \frac{5\lambda}{4} \) air-Bragg/DBR microcavity, which causes the quality factor \( Q = \frac{E}{\Delta E} \) (mode energy over linewidth, i.e., full-width-at-half-maximum (FWHM)) to change drastically. The \( Q \)-factor drop is associated with the nonproportional change of polymer layer separation compared to the air spacers within the Bragg mirror, which creates unfavorable Bragg conditions for the selected design wavelength. Along with this effect we also change (reduce) the actual cavity length under compressive external pressure. With the interplay of both these effects, the drop in the deduced \( Q \) factor is obtained. In other words, it converts the good DBR into a bad-quality DBR toward high pressures, thereby also clearly setting margins to the application of this pressure-induced tunability approach (unless one desires the simultaneous transition to weak coupling/low \( Q \) factor).

Other than the change in refractive index, minor contractions (shrinkage) at cryogenic temperature could change the optical properties of the air-Bragg structure. The possible change in mechanical properties such as shrinkage and brittleness may require experimental analysis and may limit the pressure-induced tunability of air-Bragg structures at cryogenic temperatures. Also, note that light absorption in actually transparent polymer layers could become a limiting factor for the \( Q \) factor of the cavity—expected to become relevant for large polymer layer thickness and layer pair numbers.

The cavity length of 2.6 \( \mu \)m, with \( \lambda \) being 620 nm, allows us to determine the cavity mode (C) \( q = 8 \). The cavity mode \( q = 8 \) clearly changes its spectral position upon application of pressure (Figure 4b), which compresses the overall multilayered (six pairs) air-Bragg structure. In the waterfall diagram of Figure 4b, the TMM calculated reflectivities for the microcavity with arbitrary increment of pressure in steps of 10 MPa are displayed. The resonance of the cavity mode was adjusted to be resonant with the 617 nm A-exciton mode in WS\(_2\) at room temperature by fine-tuning the cavity spacer thickness and performing the TMM calculations for this configuration in the absence of external pressure. This ensures one obtains directly resonance conditions at elevated temperatures around 300 K and also reaches a red photon–exciton detuning at low temperature, which is beneficial for pressure-based cavity mode tuning in strong-coupling measurements in cryogenic experiments. An example of the calculated strong-coupling situation in a WS\(_2\) air-Bragg microcavity for different pressure levels is displayed in Figure 5.

The theoretical reflectivity spectrum for each pressure setting is obtained by manually reading out the positions of the individual layers of the (compressed) structure from the FEA simulation results. Thus, the altered air-Bragg structure (with pressure-dependent layer thicknesses) in 1D representation can be fed into the TMM model. Accordingly, the \( Q \)-factors of the mode \( q = 8 \) at 30 and 40 MPa exhibit an unnatural trend, which results from the read-out uncertainties for the respective underlying layer structure visually delivered by the FEA simulation. In contrast, the expected blueshift of the mode is attributed to the compressed structure with reduced air-gap thicknesses, which is seemingly sufficient to obtain the tuning effect. Nonetheless, due to the increased thickness unproportionality in the polymer/air configuration for increased pressure levels, the resonance conditions in the cavity suffer and a gradually reduced \( Q \) factor is obtained.

In principle, the SiO\(_2\)/TiO\(_2\) DBR stopband width (150 nm) is much larger than that of the \( \frac{5\lambda}{4} \) air Bragg (40 nm), which allows one to practically shift the stopband of the air Bragg over a wider spectral region by external pressure. However, a large structural compression may lead to a relatively strong deformation of the air-Bragg configuration from the actual design, which

![Figure 4](image-url)

Figure 4. a) Theoretical \( Q \) factor of the cavity mode (\( q = 8 \)) as a function of applied pressure based on calculated reflectivity spectra shown in (b) as a waterfall diagram with constant vertical offset of 1. The thickness reduction of air layers in the polymer/air-Bragg structures alters the spectral position and \( Q \) factor of the cavity mode \( q = 8 \) due to the material structure deformation obtained through the uniformly applied pressure.
influences not only the spectral position of the cavity mode and stopband, but also the Q factor of the cavity mode (as shown in Figure 4). The second approach pursued utilizes a fully air-Bragg-based microcavity design (Figure 1b), and, in this study, the homogeneous external pressure is applied on the whole cavity structure (on its side bars). This particular scenario provides the unique opportunity to investigate light–matter coupling scenarios due to the flexibility with respect to mode detunings, i.e., the energy difference between cavity and emitter modes, in a substrate-independent fashion. Moreover, it can be used to insert suspended 2D-material sheets with support structures, if appropriately designed, as an additional tool to tweak the LMI by changing the position of the ML with respect to the standing electromagnetic (EM) fields inside the cavity. As a consequence of suspension, also the substrate-induced impurities and all other consequent effects get automatically eliminated.

In this configuration, the cavity spacer is similar to the first example proportionally reduced together with air gaps in the Bragg sections (6/7 layer pairs in the top/bottom reflector). Again, a gradual reduction of the Q factor is obtained (Figure 6a) and the overall cavity stopband experiences a comparable shift. Figure 6b shows the tuning of modes in the calculated reflectivity spectra of the air-Bragg microcavity system upon application of external pressure ranging between 0 and 50 MPa. The step-wise reduction of air layer thicknesses causes a controllable blueshift of the cavity mode’s spectral positions (q = 3 and 4), which is accompanied by a reduction of the Q factor with increasing pressure level.

The crucial stress analysis of the air-Bragg structures for tunability of cavity modes with sufficiently high Q factors let us conclude that the targeted strong light–matter coupling scenarios can be theoretically realized. Incorporating quantum dots, florescent dyes, or even TMDC monolayers in air-Bragg/DBR

Figure 5. Calculated angle-resolved reflection for air-Bragg/WS$_2$/planar-DBR microcavity. a) Calculated angle-resolved reflection spectrum (false-color contour diagram) for the 3/4 air-Bragg/DBR microcavity illustrating a Rabi splitting of 29 meV obtained with a cavity length of 0.77 μm. Upper (UP) and lower polariton (LP) branches labeled with exciton resonance (black horizontal line) of WS$_2$ at 2.01 eV featuring a hypothetical linewidth of 30 meV, for the bare cavity mode (q = 3). b) Calculated reflection spectra at various exciton–photon resonance detunings demonstrating tunable control over light–matter coupling with clear anticrossing behavior. The mode detuning is an effect of the gradual application of pressure upon the microcavity structure. In the model, the WS$_2$ monolayer is directly placed on the dielectric mirror’s top facet, on which the air Bragg including a cavity spacer is placed (see Figure 1a).

Figure 6. a) The influence of the applied pressure (indicated by blue arrows) on the calculated Q factor with schematic of the polymer/air-Bragg-reflector microcavity design (inset). b) Plot of calculated reflectivity spectra with constant vertical offset of 1, showing the tunability of the polymer/air-Bragg-reflector microcavity when a homogeneous pressure is applied (varied between 0 and 50 MPa).
and all-air-Bragg microcavities can open the path to flexible resonator–emitter systems for various LMI experiments. In addition, this approach delivers in situ control over LMI by an applied vertical force on the surface of the device (i.e., mechanical pressure), which provides the necessary mode tunability by compression of the microcavity structures. Inspired by these theoretical results, work is ongoing toward the optimization of the printing parameters for such air-Bragg structures to obtain the overall optical quality and mechanical stability along with the investigation of various approaches to systematically induce the necessary thickness-reducing deformations in polymer/air layers in a controlled and controllable fashion for larger and, foremost, predictable tunability of high-quality resonator modes.

4. Conclusion

Two spectrally tunable microcavity configurations based on polymer/air-Bragg reflectors (air Braggs) with an accessible open-cavity spacer were discussed for weak and strong LMI, such as with various types of nanomaterials, molecules as well as quantum dots. Building upon the capability of 3D nanoprinting these polymer/air layer-structured systems with submicrometer precision, this study explored the concept of mechanical-pressure-induced cavity mode shifts through air-Bragg-structure compression. Our modeling work indicates that by using state-of-the-art technology, one can in principle realize optical microcavity systems on demand for various spectral regions provided that the target wavelength is compatible with the printing precision and minimal feature size (voxel size) of the 3D nanoprinting technique. The crucial stress analysis based on FEA simulations reveals the tunable nature of the polymer/air-Bragg structures upon pressure application, leading to a controllable energy shift of the microresonator modes. Such a versatile light–matter interface (LMI) that can be conveniently deposited on different surfaces at the position of interest consists at minimum of one such “air-Bragg” reflector and can for the discussed designs theoretically exhibit Q factors up to 2500 with 6/7 layer-pair top/bottom air Braggs. This implies that different light–matter coupling scenarios with flexibility in the cavity–emitter resonance detuning, even after production, can be realized with the help of such polymer/air-based optical microcavities.

In the future, precise laser nanoprinting of (integrated) photonic structures directly on the chip will be a common practice, and an approach to achieve optical microreflectors and microresonators such as those presented here can be very useful in many specific scenarios, including for LEDs and photovoltaics, nanolasers and nonclassical light sources, optical filters or couplers and nonlinear optical elements, as well as optical sensing through LMI.

5. Experimental Section

Stress Analysis of CAD Structures: The stress analysis function provided by Autodesk Inventor Professional 2019 was used to determine the impact of vertical external pressure (force per area) on different polymer/air-Bragg structures using CAD models. The stress analysis function based on an FEA allows one to assign the applied force on the surface of the CAD model and to obtain mechanical deformation for every setting of externally applied force (represented by the double arrow in the shown figure) and under the influence of gravity (single arrow). The hereby obtained prediction of the overall structural response was later used to model reflectivity spectra (using manually extracted position changes of the layered structure for the given pressure level).

Calculation of Spectra: The targeted microreflector and microresonator systems were modeled using the TMM regarding their standing-wave light-field profile and reflectivity spectra. Based on theoretical data and considerations with chosen design parameters, reflectivity spectra toward strong light–matter coupling with a virtual 2D semiconductor inside the cavity were equally obtained. The optical properties such as reflection, transmission, and angle-resolved spectra of multilayered open cavity structures were calculated using the TMM-based simulation code as used in Wall et al.[46]

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.

Author Contributions

A.R.I. initiated the study and conceived the concepts for printed tunable microcavities for LMI with 2D materials and nanoparticles. C.C.P. performed the theoretical optical analysis using the TMM and simulated mechanical properties. C.C.P. and A.R.I. designed the structures, outlined the simulations, and evaluated the data. The results were summarized in a manuscript by both authors.

Data Availability Statement

Research data are not shared.

Keywords

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[1] K. Vahala, Optical Microcavities, World Scientific, Singapore 2004.
[2] I. Carusotto, C. Ciuti, Rev. Mod. Phys. 2013, 85, 259.
[3] A. V. Kavokin, J. J. Baumberg, G. Malpuech, F. P. Laussy, Microcavities, Vol. 1, Oxford University Press, Oxford, UK 2017.
[4] B. Kolaric, B. Maes, K. Clays, T. Durt, Y. Caudano, Adv. Quantum Technol. 2018, 1, 1800001.
[5] D. S. Dovzhenko, S. V. Ryabchuk, Y. P. Rakovich, I. R. Nabiev, NanoScape 2018, 10, 3589.
[6] X. C. Zhang, A. Shkurinov, Y. Zhang, Nat. Photonics 2017, 11, 16.
[7] J. Raimond, G. Rempe, in Quantum Information, Wiley, Hoboken, NJ, USA 2016, pp. 660–669.
[8] S. Slussarenko, G. J. Pryde, Appl. Phys. Rev. 2019, 6, 41303.
[9] A. M. Flatae, M. Burresti, H. Zeng, S. Nocentini, S. Wiegele, C. Parmeggiani, H. Kalt, D. Wiersma, Light Sci. Appl. 2015, 4, 282.
[10] F. Li, Y. Li, Y. Cai, P. Li, H. Tang, Y. Zhang, Adv. Quantum Technol., 2019, 2, 1900060.
[11] S. Reitzenstein, A. Forchel, J. Phys. D. Appl. Phys. 2010, 43, 03300.
[12] S. Wu, S. Buckley, J. R. Schaibley, L. Feng, J. Yan, D. G. Mandrus, F. Hatami, W. Yao, Yu. Vučković, A. Majumdar, X. Xu, Nature 2015, 520, 69.
[13] Y. J. Lu, C-Y Wang, J. Kim, H-Y. Chen, M-Y. Lu, Y-C. Chen, W-H. Chang, L-J. Chen, M-I. Stockman, C-K. Shih, S. Gwo, Nano Lett. 2014, 14, 4381.
[14] C. Weibuch, M. Nishioka, A. Ishikawa, Y. Arakawa, Phys. Rev. Lett. 1992, 69, 3314.
[15] J. P. Reithmaier, G. Sêk, A. Löffler, C. Hofmann, S. Kuhn, S. Reitzenstein, L. V. Keldysh, V. D. Kulakovskii, T. L. Reinecke, A. Forchel, Nature 2004, 432, 197.
[16] T. Yoshi, R. Scherer, J. Hendrickson, G. Khitrova, H. M. Gibbs, G. Rupper, C. Ell, O. B. Shechkin, D. G. Deppe, Nature 2004, 432, 200.
[17] J. M. Gérard, B. Sermage, B. Gayral, B. Legrand, E. Costard, V. Thierry-Mieg, Phys. Rev. Lett. 1998, 81, 1110.
[18] M. Bayer, T. L. Reinecke, F. Weidner, A. Larionov, A. McDonald, A. Forchel, Phys. Rev. Lett. 2001, 86, 3168.
[19] M. Boroditsky, R. Vrijen, T. F. Krauss, R. Caccioli, R. Bhat, E. Yablonovich, J. Light. Technol. 1999, 17, 2096.
[20] H. Deng, G. Weihs, C. Santori, J. Bloch, Y. Yamamoto, Science 2002, 298, 199.
[21] J. Kasprzak, M. Richard, S. Kundermann, A. Baas, P. Jeambrun, J. M. J. Staehli, V. Savona, P. B. Littlewood, B. Deveaud, L. S. Dang, Nature 2006, 443, 409.
[22] J. D. Plumhoff, T. Stöferle, M. Lai, U. Scherf, R. F. Mahrt, Nat. Mater. 2014, 13, 247.
[23] G. Lerario, A. Fieramosca, F. Barachati, D. Ballarini, K. S. Daskalakis, L. Dominici, M. De Giorgi, S. A. Maier, G. Gigli, S. Kéna-Cohen, D. Sanvitto, Nat. Phys. 2017, 13, 837.
[24] R. Butté, G. Delalleau, A. I. Tartakovski, M. S. Skolnick, V. N. Astratov, J. J. Baumberg, G. Malpuech, A. Di Carlo, A. V. Vakokin, J. S. Roberts, Phys. Rev. B: Condens. Matter Mater. Phys., 2002, 65, 205310.
[25] A. Rahimi-Iman, Polariton Physics, Vol. 229, Springer International Publishing, Cham, Switzerland 2020.
[26] R. F. Ribeiro, L. A. Martinez-Martinez, M. Du, J. Campos-Gonzalez-Angulo, J. Yuen-Zhou, Chem. Sci. 2018, 9, 6325.
[27] J. L. O’Brien, A. Furusawa, J. Vučković, Nat. Photonics 2009, 3, 687.