Unidirectional Light Generation in PT-symmetric Microring Lasers

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Abstract: At resonance, mircoring resonators tend to support two counter-propagating degenerate modes. By incorporating S-bend chiral elements in each resonator, unidirectional single mode lasing below and above PT-symmetry breaking point is experimentally demonstrated.

OCIS codes: (140.3410) Laser resonators; (140.3948) Microcavity devices; (140.5960) Semiconductor lasers

In recent years, parity-time symmetry has been introduced as a means to control the modal content of microring lasers [1-3]. In this regard, active coupled microring systems subject to non-uniform pumping have been demonstrated to support only one longitudinal mode while effectively suppressing emission from other cavity resonances [2]. Such lasers are in principle capable of generating light in two opposite directions, especially when operating far above their exceptional points. In most actual settings, these two counter-propagating degenerate modes couple to each other through scattering or imperfections, leading to further frequency splitting and spectral complexity. In many applications, it is imperative to design lasers that only support a single longitudinal mode that circulates in a unidirectional fashion within the rings [4-6]. While recent studies have shown that non-Hermitian ring lasers operating close to their exceptional points can indeed generate unidirectional emission [7,8], of interest will be to identify strategies to enforce such behaviors in PT-symmetric systems in a global fashion. Here, we present our experimental results in which by incorporating appropriate S-bend chiral elements in each resonator [9], unidirectional single mode lasing below and above PT-symmetry breaking point is attained.

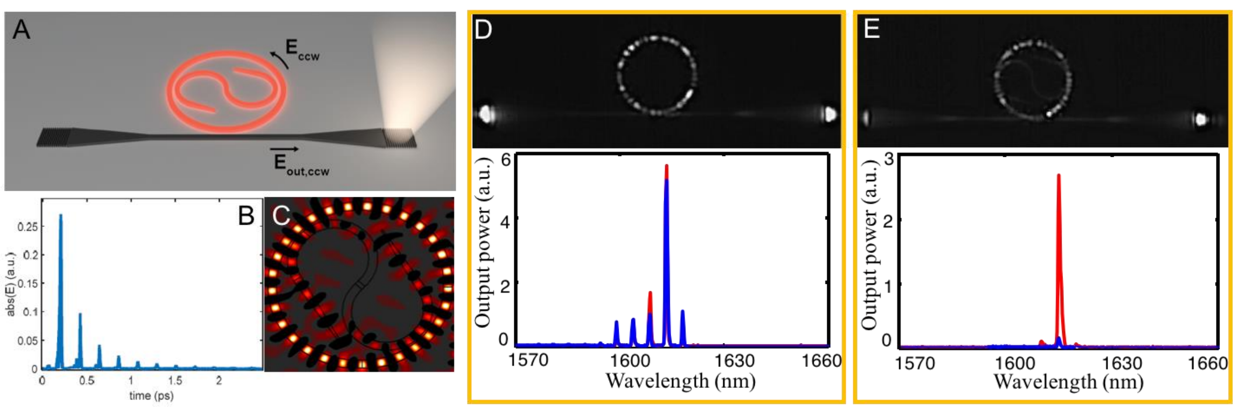

Figure 1 Unidirectional emission in micro-ring lasers. (A) Schematic of a ring resonator containing an S-bend. (B) Amplitude of a counter-clockwise pulse in an S-microcavity corresponding to the design in Fig. 1A. (C) Field distribution in an individual S-element. Recorded camera images and spectra from the out-coupling gratings for (D) without the S-bend and (E) with the S-bend, demonstrating a 12 dB extinction ratio of the clockwise mode with respect to the counter-clockwise mode.

Fig. 1A shows a schematic of a ring resonator containing an S-bend. The modal analysis of such a resonator reveals that depending on the chirality of the S, one of the two counter-propagating modes will always experience an infinitesimally small eigenvalue. This peculiarity is attributed to the fact that the S-bend provides an asymmetric coupling between the clockwise (CW) and counter clockwise (CCW) modes which tends to extract energy from one direction and deliver it into the opposite course. As a laser, since the device is operating at resonance, the mode with the lower eigenvalue will be effectively suppressed. The FDTD simulation results in Fig. 1B confirm this behavior. The field distribution in the active S-resonator is shown in Fig. 1C, featuring a high degree of power-recirculation through the S-structure that is responsible for the spin-like mode discrimination. Furthermore, we experimentally verified this effect by lithographically inscribing an S-bend in a microring resonator (radius: 20 µm, width: 500 nm, height: 200 nm) and by measuring the emission collected from extraction gratings at the two ends of a bus waveguide. To avoid scattering losses, the coupling between the S-bend and the ring is provided through proximity (S-bend is not connected to the ring). Figures 1D and E compare experimental results with and without an S-bend. In this case, we measured more than 12 dB extinction ratio between the two terminals indicating a substantial suppression of the CW/CCW mode.

Figure 2A shows an SEM image displaying how S-bends as incorporated in a PT-symmetric photonic molecule. Clearly, in such coupled systems the CW mode in one resonator couples to the CCW mode in the other ring. Therefore, the chirality of the S-bends must be switched from one resonator to the other. Figures 2 B-C display experimental results concerning the behavior of such a system below and above the PT-symmetry breaking point. Our experiments indicate that the S-bends indeed globally enforce unidirectional light emission over the entire parameter space (different pumping contrasts). Further research is underway to shed light on the behavior of such resonators at the exceptional point.

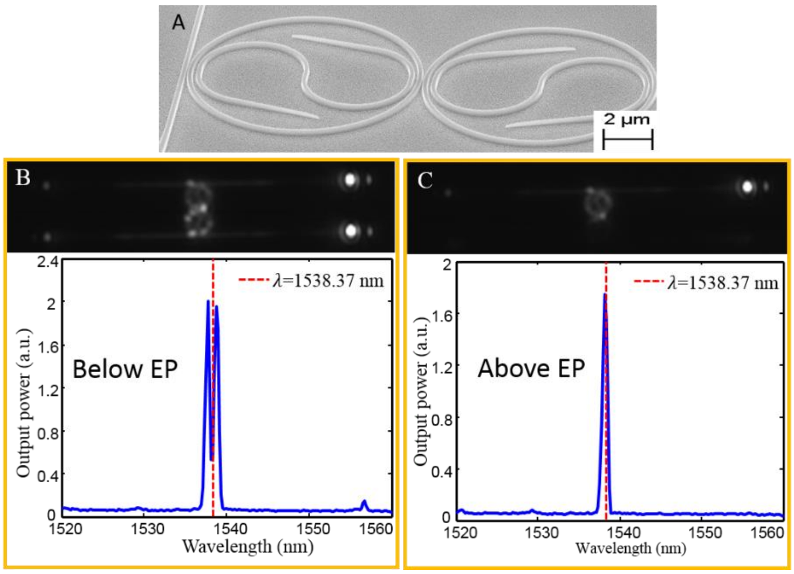

Figure 2 Unidirectional PT-symmetric microring lasers. (A) SEM image of PT-symmetric microresonators incorporated with S-bend inside the cavities. (B, C) Images of unidirectional PT-symmetric micro-ring lasers (radius 5 μm) and corresponding spectra below and above the PT-symmetric breaking point.

To further extend the use of S-bend in enforcing chiral emission from ring resonators, we also studied systems of resonators comprised of two rings (radii: 5 μm) coupled through an intermediate link cavity. Such structures are used as a building block for non-magnetic topological insulator lasers. Figure 3 shows how the incorporation of S-bends in this system (only in the rings) leads to unidirectional light emission in these more complex structures.

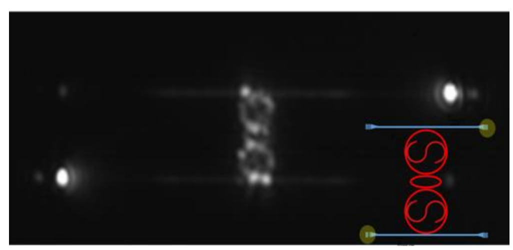

Figure 3 Intensity profile of resonators comprised of two microrings coupled through an intermediate link cavity.

In conclusion, we have demonstrated how S-bends in active photonic molecule systems enable unidirectional light generation. This technique can enforce PT-symmetric lasers to operate in a unidirectional fashion and as a result may have practical ramifications in demonstrating PT-symmetric microscale gyroscopes and lasers. The S-bend elements may additionally be used in active topological photonic systems as a strategy to endow photons with an "effective charge" as shown in recent studies.

References

[1] M. A. Miri et al., "Large area single-mode parity–time-symmetric laser amplifiers," Optics Letters **37**, 764-766 (2012).
[2] F. Liang et al., "Single-mode laser by parity-time symmetry breaking," Science **346**, 972-975 (2014).
[3] H. Hodaei et al., "Parity-time–symmetric microring lasers," Science **346**, 975-978 (2014).
[4] J. Ren et al., "Ultrasensitive micro-scale parity-time-symmetric ring laser gyroscope," Optics Letters **42**, 1556-1559 (2017).
[5] H. Hodaei et al., "Enhanced sensitivity at higher-order exceptional points," Nature **548**, 187-191 (2017).
[6] W. Chen et al., "Exceptional points enhance sensing in an optical microcavity," Nature **548**, 192-196 (2017).
[7] B. Peng et al., "Chiral modes and directional lasing at exceptional points," PNAS **113**, 6845-6850 (2016).
[8] P. Miao et al., "Orbital angular momentum microlaser," Science **353**, 464-467 (2016).
[9] J. P. Hohimer et al., "Unidirectional operation in a semiconductor ring diode laser," Applied Physics Letters **62**, 1185-1187 (1993).