Electrically driven exciton-polariton optomechanics at super high frequencies

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(Dated: March 3, 2020)

Polaritons enable the resonant coupling of excitons and photons to vibrations in the application-relevant super high frequency (SHF, 3-30 GHz) domain. We introduce a novel platform for coherent optomechanics based on the coupling of exciton-polaritons and electrically driven SHF longitudinal acoustic phonons confined within the spacer region of a planar Bragg microcavity. The microcavity structure is designed to back-feed phonons leaking the spacer region thus leading to effective acoustic quality factors approaching 6200 at 20 GHz and products $Qf \sim 10^{14}$ Hz. Piezoelectrically generated phonons induce a huge modulation of the exciton-polaritons energies with peak amplitudes of up to 8 meV. The modulation is dominated by the phonon-induced energy shifts of the excitonic polariton component, thus leading to an oscillatory transition between the regimes of weak and strong light-matter coupling. These results open the way for polariton-based optomechanics in the non-adiabatic, side-band-resolved regime of coherent control.

The coherent coupling between photons and mechanical vibrations (termed optomechanics [1]) has experienced substantial theoretical and experimental advances since the initial investigations of parametric instabilities in Fabry-Perot interferometers [2] and of the coherent optical excitation of mechanical motion in MHz range [3]. In particular, the demonstration of strong optomechanical coupling in the MHz range [4], laser cooling of a microcavity (MC) to the mechanical ground state [5], quantum-coherent coupling of NIR photons and MHz phonons [6], and optomechanically induced transparency [7] constitute important landmarks in this field.

The strong-coupling between photons and quantum well excitons results in microcavity exciton-polariton (MP) quasiparticles, which inherit the photon-like low effective mass and long-range spatial coherence from the photonic component as well as the strong exciton-like nonlinearities [8]. MPs are solid-state analogues to ultra-cold atoms with nonlinear phenomena, e.g., Bose-Einstein condensation (BEC) [9], bistability and quantum correlations in the 10-300 K temperature range [10].

The strength of the polariton interaction with vibrations normally overcomes the one for photons since the photon-related radiation pressure mechanism becomes complemented by the strong deformation potential modulation of the excitonic resonances. [11] The acoustic modulation of MPs has so far only been demonstrated for sub-GHz monochromatic strain fields induced by electrically excited surface acoustic waves (SAWs) [12] and for transient strain fields with frequencies components in the several-MHz to THz range produced by short laser pulses [13]. In the latter case, one could reach the non-adiabatic regime, where the phonon-induced energy modulation amplitude $\Delta E$ exceeds both the phonon ($\Gamma_{ph} = \hbar \omega_{ph}/Q_{pol}$) and polariton ($\Gamma_{pol} = \hbar \omega_{pol}/Q_{pol}$) decoherence rates, thus leading to side bands in the optical spectrum shifted by multiples of the phonon energy. [14] [15]. In the previous expressions, $\hbar \omega_i$ and $Q_i$ denote the energy and quality factor of the polariton ($i = \text{pol}$) and phonon ($i = \text{ph}$) resonances, respectively.

MP optomechanics profits from the ability of planar (AlGa)As MCs to confine simultaneously light and phonons within the same spatial region. [16]-[18]. The latter relies on the approximately constant ratio between the impedances and propagation velocities for light and sound in Al$_x$Ga$_{1-x}$As alloys with different compositions $x$ [17]. As a consequence of the higher optical velocities, an (Al,Ga)As-based MC designed for near-IR photons also confines longitudinal acoustic phonons in the form of bulk acoustic waves (BAWs) with GHz frequencies [17]. The resonant enhancement of the optomechanical coupling in these MCs was demonstrated in Refs. [12] and [19] and attributed to the large photoelastic coupling at the MP resonances [20].

Previous optomechanical studies in planar MCs mostly employed phonons in the form of electrically excited, sub-GHz SAWs [21] or BAWs in the several GHz range stimulated either thermally or optically using short optical pulses. Here, we introduce a platform for electrically driven MP optomechanics in the SHF region (3-20 GHz) based on phonon generation and detection using high-frequency BAW resonators (BAWRs). The BAWR enables acoustic echo spectroscopy with a very high (over 90 dB) dynamic range [22]. The latter is important to unveil the distribution of the acoustic field within the samples, which results from the resonant coupling of BAWs modes confined in three coupled acoustic cavities: the main one within the MC spacer, a surface cavity between the upper and lower distributed Bragg reflectors (DBRs) and a bulk cavity formed by the front and back surfaces of the wafer. The back-feeding of BAWs into the main cavity results in electrically measured acoustic quality factors $Q$’s up to 6200 significantly higher than the ones expected from the DBR acoustic reflectivity. The strong acoustic field in the QW region induces a huge modulation of the MP energies, which reaches amplitudes (up
FIG. 1. Hybrid microcavity (MC) for polaritons and phonons. (a) Schematic cross-section of Sample A showing the spatial distribution of photon (red-shared region) and exciton-polariton fields (yellow). oDBR and aoDBR stand for the distributed Bragg reflectors (DBRs) acting as optical and optical and acoustic mirrors, respectively. Longitudinal bulk acoustic waves (BAWs) are generated by a ring-shaped bulk acoustic wave resonator (BAWR) driven by rf-voltage. The ring-shaped BAWR has an aperture for laser excitation of the MC. (b)-(c) Profiles for the acoustic displacement field $|u|$ calculated for the mode localized (b) at the sample surface (mode with $f_S = 6.36$ GHz) and (c) at the MC spacer ($f_{MC} = 6.83$ GHz, cf. thick arrows in (d)). (d) $s_{11}$ rf-scattering parameter of the BAWR (thick red curve) and calculated $s_{11}$ profiles for thicknesses $d_{ZnO}$ of the piezoelectric ZnO layer of the BAWR varying from 300 nm (top) to 180 nm (bottom curve) in steps of 20 nm (thin black lines). The shaded area indicates the spectral extent of the acoustic stopbands of the MC.

The thick red line in Fig. 1(d) displays the $s_{11}$ rf-scattering for the BAWR (corresponding to the rf power reflection coefficient) over a frequency range covering the acoustic stop-band region of the aoDBR (cf. shaded region). Two resonances (denoted as MC and S) are found within the stop band range. The thin curves are the corresponding finite-element calculations of the $s_{11}$ response for varying thicknesses $d_{ZnO}$ of the ZnO layer, which accurately reproduce the measured response for nominal thickness $d_{ZnO} = 240$ nm (thick line),[22, 23] While the MC mode is essentially insensitive to $d_{ZnO}$, the S mode shift towards lower frequencies with decreasing $d_{ZnO}$. This behavior arises from the fact that S-mode is confined between the upper aoDBR and the BAWR surface, while the MC mode is concentrated in-between aoDBRs, as illustrated by the calculated mode profiles of Figs. 1(b) and 1(c), respectively.

The time response obtained via a Fourier transformation of $s_{11}$ over the frequency range of the acoustic stop-band yields additional information about the interplay between the acoustic modes [cf. Fig. 2(a)]. The time trace is characterized by an exponentially decaying signal at short times [$<100$ ns, denoted as $TG_1$ in Fig. 2(a)] followed by a series of echoes delayed by $t_{rt} = 151 \pm 1$ ns (region $TG_2$). The echoes are associated with round-trips of BAWs reflected at the backside of the double-polished GaAs substrate. Indeed, by taking the LA phonon velocity in GaAs $v_{LA} = 4.7 \mu m/\mu s$ and the nominal substrate thickness $d_{sub} = 350 \pm 20 \mu m$, one obtains a round-trip time delay $2d_{sub}/v_{LA} = 149 \pm 15$ ns very close to $t_{rt}$. Although only 5 reflections are shown in Fig. 2(a), up to 9 echoes could be detected thus yielding a BAW lifetime exceeding 0.3 $\mu s$.

The spectral contributions of the individual acoustic...
The wide frequency range of low-frequency echoes in the TG1 and TG2 time (echoes in Fig. 2(a), which far exceeds the short transit time of the aoDBR also accounts for the long decay time of the cavity resonance mode of the upper aoDBR. The absence of the mode at $f_{MC}$ in the spectrum for the TG1 is probably due to the large background induced by incomplete suppression of the electromagnetic contribution at short echo delays.

A closer examination of the frequency response of the TG2 range reveals a frequency comb with the free spectral range (FSR) $\Delta f_{Sub} = 1/t_{1} = 6.4$ MHz [cf. Figs. 2(c)-(e), which correspond to the colored regions in Fig. 2(b)]. The frequency comb arises from constructive interference of BAWs after multiple round-trips through the substrate. The quality factors of the comb resonances reach values of $Q_{ph} \geq 2800$ at 6.937 GHz, which are considerably larger than the bare quality factor ($Q_{ph,b} = 172$) of the main cavity calculated from the reflectivity of the aoDBRs.

We now turn our attention to the interaction between BAWs and MPs formed by the strong coupling between the MC photons and excitons in the two InGaAs QWs inserted into the MC spacer of sample A (see Section SM3). Figure 3(d) displays spectral PL profiles as a function of the frequency applied to the BAW in the range of the $f_{MC}$ resonance, which shows a frequency comb with the same free spectral range as $s_{11}$ in Fig. 2(d). The sharp PL comb lines have an effective quality factor of approx. 5000. At the comb frequencies, the PL energy is modulated with amplitudes reaching up to $\Delta E = 8$ meV, which by far exceed the Rabi coupling energy. Fig. 3(e) shows that $\Delta E$ can be continuously tuned by changing the rf-power applied to the BAW.

In order to unveil the mechanisms responsible for the phonon-induced modulation of the MP energies, we compare in Figs. 3(a)-(c) time-averaged PL spectra of the MC recorded at different temperatures (thin blue lines) acquired under the excitation of a comb frequency in the $f_{MC}$ range (thick red lines). The InGaAs QWs in sample A are separated by a narrow (5 nm-thick) GaAs barrier, which tunnel-couples their excitonic states to produce bonding ($X_{1}$) and anti-bonding resonances ($X_{2}$). At temperatures above 50 K, these states are red-shifted and only weakly coupled to the cavity resonance (C), giving rise to the three PL peaks in Figs. 3(a) and (b) [further details in Section SM3]. The sinusoidal time-modulation of the excitonic energy levels with amplitude $\Delta E$ by the BAW leads to two maxima in the time-averaged PL intensity shifted by $\pm \Delta E$ with respect to the unperturbed excitonic energy. The red-shifted maximum is much weaker than the blue-shifted ones (dotted vertical lines) since the large detuning with respect to the photonic MC mode reduces their coupling to the mode. More importantly, the photonic mode remains essentially un

**FIG. 2. Acousto-electric response of a hybrid MC at 10 K.** (a) Time-dependence of rf BAWR reflection of sample A determined from the spectral response of the $s_{11}$ rf-scattering parameter in the 5.5-7.5 GHz spectral range. The multiple acoustic echoes $t_{i}$ (i = 1 to 5) result from acoustic reflections at the back surface of the substrate. (b) Spectral dependence of the echoes within the time ranges TG$_{1}$ (0-100 ns, orange) and TG$_{2}$ (150-550 ns, blue, encompassing three acoustic echoes) defined in (a). The grey area is the stopband range. Two acoustic modes can be seen within the stopband (see text for discussion). (c)-(e) Close-ups of the stopband range. Two acoustic modes can be identified by an inverse Fourier transformation of the time trace in Fig. 2(a) within the TG$_{1}$ and TG$_{2}$ delay regions [cf. spectra $s_{11,TG}$ displayed Fig. 2(b)]. The acoustic response at short times (TG$_{1}$ range) is dominated by the strong resonance at $f_{S} = 6.46$ GHz corresponding to the surface cavity resonance mode of Fig. 1(b). The confinement near the surface by the upper aoDBR also accounts for the long decay time of the echoes in Fig. 2(a), which far exceeds the short transit time (\(\sim 1/f_{S} = 0.15\) ns) across the BAWR. The spectrum of the TG$_{2}$ time range shows two peaks located on the wide a frequency range of low $s_{11,TG}$ response (gray shading). The latter is attributed to the acoustic stop band of the aoDBRs, which can be detected due to the high dynamic range and time resolution (or, equivalently, wide frequency response) of the BAWRs. The two peaks at $f_{S} = 6.46$ GHz and $f_{MC} = 6.94$ GHz are attributed to acoustic modes of the surface (S) and the main (MC) cavities, respectively, which become hybridized due to the finite reflectivity of the upper aoDBR. The absence of the mode at $f_{MC}$ in the spectrum for the TG$_{1}$ is probably due to the large background induced by incomplete suppression of the electromagnetic contribution at short echo delays.
Polariton-phonon interaction in a hybrid microcavity. Time-averaged PL spectra of sample A recorded in the absence (thin blue lines) and presence (thick red lines) of a BAW with frequency $f_{\text{BAW}} = 6.931$ GHz recorded at (a) 65 K, (b) 50 K, and (c) 10 K. $\Delta E$ denotes the energy modulation amplitude of the excitonic levels. (d) rf-frequency dependence of the PL recorded for a fixed rf-power $P_{\text{rf}} = 8$ dBm applied to the BAWR at 10 K, showing the effects of the frequency comb with $\Delta f_{\text{Sub}} = 6.4$ MHz. The inset displays the temperature (T) dependence of the energy modulation amplitude $\Delta E$. (e) rf-power dependence of the PL recorded for a fixed rf-frequency $F_{\text{rf}} = 6.9312$ GHz applied to the BAWR at 10 K.

Another interesting observation in Fig. 3 is the strong increase of $\Delta E$ with decreasing temperature (T) and fixed rf-excitation [cf. symbols in lower inset of Fig. 3(d)]. The superimposed thin line yields $\Delta E \propto 1/\sqrt{T}$. In a recent study, we showed that the acoustic propagation losses in similar GaAs substrates increase with temperature[26]. The large increase in $\Delta E$ with decreasing temperature is thus attributed to the reduction of acoustic losses.

Finally, phonons with significantly higher acoustic frequencies (approximately 20 GHz) can be confined in a MC with aoDBRs designed as a first-order reflector for a wavelength $\lambda_{ao} = \lambda_a$ (Sample B, cf. Methods). The electrical response of this sample [cf. Fig. 4(a)] shows again the signature of the surface ($f_S$) and MC mode ($f_{MC}$) at a frequency approximately three times higher than in Fig. 1(d). A detailed analysis of the $s_{11}$ response shows that a frequency comb in within the $f_{MC}$ frequency range consisting of resonances with a quality factor $Q_n = 6200$ and huge products $Qf \sim 10^{14}$ Hz [cf. Sec. SM2]. Driving the BAWR within the $f_{MC}$ frequency range (19.92–19.97 GHz) induces again a comb of resonances in the PL spectrum, as illustrated in Fig. 4(b), which modulates the excitonic energies with an ampli-

perturbed thus indicating that the energy modulation is dominated by photo-elastic contribution arising from the modulation of the excitonic resonances. At lower temperatures, the excitonic lines blue-shift and strongly couple to the photonic mode to form the lower (LP), middle (MP), and upper polariton states (UP) indicated in Fig. 3(c) [cf. Sec. SM3]. The BAW-induced energy modulation in Figs. 3(c) and 3(d) is sufficiently large to blue-shift the excitonic levels beyond the regime of strong coupling, thus leading to the appearance of a shoulder at a huge blueshift of approximately $\Delta E = 8$ meV [dotted vertical line in Fig. 3(c)].

The modulation of the exciton energy is attributed to the deformation potential mechanism, which yields $\Delta E = (a_h)\eta_u u_{zz,0}$. Here, $\eta_u u_{zz,0}$ is the amplitude of the strain field at the QW position, which is factor $\eta_u \approx 0.8$ smaller than the amplitude $u_{zz,0}$ of the strain field in the MC spacer (see Sec. SM1), and $a_h \approx 10$ eV is the hydrostatic deformation potential for electron-hole transitions. From the $\Delta E$ value in Fig. 3(c) we obtain $\eta_u u_{zz,0} = 8 \times 10^{-4}$. Since the amplitude of the phonon displacement field $u_{zz,0} \hat{z}$ is given by $u_{zz,0} = (\lambda_a/2\pi)u_{zz,0}$, the effective opto-mechanical coupling can be defined as $g_{\text{eff}} = \Delta E/u_{zz,0} = (\eta_u 2\pi/\lambda_a) a_h = 18$ THz/nm.
FIG. 4. Optomechanical response of a hybrid MC for 20 GHz BAWs. (a) $s_{11}$ rf-scattering parameter for sample B showing the surface ($f_s = 19.6$ GHz) and MC ($f_{MC} \approx 20$ GHz) acoustic resonances. (b) The rf-frequency dependence of the PL recorded for a fixed rf-power $P_{rf} = 24$ dBm applied to the BAWR displaying the effect of the BAW on the PL emission. (c) Time-averaged PL spectra recorded at 10 K in the absence (thin blue line) and presence (thick red line) of a BAW with frequency $f_{BAW} = 19.926$ GHz [cf. red arrow in (b)]. LP and UP denote the polariton exciton-like and photon-like branches, respectively. All measurements were carried out at 10 K.

Conclusion, we have introduced a novel platform for electrically driven GHz polariton-optomechanics in the SHF range based on the coupling between polaritons and electrically generated BAWs confined in a planar MC. This platform profits, on one side, from the long effective lifetimes of phonons confined in the MC, which less susceptible to adverse surface degradation of the quality factor and yield huge $Qf$ products exceeding $10^{14}$ Hz. On the other side, it exploits the high sensitivity of the excitonic resonances to confined strain field, which enables the modulation of the polaritonic energies over a range exceeding the light-matter Rabi coupling strength and reaching effective optomechanical couplings exceeding $g_{eff} \sim 20$ THz/nm. As a prospect, the results open the way to resonant optomechanics in the non-adiabatic regime, side-band limited, using polariton condensates with spectral linewidths ($< 10 \mu$eV) considerably smaller than the ones for the sub-condensation regime reported here. In particular, polariton linewidths below the inverse phonon frequencies will enable the study of interesting phenomena such as mechanical self-oscillations and phonon lasing. Finally, the recent developments in MC structures have demonstrated the feasibility of zero-dimensional confinement of polaritons and phonons in structured MCs. Electrically driven, high BAWs in these structures thus provide access to the single-phonon regime at temperatures (of $\sim 1$ K) substantially larger than for sub-GHz vibrations.

I. METHODS

The hybrid planar (Al,Ga)As MCs for the polariton-phonon confinement [cf. Fig. 1(a)] were grown by molecular beam epitaxy. In sample A [cf. Fig. 1(b)], the outer optical DBR (oDBR) stacks consists of six pairs of $\lambda/4$-thick GaAs/Al$_{0.85}$Ga$_{0.15}$As layers and provide optical confinement. Here, $\lambda = \lambda_0/n_i$ is the optical resonance wavelength in medium i with refractive index $n_i$ for a free space wavelength of $\lambda_0 = 850$ nm. The inner acoustic DBR (aoDBR) stacks ensure acoustic as well as optical confinement. It consist of 10 GaAs/Al$_{0.85}$Ga$_{0.15}$As layer pairs with thickness per layer of $3\lambda/4$, thus acting as a first order acoustic DBR for longitudinal phonons with a center wavelength $\lambda_a = 250$ nm and as a third order optical grating for a free space optical wavelength $\lambda_0$. The spacer region of sample A concurrently acts as an optical $5\lambda/2$ and as an acoustic $2\lambda_a/2$ MC spacer. This region embeds two 15 nm-thick In$_{0.04}$Ga$_{0.96}$As quantum wells (QW) separated by a 5 nm-thick GaAs barrier. The latter are positioned at a depth corresponding to an antinode of both the optical and the acoustic strain fields inside the MC spacer (see further details in Sec. SM1 of the Supplementary Material, SM). Transfer matrix simulations were used to estimate an optical quality factor $Q_o = 5600$ and a Rabi splitting $\Omega_{\text{Rabi}} = 4.3$ meV at 10 K. The measured $\Omega_{\text{Rabi}}$ is about 2 meV (cf. Sec. SM3). Similar simulations for the acoustic field yield a bare (i.e., neglecting BAW reflections at sample borders, see below for details) acoustic quality factor $Q_a = 172$.

Sample B consists of a $\lambda/2$ wide spacer including a single, 15 nm thick In$_{0.04}$Ga$_{0.96}$As QW. The spacer is sandwiched between DBRs with $\lambda/4$ layers, which act...
as first order reflectors for 840 nm phonons and 20 GHz phonons.

The BAWs were excited by bulk acoustic wave resonators (BAWRs) deposited on the sample surface, as illustrated schematically in Fig. 1(a). The active region of the BAWRs on sample A (sample B) consists of a nominally 260 nm-thick (70 nm for sample B) textured ZnO film sputtered with the hexagonal c-axis oriented perpendicular to the MC surface. This piezoelectric film is sandwiched between two 50 nm thick-metal contacts. A special feature of the BAWR design is the ring-shape geometry with apertures in the bottom and top contacts for optical access to the underlying MC (cf. Sec. SM4). The piezoelectrically active area is thus defined by the overlap region of the top and bottom electrodes. The piezoelectrically active area is thus defined by the overlap region of the top and bottom electrodes. The piezoelectrically active area is thus defined by the overlap region of the top and bottom electrodes.

The piezoelectrically active area is thus defined by the overlap region of the top and bottom electrodes. The electrical response of the BAWRs was measured using a vector network analyzer with time-gating capabilities (cf. Sec. SM2). The photoluminescence (PL) studies were carried out at 10 K in a optical cryostat with rf-cables for the BAWR excitation. Optical excitation was provided by a 651 nm pulsed semiconductor laser focused at the center of the BAWR aperture.

Authors contributions: A.S.K. has participated in the inception of the idea, proposed the design of the transducer aperture-electrodes, carried out all optical and electrical measurements and analyzed data. D.H.O.M. has fabricated acoustic devices. K.B. has designed (using optical and acoustic transfer matrix simulations) and fabricated the MC sample, and critically reviewed the manuscript. P.V.S has proposed the idea, provided finite element method acoustic simulations and participated in critical discussions. A.S.K. and P.V.S. have equally contributed to the analysis of the results as well as to the preparation of the manuscript.

Acknowledgements: We thank Dr. Timur Flissikowski for discussions and for a critical review of the manuscript. We also acknowledge the technical support from R. Baumann, S. Rauwerdink, and A. Tahraoui in the sample fabrication process. We acknowledge financial support from the German DFG (grant 359162958), the QuantERA grant Interpol (EU-BMBF (Germany) grant nr. 13N14783), and FAPESP (Brazil, grant 2017/24311-6).

Competing interests: Authors declare no competing interests.

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Electrically driven exciton-polariton optomechanics at super high frequencies

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SM1. FIELD DISTRIBUTION IN HYBRID MICROCAVITIES

The modulation of the quantum well (QW) energy levels by the strain field \( u_{zz} = \partial u/\partial z \) of the BAW is the dominating mechanism determining the opto-mechanical coupling in these structures. Here, \( u = (0, 0, u_z) \) is the BAW displacement field as a function of the \( z \) coordinate perpendicular to the MC surface. Optimization of this coupling requires, therefore, that the QWs embedded in the microcavity (MC) spacer are placed close to the anti-nodes of both the optical and the acoustic strain fields.

It turns out that the requirement stated above can never be strictly satisfied. In Al\(_x\)Ga\(_{1-x}\)As alloys, the coincident ratio between the light and sound velocities as well as between the inverse acoustic impedance is approximately independent of the composition \( x \) mentioned in the main text also implies that the anti-nodes of the acoustic (\( u_z \)) and optical field (\( F_x \), assumed to be polarized along the surface direction \( x \)) occur at the same \( z \) coordinate \([17]\). The anti-nodes of \( u_z \) are, however, nodes of \( u_{zz} \), thus implying in a vanishing modulation of the excitonic energy.

![Figure SM1](image-url)

FIG. SM1. (a) Layer structure of the hybrid microcavity (Sample A). Depth profiles within the spacer region of the hybrid microcavity of the (b) optical field \( F_x \) at the photonic resonance energy, where \( x \) is the polarization direction on the MC surface, (c) refractive index, \( n \), and (d) normalized acoustic strain field \( u_{zz} \) for the acoustic resonance frequency \( f_{MC} = 6.9 \). The green band designates depth of the two quantum wells (QWs).

Fortunately, a very good matching of \( u_{zz} \) and \( F_x \) can still be achieved in the hybrid MC of sample A by slightly displacing the QWs with respect to the anti-nodes of \( u_{zz} \). Figure SM1(b) and (d) shows calculations of the optical
(\(F_x\)) and acoustic (\(u_{zz}\)) field distributions within the spacer of the MC [cf. Fig. [SM1(a)]] carried out using a transfer matrix approach. Figure [SM1(c)] shows, for reference, the depth modulation of refractive index \(n\) in the same regions indicating the position of the QWs. These plots show that the anti-nodes of \(u_{zz}\) coincide with the nodes of \(F_x\). Note that the separation between the QWs is much smaller than the wavelength of both the optical and acoustic fields, so that they can be considered to be subjected to the approximately the same field amplitude. The middle \(z\) coordinate of the two QWs is slightly shifted away from the anti-node of \(u_{zz}\) to match an anti-node of \(F_x\). The strain field at the QWs is still about \(\eta_s = 80\%\) of its maximum value, so that the small shift only marginally reduces the opto-electronic coupling.

A similar approach was used in Sample B: this sample contains a single (In,Ga)As QW, which was slightly displaced from the anti-nodes of the optical field to ensure a higher coupling to the acoustic field.

**FIG. SM2.** (a) Electrical response of the BAWR on sample A at 300K. The red curve shows the \(s_{11}\) scattering parameter for a BAWR on a bare GaAs substrate, while the blue one gives the response of a device on a MC (Sample A). Both devices have nominally identical ZnO thickness of 260 nm. The gray-shaded area designates the spectral range of acoustic stopband created by the aoDBR displayed Fig. 1(a) of the main text. The two modes within the stopband correspond to the MC acoustic mode with \(f_{MC} = 6.9\) GHz and the surface mode \(f_S = 6.4\) GHz confined between the BAWR surface and the upper aoDBR. (b) Simulated acoustic reflectivity of the MC with a BAWR device on its surface.

**SM2. FREQUENCY RESPONSE OF BULK ACOUSTIC RESONATORS**

Figure [SM2(a)] compares the frequency response of BAWRs deposited on a plain (001) GaAs substrate (red line) with the and on top of the MC structure of Sample A. In the former case, the rf-frequency response is dominated by a single broad resonance with a frequency bandwidth of approximately 1 GHz. On the surface of the MC, the BAWR develops a frequency spectrum characterized by multiple resonances [cf. Fig. [SM2(a)]]. As discussed in the main text, one can identify two acoustic modes - \(f_S\) and \(f_{MC}\), both located within the acoustic stopband of the MC. In this case, the ZnO thickness was larger than the nominal one, resulting in the MC acoustic stopband localized on the shoulder of the BAWR peak [red line in Fig. [SM2(a)]]]. The experimental results are in agreement with the transfer-matrix simulations, cf. Fig. [SM2(b)] that accurately reproduce all spectral features of acoustic response.

Figures [SM3(a)] and [SM3(a)] compare the electrical response of a BAWR on sample B in the frequency and time domains, respectively. The measurements were recorded on a BAWR with circular (rather than ring-shaped) electrodes with a diameter of 20 \(\mu\)m: at the high frequencies, the rf-spectra of these devices have much less noise than for the
ring-shaped ones. In agreement with the results for the 7 GHz devices of Fig. SM2, the $s_{11}$ spectra shows a sharp dip associated with the MC mode ($f_{MC}$) as well as echoes resulting from multiple reflections of the BAW at the sample boundaries. The inset in Fig. SM3(a) displays the acoustic reflection $s_{11,TG}$ determined by Fourier back-transforming the spectrum in (b) within the delay region of the acoustic echoes (i.e., for long delays). The frequency comb within the $f_{MC}$ range contains sharp lines with a line width yielding an acoustic quality factor of $Q_a = 6200$.

SM3. TEMPERATURE DEPENDENCE OF THE OPTO-ELECTRONIC RESONANCES

The nature of the light-matter coupling in the MCs can be accessed by studying the temperature dependence of the PL. As mentioned in the main text, two InGaAs QWs in Sample A are (unintentionally) tunnel-coupled. This coupling produces excitonic bonding ($X_1$) and anti-bonding ($X_2$) resonances, which are red-shifted with respect to the photonic mode ($C$) at temperature above 50 K. As a consequence, PL spectra recorded at temperatures above 50 K shows three branches, as illustrated in Fig. SM4. As the temperature reduces, the excitonic resonances blue-shift and strongly couple to the photonic mode, giving rise to the lower (LP), middle (MP), and upper (UP) polariton branches indicated in Fig. SM4(a).

The energy dispersion of the $X_1$, $X_2$, and $C$ obtained from angular-resolved PL spectra and displayed Figs. SM4(b)-(e) for different temperatures gives further evidence for the strong coupling between the excitonic and photonic resonances. At temperatures above 50 K the photonic resonance shows a strong dispersion, which contrast with the essentially flat dispersion of the excitonic states. This behavior is typical for excitonic resonances in the regime of the weak-coupling to photonic modes. At lower temperatures [cf. Figs. SM4(d)-(e)], all resonance lines are dispersive, thus showing that they couple to form polaritons. By fitting the angular-resolved PL map at 10 K to a model of three coupled resonances, we obtain a light-matter coupling strength $\omega_{Rabi} = 2 \pm 0.3$ meV.

SM4. LATERAL FIELD DISTRIBUTION IN RING-SHAPED BAWR

The results in the main text prove that the MCs confine BAWs in the direction perpendicular to the surface. Here, we show that the ring geometry of the BAWR displayed in Fig. SM5(a) confines the acoustic field in the aperture for light access, thus increasing the acoustic field while providing a favorable geometry for optical access to the active region of the MCs (i.e., the MC spacer containing the QWs).

The investigations of the lateral distribution of the BAW field were carried out by exciting polaritons in Sample A using a 631 nm pulsed laser diode focused onto the center of a BAWR aperture, as shown in Fig. SM5(a). The MHz-pulsed electrical output of the laser diode controller was used to trigger the rf generator to deliver 1 ns pulse trains of a few uW power to the BAWs. The PL signal was imaged on the slit of a single pass spectrometer, producing spatially resolved PL spectra across the BAWR aperture. In order to rule out the heating effect we first measured PL...
FIG. SM4. Temperature dependence of the photoluminescence (PL) of the hybrid MC (Sample A). (a) Temperature dependence of the PL spectrum. \(X_1\) and \(X_2\) are excitonic resonances of the coupled InGaAs QWs, which couple to the photonic (C) mode of the MC to form the lower (LP), middle (MP) and upper (UP) states at low temperatures. Momentum resolved PL at (b) 10 K, (c) 30 K, (d) 55 K and (e) 70 K. Below 50K the system is in the strong-coupling regime. The solid lines in (e) are three coupled oscillator fits to the data. The dashed lines are bare energies. The calculated Rabi energy \(\Omega_{\text{Rabi}} = 2 \pm 0.3\) meV.

with acoustic \((f_{rf} = 6.9247\) GHz\) and laser pulses driven out-of-phase. The corresponding image shows no spectral modification of the PL collected within the confines of the BAWR aperture [cf. Fig. SM5(b)]. The studies were carried out at 50 K, where the excitonic lines \((X_1\) and \(X_2\) in sample B) are red-shifted with respect to the phononic mode (C). When the laser pulses are in phase with the rf ones (the in-phase condition), we observe a large spectral change in the detected PL [cf. Fig. SM5(c)]. The most pronounced change is the apparent broadening of the spectrum due the modulation of the excitonic resonances with an amplitude \(\Delta E\). A comparison of the out-of-phase and in-phase spectra at the aperture center shows that the main changes arise from the acoustic energy modulation of the excitonic levels with the amplitude \(\Delta E\) indicated in the plot [cf. Fig. SM5(c)]. In addition, the acoustic modulation induces a decrease of the time-integrated PL intensity since it, in average, energetically shifts the excitonic modes away from the photonic resonance.

The dashed line in Fig. SM5(c) is a guide-to-the-eye following the maxima of the exciton-related PL intensity, which shows that that \(\Delta E\) slight increases towards the center of the aperture, thus indicating that the ring-geometry concentrates the acoustic field in the center of the aperture.
FIG. SM5. Photoluminescence (PL) spectroscopy in the hybrid MC of Sample A with ring-shaped BAWR at 50 K. (a) Optical micrograph of the ring-shaped BAWR indicating the 635 nm laser excitation spot focused at the center of the BAWR aperture. (b)-(c) Maps of PL intensity as a function of energy (horizontal axis) and position along the slit (vertical axis) without (b) and under BAW excitation of the acoustic MC mode $f_{\text{MC}} = 6.9247 \text{ GHz}$ (c). These maps were recorded by collecting the PL emitted within the dashed rectangle in (a). (d) Comparison of PL spectra recorded in the center of the BAWR aperture in the absence (blue) and presence of the BAW (red). The spectra were produced by spatial integration over the regions delimited by dashed lines in (b) and (c), respectively. $\Delta E$ is the energy amplitude modulation of the excitonic resonances.