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Parity-Time Chain of Whispering-Gallery Mode Resonators

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Abstract-The paper analyses the dispersion characteristics of an infinitely long PT chain made of whispering gallery resonators with gain/loss modulation. The results show that the appearance of the threshold breaking point depends not only on both of coupling and gain/loss modulation but also on the Bloch phase. The Bloch phase is seen as an additional parameter that can reduce or even completely eliminate PT-breaking threshold.

Recently, structures with balanced gain and loss, commonly referred to as Parity-Time (PT) symmetric structures, have been the subject of intense investigation, mainly due to the fact that the structures mimic PT Hamiltonians in quantum field theory. PT symmetric structures feature a unique threshold condition; at this point the real eigenfrequencies coalesce to become complex conjugates. Several structures such as PT Bragg gratings, PT coupled waveguides, PT plasmonics and PT coupled cavities have been studied theoretically and experimentally, and have shown unique properties such as loss-induced transparency, simultaneous lasing-absorption, and loss-induced lasing. These featuring properties have been reported to be useful for applications such as switching, optical logic-gates, memory and lasers [1–6].

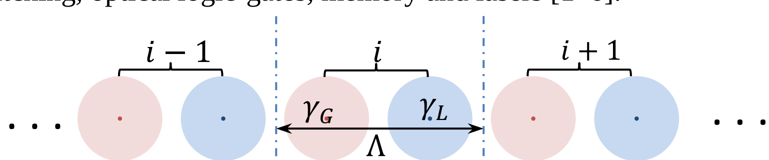

Figure 1 Schematic diagram of an infinitely long PT chain of whispering gallery resonators with a unit cell of length Λ. Each unit cell comprises of a gain and lossy resonator with equal dimension and gain/loss parameter $\gamma_0 = -\gamma_G = \gamma_L$.

Our recent work on the inclusion of a practical implementation of material properties into PT structure have found that causality restricts the PT condition to be satisfied only at a single frequency [3,7]. This leads to a single frequency PT operation and inhibits multi-mode PT symmetry breaking. In this paper we use a weak-coupling analytical model to analyze an infinitely long PT cavity chain as schematically illustrated in Fig. 1, where a unit element of length Λ is comprised of a pair of coupled cavities. The coupled cavities have balanced gain and loss where γ_G and γ_L denote gain and loss respectively, satisfy $\gamma_0 = -\gamma_G = \gamma_L$. Throughout this paper, the material is modelled with a Lorentzian dispersive material model [8] which satisfies the Kramers-Kronig relationship as

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

where ε_∞ denotes the dielectric constant at infinity, ω_σ is the atomic transitional frequency, τ is the relaxation time parameter and σ_0 is related to the peak of gain/loss at the given ω_σ.

Figure 2 shows the eigenfrequencies of the infinitely long sequence of coupled microcavities as a function of gain/loss parameter γ_0 and the Bloch phase $\beta\Lambda$. The cavities have a radius of $r = 0.54\mu m$ with material parameters of refractive index at infinity $n_\infty = 3.5$ and $\omega_\sigma\tau = 212$, as in [3]. The red lines in Fig. 2 indicate the threshold point for a given gain/loss parameter and for different Bloch wavelengths. In contrast to a typical PT-symmetric structure, where the appearance of a threshold point depends on a finite strength of gain/loss modulation, in the infinitely periodic case the appearance of the threshold point additionally depends on the Bloch phase. For example, at a Bloch phase of $\beta\Lambda = \pi$, the threshold occurs even in the absence of gain/loss, i.e. the PT breaking condition occurs immediately for no gain/loss modulation ($\gamma_0 = 0$). This is in agreement with [6] where a PT micro-ring resonator is made by periodically modulating the ring refractive index with large number of gain and loss sections along the azimuthal direction, and where the observed thresholdless condition is associated with the continuous rotational symmetry for the desired WGM mode. The presentation will further discuss ways of introducing a bandgap in the $\omega - \beta\Lambda$ response of the infinitely long chain and how it might be exploited for optical amplification or attenuation applications.

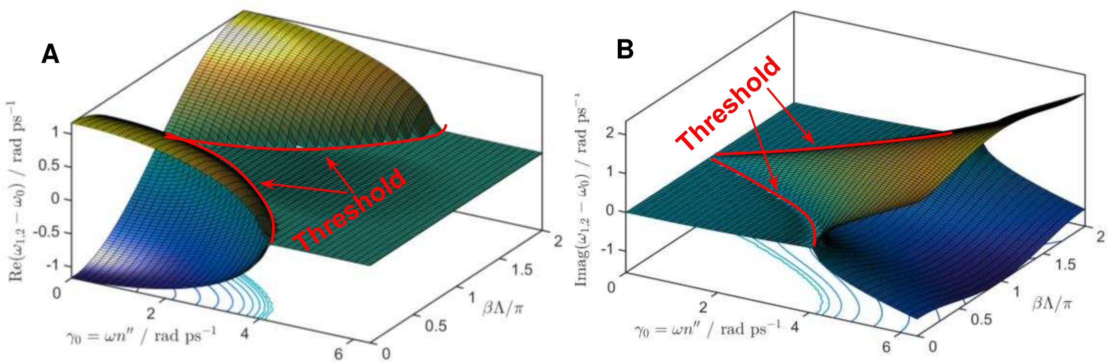

Figure 2 Normalized (**A**) real part and (**B**) imaginary part of eigenfrequency of an infinitely long chain of PT symmetric cavities, as illustrated in Fig.1, as a function of gain/loss parameter γ_0 and Bloch phase $\beta\Lambda$.

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