Electromagnetic Radiation in quantum metamaterial:Realization of $\mathcal{PT}$-symmetric quantum metamaterial by means of the Self–induced transparency

Nikos Lazarides[1], George Tsironis[1,3] and Zoran Ivić[1,2,3].

[1] CQCN, Department of Physics, University of Crete,Heraklion, Greece
[2]"Vinča" Institute of Nuclear Sciences, University of Belgrade, Serbia
[3]National University of Science and Technology MISiS, Moscow, Russia

Quantum Metamaterials & Quantum Technology 2016
Workshop, 20-24 June 2016, Spetses, Greece

Outline

Collaboration and support

- Nikos Lazarides[1],
- George Tsironis[1,3],
- Zoran Ivić[1,2,3],
- Andrei Malishevski
- [1] CQCN, Department of Physics, University of Crete,Heraklion, Greece
- [2]"Vinča" Institute of Nuclear Sciences, University of Belgrade, Serbia
- [3]National University of Science and Technology MISiS, Moscow, Russia
- [4] Department of Physics, School of Science and Technology, Nazarbayev University, 53 Kabanbay Batyr Ave., Astana 010000, Kazakhstan

Support

- European Union Seventh Framework Programme (FP7-REGPOT-2012-2013-1) under grant agreement no 316165,
- Serbian Ministry of Education and Science under Grants No. III-45010, No. OI-171009,
- Ministry of Education and Science of the Republic of Kazakhstan (Contract No. 339/76-2015),
- Ministry of Education and Science of the Russian Federation in the framework of the Increase Competitiveness Program of NUST "MISiS"(No. K2-2015-007)

Outline

Main idea: Realization of the $\mathcal{PT}$–symmetric QMM via Self–induced transparency

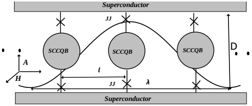
Merging the two novel fundamental concepts in modern physics

- quantum meta–materials
  - Artificial media built of periodically arranged artificial atoms
  - Unique optical properties which provide the means to control the light propagation through the media.
- $\mathcal{PT}$–symmetry
  - Non–Hermitian Hamiltonians invariant under the parity–time reversal possesses real spectrum
  - $[\mathcal{PT}, H] = 0$
  - $\mathcal{P}$–parity $x \to -x$, $\mathcal{T}$–time reversal: $t \to -t$, $i \to -i$
    - implications
- Possible benefit: the extension of the concept of QMM,
- further improvement
  - of the quantum-based electronic devices
  - quantum information processing

Outline

Reminder

- *Self–induced transparency* and *superradiance* in QMM
- Ivić, Lazarides, Tsironis, arXiv:1509.07662 [cond-mat.mes-hall]
    - Device: 1D transmission line built of SCC–qubits embedded in superconducting microwave resonator
        - QMM is transparent if the radiation power exceeds some critical value
        - Dicke superradiance



- Reshaping of initial "beam": output radiation attains soliton form
- Pulse features are determined by preparation of "medium"
    - Initial conditions: collection of "absorbers", "emitters" or their mixture
    - Values of parameters
- Reshaped pulse is delayed–slowing down of EM radiation
    - Possible manipulation with light–storage of memory

Further work on SIT in QMM

Strong indication of possible occurrence of SIT in variety of QMM irrespectively of type of constituent qubits. Prediction of the soliton–like propagation of EM in

- Josephson qubit transmission lines
  - Flux qubit inductively coupled to SC transmission line, unpublished results based on model of Zagoskin and co-workers, Phys. Status Solidi B 246 (2009)
  - Different architectures SC charge qubit based QMM,
- Quantum dot based QMM, part of the present work,
- Coupled–cavity arrays,
- Two-level topological insulator, L. Pilozzi and C. Conti, Phys. Rev. B 93, 195317 (2016)
- Various media which may be described within the JC model

QMM with gain and loss

Model

$$H = H_S + H_i + H_B$$

$$H_s = \sum_{n,p=g,e} E_p(n) a^\dagger_{n,p} a_{n,p} + \sum_n \left[\dot{\alpha}_n^2 + \beta^2(\alpha_{n+1} - \alpha_n)^2\right] + \sum_{n,p,p'} V_{p,p'}(n) a^\dagger_{n,p} a_{n,p'} F(\alpha_n, \dot{\alpha}_n)$$

Particular forms of coefficients are determined by the particular set–up of device
$F \sim \sin\alpha/2$–SC charge qubit transmission line
$F \sim \dot{\alpha}$–SC charge qubit transmission line

$$H_i + H_B = \sum_{n,p=g,e} \lambda^p a^\dagger_{n,p} a_{n,p} (b_q + b^\dagger_{-q}) + \sum_q \hbar\omega_q b^\dagger_q b_q$$

Qubit dynamics with gain and loss

$\Psi_p <=> \langle a_p \rangle \equiv Tr\varrho a_p$.
Here ϱ is non–equilibrium statistical operator satisfying Liouvile equation

$$\rho = \rho_q - \frac{i}{\hbar} \int_{-\infty}^{0} d\tau e^{\varepsilon\tau} [V(\tau), \rho_q]$$

while operator average values reads

$$\frac{d}{dt} \langle a_p \rangle = \frac{1}{\hbar} \langle [H_o, a_p] \rangle - \frac{1}{\hbar^2} \int_{-\infty}^{0} e^{\varepsilon\tau} d\tau \langle [[a_p, V], V(\tau)] \rangle$$

Maxwell Schrödinger equation with balanced gain and loss

$$i\dot{\Psi}_p(t) = (\varepsilon_p \pm i\gamma)\Psi_p(t) + \sum_{p'} V_{p,p'}\Psi'_p G(\alpha_n, \dot{\alpha})$$

$$\ddot{\alpha}_n(t) - \beta_0^2(\alpha_{n+1} + \alpha_{n-1} - 2\alpha_n) - \sum_{p,p'} V_{p,p'}\Psi^*_{n,p}\Psi_{n,p'}G(\alpha_n, \dot{\alpha}) = 0.$$

$$\gamma_p = \sum_q |F_q|^2 \left[(\nu_{q,p} + 1)\delta(\hbar\omega_{q,p} - \varepsilon_p) + \nu_{q,p}\delta(\hbar\omega_{q,p} + \varepsilon_p)\right]$$

Maxwell–Bloch equations with balanced gain and loss

QMM composed of the *quantum dot* based qubits

$$\frac{d}{dt}\left[|\Psi_1|^2+|\Psi_2|^2\right]=-2\gamma\left[|\Psi_1|^2-|\Psi_2|^2\right]$$

Thus the set of Bloch variables has four components

$$\begin{aligned}
\dot{R}_0 &= -2\gamma R_1, & R_0 &= |\Psi_1|^2+|\Psi_0|^2,\\
\dot{R}_1 &= -2\gamma R_0-\frac{\mu}{2}ER_2, & R_1 &= |\Psi_1|^2-|\Psi_0|^2,\\
\dot{R}_2 &= -\Delta R_3+\frac{\mu}{2}ER_1, & R_2 &= i(\Psi_1^*\Psi_0-\Psi_0^*\Psi_1),\\
\dot{R}_3 &= \Delta R_2, & R_3 &= \Psi_1^*\Psi_0+\Psi_0^*\Psi_1,
\end{aligned}$$

$$\ddot{E}-c^2E''=k\ddot{P},\ P\sim R_3 \tag{3.1}$$

Maxwell–Bloch equations with balanced gain and loss

SC qubit transmission line

$$\frac{d}{dt}\left[|\Psi_1|^2+|\Psi_2|^2\right]=-2\gamma\left[|\Psi_1|^2-|\Psi_2|^2\right]$$

Thus the set of Bloch variables has four components

$$\ddot{\alpha}-l^2\beta^2\alpha''+\Omega^2\alpha=0 \tag{3.2}$$

$$\begin{aligned}
\dot{R}_0 &= -2\gamma R_1, & R_0 &= |\Psi_1|^2+|\Psi_0|^2,\\
\dot{R}_1 &= -2\gamma R_0-\frac{\mu}{2}\alpha_n^2 R_2, & R_1 &= |\Psi_1|^2-|\Psi_0|^2,\\
\dot{R}_2 &= -[\Delta+\frac{\Omega}{2}\alpha_n^2]R_3+\frac{\mu}{2}\alpha_n^2 R_1, & R_2 &= i(\Psi_1^*\Psi_0-\Psi_0^*\Psi_1),\\
\dot{R}_3 &= [\Delta+\frac{\Omega}{2}\alpha_n^2]R_2, & R_3 &= \Psi_1^*\Psi_0+\Psi_0^*\Psi_1,
\end{aligned}$$

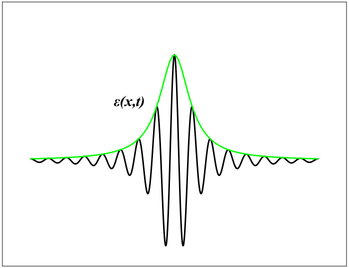
Outline

Resonance propagation of EM-radiation

- Assumption: EM field consists of slow amplitude and rapidly oscillating carrier wave

$$\alpha(x,t) = \varepsilon(x,t)\cos\Psi(x,t)$$

$$\Psi(x,t) = kx - \omega t + \varphi(x,t)$$



- rotation in abstract space, around R_y axis.

Slowly varying envelope approximation

Rotating Bloch variables around Z-axis

$$\begin{aligned} S_0 &= R_0, \\ S_x &= R_1 \cos\Theta + R_2 \sin\Theta, \\ S_y &= R_2 \cos\Theta - R_1 \sin\Theta, \end{aligned} \quad , \tag{4.1}$$

Realization of PT symmetry

$$\begin{aligned}\dot{R}_0 &= -2\gamma R_1,\\ \dot{R}_1 &= -2\gamma R_0 - \frac{\mu}{2}E^n R_2,\\ \dot{R}_2 &= -(\Delta - n\omega)R_3 + \frac{\mu}{2}E^n R_1,\\ \dot{R}_3 &= (\Delta - n\omega)R_2,\end{aligned}$$

In the case of QMM composed of quantum dot based qubits field obey

$$\ddot{E} - c^2 E'' = k\ddot{P},\ P \sim R_3 \tag{4.2}$$

In the case of QMM composed of superconducting charge qubits field obey

$$\dot{E} + \frac{k\beta^2}{\omega} = -\frac{\mu}{2\omega}\,\varepsilon R_2. \tag{4.3}$$

Outline

collaboration and support

Abstract

Introduction

Realization of PT symmetry via SIT

Conclusion

Conclusions

- QMMs-control light propagation
- Light may realize $\mathcal{PT} - symmetric$ QMM
- Condition: resonant propagation

$$\Delta - 2\omega = 0$$