Polariton Bonanza

Oct 30, 2025

Spenser Talkington

What do we want to apply io theory to?

- 1. models that illustrate the key features of the formalism
- 2. well studied models, such as the Hopfield exciton-polariton model
- 3. physically plausible models?
    - 2D vdw magnets seem interesting, but the focus of the current work is the output light rather than the material in the cavity

The "Polariton Panorama" of Basov + Rubio

- Reasonable models
  - Higgs polaritons [12-14]
  - Exciton polaritons [138-145]
  - Magnon polaritons [274-275]
  - Phonon polariton [198, 322-3]
    - Either direct coupling or raman
  - ~~Plasmon polaritons [345-347]~~
  - Landau polaritons [268-269, 460-461]
  - Trion polaritons [494-5]

D. N. Basov*, Ana Asenjo-Garcia, P. James Schu

Polariton panorama

https://doi.org/10.1515/nanoph-2020-0449
Received August 5, 2020; accepted October 2, 2020;
published online November 11, 2020

Abstract: In this brief review, we summarize and elaborate on some of the nomenclature of polaritonic phenomena and systems as they appear in the literature on quantum materials and quantum optics. Our summary includes at least 70 different types of polaritonic light–matter dressing effects. This summary also unravels a broad panorama of the physics and applications of polaritons. A constantly updated version of this review is available at https://infrared.cni.columbia.edu.

Higgs and CDW (amplitude) Polaritons

- Already worked out, could do similar for CDW materials like $TiSe_2$
- Double photon absorption

Exciton polaritons

- Well established, e.g. PRL 69, 3314 (1992); RMP 85, 299 (2013)
- Hopfield model (PR 112, 1555 (1958)); see also PRB 72, 115303

$$H = \sum_{\mathbf{k},\lambda_\perp} \Bigg(\hbar c|\mathbf{k}|(a_{\mathbf{k},\lambda}{}^* a_{\mathbf{k},\lambda} + \tfrac{1}{2}) + \hbar\omega_0 (b_{\mathbf{k},\lambda}{}^* b_{\mathbf{k},\lambda} + \tfrac{1}{2})$$

$$+ \frac{i\hbar\omega_0{}^2 (4\pi\beta)^{\frac{1}{2}}}{2(c|\mathbf{k}|\omega_0)^{\frac{1}{2}}} \times [(a_{\mathbf{k}\lambda}{}^* b_{\mathbf{k}\lambda} - a_{\mathbf{k}\lambda} b_{\mathbf{k}\lambda}{}^*) + (a_{-\mathbf{k}\lambda} b_{\mathbf{k}\lambda} - a_{-\mathbf{k}\lambda}{}^* b_{\mathbf{k}\lambda}{}^*)]$$

$$+ \pi\beta\omega_0{}^2 \frac{\hbar}{c|\mathbf{k}|} \times [a_{\mathbf{k}\lambda} a_{\mathbf{k}\lambda}{}^* + a_{\mathbf{k}\lambda}{}^* a_{\mathbf{k}\lambda} + a_{\mathbf{k}\lambda}{}^* a_{-\mathbf{k}\lambda}{}^* + a_{-\mathbf{k}\lambda} a_{\mathbf{k}\lambda}] \Bigg),$$

Often k=0 is enough

- CrSBr, NiPS3, MnPS3 have excitons, but may need extra ingredients to fully explain their phenomenology

Can be in many materials, including WSe2 (PRB 94, 081402 (2016))

Magnon polaritons (direct coupling)

- In YIG,e.g. PRB 94, 224410 (2016) and PRL 120, 057202 (2018)

PRL 130, 046703 (2023)

For a small YIG sphere driven by a microwave field with frequency ω_d, when its [100] crystallographic axis is aligned parallel to the static magnetic field, the cavity magnonics system has the Hamiltonian (setting $\hbar = 1$) [25]

$$H = \omega_c a^\dagger a + \omega_m b^\dagger b + K b^\dagger b b^\dagger b + g_m(a^\dagger b + a b^\dagger) + \Omega_d(b^\dagger e^{-i\omega_d t} + b e^{i\omega_d t}), \quad (1)$$

where $a^\dagger(a)$ is the creation (annihilation) operator of the cavity photons at frequency ω_c, $b^\dagger(b)$ is the creation (annihilation) operator of the Kittel-mode magnons at frequency ω_m, and Ω_d is the drive-field strength. As shown in [25], the Kerr term $K b^\dagger b b^\dagger b$, with a positive coefficient $K = \mu_0 K_{\mathrm{an}} \gamma^2/(M^2 V_m)$, is intrinsically due to the magnetocrystalline anisotropy in the YIG material. Here, μ_0 is the magnetic permeability of free space, K_{an} is the first-order anisotropy constant, $\gamma = g\mu_B/\hbar$ is the gyromagnetic ratio (with g being the g factor and μ_B the Bohr magneton), M is the saturation magnetization, and V_m is the volume of the YIG sphere. Note that the Kerr effect is strengthened when reducing V_m.

There are also old works by D.L. Mills and R.E. Camley
On magnon polaritons but they don't use second quantization
Instead they study the microscopic magnetization dynamics

Magnon polaritons (indirect coupling)

- We expected that there might be indirect coupling
  - E.g. a photon annihilating to create a bimagnon
  - E.g. a raman process creating a q=0 magnon
- Curiously I haven’t found these in the literature

- PRR 4, 013101 (2022) briefly touches on bimagnons but doesn’t do so in second quantization

Phonon polaritons (direct)

- Optical phonons?
  - See Mills and Burstein Rep. Prog. Phys. 37 817 (1974)
  - 2^{nd} quantized expression is basically the same as for excitons

- $SrTiO_3$, $BaTiO_3$ (Paraelectric → ferroelectric)—alternate approach
  - Couple to electric order and then drive the phonon

Phonon polaritons (indirect)

- Observed in GaP by Henry and Hopfield, PRL 15, 964 (1965)
  - Also observed in GaP in PRL 17, 1265 (1966)
  - Some theory by E. Burstein (Penn) Solid State Comm. 6, 407 (1968)

- Theory is more clearly laid out in Solid State Comm. 102, 207 (1997), PRB 65, 144304 (2002), and Nature Physics 7, 854 (2011)
- Seen in other materials too… Ti2O3, LaAlO3, etc

pump. The simplest Hamiltonian of interest to our problem is

$$H = \sum_{bk} \epsilon_{bk} c^\dagger_{bk} c_{bk} + \frac{1}{2}\sum_q |P_q^2| + \Omega_q^2 |Q_q^2| + \mathcal{V}^{-1/2} \sum_{kk'} \sum_{bb'} \Xi^{bb'}_{kk'} Q_{k-k'} c^\dagger_{bk} c_{b'k'} + V(t). \quad (4)$$

$c^\dagger_{bk}$ and c_{bk} are electron creation and annihilation operators for the state of energy ϵ_{bk}, wavevector $\mathbf{k}$ and band index b. Q_q is the amplitude of the phonon of wavevector $\mathbf{q}$ and frequency Ω_q and P_q is the associated canonical momentum. $\Xi^{bb'}_{kk'}$ are matrix elements of the electron–phonon interaction and $\mathcal{V}$ is the volume. The

Can truncate to small q/k because of speed of light

Landau polaritons

- GaAs in Li, ..., J. Kono, Nature Photonics 12, 324 (2018)
- Also in GaAs in Bagliani, ..., J. Faist Nature Physics 15, 186 (2019)

$$\hat{H} = \hat{H}_{\mathrm{CR}} + \hat{H}_{\mathrm{cav}} + \hat{H}_{\mathrm{int}} + \hat{H}_{A^2}$$

$$\hat{H}_{\mathrm{CR}} = \hbar\omega_{\mathrm{c}}\hat{b}^{\dagger}\hat{b}$$

$$\hat{H}_{\mathrm{cav}} = \sum_{n_z=1}^{\infty}\sum_{\xi=\pm}\hbar\omega_{\mathrm{cav}}^{n_z}\hat{\mathrm{a}}_{n_z,\xi}^{\dagger}\hat{\mathrm{a}}_{n_z,\xi}$$

They then truncate to just one cavity mode!

$$\hat{H}_{\mathrm{int}} = \sum_{n_z=1}^{\infty} i\hbar\bar{g}_{n_z}[\hat{b}^{\dagger}(\hat{\mathrm{a}}_{n_z,+} + \hat{\mathrm{a}}_{n_z,-}^{\dagger}) - \hat{b}(\hat{\mathrm{a}}_{n_z,-} + \hat{\mathrm{a}}_{n_z,+}^{\dagger})]$$

$$\hat{H}_{A^2} = \sum_{n_z=1}^{\infty}\sum_{n_z'=1}^{\infty}\frac{\hbar\bar{g}_{n_z}\bar{g}_{n_z'}}{\omega_{\mathrm{c}}}(\hat{\mathrm{a}}_{n_z,-} + \hat{\mathrm{a}}_{n_z,+}^{\dagger})(\hat{\mathrm{a}}_{n_z',+} + \hat{\mathrm{a}}_{n_z',-}^{\dagger})$$

Trion polaritons

- MoSe2 in Dhara, ..., A. Vamivakas Nature Physics 14, 130 (2018)
- Also MoSe2 in Nature Communications 11, 3589 (2020)

To understand the microscopic mechanism responsible for the observed inverted dispersion relation and the negative trion mass, we introduce the following Hamiltonian written in momentum space

$$H = \sum_{k} \Delta_k^{\mathrm{el}} c_k^\dagger c_k + \sum_{k,l} E_k^l \Gamma_{lk}^\dagger \Gamma_{lk} + \sum_{k} \omega_k^{\mathrm{tr}} \psi_k^\dagger \psi_k + v_2 \sum_{k,q} (a_k c_q \psi_{k+q}^\dagger + \mathrm{h.c.}) + v_3 \sum_{k,q} (\Gamma_{2,k} c_q \psi_{k+q}^\dagger + \mathrm{h.c.}) \quad (1)$$

where $c_k^\dagger$ (c_k), $a_k^\dagger$ (a_k), $\psi_k^\dagger$ (ψ_k), and $\Gamma_{l,k}^\dagger$ ($\Gamma_{l,k}$) are the electron, photon, trion, upper ($l=1$) and middle ($l=2$) polariton creation (annihilation) operators, respectively; $\Delta_k^{\mathrm{el}}, \omega_k^{\mathrm{tr}}, E_k^1, E_k^2$, are the bare electron, trion, upper, and middle polariton resonance energies. v_2 quantifies the interaction strength of the cavity photon, electron and trion and v_3 quantifies the interaction strength of the middle polariton, the

They keep the k index explicit throughout...