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All-Fiber Optical Nonreciprocity Based on Parity-Time-Symmetric Fabry-Perot Resonators

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Abstract

Nonreciprocal light transmission in an all-fiber device with remotely tunable isolation ratio and switchable isolation direction is proposed and demonstrated. Three cascaded fiber Bragg gratings (FBGs) are inscribed in an erbium-ytterbium co-doped fiber (EYDF) to form two mutually coupled Fabry-Perot (FP) resonators. The two FP resonators have an identical geometry, but the gain and loss of the FP resonators, and their mutual coupling are manipulated by controlling the pumping power to realize broken parity-time (PT) symmetry. Strong optical nonreciprocity is achieved due to gain saturation nonlinearity that is enhanced by the broken PT symmetry. The proposed device is fabricated, and its operation is experimentally evaluated. Nonreciprocal light transmission with an isolation ratio of 8.58 dB at 1550 nm and a 3-dB bandwidth of 125 MHz is experimentally demonstrated. Our study also indicates, by optimizing the design, an isolation ratio up to 33 dB can be achieved. The proposed approach provides an all-fiber solution for a remotely tunable and optically controlled isolator, which may find great applications in software-defined optical networks.

Introduction

Optical nonreciprocity is of fundamental importance for signal processing in modern optical communication systems¹. Nonreciprocal devices, such as optical isolators¹ and circulators² are widely used to implement routing in optical networks and to remove back reflections at optical interfaces³. To date, several techniques have been proposed to realize optical nonreciprocity, including magneto-optic effects⁴⁻¹⁰, temporal modulation¹¹⁻¹⁴ and optical nonlinearity¹⁵⁻³⁰. The most widely used technique to realize optical isolators is based on magneto-optic effects.^{5-9,10} However, a magneto-optical isolator implemented based on the magneto-optic effects requires a strong external magnetic field, which makes the device bulky and difficult to implement, especially in a photonic integrated circuit (PIC). Temporal modulation is regarded as a promising solution to realize on-chip isolation, but strong modulation is usually needed which makes the device have high energy consumption¹¹⁻¹⁴. Optical nonlinear process such as nonlinear parametric amplification¹⁵, Raman amplification¹⁶, stimulated Brillouin scattering (SBS)¹⁷⁻²⁰, Kerr nonlinearities^{21,22}, optomechanical interactions²³⁻²⁸, and

gain/absorption saturation^{29,30} were also used to achieve nonreciprocal transmission. However, those approaches usually require specially designed waveguides with strong optical nonlinearities to effectively exploit optical nonreciprocity, again making the device have high energy consumption.

Parity-time (PT) symmetric systems have non-Hermitian Hamiltonians but exhibit real eigenvalues^{31,32}, which have been demonstrated on various physical platforms, including electronic³³, acoustic³⁴⁻³⁹ and photonic platforms⁴⁰⁻⁴⁶. In particular, photonics has been proven to be a powerful platform to implement PT symmetry due to the ease in manipulating the gain, loss and refractive index of an optical waveguide, leading to the observation of many new phenomena that are generally difficult or impossible to achieve in classical systems, including loss-induced transparency⁴¹, unidirectional invisibility^{42,43}, mode selection for single-mode lasing⁴⁴⁻⁴⁶, and nonreciprocal transmission^{29,30}. In a PT-symmetric system, optical nonlinearity can be strongly enhanced due to the highly confined localized eigenmodes. For example, the gain saturation effect can be exploited using PT symmetry to achieve nonreciprocal light transmission based on photonic integrated components, such as two directly coupled microtoroidal whispering gallery mode resonators (WGMRs)^{29,30}, which provides a promising solution for on-chip isolators. However, the employment of isolators based on integrated resonators in an optical fiber network is usually inconvenient and lossy due to the fiber to resonator interfaces. An all-fiber isolator may be of great interest for applications in optical networks due to the low cost, small insertion loss and simplicity for deployment.

In this paper, we propose a novel approach to implement nonreciprocal light transmission in an all-fiber device with remotely tunable isolation ratio and switchable isolation direction. Three cascaded fiber Bragg gratings (FBGs) are inscribed in an erbium-ytterbium co-doped fiber (EYDF) to form two mutually coupled Fabry-Perot (FP) resonators. The two FP resonators have an identical geometry with identical resonance wavelengths. The gain and loss of the FP resonators are manipulated by controlling the pumping power to make the device work in the PT symmetry breaking regime. Thanks to the PT symmetry, the eigenmodes in the resonators are strongly localized, which would strongly increase the gain saturation, making nonreciprocal light transmission significantly enhanced. The proposed all-fiber device is fabricated, and its operation is experimentally evaluated. An isolation ratio of 8.58 dB at 1550 nm with a 3-dB bandwidth of 125 MHz is demonstrated. Our study also shows that the isolation ratio can be further improved to 33 dB if the design is optimized. The key advantages of the proposed all-fiber isolator include a remotely switchable isolation direction, a tunable isolation ratio and a tunable bandwidth. It opens new avenues for all-fiber light control in fiber-optic communication systems.

Principle

Figure 1a shows the schematic of the proposed all-fiber isolator. It consists of three uniform FBGs (FBG1, FBG2 and FBG3) inscribed in a short and highly doped EYDF to form two FP resonators (FP1 and FP2). The FP resonators are geometrically identical (i.e., FBG1 and FBG3 are identical, the lengths of FP1 and FP2 are the same, and FBG2 is a symmetrical FBG) and are mutually coupled, which ensures the degeneracy of the localized resonance frequencies. The net gain and loss in FP2 and FP1 can be tuned by controlling the pumping power and the pumping direction into the EYDF. If the pumping power is launched into the EYDF from the right side (the FP2 side), the pumping power in FP2 will be higher than that in FP1 due to the absorption along the EYDF. By controlling the pumping power, a net gain and loss can be achieved for FP2

and FP1, respectively. To achieve a high gain to loss ratio between FP2 and FP1, one can make the middle FBG (FBG2) have an additional reflection band at 980 nm to enable FP2 have more gain, or, in our case, apply a bending to the FP1 to make FP1 have higher loss. The details of the PT-symmetric FP resonators and their optical characteristics are discussed in detail in Supplementary Note 1.

Fig. 1b shows the transmission spectrum of an individual FBG (FBG1, as an example). As can be seen, the FBG has 3-dB bandwidth of 0.2 nm, a reflection of 12 dB. Fig. 1b and 1c shows the spectrums of the isolator when operating in the unbroken PT-symmetric regime (top) and in the broken PT-symmetric regime. Within the reflection bandwidth of the FBGs, the two coupled resonators support four resonance modes. The mode spacing is 0.067 nm, corresponding to an effective cavity length of 12.4 mm. The resonance wavelength mismatch between FP1 and FP2 is removed by applying a stain to FP1 to compensate for the fabrication error that results in a cavity length difference between FP1 and FP2 (see Supplementary Note 2). Degeneracy of the eigenmodes of FP1 and FP2 is then realized. The operation of the system involves the coupling between the forward and backward light waves in both FP1 and FP2 resonators. The coupled differential equations can be written as

Fig. 1. **a** Schematic of the PT-symmetric FP resonators for nonreciprocal transmission of light. FP1 and FP2 are the two resonators with FP1 having a loss and FP2 a gain. FBG: fiber Bragg grating; EYDF: erbium-ytterbium co-doped fiber. Based on the probe input directions, forward and backward propagation configurations are denoted by blue and red arrows, respectively. The purple arrow denotes the pump input direction. **b** Measured transmission spectrum of FBG1. **c** Measured transmission spectra of the device in the unbroken PT-

symmetric regime (top) and in the broken PT-symmetric regime (bottom). Resonances are observed in the reflection band (shaded brown) of the FBGs.

$$\begin{cases} \frac{da_1}{dt} = (i\Delta\omega_1 - \gamma)a_1 - i\mu a_2 + \sqrt{\kappa}\varepsilon_{in} \\ \frac{da_2}{dt} = (i\Delta\omega_2 + g_a)a_2 - i\mu a_1 \\ \frac{db_1}{dt} = (i\Delta\omega_1 - \gamma)b_1 - i\mu b_2 \\ \frac{db_2}{dt} = (i\Delta\omega_2 + g_b)b_2 - i\mu b_1 + \sqrt{\kappa}\varepsilon_{in} \end{cases} \quad (1)$$

where a_1 and a_2 are the amplitudes of the forward light waves in FP1 and FP2, respectively; b_1 and b_2 are amplitudes of the backward light waves in FP1 and FP2, respectively; ω_1 and ω_2 are the local resonance frequencies of FP1 and FP2, respectively, μ is the coupling coefficient between FP1 and FP2 determined by the transmission coefficient of FBG2, and $\Delta\omega_1 = \omega_0 - \omega_1$ and $\Delta\omega_2 = \omega_0 - \omega_2$ are the frequency detuning of the input optical signal from the local resonance frequencies of FP1 and FP2, respectively. The net gain of FP2 for forward and backward propagating probe lights are given by $g_{a,b} = g'/2 - \gamma_0/2 - \kappa/2$, where $g' = g_0 / (1 + |A/a_{sat}|^\alpha)$, A is the amplitude of the forward ($A=a_2$) or backward ($A=b_2$) transmission light in FP2, κ is the external coupling coefficient determined by the transmission coefficient of FBG1 and FBG3, g' is the effective gain of the EYDF in FP2 taking into consideration the gain saturation effect, g_0 is the small-signal gain coefficient of FP2, a_{sat} and α are the saturation amplitude and the saturation index, respectively, $|\varepsilon_{in}|^2$ is the power of the input signal, and γ is the loss of FP1.

By solving Eq. (1) in the steady-state approximation, the transmittance of the system, which is the power ratio between input and output intensities for both directions, are given by

$$\begin{aligned} T_f &= \left| \frac{S_{out}^f}{\varepsilon_{in}} \right|^2 = \frac{\mu^2 \kappa^2}{(-\Delta^2 + \mu^2 - g_a \gamma)^2 + \Delta^2 (g_a - \gamma)} \\ T_b &= \left| \frac{S_{out}^b}{\varepsilon_{in}} \right|^2 = \frac{\mu^2 \kappa^2}{(-\Delta^2 + \mu^2 - g_b \gamma)^2 + \Delta^2 (g_b - \gamma)} \end{aligned} \quad (2)$$

where $|S_{out}^f|^2$ and $|S_{out}^b|^2$ are the output powers of the system when the input signal is launched in the forward and backward directions, respectively. We have $T_f \neq T_b$ when $g_a \neq g_b$, and the nonreciprocal light transmission can thus be achieved. To quantify the isolation performance of the system, we define a nonreciprocal isolation $\eta = 10 \times \log_{10}(T_f/T_b)$, where T_f and T_b are the peak transmittivities of the forward and backward transmission spectra, respectively.

Experiment

Figure 2a illustrates the experimental setup to characterize the optical nonreciprocity of the device. The device is fabricated with three cascaded FBGs in an

EYDF to form two mutually coupled FP resonators. The three FBGs have an identical length of 4 mm and a reflectivity of 12 dB. The physical spacing between two FBGs is 10 mm, as shown in Fig. 2b. An optical vector analyzer (OVA) is used to generate a wavelength-sweeping probe light which is applied to the device to measure its transmission spectrum. A 980-nm laser source is used to pump the EYDF. The polarizations of the probe and pump light waves are adjusted by two polarization controllers (PC1 and PC2), respectively. A gain-variable erbium-doped fiber amplifier (EDFA) is used to tune the power of the probe light launched into the device, with its output power being monitored in real time using a power meter (PM) via an optical coupler (OC1). For forward light transmission measurements, the probe light goes through OC2 and is launched into the device through the 1550-nm port of a wavelength division multiplexer (WDM1). After passing through FP1 and FP2, the probe light is obtained at the output of the device through the 1550-nm port of a second WDM (WDM2). The transmitted probe light goes through OC3 and is detected at the OVA after being attenuated at a variable optical attenuator. For backward light transmission measurements, the probe light goes into the device through the 1550-nm port of WDM2. After passing through FP2 and FP1, the probe light is obtained at the output of the device through the 1550-nm port of WDM1. In both measurements, the pumping light is launched into the device from the 980-nm port of WDM2, and the residual pump light is terminated at a terminator connected to the 980-nm port of WDM1.

Fig. 2. **a** Experimental setup for forward and backward transmission measurements. OVA: optical vector analyzer; VOA: variable optical attenuator; PC: polarization controller; EDFA: erbium-doped fiber amplifier; OC: optical coupler; PM: power meter; WDM: wavelength division multiplexer. Optical paths for forward and backward transmission are shown by the blue and red lines, respectively. The shared optical paths for both forward and backward transmission are shown by the yellow lines. The optical path for the pump light is shown by the purple line. **b** A fabricated all-fiber nonreciprocal device based on parity-time-symmetric FP resonators. **c** A fabricated single FP resonator on an EYDF to characterize the gain-saturation nonlinearity in the FP resonator.

Fig. 3. Gain saturation response of a single FP resonator shown in Fig. 2c, **a** with a fixed probe power of -15 dBm. **b** with a fixed pumping power of 100 mW.

First, we investigate the gain saturation behavior of a single FP resonator. To do so, an FP resonator consisting of two FBGs with an identical length of 4 mm and a reflectivity of 12 dB is fabricated in an EYDF. The two FBGs are placed with a physical spacing of 10 mm, as shown in Fig. 2c. We first measure the output power when the input probe power is fixed at -15 dBm while increasing the 980-nm pumping power from 0 to 200 mW. As can be seen from Fig. 3a, a maximum gain is achieved when the pumping power is equal to 100 mW. Further increasing the pumping power will not increase the gain. Then, we fix the pumping power at 100 mW while increasing the probe power from -15 to 10 dBm. As shown in Fig. 3b, when the probe power is less than -10 dBm, we have the highest gain. Further increasing the probe power will lead to gain saturation. The results indicate that the gain saturation can be achieved by choosing a proper pumping power and a proper probe power. For a single FP resonator, optical nonreciprocity is not possible since an optical signal, injected into the cavity from either direction, will be trapped in the cavity and will experience the same gain. For a device with two mutually coupled PT-symmetric FP resonators, optical nonreciprocity is possible since an optical signal injected into the device from the gain FP resonator side will first experience gain saturation and then a loss in the loss FP resonator, while an optical signal injected into the device from the loss FP resonator side will not experience gain saturation in the gain section since the signal is very weak due to the loss in the loss section. This is the fundamental concept to achieve optical nonreciprocity based on PT symmetry using two mutually coupled FP resonators.

Next, the optical nonreciprocity of the proposed all-fiber device consisting of two mutually coupled FP resonators is experimentally evaluated. To do so, we fabricate three cascaded FBGs in an EYDF to form two mutually coupled FP resonators. The three FBGs have an identical length of 4 mm and a reflectivity of 12 dB. The physical spacing between two adjacent FBGs is 10 mm, as shown in Fig. 2c. The device is partially mounted on a micro-positioning platform, which allows stretching only FP1, so that the lengths of the two resonators can be controlled to match accurately. The tuning process is shown in detail in Supplementary Fig. 3. To obtain nonreciprocal transmission, the system should work in the PT-symmetric broken regime. In the experiment, the gain is introduced to FP2 by optically pumping the EYDF. The system become PT-symmetric by adjusting the pump power to balance the gain/loss ratio between the two coupled FP resonators (i.e., $g = \gamma$). With a balanced gain/loss ratio, the system is in the broken PT-symmetric regime when $\mu < \gamma$, and the eigenfrequencies share the same real parts but complementary imaginary parts. In this case, the transmission spectrum of the device

is similar to that of a single FP resonator, with a single transmission peak at each resonance wavelength of FP1 or FP2, as shown in Fig. 1c. The transmission peak corresponds to two degenerate eigenmodes of the PT-symmetric FP resonators, with a gain mode having a positive imaginary part and a loss mode having a negative imaginary part. The gain mode is strongly confined in the gain resonator FP2⁴⁴, thus enhancing the gain saturation to allow optical nonreciprocity with a high isolation ratio. As shown in Fig. 4a, the transmittances at the eigenfrequency of the PT-symmetric FP resonators for the backward and forward lights are measured to be 0.13 and 0.02, respectively, corresponding to an isolation ratio of $\eta = 8.58$ dB with the pumping power of 100 mW for an input probe power of 0 dBm.

We also investigate the operation of the device when operating in the PT-symmetric unbroken regime. At the same input probe power of 0 dBm, the pumping power and the bending loss of the FP1 are reduced such that the magnitude of the gain and loss coefficients is smaller than that of the coupling coefficient, or $\mu > \gamma$. Mode splitting is observed in the transmission spectrum, as shown in Fig. 4b. Due to the weak eigenmode localization⁴⁴, the nonreciprocal transmission is only a result of gain saturation of the EYDF without the enhancement by the PT symmetric modes. The transmittances of the nondegenerate eigenmodes are measured to have similar values for both forward and backward light waves. Fig. 4c and d shows the simulated results, showing a good agreement with those experimentally measured results. The details on light transmission in the PT-symmetric FP resonators with broken and unbroken symmetries are discussed in Supplementary Note 3.

Fig. 4. Experimental results of nonreciprocal light transmission of the device in **a** the broken PT-symmetric regime, and **b** in the unbroken PT-symmetric regime. Insert: the total transmission spectrum of the device in a logarithmic scale. **c** and **d**, Simulation results corresponding to those in **a** and **b**.

Since the optical nonreciprocity is resulted from an enhanced gain saturation in the PT-symmetric FP resonators, it is dependent on the probe power. Fig. 5a shows the transmittances of the forward and backward light waves with a varying probe power from -15 to 10 dBm at a fixed the pumping power of 100 mW. At a low probe power, gain saturation would not occur, and the nonreciprocity is weak. At a high probe power, the EYDF is fully depleted, providing a negligible gain for the probe signal entering the device from either direction, the nonreciprocity is also weak. Strong nonreciprocity is observed at a probe power of 0 dBm, as shown in Fig. 5b. In this case, the probe light entering the device from the backward direction will be strongly confined in FP2, leading to strong gain saturation. On the contrary, when the probe light entering the device from the forward direction, the probe signal is first attenuated in FP1 before launching into FP2. The effective gain coefficient of FP2 is higher due to a smaller input power. As a result, the unequal gains in the forward and backward propagating directions lead to a nonreciprocal response of the device. To further study the nonreciprocity performance, a simulation is performed in which the parameters are optimized. The result shows that, by optimizing the design of the FBGs and utilizing active fibers with better amplification performance, the isolation ratio can be further improved to 33 dB (See Supplementary Note 4).

Fig. 5. Experimental results of the isolation performance in the broken-PT-symmetric FP resonators. **a.** The transmittances of the probe signal entering the device in the forward and backward propagation directions, measured as a function of the probe power when the pump power and the coupling strength are fixed. **b.** The isolation ratio as a function of the probe power.

Discussion

The key to achieve optical nonreciprocity in the proposed all-fiber device was to use broken PT symmetry, by which the probe light entering the device from the gain section was highly saturated with less gain due to the strong confinement of the probe light in the gain FP resonator. For the probe light entering the device from the loss section, the probe signal was first attenuated at the loss section and then amplified at the gain section, where no or less gain saturation, leading to the overall gain for the second case is higher than that in the first case, optical nonreciprocity was then achieved. The proposed all-fiber nonreciprocal device was fabricated, and its operation was experimentally demonstrated. Nonreciprocal light transmission with an isolation ratio of 8.58 dB at 1550 nm and a 3-dB bandwidth of 125 MHz was experimentally demonstrated. By optimizing the design, the isolation ratio up to 33 dB could be achieved.

In conclusion, we have proposed and experimentally demonstrated a new

approach to implement an all-fiber nonreciprocal device using two mutually coupled PT-symmetric FP resonators. Thanks to the geometrical arrangement of the two FP resonators, PT symmetry of the system was achieved by controlling the pumping power to the FP resonators, to make the gain and the loss in the two FP resonators identical in magnitude. When the gain/loss coefficient was greater than the coupling coefficient, PT symmetry was broken, then the light in the gain FP resonator was highly confined, which was used to increase the gain-saturation nonlinearity, a key effect that leads to optical nonreciprocity. The key advantages of the proposed device include all-fiber nature, which makes it possible to have the device integrated in an optical network without additional packaging. In addition, the device is all optically controlled and the isolation direction can be reversed by altering the direction of the pumping light, which can find potential applications in the future software-define reconfigurable optical interconnect networks. The bandwidth, due to the use of FP resonators was limited to few hundred of megahertz, which can be extended up to gigahertz by designing the FP resonators with lower Q-factors.

Method

Device fabrication. The device was fabricated by inscribing three FBGs to form a pair of FP resonators in an EYDF using a phase mask which was illuminated by a 193-nm ArF excimer laser. The pulse energy and the repetition rate of the excimer laser were 110 mJ and 30 Hz, respectively. The phase-mask has a period of 1070.49 and a corresponding Bragg wavelength of 1551 nm. The reflectivity and bandwidth of the three FBGs are 94% and 0.2 nm, respectively. The lengths of the three FBGs and the two FP cavities are 4 mm and 10 mm, respectively. The device has a total length of 32 mm. The distance between adjacent gratings was controllable by adjusting a positioning stage during FBG fabrication process. The peak absorption of the EYDF at 975 nm and 1535 nm are 1337 dB/m and 22 dB/m, respectively. The refractive index of the EYDF at 1550 nm is about 1.4485.

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Author contributions

J.Z. and J.Y. conceived the idea; J.Z. designed the experiment and wrote the paper; Z.L. conducted the theoretical simulation, device fabrication and testing, and wrote the paper; L.L. and B.L. contributed to device fabrication and testing; J.Y. analyzed the data and wrote the paper; Y. Z. wrote the paper.

Reference

- 1 Jalas, D. *et al.* What is—and what is not—an optical isolator. *Nature Photonics* **7**, 579–582 (2013).
- 2 Fujii, Y. High-isolation polarization-independent optical circulator. *Journal of Lightwave Technology* **9**, 1238–1243 (1991).
- 3 Petermann, K. External optical feedback phenomena in semiconductor lasers. *IEEE Journal of Selected Topics in Quantum Electronics* **1**, 480–489 (1995).
- 4 Haldane, F. & Raghu, S. Possible realization of directional optical

- waveguides in photonic crystals with broken time-reversal symmetry. *Physical review letters* **100**, 013904 (2008).
- 5 Bi, L. *et al.* On-chip optical isolation in monolithically integrated non-reciprocal optical resonators. *Nature Photonics* **5**, 758 (2011).
 - 6 Yan, W. *et al.* Waveguide-integrated high-performance magneto-optical isolators and circulators on silicon nitride platforms. *Optica* **7**, 1555-1562 (2020).
 - 7 Stadler, B. J. & Mizumoto, T. Integrated magneto-optical materials and isolators: a review. *IEEE Photonics Journal* **6**, 1-15 (2013).
 - 8 Zhang, Y. *et al.* Monolithic integration of broadband optical isolators for polarization-diverse silicon photonics. *Optica* **6**, 473-478 (2019).
 - 9 Zhang, C., Dulal, P., Stadler, B. J. & Hutchings, D. C. Monolithically-integrated TE-mode 1D silicon-on-insulator isolators using seedlayer-free garnet. *Scientific reports* **7**, 1-8 (2017).
 - 10 Sun, L., Jiang, S., Zuegel, J. & Marciante, J. All-fiber optical isolator based on Faraday rotation in highly terbium-doped fiber. *Optics letters* **35**, 706-708 (2010).
 - 11 Sounas, D. L. & Alù, A. Non-reciprocal photonics based on time modulation. *Nature Photonics* **11**, 774-783 (2017).
 - 12 Estep, N. A., Sounas, D. L., Soric, J. & Alù, A. Magnetic-free non-reciprocity and isolation based on parametrically modulated coupled-resonator loops. *Nature Physics* **10**, 923-927 (2014).
 - 13 Guo, X., Ding, Y., Duan, Y. & Ni, X. Nonreciprocal metasurface with space-time phase modulation. *Light: Science & Applications* **8**, 1-9 (2019).
 - 14 Yu, Z. & Fan, S. Complete optical isolation created by indirect interband photonic transitions. *Nature photonics* **3**, 91-94 (2009).
 - 15 Hua, S. *et al.* Demonstration of a chip-based optical isolator with parametric amplification. *Nature communications* **7**, 1-6 (2016).
 - 16 Krause, M., Renner, H. & Brinkmeyer, E. Optical isolation in silicon waveguides based on nonreciprocal Raman amplification. *Electronics Letters* **44**, 691-693 (2008).
 - 17 Dong, C.-H. *et al.* Brillouin-scattering-induced transparency and non-reciprocal light storage. *Nature communications* **6**, 1-6 (2015).
 - 18 Kim, J., Kuzyk, M. C., Han, K., Wang, H. & Bahl, G. Non-reciprocal Brillouin scattering induced transparency. *Nature Physics* **11**, 275-280 (2015).
 - 19 Poulton, C. G. *et al.* Design for broadband on-chip isolator using stimulated Brillouin scattering in dispersion-engineered chalcogenide waveguides. *Optics express* **20**, 21235-21246 (2012).
 - 20 Ma, J. *et al.* Chip -Based Optical Isolator and Nonreciprocal Parity -Time Symmetry Induced by Stimulated Brillouin Scattering. *Laser & Photonics Reviews* **14**, 1900278 (2020).
 - 21 Grigoriev, V. & Biancalana, F. Nonreciprocal switching thresholds in coupled nonlinear microcavities. *Optics letters* **36**, 2131-2133 (2011).

- 22 Del Bino, L. *et al.* Microresonator isolators and circulators based on the intrinsic nonreciprocity of the Kerr effect. *Optica* **5**, 279–282 (2018).
- 23 Shen, Z. *et al.* Experimental realization of optomechanically induced non-reciprocity. *Nature Photonics* **10**, 657–661 (2016).
- 24 Ruesink, F., Miri, M.-A., Alu, A. & Verhagen, E. Nonreciprocity and magnetic-free isolation based on optomechanical interactions. *Nature communications* **7**, 1–8 (2016).
- 25 Fang, K. *et al.* Generalized non-reciprocity in an optomechanical circuit via synthetic magnetism and reservoir engineering. *Nature Physics* **13**, 465–471 (2017).
- 26 Shen, Z. *et al.* Reconfigurable optomechanical circulator and directional amplifier. *Nature communications* **9**, 1–6 (2018).
- 27 Hafezi, M. & Rabl, P. Optomechanically induced non-reciprocity in microring resonators. *Optics express* **20**, 7672–7684 (2012).
- 28 Ruesink, F., Mathew, J. P., Miri, M.-A., Alù, A. & Verhagen, E. Optical circulation in a multimode optomechanical resonator. *Nature communications* **9**, 1–6 (2018).
- 29 Chang, L. *et al.* Parity-time symmetry and variable optical isolation in active-passive-coupled microresonators. *Nature photonics* **8**, 524–529 (2014).
- 30 Peng, B. *et al.* Parity-time-symmetric whispering-gallery microcavities. *Nature Physics* **10**, 394–398 (2014).
- 31 Bender, C. M. & Boettcher, S. Real spectra in non-Hermitian Hamiltonians having P T symmetry. *Physical Review Letters* **80**, 5243 (1998).
- 32 El-Ganainy, R. *et al.* Non-Hermitian physics and PT symmetry. *Nature Physics* **14**, 11–19 (2018).
- 33 Schindler, J., Li, A., Zheng, M. C., Ellis, F. M. & Kottos, T. Experimental study of active LRC circuits with PT symmetries. *Physical Review A* **84**, 040101 (2011).
- 34 Shi, C. *et al.* Accessing the exceptional points of parity-time symmetric acoustics. *Nature communications* **7**, 1–5 (2016).
- 35 Aurégan, Y. & Pagneux, V. P T-symmetric scattering in flow duct acoustics. *Physical review letters* **118**, 174301 (2017).
- 36 Zhu, X., Ramezani, H., Shi, C., Zhu, J. & Zhang, X. P t-symmetric acoustics. *Physical Review X* **4**, 031042 (2014).
- 37 Fleury, R., Sounas, D. & Alu, A. An invisible acoustic sensor based on parity-time symmetry. *Nature communications* **6**, 1–7 (2015).
- 38 Zhang, J. *et al.* Giant nonlinearity via breaking parity-time symmetry: A route to low-threshold phonon diodes. *Physical Review B* **92**, 115407 (2015).
- 39 Shao, L. *et al.* Non-reciprocal transmission of microwave acoustic waves in nonlinear parity-time symmetric resonators. *Nature Electronics* **3**, 267–272 (2020).
- 40 Rüter, C. E. *et al.* Observation of parity-time symmetry in optics. *Nature physics* **6**, 192–195 (2010).

- 41 Guo, A. *et al.* Observation of P T-symmetry breaking in complex optical
potentials. *Physical Review Letters* **103**, 093902 (2009).
- 42 Regensburger, A. *et al.* Parity-time synthetic photonic lattices. *Nature*
488, 167-171 (2012).
- 43 Feng, L. *et al.* Experimental demonstration of a unidirectional
reflectionless parity-time metamaterial at optical frequencies. *Nature*
materials **12**, 108-113 (2013).
- 44 Feng, L., Wong, Z. J., Ma, R.-M., Wang, Y. & Zhang, X. Single-mode laser by
parity-time symmetry breaking. *Science* **346**, 972-975 (2014).
- 45 Hodaei, H., Miri, M.-A., Heinrich, M., Christodoulides, D. N. &
Khajavikhan, M. Parity-time-symmetric microring lasers. *Science* **346**, 975-
978 (2014).
- 46 Li, L. *et al.* Polarimetric parity-time symmetry in a photonic system.
Light: Science & Applications **9**, 1-8 (2020).

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