Single mode PT symmetric large area lasers

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ABSTRACT

We experimentally demonstrate single longitudinal mode operation in microring laser using the concept of PT symmetry. A PT-symmetric coupled resonator arrangement can considerably enhance the maximum achievable gain of single mode microring cavity. The method is broadband thus work well for inhomogenously broadened gain mediums. It doesn't rely on any additional component to ensure its mode selective performance, and it is robust with respect to fabrication inaccuracies. This result may pave the way for a novel way of designing integrated laser sources based on PT symmetry.

Keywords: PT-symmetry, Micro-ring, Laser resonator, Guided waves

1. INTRODUCTION

Among various types of laser cavities, microrings have characteristics such as high mode confinement, high quality factor, and small footprint, which advocate them as a prominent class of laser cavities. However, like many other semiconductor laser, these resonators tend to support many longitudinal modes within the gain bandwidth of their active medium. The ability to control these oscillating modes is one of the main challenges holding up the application of microring lasers. Since multimode operation causes power fluctuation in both temporal and special domains [1]. Several techniques have been introduced in order to address this issue, for example spatially modulated the pumping [2], exploiting the Vernier effect by coupling an external cavity to the laser resonator [3], or introducing an intra-cavity dispersive element such as DFB grating [4]. However implementing each one of these approaches on a microring resonator demands great amount of design complexity and fabrication precision. Therefore a simple, yet robust method to enforce single mode operation in microring laser seems much needed. Which can be proposed using the notion of PT symmetry.

The concept of parity-time (PT) symmetry first has been introduced in context of quantum mechanics [5]. This area of research base on non-Hermitian systems, which their associated Hamiltonian commutes with the parity-time (PT) operator. This so called PT- symmetric arrangements provide real-valued spectrum in the unbroken symmetry regime, despite the presence of gain and loss. However introducing a gain-loss contrast above a specific threshold leads to spontaneous PT-symmetry breaking. In this scenario, some of the modes experience either gain or loss, while the rest remains neutral. Recently it has been shown theoretically that PT symmetry is applicable to realize large area single mode lasers [6].

In this article we establish our PT arrangement by introducing a lossy complement to our active ring resonator. The main idea is to adjust the amount of gain/loss and coupling in such way that just the fundamental mode oscillate in broken PT symmetry regime, while all the higher order modes remain below PT threshold. As a result only the strongest mode gets the chance to participate in lasing, and single mode operation of the cavity is ensured. Although any laser cavity can operate in single mode regime, our mode selective method systematically enhances the maximum achievable gain. It is also independent of gain bandwidth of the medium. As a consequence, our approach naturally exhibits a type of broadband self-adaptive behavior and is, in principle, applicable to any active resonator configuration.

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2. PT SYMMETRIC MICRORING LASER

In order to implement our method, first we consider a pair of identical microring resonators, each of them supporting a number of modes throughout the amplification bandwidth. When placed in close proximity to one another, the coupling between the structures breaks the degeneracy between their respective modes. The frequency splitting $\delta\omega$ of the resulting supermode doublets is determined by the mutual coupling coefficient κ. If both rings provide equal amounts of amplification, each of these modes can oscillate, thereby effectively doubling the number of involved frequency components (see Fig. 1(b)). On the other hand if instead of gain we have its balanced amount of loss in one of the rings, this structure will form our proposed PT symmetric arrangement (see Fig. 1(c)).

Solving the coupled mode equation for longitudinal modes of the structure, eigenfrequencies can be calculated:

$$\omega_n^{(1,2)} = \omega_n + i\frac{\gamma_a + \gamma_b}{2} \pm \sqrt{\kappa_n^2 - (\frac{\gamma_a - \gamma_b}{2})^2} \tag{1}$$

where γ_a and γ_b represent the net gain/loss in each cavity, and κ_n is the coupling between the two rings. Obviously, the eigenfrequencies can be complex and their imaginary part describes amplification or attenuation, respectively. In the PT-symmetric case Eq. (1) will be simplified:

$$\omega_n^{(1,2)} = \omega_n \pm \sqrt{\kappa_n^2 - \gamma_n{}^2} \tag{2}$$

This last relation clearly indicates that the threshold for PT-symmetry-breaking signifies the boundary between amplification/attenuation and bounded neutral oscillations. Any pair of modes, whose gain/loss remains below the coupling coefficient ($\gamma\ n\ (\omega) < \kappa\ n\ (\omega)$), will remain neutral. The absence of any overall gain or loss is easily understood considering that the modes reside equally in the amplifying and lossy regions, as shown in Fig. 2. However, as soon as the gain/loss exceeds the coupling ($\gamma\ n\ (\omega) > \kappa\ n\ (\omega)$), PT symmetry will be broken and a conjugate pair of lasing/decaying modes emerges. Clearly, a judicious placement of this PT threshold will allow a complete suppression of all non-broken mode pairs in favor of a single amplified mode (see Fig. 1(c)). As the imaginary parts of the eigenvalues diverge from one another, degeneracy between their real parts is restored. While principle any single resonator with a non-uniform gain distribution $g(\omega)$ can exhibit single-mode operation, provided that for all except one resonance the losses overcompensate the gain. However, in this regime, the amplification cannot exceed the gain contrast $g_{max} = g_0 - g_1$ between adjacent resonances (see Fig. 1(a)). Here, $g0$ refers to the gain of the principal mode, whereas $g1$ to that of the strongest competing resonance. Obviously, this approach will impose severe constraints on the operating parameters – especially in the case of broad gain windows and/or closely spaced resonator modes, where g_{max} is very small. On the other hand, in the PT-symmetric setting, the coupling κ plays the role of an artificial loss. As such, all undesirable modes must fall below its corresponding threshold. According to Eq. (2), we can therefore calculate the maximum achievable gain by setting $g_1 = \kappa$:

$$g_{\max,PT} = \sqrt{g_0^2 - g_1^2} = g_{\max}\sqrt{\frac{g_0 / g_1 + 1}{g_0 / g_1 - 1}} \tag{3}$$

Evidently, selective breaking of PT symmetry can systematically increase the available amplification during single-mode operation.

3. EXPERIMENTAL RESULTS

In order to illustrate the validity of our theoretical discussion we fabricated InGaAsP rings in SiO_2 substrate and air as the cover. Also a pulse laser at 1064 nm (15 ns pulses with a repetition rate of 290 kHz) was employed to pump the structure. Figure. 2(a) shows the spectrum of a single active ring with outer radius of 10 μm and width of 500nm subjected to 7.4 mW of pump power. Under this conditions, several longitudinal modes resonating in the cavity. Furthermore the intensity pattern of this scheme is depicted in figure. 2(b) When tow such rings placed in 200nm distance of each other, emerging of the supermodes can be detected (Figure. 2(c,d)). Finally, if As expected, once PT-symmetry is established by withholding the pump from one of the resonators (Figure. 4(e,f)), lasing occurs exclusively in the active ring, where single-mode operation is now achieved. The presence of the lossy ring serves to suppress the unwanted longitudinal modes with a contrast of nearly 30 dB.

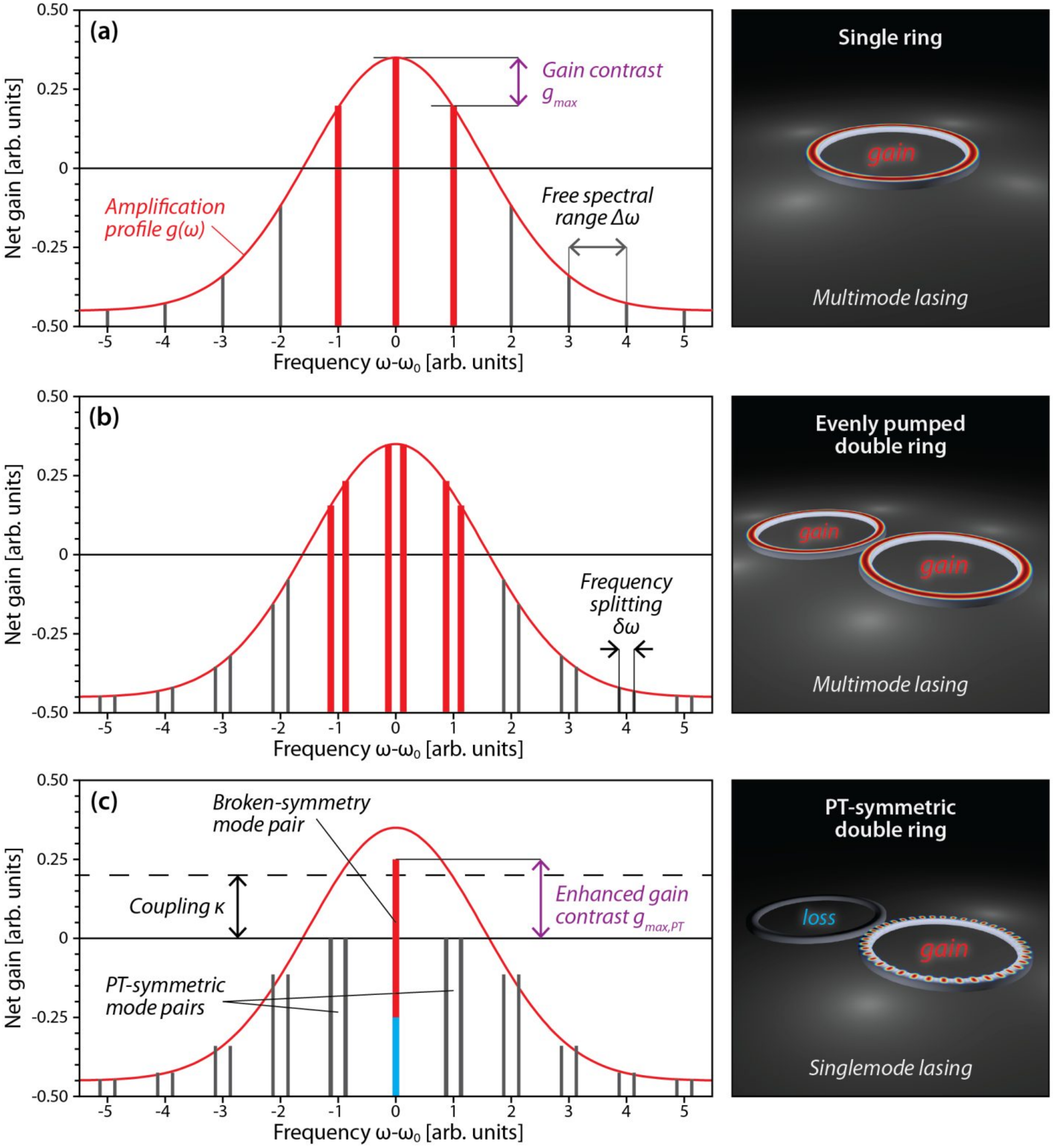

Figure 1 (a) An isolated ring resonator allows lasing of all longitudinal modes with positive net gain. To achieve single-mode operation, maximum permissible gain is limited by the gain contrast between the resonances. (b) In a coupled arrangement of two identical and evenly pumped rings, the degeneracy of resonator modes is broken and mode pairs emerge (c) PT-symmetric arrangement: As long as the coupling exceeds the amplification, loss and gain in the two respective rings balance each other, whereas above this threshold, PT symmetry breaking occurs. This mechanism can be exploited to enforce stable single-mode operation in otherwise highly multi-moded resonators. Note that the gain contrast is systematically enhanced.

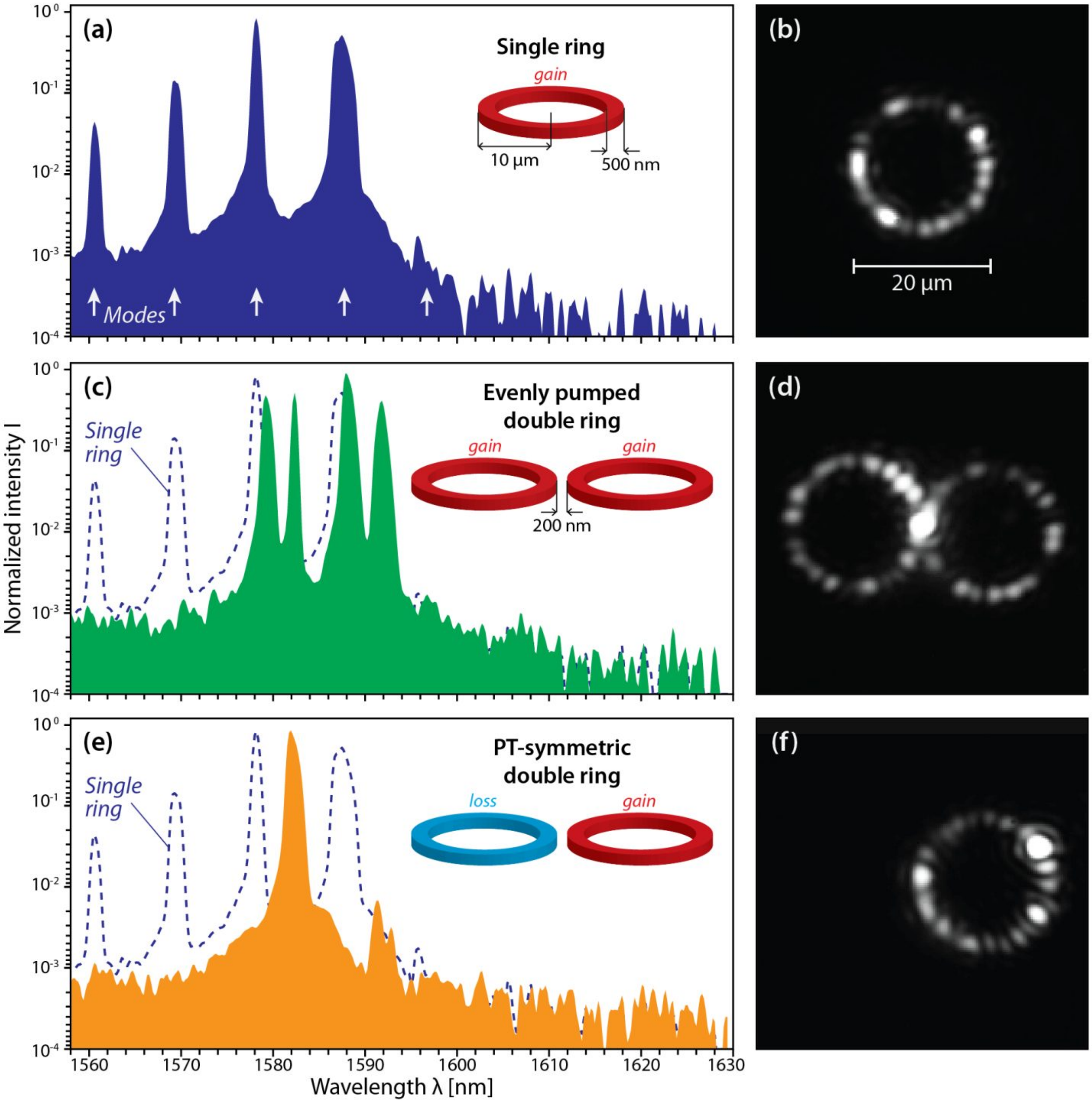

Figure 2. (a) Emission spectrum of single active ring with radius of 10μm and width of 500nm subjected to 7.4 mW pump power (b) corresponding intensity profile observed from the scattered light (c) Spectrum of two coupled active rings each receiving 7.4 mW of pump power (d) Intensity profile of two evenly pumped rings (e) spectrum of PT symmetric scenario depicting single mode operation, where 7.4 mW of pump power is directed exclusively to one of the rings (f) Intensity profile of PT symmetric microring laser

4. CONCLUSION

In conclusion, we have demonstrated how the selective breaking of PT symmetry can be utilized to enforce stable single mode operation in microring laser resonators. In particular, the maximum achievable gain in PT-symmetric ring pairs is systematically enhanced with respect to the onset of undesired lasing in competing modes. Our experiments indicate that this mechanism of mode selectivity is robust with respect to fabrication inaccuracies, and can accommodate active media with wide gain spectra. Moreover, as the occurrence of PT symmetry breaking is exclusively determined by the relation between net gain and coupling, the arrangement is self-adapting: Its functionality does not rely on external parameters or a specific design. While PT-symmetric arrangements can in principle be adopted for any type of laser cavity, they are particularly suited for the control of longitudinal modes in microring resonators, a previously challenging task. Our results may pave the way for a new family of compact laser designs combining the advantages of multimode cavities and stable single-mode emission.

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REFERENCES

[1] Siegman, A. E., [Lasers], University Science Books (1986).
[2] Liew, S. F., Redding, B., Ge, L., Solomon, G. S., and Cao, H., "Active control of emission directionality of semiconductor microdisk lasers," arXiv:1404.6709 (2014)
[3] Claes, T., Bogaerts, W., and Bienstman, P., " Experimental characterization of a silicon photonic biosensor consisting of two cascaded ring resonators based on the Vernier-effect and introduction of a curve fitting method for an improved detection limit," Optics Express, Vol. 18, Issue 22, pp. 22747-22761 (2010)
[4] Van Derlofske, J. F., "Computer modeling of LED light pipe systems for uniform display illumination," Proc. SPIE 4445, 119-129 (2001).
[5] Bender, C. M., and Boettcher, S., "Real spectra in non-Hermitian hamiltonians having PT symmetry," Phys. Rev. Lett. 80 (1998).
[6] Miri, M. A., LiKamWa. P., and Christodoulides, D. N., " Large area single-mode parity–time-symmetric laser amplifiers," Optics letters 37.5, 764-766 (2012)