The University of Nottingham
UNITED KINGDOM · CHINA · MALAYSIA

Parity-Time Coupled μResonators : Kramers-Kronig Limit

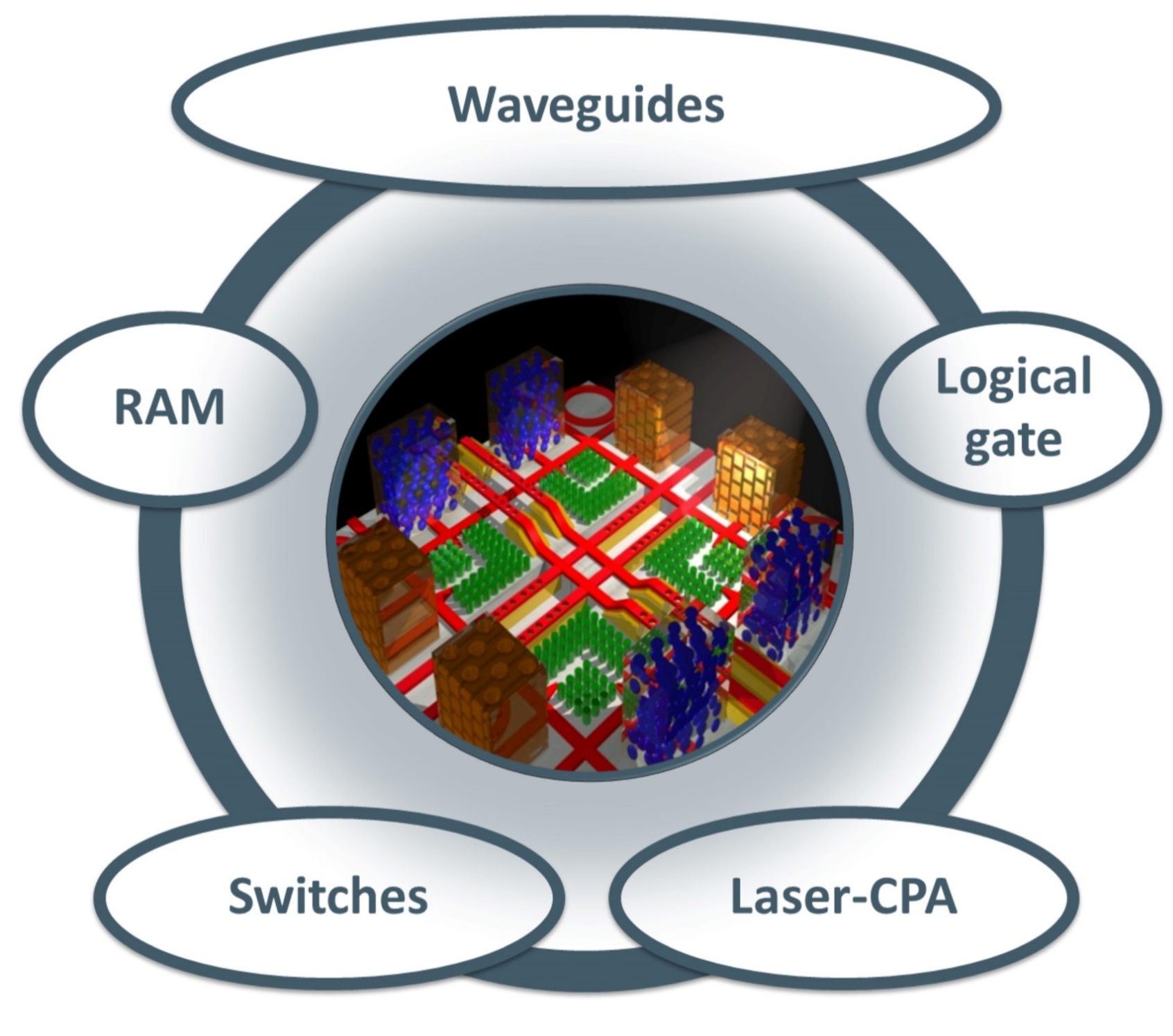
Sendy Phang, Ana Vukovic, Phillip D. Sewell, Stephen C. Creagh and Trevor M. Benson

Introduction

Recently, a new class of optical structures mimicking the Parity-Time symmetry potential in quantum mechanics, namely **parity-time (PT)-symmetric structures**, has opened an innovative way to design and engineer photonic devices.

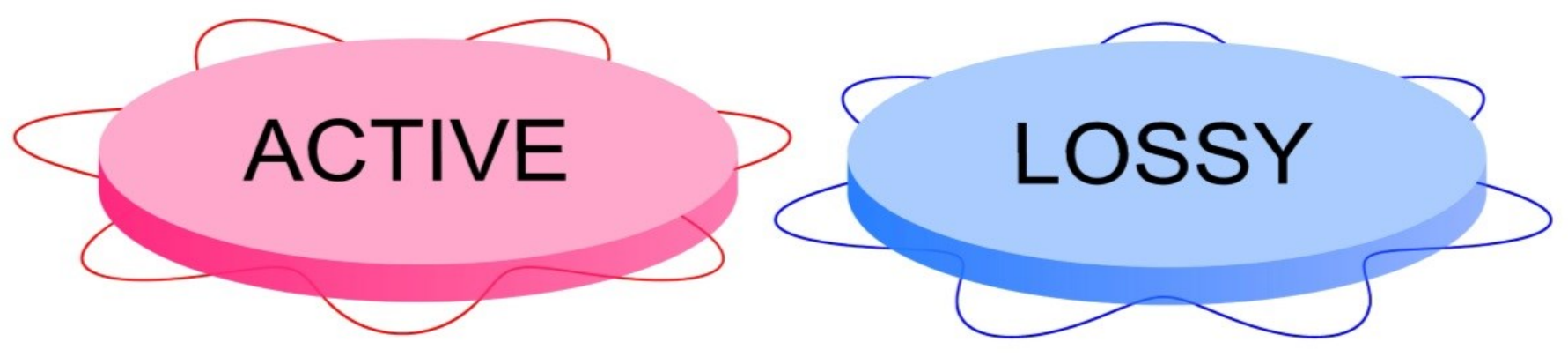
PT-symmetric photonics can be exploited to **enhance** the performance of optical devices such as:

- Switches[1];
- Memory devices [2] and logic gates [3,4];
- Lasers [5].



Optical network and its building blocks

PT-symmetric μResonators Dimer



A PT-symmetric structure is a new class of optical system which combines **gain** and **loss** in the same structure.

A PT-symmetric µResonator dimer is comprised of **coupled gain and lossy µResonators**.

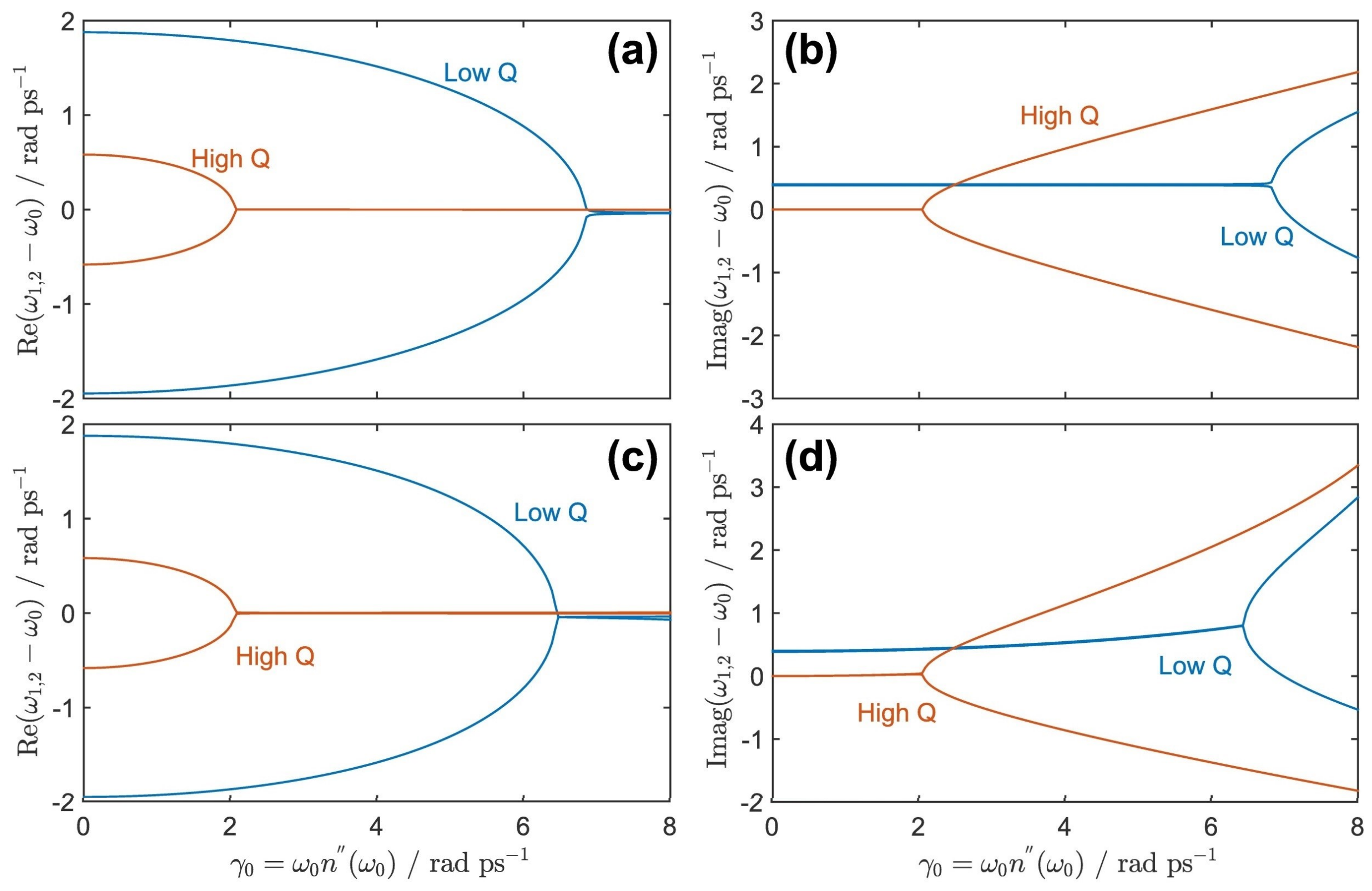
This poster focuses on the **practical issues,** such as the impact of **dispersion** due to **Kramers-Kronig** relations, which may limit the operation and applicability of photonic PT-symmetric structures.

Consider a homogeneously broadened gain/loss medium with Lorentzian profile as,

$$\varepsilon(\omega) = \varepsilon_\infty - j\frac{\sigma_0}{2\varepsilon_0\omega}\left(\frac{1}{1+j(\omega+\omega_\sigma)\tau} + \frac{1}{1+j(\omega-\omega_\sigma)\tau}\right),$$

ε_∞ = constant dielectric permittivity = 12.25
σ_0 = constant electric conductivity, $\sigma_0 < 0 \rightarrow$ gain, v.v
ω_σ = atomic transitional frequency
τ = atomic relaxation time

Case:
Radius = $0.54\mu m$ & Gap between $g = 0.24\mu m$
Coupling of mode:
Mode $(10,1)$, $f_0 = 336.85$THz, High-$Q = 1\times10^7$
Mode $(7,2)$, $f_0 = 341.59$THz, Low-$Q = 2.73\times10^3$



Eigenfrequencies

1. **Spectral properties for matched case $\omega_\sigma = \omega_0$**

(a)-(b)
Dispersion-less case
$\omega_\sigma\tau = 0$

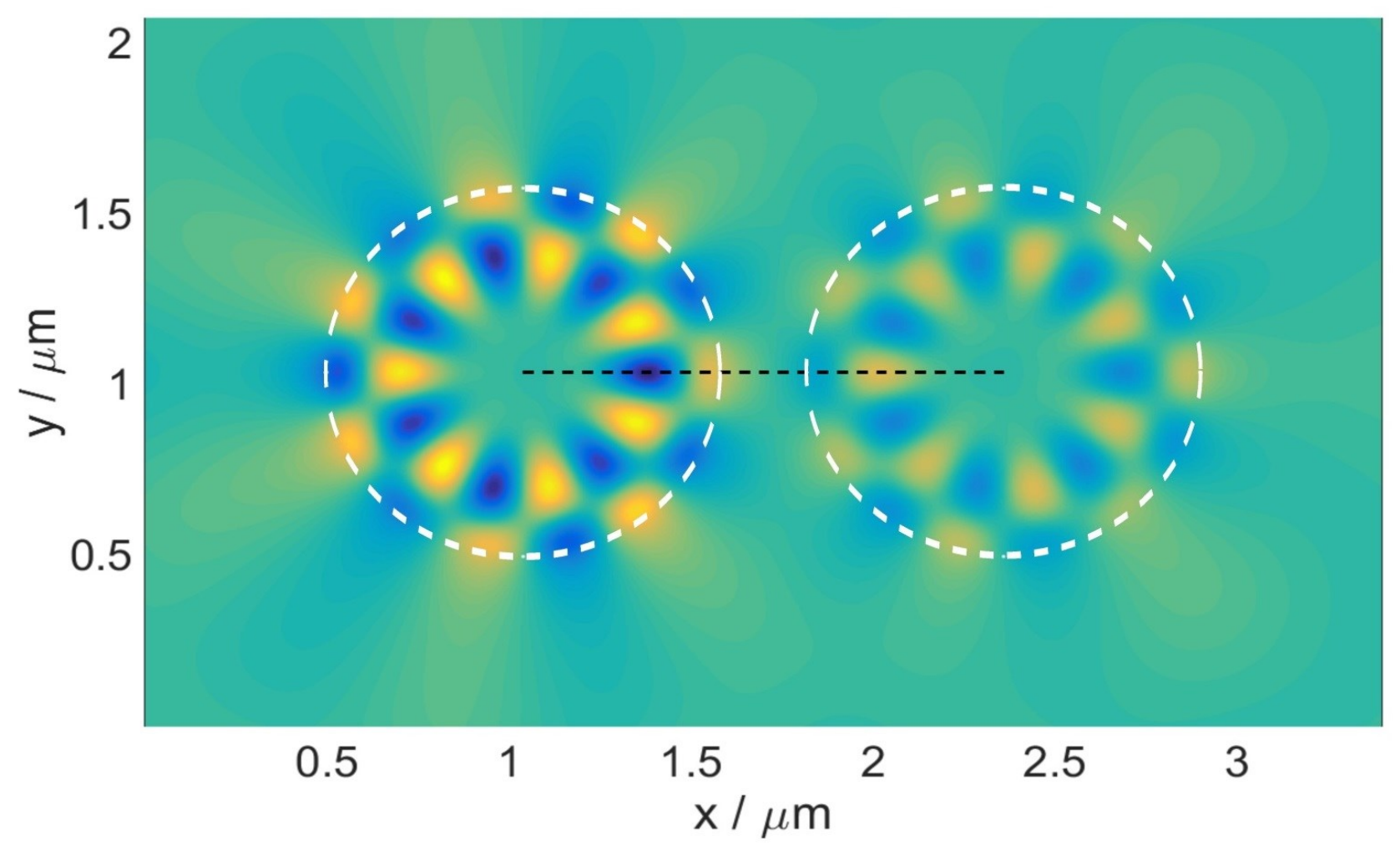
- Imag(f) *constant* as gain/loss increases to definite threshold
- Complex conjugate pair after threshold

(c)-(d)
High Dispersion case
$\omega_\sigma\tau = 212$

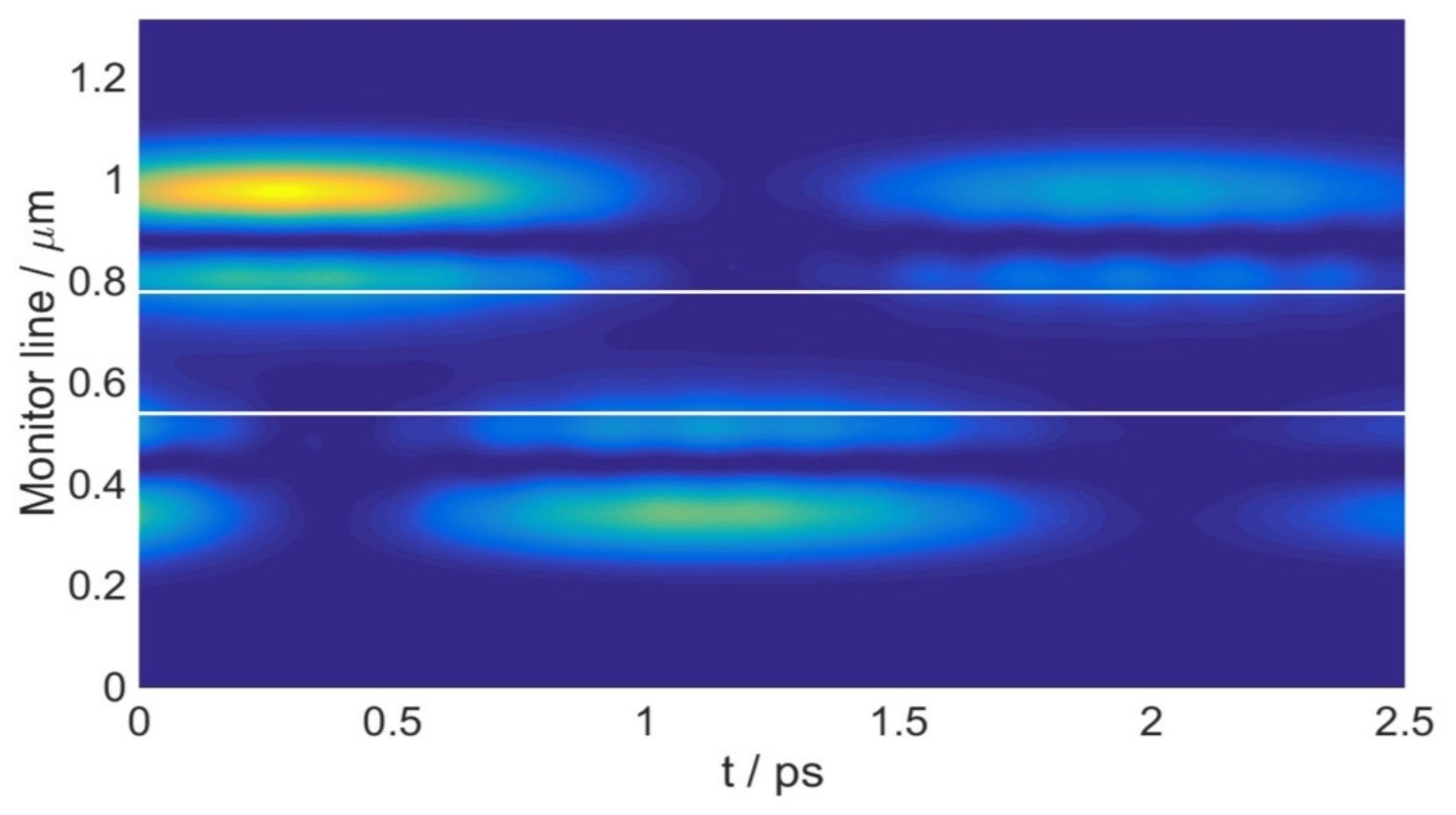
- Imag(f) *skewed* as gain/loss increases
- No longer complex conjugate pair after threshold
- Definite threshold point

2. **Time-Domain analysis – Using the Transmission-Line Modelling Method**

Features:
*Frequency **beating** between µ-Resonators before threshold point.*

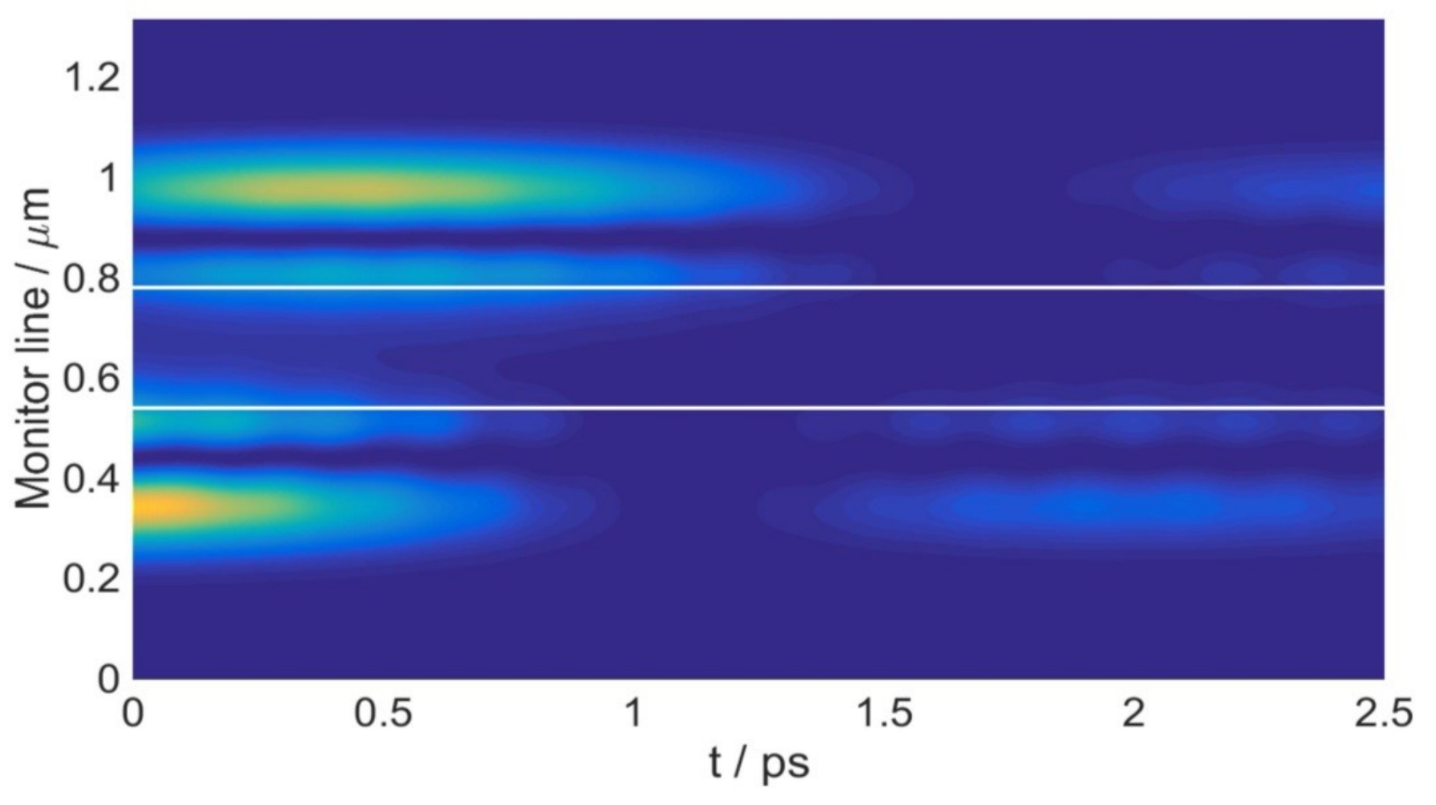


Super-mode in a coupled µR for mode (7,2)



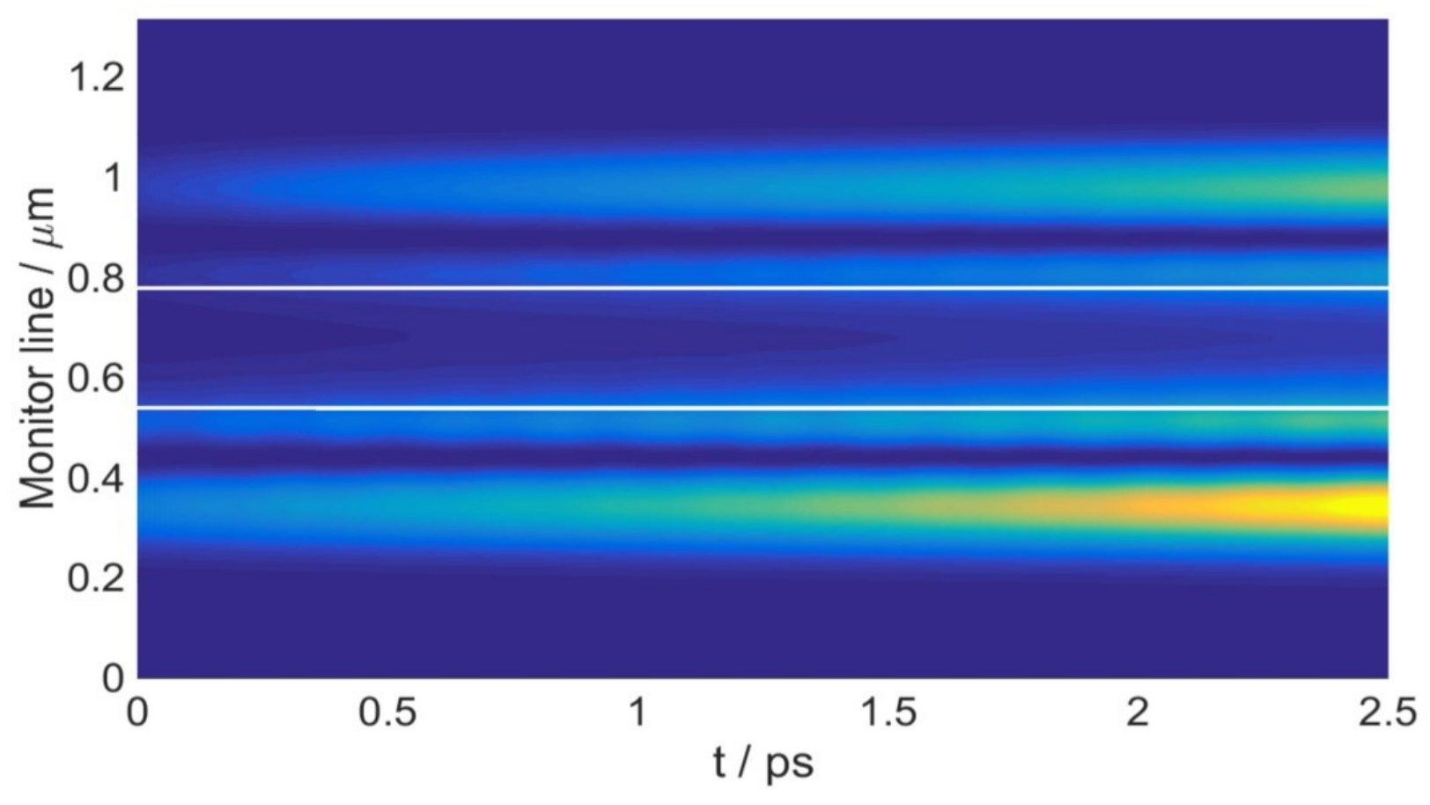
Electric field intensity in a ***passive*** structure

- **Frequency beating**
- **Lossy** due to radiation loss



High dispersion & ***before*** threshold:

- **Longer** coupling time
- **Less loss** due to coupling to gain

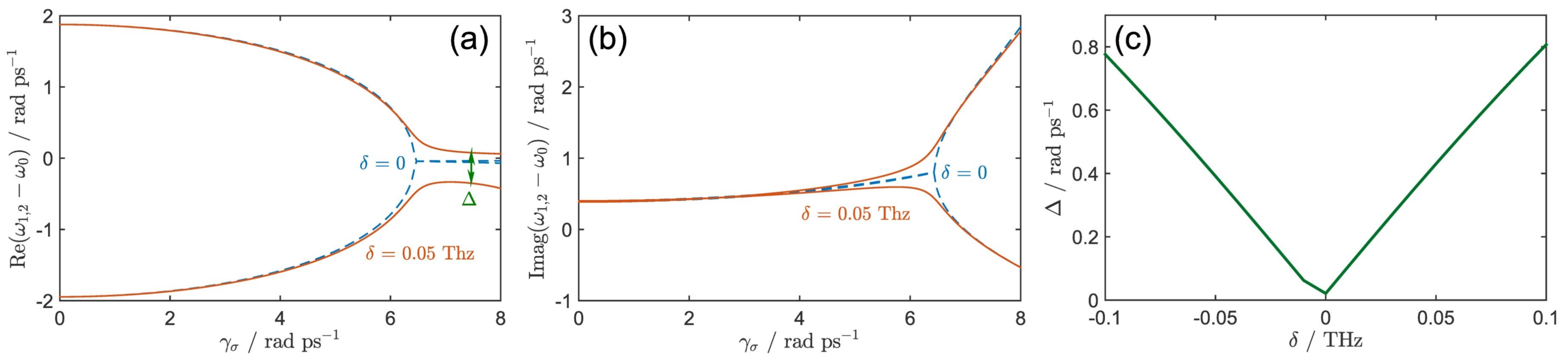


High dispersion & ***after*** threshold:

- **No** coupling
- **Lasing** mode dominates and the field in both µResonator grows

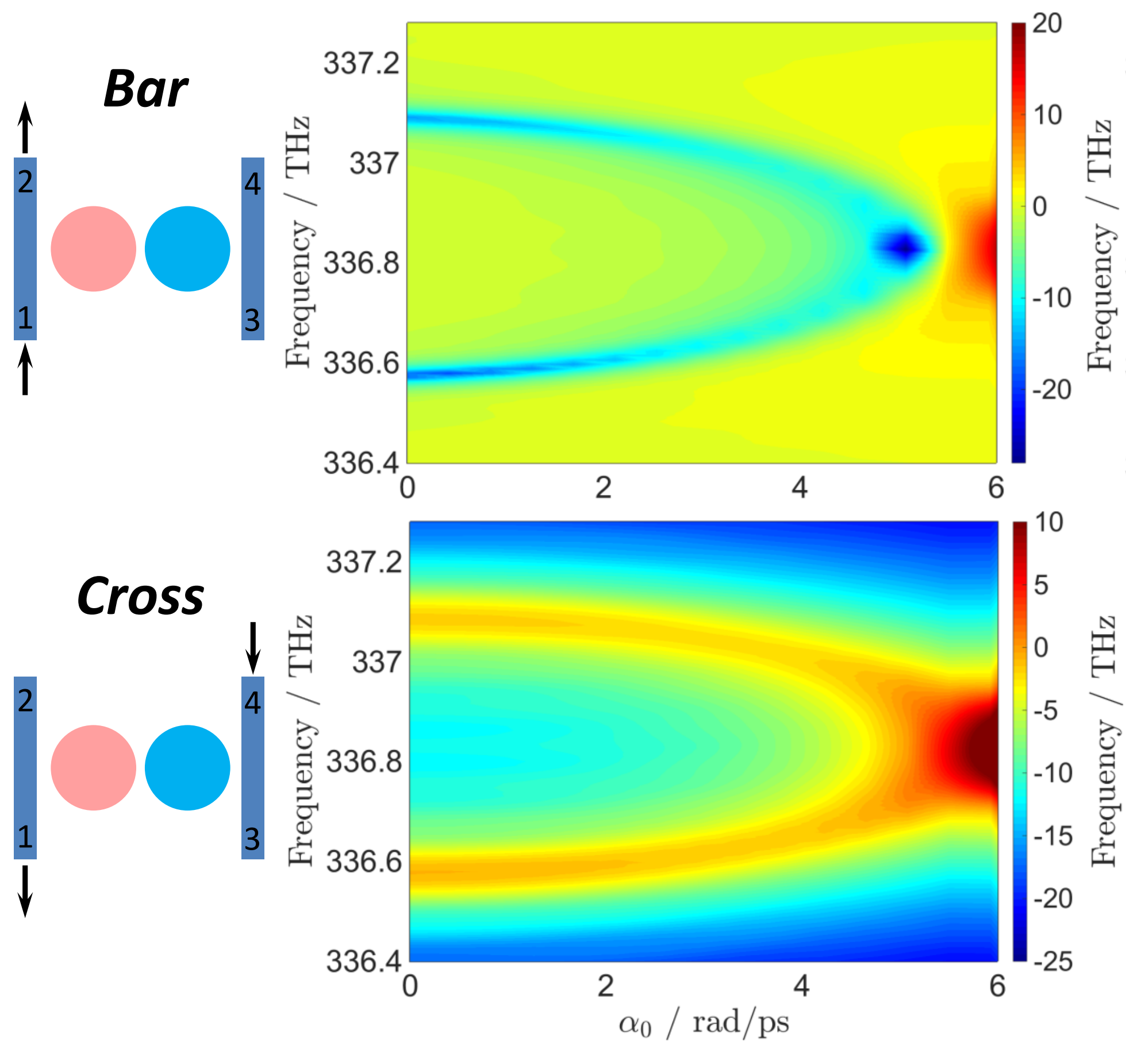
3. **Impact of mismatching $\delta = \omega_\sigma - \omega_0$**

Features: *Threshold exists only in the matched case*

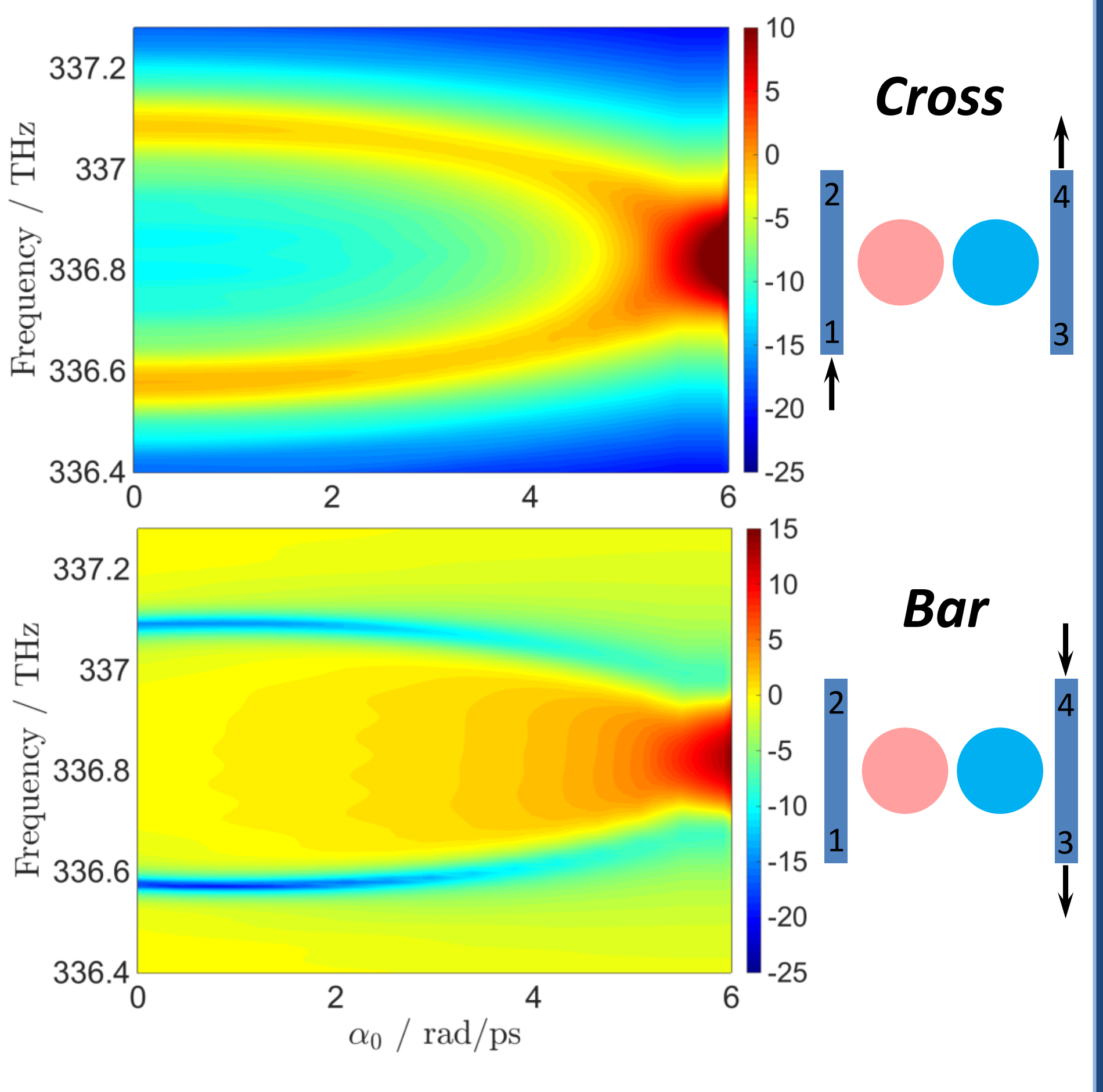


4. **Coupled with waveguide in/out channels**

***Transmittance** for different gain/loss – calculated by the TLM*



Reciprocal cross-transmittance
Lasing operation after threshold point



Asymmetric bar-transmittance

Related Publications

1. **S. Phang**, A. Vukovic, H. Susanto, T. M. Benson, P. Sewell, "Ultrafast optical switching using parity-time symmetric Bragg grating," J. Opt. Soc. Am. B 31, 11 (2013)
2. **S. Phang**, A. Vukovic, H. Susanto, T. M. Benson, P. Sewell, "Impact of dispersive and saturable gain/loss on bistablity of nonlinear parity-time Bragg gratings," Opt. Lett. 39, 2603-2606 (2014)
3. **S. Phang**, A. Vukovic, H. Susanto, T. M. Benson, P. Sewell, "Practical limitation on operation of nonlinear parity-time Bragg gratings," in Meta'14 Conference 2014, Singapore, Singapore, (2014)
4. **S. Phang**, A. Vukovic, H. Susanto, T. M. Benson, P. Sewell, "A Versatile all-optical parity-time signal processing device using a Bragg grating induced using positive and negative Kerr non-linearity," Opt. Quant. Electronics (2015)
5. **S. Phang**, A. Vukovic, S. C. Creagh, G. Gradoni, T. M. Benson, P. Sewell, "Parity-Time Symmetric Coupled Microresonators with a Dispersive Gain/Loss," Opt. Express. 23, 9, 11493-11507 (2015)

The George Green Institute for Electromagnetic Research
Electrical Systems and Optics Research Division
sendy.phang@nottingham.ac.uk