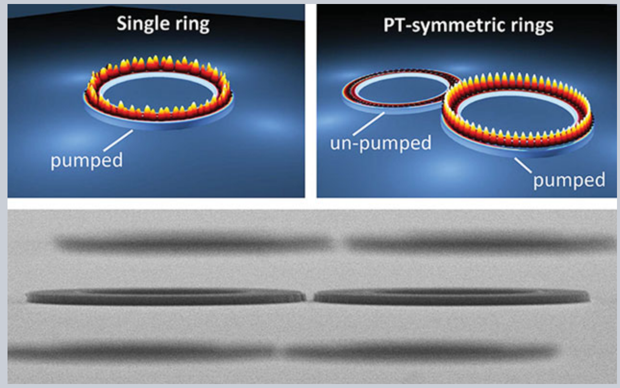
LASER & PHOTONICS REVIEWS

Laser Photonics Rev. **10,** No. 3, 494–499 (2016) / **DOI** 10.1002/lpor.201500292

ORIGINAL PAPER

Conventional techniques for transverse mode discrimination rely on introducing differential external losses to the different competing mode sets, enforcing single-mode operation at the expense of additional losses to the desirable mode. We show how a parity-time (PT) symmetric design approach can be employed to achieve single mode lasing in transversely multi-moded microring resonators. In this type of system, mode selectivity is attained by judiciously utilizing the exceptional point dynamics arising from a complex interplay of gain and loss. The proposed scheme is versatile, robust to deviations from PT symmetry such as caused by fabrication inaccuracies or pump inhomogeneities, and enables a stable operation considerably above threshold while maintaining spatial and spectral purity. The experimental results presented here were obtained in InP-based semiconductor microring arrangements and pave the way towards an entirely new class of chip-scale semiconductor lasers that harness gain/loss contrast as a primary mechanism of mode selectivity.



Single mode lasing in transversely multi-moded PT-symmetric microring resonators

Hossein Hodaei[1], Mohammad-Ali Miri[1], Absar U. Hassan[1], William E. Hayenga[1], Matthias Heinrich[2], Demetrios N. Christodoulides[1], and Mercedeh Khajavikhan[1,*]

1. Introduction

Integrated photonic laser systems with larger cross sections are desirable for many applications since they allow for higher energies within the cavities while managing the thermal load and keeping the impact of optical nonlinearities in check. Unfortunately however, merely enlarging the transverse dimensions of the waveguides inevitably gives rise to competing higher-order spatial modes. This, in turn, compromises the spectral and spatial fidelity of the laser and limits the power that can be extracted from a specific mode [1]. These limitations exist on all scales, and may even be exacerbated in chip-scale semiconductor lasers, where the large gain bandwidths of the active media already pose a challenge in promoting single-mode operation [2].

So far, utilizing intra-cavity dispersive elements has been the primary approach for longitudinal mode selection [3], while tapering along the direction of propagation, engineering the refractive index in the cross section, as well as evanescent filtering are some of the extensively explored techniques to enforce single spatial mode operation in such arrangements [4–7]. Yet, in spite of their success, they are not always compatible with on-chip microcavity structures and in most cases are quite sensitive with respect to fabrication inaccuracies. In this respect, it would be desirable to explore alternative avenues to address these issues.

Recently, the selective breaking of parity-time (PT) symmetry has been proposed as a viable strategy for obtaining single transverse mode operation [8]. By pairing an active resonator/waveguide with a lossy but otherwise identical partner, it is possible to enforce single-spatial-mode performance even in the presence of strong mode competition in multi-moded laser/amplifier configurations. In general, a structure is considered to be PT-symmetric if it is invariant under the simultaneous action of the P (space) and T (time) inversion operations [9]. Despite having a non-Hermitian representation, such a system may still support an entirely real spectrum. While originally developed in the context of quantum mechanics [9, 10], such notions have lately attracted considerable attention in different areas of optics such as photonic lattices, microresonators, gratings, and lasers [11–23]. In optical settings, a structure is PT symmetric if the real part of the refractive index is an even function of position, whereas the imaginary component (representing gain and loss) exhibits an odd profile.

In a recent work, we have shown experimentally how PT symmetry can be utilized to enable *longitudinal* (or azimuthal) mode discrimination in spatially single-moded, but spectrally multi-moded microring laser arrangements without compromising the output power [22]. The principle of operation is based on the spontaneous breaking of PT symmetry, which serves as a virtual lasing threshold

[1] CREOL, The College of Optics and Photonics, University of Central Florida, Orlando, Florida 32816-2700, USA
[2] Institute of Applied Physics, Abbe Center of Photonics, Friedrich-Schiller-Universität Jena, Max-Wien-Platz 1, 07743 Jena, Germany
*Corresponding Author: e-mail: mercedeh@creol.ucf.edu

Wiley Online Library

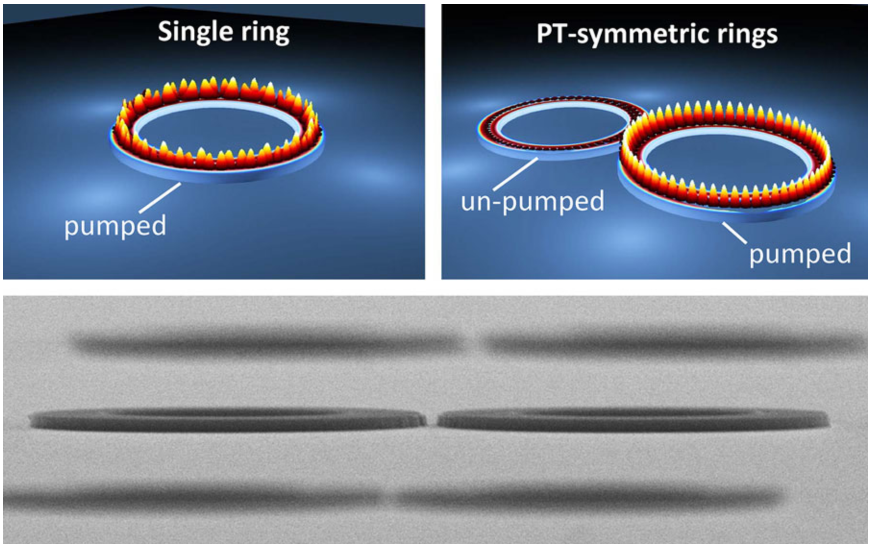


Figure 1 Schematic representation of a multimode isolated ring versus a single mode PT symmetric arrangement. (a) In an isolated microring resonator, multiple transverse and longitudinal modes can lase simultaneously. (b) On the other hand, in a PT-symmetric arrangement, only one longitudinal mode with the lowest order transverse profile can lase. (c) Typical SEM image of a PT-symmetric double ring structure during an intermediate fabrication step.

and encourages single longitudinal mode operation. The PT-symmetry is achieved using a coupled microring system in which the pump power is selectively withheld from one of the cavities. In such settings, the net differential gain associated with the spectral envelope of the line shape function is systematically enhanced – a direct byproduct of the existence of a non-Hermitian exceptional point [23]. Exceptional points have been also shown to reverse the dependence of lasing threshold on pump power [18, 19].

In this paper, we show that PT symmetry can also be utilized in promoting the fundamental *transverse* (or radial) mode in spatially multi-moded micro-ring lasers. In fact, as shown in [8], the virtual threshold at the exceptional point $g/\kappa = 1$ introduces an additional degree of freedom, e.g., the coupling constant κ between the active and the lossy cavity, mediated by the evanescent overlap of their respective modes. As it is well-known, higher order spatial modes systematically exhibit stronger coupling coefficients due to their lower degree of confinement. Consequently, in a PT symmetric arrangement, the fundamental mode is the first in line to break its symmetry as the gain increases (when $g > \kappa g > \kappa$), thus experiencing a net amplification. On the other hand, for this same gain level, the rest of the modes retain an unbroken symmetry and therefore remain entirely neutral. Indeed, following our approach, one can globally enforce single-mode behavior both in the spatial and spectral domain. The coupled mode analysis of the PT-symmetric coupled microring systems is presented in Section 1 of the Supporting Information.

2. Fundamentals

Figures 1(a) and (b) schematically illustrate the transition from multimode behavior in a microring laser to single mode operation in a twin-ring configuration as enabled by preferential PT symmetry breaking. Our experiments were conducted in high-contrast active ring resonators of quaternary Indium-Gallium-Arsenide-Phosphide (InGaAsP) multiple quantum wells embedded in silicon dioxide (SiO_2) and air. An electron micrograph of such rings during an intermediate fabrication step is shown in Fig. 1(c). Based on our measurements, we estimate the quality factor of the fabricated microrings to be on the order of 120,000 (for more information regarding the fabrication and cavity Q-factor, please refer to the Supporting Information document of [22]). The gain bandwidth of the active medium spans the spectral region between 1290 and 1600 nm [24]. Whereas the quantum wells are present in all wave-guiding sections, gain and loss are implemented by selectively pumping the respective rings (pump wavelength: 1064 nm). Accordingly, the effective pump powers are proportional to the geometric overlap between the active medium and the pump profile. In our proof-of-principle design, a ring of an outer radius of 6 μm and waveguide dimensions of 0.21 μm $\times$ 1.5 μm was chosen to simultaneously realize a comparably large free spectral range ($\Delta\lambda_{FSR}\sim$16 nm) and three readily discernible sets of transverse modes (see Fig. 2).

Figures 2(a-c) depict the transverse intensity profiles of different spatial modes supported by such a single microring resonator. The curvature of the ring imposes a radial potential gradient, which deforms the mode fields into whispering-gallery-like distributions. Whereas the centroid of all modes shifts towards the ring center, the exponential decay outside the ring still grows strongly with the mode order. Note that the curvature-induced deformation and lateral displacement of the mode profiles slightly reduce the mutual overlap of their respective intensity profiles compared to a straight waveguide. Nevertheless, the competition for gain from the commonly occupied area of the active medium persists. As a result, even in microscopic ring geometries, locally introduced losses in principle cannot be prevented from impacting the desirable mode as well. Indeed, it is this fundamental limitation that the PT-symmetric approach can overcome.

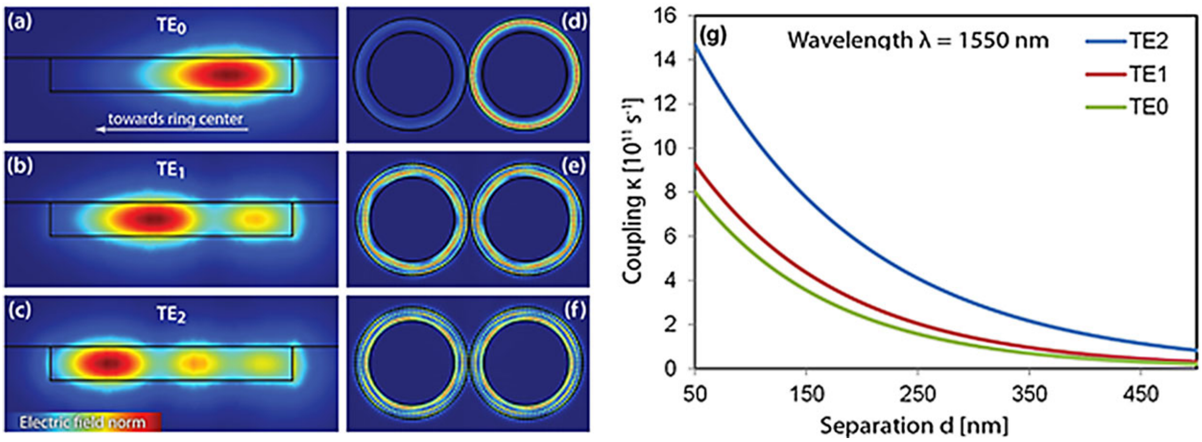


Figure 2 Spatial mode profiles and coupling strength for different transverse modes in the structure (a-c) Intensity distributions in a microring resonator with a cross section 0.21 μm $\times$ 1.5 μm and a radius of R = 6 μm as obtained by finite element simulations for the first three transverse modes, (d-f) corresponding intensity distribution of these same modes within the PT symmetric ring resonators. While the TE_0 mode operates in the broken PT symmetry regime and lases, all other modes remain in their exact PT phase and therefore exhibit no net gain whatsoever. (g) Exponential decay of the temporal coupling coefficients κ with cavity separation *d*. Higher order modes exhibit larger coupling coefficients than their lower-order counterparts, providing an additional degree of freedom for tailoring the virtual lasing threshold.

As shown in Figs. 2(d-f), an appropriate choice of the coupling coefficient set by the distance between the two rings yields a selective breaking of PT symmetry for the TE_0 mode, while all the higher order mode sets (TE_1, TE_2) remain in the unbroken PT phase and hence occupy both rings equally. This behavior is mediated by the modal dispersion of the coupling strength as a function of the geometric separation between the two rings (see Fig. 2(g)). For a given width of this gap, the coupling coefficient increases with the order of the transverse mode, since the effective indices of higher order modes lie closer to that of the surrounding medium and therefore allow for stronger evanescent interactions across the cladding region. This trend persists for all wavelengths, and in conjunction with the difference in confinement enables the PT symmetry breaking transition to be employed as a mode-selective virtual loss. More information regarding the coupling factor and mode confinement is provided in Section 2 of the Supporting Information.

3. Experimental characterization

The emission spectra of the fabricated microring structures were collected using a micro-PL characterization set-up as described in Section 3 of the Supporting Information. Utilizing a rotating diffuser, the output of a single mode pump laser is converted to spatially incoherent light with a large and uniform spot size at the sample plane. The knife-edge in the path of the pump beam allows the selective withholding of illumination from specific rings. The location of the shadow in respect to the rings is adjusted by translating the knife-edge and is monitored via the incorporated confocal microscope. The intensity distribution and the spectrum of the light oscillating in the microrings are then observed via scattering centers by means of an infrared camera and a grating spectrometer, respectively.

In order to illustrate the selective breaking of PT symmetry, we consider a scenario where a coupled arrangement of identical microring resonators is evenly illuminated by the pump beam. In this case, as shown in Fig. 3(a), every resonance in each ring bifurcates into a doublet. In our system, the modes can be distinguished both theoretically and experimentally by considering their wavelength splitting (coupling strength) as well as their corresponding free spectral ranges. For example, the TE_1 supermodes exhibit greater frequency splitting compared to the TE_0 ones due to their higher coupling coefficient. In the PT-symmetric system where only one of the two rings is pumped, the TE_0 modes preferentially undergo PT symmetry breaking due to their higher modal confinement and fuse into a singlet. In addition, given that different longitudinal modes experience different amounts of gain, one can restore the PT symmetry of one of the TE_0 modes by adjusting the pump level. As a result, global single mode operation (spectrally and spatially) can be achieved in this twin-microring system, as only one single longitudinal resonance of the fundamental TE_0 mode experiences sufficient gain to induce PT symmetry breaking. Figure 3(b) shows the fusion of a doublet in the frequency domain and the formation of a single lasing mode. The effect of the deviation from the perfect PT-symmetry condition due to nonlinear and thermal mismatches between the two rings is discussed in Section 4 of the Supporting Information.

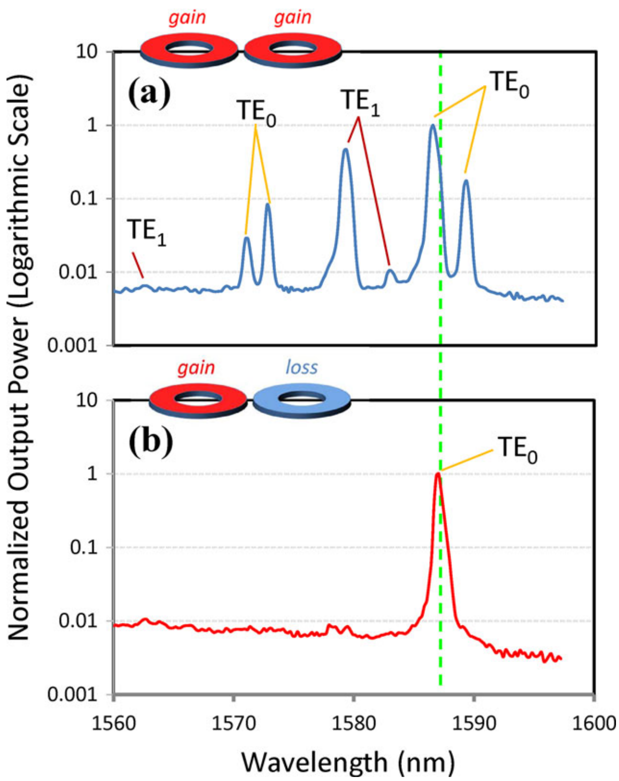


Figure 3 PT-mediated single mode operation in the presence of higher order transverse modes. (a) Measured emission spectrum from a coupled arrangement of evenly pumped microrings, comprised of various TE_0 and TE_1 modes. (b) Global single-mode operation in the PT arrangement. Selective breaking of PT symmetry is used to suppress the entire set of TE_1 modes as well as all competing longitudinal resonances from the TE_0 set. The minimum separation between the coupled rings is 50 nm. The resolution of the spectrometer is set at ~0.5 nm. More refined measurements using scanning Fabry-Perot techniques reveal a line width of ~10 GHz at 1.5 times the threshold.

Figure 4 compares the modal behavior of a single ring and a PT-symmetric double ring system. Figure 4(a) shows the spectrum obtained from a single microring resonator supporting up to three transverse modes. Due to their relatively close lasing thresholds, TE_0, TE_1 and TE_2 simultaneously lase. Note that, in an isolated ring, a decrease of the overall pump power does in practice yield very small selectivity between these modes. On the other hand, when the active ring of the PT-symmetric double-ring arrangement is supplied with the same pump power as in Fig. 4(a), the higher order modes are readily suppressed with a fidelity of over 25 dB (Fig. 4(b)).

It is also instructive to compare the output efficiency of the PT-symmetric laser with that of a standalone microring resonator. The characteristic light-light curves shown in Fig. 5(a) demonstrate that despite a slightly higher lasing threshold, the PT arrangement exhibits approximately the same slope efficiency as the single ring. Crucially, however, the PT arrangement channels the entire available power into a single (i.e. the the broken-PT) resonance, whereas in the conventional isolated ring system it is shared among a mixture of competing modes (Fig. 5(b)). It should be noted that the threshold in the PT system is set by the coupling between the rings and the loss of the un-pumped cavity, and can be further modified through design.

4. Conclusion and Outlook

Conventional approaches for the suppression of transverse modes rely on implementing mode-dependent losses, e.g. by means of evanescent coupling to a lossy waveguide [1, 25]. Although widely used, these schemes invariably introduce losses to all modes – including the desirable, fundamental one. Although the PT-inspired design approach presented here likewise exploits the fact that various transverse modes exhibit different degrees of confinement, it differs fundamentally from traditional filtering techniques. The abrupt onset of PT symmetry breaking at the exceptional point relocates the selected mode to the active region, whereas all higher order modes remain equally distributed between loss and gain. Consequently, our approach offers a high degree of mode discrimination, without any detrimental effect on the overall lasing efficiency. A detailed theoretical comparison between these two methodologies also supports this conclusion (see Section 5 of the Supporting Information). Our analysis shows that the achievable maximum gain to operate in a single mode for the above parity-time symmetric system is approximately 20 times larger than that for a ring that is evanescently coupled to a waveguide in an optimal condition.

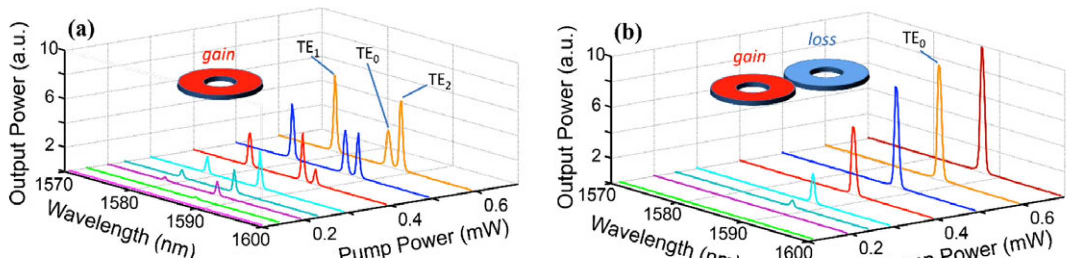


Figure 4 Comparison between the spectral evolution of a single microring laser and the corresponding PT-symmetric arrangement as a function of the pump power. (a) Higher order transverse modes TE_1 and TE_2 appear in the lasing spectrum of the single microring laser. (b) The PT laser remains purely single-moded.

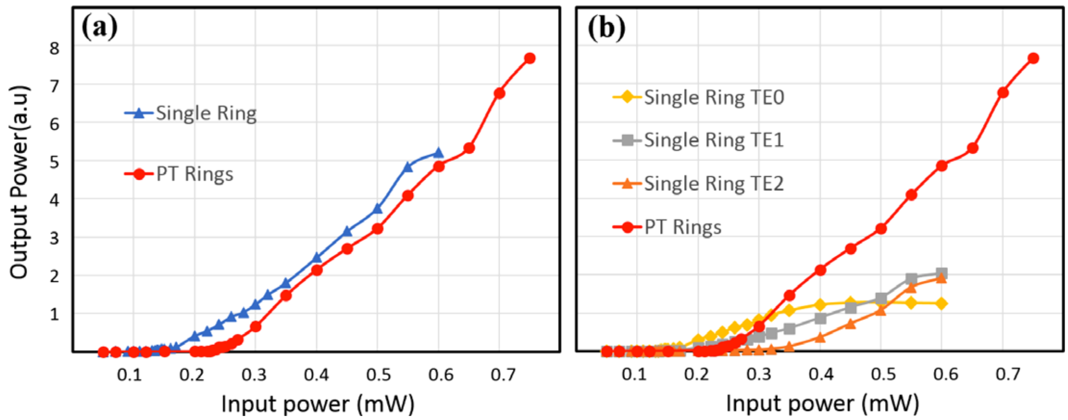


Figure 5 Light-light characteristics. (a) Despite a slightly higher lasing threshold, the PT-symmetric arrangement exhibits the same slope efficiency as an isolated microring. (b) The desirable TE_0 mode of the PT system carries significantly more power than any mode in the comparable single microring. (Note: In the single ring, different transverse modes can be distinguished from their onset of lasing.)

In conclusion, we have demonstrated how parity-time symmetric design approaches can be utilized to efficiently enforce global single-mode behavior in transversely multi-moded coupled cavities. The proposed method establishes mode selectivity through the particular dynamics of an exceptional point, and yields a significant increase in the extracted power from the fundamental mode without compromising the slope efficiency. By virtue of the robustness of its underlying physical principle, our approach is versatile, readily scalable and can be applied to a wide range of on-chip laser systems. Taking a broader perspective, it will be interesting to see how the reach of PT-symmetric mode manipulation can be extended and enhanced by recently developed supersymmetry-based techniques and isospectral optical transformations [26–28], potentially giving rise to an entirely new class of non-Hermitian integrated photonic circuitry.

Supporting Information

Additional supporting information may be found in the online version of this article at the publisher's website.

Acknowledgements. The authors acknowledge the financial support from NSF CAREER Award (ECCS-1454531), ARO (W911NF-14-1-0543), NSF (ECCS-1128520), AFOSR (FA9550-12-1-0148, FA9550-14-1-0037), and ARO (W911NF-16-1-0013). M.H. was supported by the German National Academy of Sciences Leopoldina (LPDR 2014-03). We would also like to acknowledge M.S. Mills for helpful discussions.

Received: 19 November 2015, **Revised:** 8 April 2016,
Accepted: 11 April 2016

Published online: 27 April 2016

Key words: single-mode lasers, PT-symmetry, microring devices, laser resonators, Guided waves.

References

[1] G. P. Agrawal and N. K. Dutta, Semiconductor Lasers (New York, 1993).
[2] L. A. Coldren, S. W. Corzine, and M. L. Mashanovitch, Diode Lasers and Photonic Integrated Circuits (Wiley; 2nd ed., 2012).
[3] J. E. Carroll, J. Whiteaway, and D. Plumb, Distributed Feedback Semiconductor Lasers, (The Institution of Engineering and Technology; 1998).
[4] M. Mikulla, P. Chazan, A. Schmitt, S. Morgott, A. Wetzel, M. Walther, R. Kiefer, W. Pletschen, J. Braunstein, and G. Weimann, IEEE Photon. Technol. Lett. **10**, 654 (1998).
[5] J. J. Plant, P. W. Juodawlkis, R. K. Huang, J. P. Donnelly, L. J. Missaggia, and K. G. Ray, IEEE Photon. Technol. Lett. **17**, 735 (2005).
[6] J. N. Walpole, Opt. Quantum Electron. **28**, 623 (1996).
[7] J. N. Walpole, J. P. Donnelly, P. J. Taylor, L. J. Missaggia, C. T. Harris, R. J. Bailey, A. Napoleone, S. H. Groves, S. R. Chinn, R. Huang, and J. Plant, IEEE Photon. Technol. Lett. **14**, 756 (2002).
[8] M.-A. Miri, P. LiKamWa, and D. N. Christodoulides, Opt. Lett. **37**, 764 (2012).
[9] C. M. Bender and S. Boettcher, Phys. Rev. Lett. **80**, 5243 (1998).
[10] C. M. Bender, D. C. Brody, and H. F. Jones, Phys. Rev. Lett. **89**, 270401 (2002).
[11] K. G. Makris, R. El-Ganainy, D. N. Christodoulides, and Z. Musslimani, Phys. Rev. Lett. **100**, 103904 (2008).
[12] A. Guo, G. J. Salamo, D. Duchesne, R. Morandotti, M. Volatier-Ravat, V. Aimez, G. A. Siviloglou, and D. N. Christodoulides, Phys. Rev. Lett. **103**, 093902 (2009).
[13] C. E. Ruter, K. G. Makris, R. El-Ganainy, D. N. Christodoulides, M. Segev, and D. Kip, Nat. Phys. **6**, 192 (2010).
[14] S. Longhi, Phys. Rev. A **82**, 031801 (2010).
[15] A. Regensburger, C. Bersch, M.-A. Miri, G. Onishchukov, D. N. Christodoulides, and U. Peschel, Nature **488**, 167 (2012).

[16] Z. Lin, H. Ramezani, T. Eichelkraut, T. Kottos, H. Cao, and D. N. Christodoulides, Phys. Rev. Lett. **106**, 213901 (2011).
[17] L. Feng, Y.-L. Xu, W. S. Fegadolli, M.-H. Lu, J. E. B. Oliveira, V. R. Almeida, Y.-F. Chen, and A. Scherer, Nature Mater. **12**, 108 (2012).
[18] M. Brandstetter, M. Liertzer, C. Deutsch, P. Klang, J. Schöberl, H. E. Türeci, G. Strasser, K. Unterrainer, and S. Rotter, Nature Comm. **5**, 5034 (2014).
[19] B. Peng, S. K. Özdemir, S. Rotter, H. Yilmaz, M. Liertzer, F. Monifi, C. M. Bender, F. Nori, and L. Yang, Science **346**, 328 (2014).
[20] L. Chang, X. Jiang, S. Hua, C. Yang, J. Wen, L. Jiang, G. Li, G. Wang, and M. Xiao, Nat. Photon. **133**, 524 (2014).
[21] L. Feng, Z. J. Wong, R. Ma, Y. Wang, and X. Zhang, Science **346**, 972 (2014).
[22] H. Hodaei, M.-A. Miri, M. Heinrich, D.N. Christodoulides, and M. Khajavikhan, Science **346**, 975 (2014).
[23] H. Hodaei, M.-A. Miri, A. U. Hassan, W. E. Hayenga, M. Heinrich, D. N. Christodoulides, and M. Khajavikhan, Optics Lett. **40**, 4955 (2015).
[24] M. Khajavikhan, A. Simic, M. Katz, J. H. Lee, B. Slutsky, A. Mizrahi, V. Lomakin, and Y. Fainman, Nature **482**, 204 (2012).
[25] J. Leidner, and J. Marciante, IEEE J. Quantum Electron. **48**, 1269 (2012).
[26] M.-A. Miri, M. Heinrich, R. El-Ganainy, and D. N. Christodoulides, Phys. Rev. Lett. **110**, 233902 (2013).
[27] M.-A. Miri, M. Heinrich, and D. N. Christodoulides, Phys. Rev. A **87**, 043819 (2013).
[28] M.-A. Miri, M. Heinrich, and D. N. Christodoulides, Optica **1**, 89 (2014).