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Observation of PT-symmetry in a fiber ring laser

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A wavelength-tunable single-mode laser with a sub-kilohertz linewidth based on parity-time (PT)-symmetry is proposed and experimentally demonstrated. The proposed PT-symmetric laser is implemented based on a hybrid use of an optical fiber loop and a thermally tunable integrated microdisk resonator (MDR). The MDR, implemented based on the silicon-on-insulator, operates with the optical fiber loop to form two mutually coupled cavities with an identical geometry. By controlling two light waves passing through the two cavities, with one having a gain coefficient and the other a loss coefficient but with an identical magnitude, a PT-symmetric laser is implemented. Thanks to an ultranarrow passband of the cavity due to PT-symmetry, single-longitudinal mode lasing is achieved. The tuning of the wavelength is implemented by thermally tuning the MDR. The proposed PT-symmetric laser is demonstrated experimentally. Single-longitudinal mode lasing at a wavelength of around 1555 nm with a sub-kilohertz linewidth of 433 Hz is implemented. The lasing wavelength is continuously tunable from 1555.135 to 1555.887 nm with a tuning slope of 75.24 pm/°C.

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Single-mode lasers having a continuously tunable wavelength and a sub-kilohertz linewidth are of fundamental importance for high-performance optical communications [1], optical imaging [2], and spectroscopy [3]. Numerous types of lasers with a narrow linewidth have been proposed. For example, the linewidth of a fiber laser with significant performance advantages such as high power efficiency and excellent capacity for heat dissipation can be narrowed to a sub-kilohertz level [4]. According to the well-known Schawlow-Townes formula [5], a longer lasing cavity means a longer photon lifetime and a narrower laser linewidth. However, a long-lasing cavity will cause a large number of closely spaced modes, making single-mode lasing difficult to achieve.

To achieve a single-mode lasing operation, numerous methods have been presented in the past few decades. A simple and effective way is to shorten the optical cavity such as using an ultrashort (~ 5.5 µm) Fabry–Perot etalon [6] or a subwavelength metallic structure [7], which increases the free spectral range (FSR) and, thus, enhances the mode selectivity of the laser. Dispersive elements such as distributed feedback gratings [8] or distributed Bragg mirror [9] can also be employed in the lasing cavity to achieve single-mode lasing. However, the short lasing cavity in both methods presented above limits the linewidth of the laser [5]. Another approach is to use spatially varied optical pumping to select a desired lasing mode, which is implemented by using a spatial light modulator (SLM) to control the pumping power distribution determined by a genetic algorithm [10]. However, the system is complicated and an SLM, in particular, is needed. The use of dual- or multi-loops can increase the FSR due to the Vernier effect, which is another approach to realize a single-mode lasing [11]. The major limitation of using dual- or multi-loops is that either the wavelength cannot be tuned or the laser has limited tunability.

Recently, parity-time (PT)-symmetry, which was first developed within the framework of quantum field theory [12], is proved to be applicable to the field of optics for mode selection [13]. Numerous configurations have been proposed to implement lasers to support single-mode operation [14–16]. In a PT-symmetric laser, a coupled arrangement of two structurally identical cavities with one having a gain coefficient and the other a loss, but identical in magnitudes, is employed. By controlling the relationship between the gain and loss between the two cavities, PT-symmetry for one selected mode is broken and, thus, the selected mode will experience a net amplification, while the other unbroken modes will undergo bounded neutral oscillations. Thanks to the simple but effective mode-selection mechanism, stable single-mode lasing can be achieved. However, the linewidths of the PT-symmetric lasers [14–16] are large due to their short cavity lengths.

In this Letter, for the first time, to the best of our knowledge, we introduce the PT-symmetry concept to the field of fiber optics, to implement single-mode fiber lasers. Since a fiber laser has a long cavity length, the mode spacing is very small, mode selection is a challenging task, and single-mode lasing is very hard to achieve. The use of PT-symmetry can solve the mode-selection challenge. In this Letter, a wavelength-tunable PT-symmetric single-mode fiber laser with a sub-kilohertz linewidth is experimentally demonstrated, in which the mutually coupled cavities are realized using an integrated microdisk resonator (MDR). By injecting two light waves into one bus waveguide of the MDR bidirectionally, two cavities with an identical geometry are implemented. The gain and loss of the two cavities can be controlled by tuning the polarization states of the light waves injected into the MDR from the two ends of the bus waveguide. Once the PT-symmetry of one mode is broken, a stable single-mode lasing at the selected wavelength is achieved. The wavelength tunability of the proposed PT-symmetric fiber laser is realized by thermally tuning the dual-waveguide MDR. Thanks to the long fiber length in the cavity, a lightwave with a sub-kilohertz linewidth is generated. The performance of the proposed PT-symmetric laser is evaluated experimentally. Single-mode lasing at a wavelength of around 1555 nm is implemented with a sub-kilohertz linewidth of 433 Hz. By thermally tuning the MDR from 20 to 30°C, the wavelength of the proposed laser can be continuously tuned with a tuning range from 1555.135 to 1555.887 nm and a tuning slope of 75.24 pm/°C.

Figure 1 is the schematic diagram of the proposed PT-symmetric fiber laser. As can be seen, the laser has two mutually coupled loops with an identical geometry with one having a gain and the other a loss. In the two cavities, an erbium-doped fiber amplifier (EDFA) is used to provide the gain. The lightwave from the EDFA is transmitted through an optical bandpass filter (OBPF), and divided into two branches by an optical divider (OD1). The upper branch is connected to the input port (point A) of an MDR via a polarization controller (PC1) and an optical isolator (ISO1). The lightwave coupled into the MDR via input port A is then transmitted through its corresponding drop port (point B) and a second polarization controller (PC2), and applied to a polarization combiner (PBC). The lower branch is connected to the other input port (point C) of the MDR via a third polarization controller (PC3) and a second isolator (ISO2). The lightwave coupled into the MDR via input port C is then transmitted through its corresponding drop port (point D) and a fourth polarization controller (PC4), and applied to the PBC. The combined lightwave at the output of the PBC is then fed back to the EDFA to close the loop. Since only the transverse electronic (TE) mode can be excited in the bus waveguide of the MDR, the gain and loss of the two loops can be controlled by adjusting the polarization states of the light waves into the waveguide by PC1 and PC3. By thermally tuning the MDR, the tunability of the proposed PT-symmetric fiber laser is implemented. A second optical divider (OD2) is used to tap part of the lasing light for spectrum measurement by an optical spectrum analyzer (OSA). The lasing mode and the linewidth of the output are analyzed through a delayed self-heterodyne system [17].

In the proposed PT-symmetric laser, there are two mutually coupled loops having an identical geometry with one having a gain and the other a loss. The eigenfrequencies of the PT-symmetric laser are given by Ref. [15]:

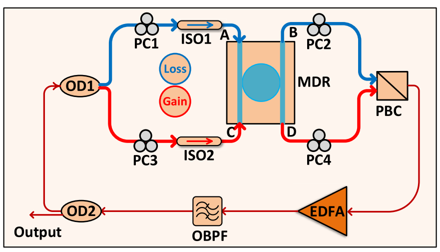

Fig. 1. Schematic diagram of the proposed PT symmetric fiber laser. OD, optical divider; PC, polarization controller; MDR, microdisk resonator; PBC, polarization beam combiner; EDFA, erbium-doped fiber amplifier; OBPF, optical bandpass filter.

$$\omega_n^{(1,2)} = \omega_n + i\frac{g_{a_n} + g_{b_n}}{2} \pm \sqrt{\kappa_n^2 - \left(\frac{g_{a_n} - g_{b_n}}{2}\right)^2}, \tag{1}$$

where ω_n is the eigenfrequency of the nth modes of the two cavities without PT-symmetry, g_{a_n} and g_{b_n} are the net gain and loss coefficients of the two loops for the nth modes, and κ_n is the coupling coefficient between the two loops for the nth modes. By tuning the gain and loss coefficients of the two loops to be identical in magnitude, that is, $g_{a_n} = -g_{b_n} = g_n$, the PT-symmetric condition is achieved, and thus Eq. (1) can be rewritten as

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

There is a transition point when the gain or loss of the two loops equals the coupling coefficient between them, that is, $g_n = \kappa_n$. Any pair of lasing modes, whose gain or loss remains below the coupling coefficient ($g_n < \kappa_n$), will undergo bounded neutral oscillations, which means the PT-symmetry is unbroken. In contrast, once the gain or loss exceeds the coupling coefficient ($g_n > \kappa_n$), there will be a conjugate pair of lasing and decaying modes, which indicates that the PT-symmetric condition is broken.

When only the lasing mode with the largest gain, say the 0th mode, is under the broken PT-symmetric condition ($g_0 > \kappa_0$), and all the other modes are under the unbroken PT-symmetry condition ($g_n < \kappa_n$, $n \neq 0$), only the broken PT-symmetric 0th mode is selected to oscillate, and all the other unbroken PT-symmetric modes are suppressed.

We should emphasize that single-mode lasing can also be achieved in the absence of PT-symmetry, when only one mode with a gain exceeding the loss exists in the cavity. However, this approach will impose a strict requirement on the bandwidth of the mode-selection filter in the loop, especially when there are a series of closely spaced modes in the broad gain window. One solution to ease the requirement is to make the second highest modes to have lower powers or, equivalently, to make the gain contrast ratio greater. Note that the gain contrast ratio is defined as the ratio between the gains of the primary mode and the secondary mode. This can be done by employing PT-symmetry. Assume the gain contrast ratio of a single loop fiber laser is γ_s, under the PT-symmetric condition, the gain contrast ratio between the primary mode and the secondary mode can be increased by G times [15]:

$$\gamma_{\mathrm{PT}} = G \cdot \gamma_s, \tag{3}$$

where G is the gain contrast enhancement factor, which is given by Ref. [15]:

$$G = \sqrt{\frac{g_0/g_1 + 1}{g_0/g_1 - 1}}. \tag{4}$$

A proof-of-concept experiment is carried out based on the setup shown in Fig. 1. The EDFA (FiberPrime Inc. EDFA-C-14-S-FA) has a 25 dB gain and a 13 dBm saturated output power. The OBPF has a center wavelength of 1555 nm and a 3 dB bandwidth of 10 nm, which is a commercial waveshaper (Finisar, WaveShaper 4000S). The dual-waveguide MDR is fabricated based on a standard silicon photonics foundry process. It contains a disk with a diameter of 10 µm, two bus waveguides

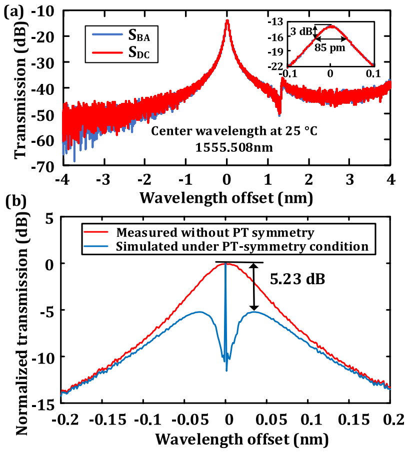

Fig. 2. (a) Measured transmission spectra at the corresponding drop ports when the input ports are chosen to be ports A and C at a temperature of 25°C. (b) Equivalent transmission spectrum with a gain contrast enhancement factor G in the PT-symmetry condition.

with a width of 600 nm, and a slab waveguide with a height of 90 nm. Both the disk and the bus waveguides have an identical height of 220 nm. The coupling gap between the disk and the bus waveguides is chosen to be 200 nm. The temperature of the MDR is controlled by using a temperature controller (ILX Lightwave LTD-5910B). Figure 2(a) shows the measured transmission spectra at the drop ports of the dual-waveguide MDR at a temperature of 25°C. The measured transmission spectra at the corresponding drop ports are identical when the input ports are chosen to be ports A and C (shown in Fig. 1). The center wavelength and the 3 dB bandwidth of the passband for the MDR are measured to be 1555.508 nm and 85 pm, respectively.

Observing the effectiveness of using PT-symmetry in enhancing gain contrast to enable stable single-mode lasing, the equivalent transmission spectrum with a gain contrast enhancement factor G under PT-symmetry condition is simulated according to Eq. (4) and the measured transmission spectrum (S_{DC}) shown in Fig. 2(a), with the simulation result shown in Fig. 2(b). As can be seen, the equivalent gain contrast between the primary mode and the second largest mode is increased by more than 5.23 dB. In other words, an infinitely small equivalent 3 dB bandwidth is realized under PT-symmetry condition, which provides an effective solution for mode selection, to guarantee stable single-mode lasing of the fiber laser.

By tuning PC1 and PC3 to match the gain and loss of the two loops, single-mode lasing is achieved. The optical spectrum is measured at a temperature of 25°C by an OSA and shown in Fig. 3. Single-mode lasing at a wavelength of 1555.508 nm corresponding to the center wavelength of the passband in the MDR is achieved. The sidemode suppression ratio exceeding 47 dB is observed. A zoom-in view of the optical spectrum is also shown as an inset in Fig. 3.

To verify that single-mode lasing is really realized, we measure the self-heterodyne RF spectra by using a delayed self-heterodyne system, as shown in Fig. 4(a). Note that a 1 GHz signal is used to shift the modes of one heterodyne channel by 1 GHz to make the observation of the beating signals more easily seen. The measurements are made for two cases with and without PT-symmetry, and the results are shown in Figs. 4(b) and 4(c). As can be seen from Fig. 4(b), the RF beating spectrum

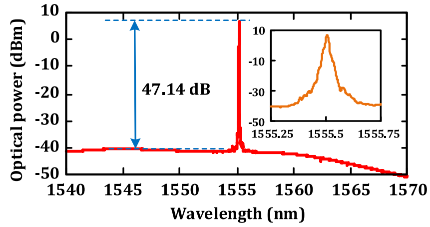

Fig. 3. Measured optical spectrum at the output of the PT-symmetric fiber laser.

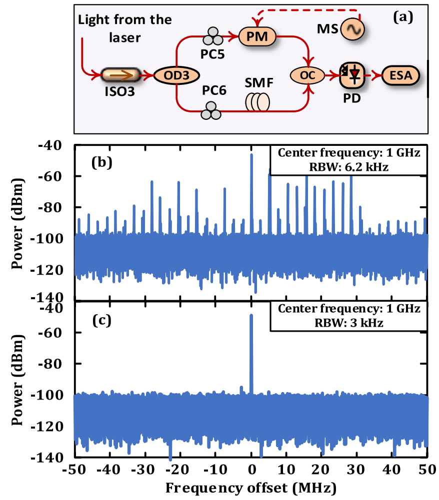

Fig. 4. (a) Schematic diagram of a delayed self-heterodyne system. (b) Measured self-heterodyne RF beating spectra at 1555 nm without PT-symmetry and (c) with PT-symmetry. ISO, isolator; OD, optical divider; PC, polarization controller; PM, phase modulator; SMF, single-mode fiber; OC, optical coupler; PD, photodetector; MS, microwave source; ESA, electrical spectrum analyzer.

without PT-symmetry has a series of closely spaced beating signals, indicating that multi-mode lasing occurs in the laser. This is caused due to the long time-delay in the cavities. The FSR is measured to be 2.567 MHz, corresponding to a long fiber delay line of around 80.178 m. If PT-symmetry is enabled, no beating signals are found, except a signal with a frequency of 1 GHz is observed, as shown in Fig. 4(c). Clearly, single-mode lasing is achieved.

The linewidth of the lightwave at the output of the fiber laser is also measured. In the delayed self-heterodyne system, a long fiber delay line with a length of 10 km is employed, corresponding to a measurement resolution of 20.6 kHz. The RF beating spectrum is measured by using an electrical spectrum analyzer (ESA), averaged for 100 times, as shown in Fig. 5. The Lorentz fitting curve is also shown. An adjusted R-square value of 0.9909 is achieved. Considering the unavoidable $1/f$ noise at the center frequency caused by the long delay line [18], we measure the 20 dB linewidth to ensure better accuracy. The 20 dB linewidth is 8.667 kHz, corresponding to a 3 dB linewidth of 433.5 Hz. Theoretically, the exact linewidth of a laser with a sub-kilohertz linewidth should be measured using a delay line of over 1000 km to achieve completely incoherent mixing of the two signals from the two arms in a Mach–Zehnder interferometer, because

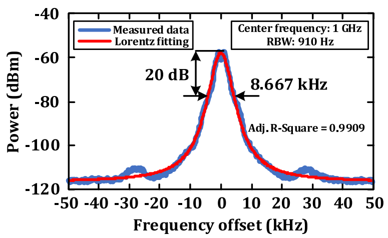

Fig. 5. Measured linewidth of the proposed PT-symmetric fiber laser at a wavelength of 1550 nm.

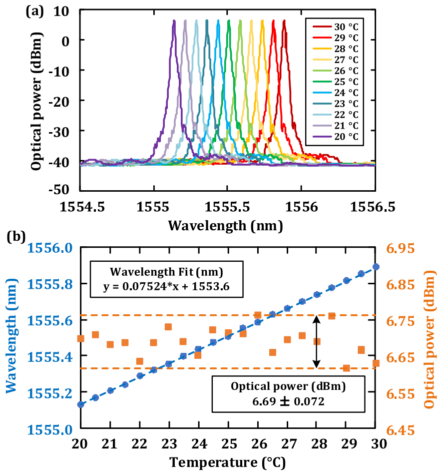

Fig. 6. (a) Measured optical spectra by thermally tuning the MDR. (b) Measured center wavelength and the output power of the laser when the MDR is thermally tuned.

the interference effect will lead to the broadening of the self-heterodyne spectrum. In fact, it is impossible to obtain a pure Lorentz linewidth spectrum due to the limited laser power and $1/f$ noise [11]. Thus, considering the fitted result is mixed with the unavoidable broadening effects, the linewidth of 433.5 Hz is larger than the actual linewidth of the laser.

By thermally tuning the MDR, the wavelength of the PT-symmetric laser is tuned. Figure 6(a) shows the measured optical spectra when the temperature of the MDR is tuned from 20 to 30°C. The center wavelength and the output power of the lasing output are plotted in Fig. 6(b). A continuously tuning with a tuning range from 1555.135 to 1555.887 nm and a tuning slope of 75.24 pm/°C is implemented. The output power of 6.69 dBm with a slight fluctuation of ±0.072 dB is also demonstrated during the tuning.

In summary, a wavelength-tunable PT-symmetric single-mode fiber laser with a sub-kilohertz linewidth was proposed and experimentally demonstrated. The key device in the laser is a silicon photonic integrated MDR, which was employed in the laser to form two mutually coupled cavities with an identical geometry. The PT-symmetry was realized by controlling the magnitude of the gain of one cavity to be equal to that of the loss of the other cavity. When the PT-symmetry for one selected mode was broken, the selected mode would experience a net amplification and would lase, and the other unbroken modes would be suppressed. By thermally tuning the MDR, the wavelength was tuned. During the experiment, a single-mode lasing was achieved during the wavelength tuning with a tuning range from 1555.135 to 1555.887 nm and a tuning slope of 75.24 pm/°C. The linewidth of the proposed single-mode laser was measured to be 433 Hz. The use of PT-symmetry overcomes the long-existing mode-selection challenge in a fiber ring laser, which would make it a primary solution for the implementation of simple, low-cost, and high-performance fiber lasers for light generation for applications where an ultranarrow-linewidth and wavelength-tunable light source is needed.

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Disclosures. The authors declare no conflicts of interest.

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