A single-loop PT-symmetric sub-kHz fiber laser based on an integrated microdisk resonator

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Abstract: A single physical loop parity-time symmetric sub-kHz laser based on a microdisk resonator is demonstrated. Single-mode lasing with a wavelength-tunable range from 1552.953 to 1554.147 nm and a linewidth of 640 Hz is achieved experimentally. © 2020 The Author(s)

1. Introduction

Non-Hermitian physics having parity-time (PT) symmetry has been employed in photonic [1] and microwave photonic [2,3] systems to implement single-mode oscillation due to its powerful mode selection ability. In a PT-symmetric signal generation system, PT-symmetry is achieved by balancing the gain and loss coefficients of two mutually coupled loops. By tuning the coupling coefficient between the two loops and the gain/loss coefficients, only the primary mode is chosen to break the PT-symmetry, and thus only the primary mode will oscillate. Consequently, single-mode oscillation is achieved. By employing this concept, single-longitudinal-mode lasers have been reported in the last few years [4-6].

In general, PT-symmetry can be implemented in a transverse PT symmetric [4,5] or longitudinal PT symmetric [6] system. In a transverse PT-symmetric system [4,5], there are two physically separated mutually coupled cavities with identical geometry. Its implementation is challenging due to the fabrication difficulty since two cavities with exactly identical geometry are needed. In a longitudinal PT-symmetric system, there is only one physical cavity, and the implementation is performed by modulating the refractive index along the cavity. The implementation is also difficulty due to the requirement for precise refractive index modulation along the cavity. In addition, the linewidth of the PT-symmetric lasers reported so far is large due to their short cavities since they are implemented based on integrated ring resonators.

In this paper, we propose and experimentally demonstrate a wavelength-tunable transverse PT-symmetric fiber laser with a sub-kHz linewidth with a single physical loop. To reduce the linewidth, a long loop length is employed [7] with mode selection supported by PT-symmetry. Instead of using two physically separated mutually coupled loops, a single physical loop with two equivalent mutually coupled loops is realized by a hybrid use of a Sagnac loop and a thermally tunable integrated microdisk resonator (MDR). By tuning the polarization states of the two light waves that are propagating along with the clockwise (CW) and counter-clockwise (CCW) directions in the Sagnac loop, two equivalent mutually coupled loops are formed. When the gain and loss coefficients of the two loops are balanced, PT-symmetry is achieved. Then, by selecting only the primary mode to break the PT-symmetry condition, single-mode lasing is implemented. The tunability is also achieved by thermally tuning the MDR. In the experiment, a continuously tunable single-mode laser with a sub-kHz linewidth of 640 Hz and a tunable wavelength range from 1552.953 to 1554.147 nm is realized.

2. Principle

Figure 1(a) shows the schematic diagram of the proposed PT-symmetric fiber laser. An erbium-doped fiber laser (EDFA) is used in the fiber laser as the gain medium. The amplified light wave from the EDFA is sent through an optical divider (OD), an isolator, and an optical coupler (OC), to the Sagnac loop. Along the CCW, the light at port B of the OC is connected to input port C of an integrated MDR via a polarization controller (PC1), and transmitted to drop port D of the MDR. The light from port D is transmitted through a second polarization controller (PC2), ports E and F of the OC, and fed back to the EDFA via an optical bandpass filter (OBPF), which is adopted to select the lasing wavelength. Along the CW direction, the light at port E of the OC is connected to port D of the MDR via PC2, and transmitted to port C of the MDR. The light from port C is transmitted through PC1, ports B and F of the OC, and fed back to the EDFA via the OBPF. Then, two oscillation loops, oscillation loop 1 with a light path of A->B->C->D->E->F and oscillation loop 2 with a light path of A->E->D->C->B->F, are achieved in a single physical loop. Since only the transverse electronic (TE) mode can be supported in the bus waveguide of the MDR, the gain and loss of the two oscillation loops can be independently controlled by adjusting the polarization states of the light waves by tuning PC1 and PC2. By thermally tuning the MDR, the wavelength tunability of the proposed PT-symmetric optical fiber laser is implemented.

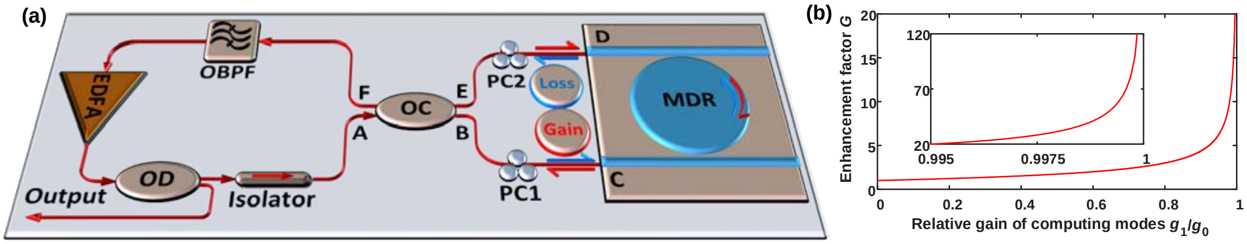

Fig. 1. (a) Schematic diagram of the proposed PT-symmetric fiber laser. (b) Gain contrast enhancement in the PT-symmetric laser. EDFA: erbium-doped fiber amplifier; OD: optical divider; OC: optical coupler; PC: polarization controller; MDR: microdisk resonator; OBPF: optical bandpass filter.

In the PT-symmetric laser, the PT-symmetric condition is achieved by balancing the gain and loss coefficients of the two oscillation loops. Under PT-symmetry condition, the eigenfrequency of the laser is given by [4]

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

where ω_n is the eigenfrequency of the nth-modes of the two loops, g_n is 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. An exceptional point (EP) is found when the gain or loss of the two loops equals the coupling coefficient between them, that is $g_n = \kappa_n$. If the gain or loss is lower than the coupling coefficient ($g_n < \kappa_n$), any pair of lasing modes will undergo bounded neutral oscillation. That means the PT-symmetry is unbroken. In contrast, once the gain or loss exceeds the coupling coefficient ($g_n > \kappa_n$), a conjugate pair of lasing and decaying modes are achieved. That indicates the PT-symmetry condition is broken.

It should be noted that there is an enhancement in the gain contrast between the primary mode and the secondary mode in the PT-symmetric laser. The enhancement factor is given by [4]

$$G = \sqrt{\frac{g_0/g_1 + 1}{g_0/g_1 - 1}} \tag{2}$$

where G is the gain contrast enhancement factor, g_0 and g_1 are the gain/loss coefficients for the primary and secondary modes, respectively. Fig. 1(b) shows the simulated gain contrast enhancement factor. A sharply increasing for the enhancement factor is found when the gain of the primary mode is close to the gain of the secondary mode. It provides an effective solution for mode selection to achieve a very stable single-mode lasing.

3. Experimental results

A proof-of-concept experiment is carried out based on the setup in Fig. 1(a). 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 realized by using a commercial waveshaper (Finisar, Wave Shaper 4000S). The dual-waveguide MDR is implemented based on a standard silicon photonics foundry process. It contains a disk with a diameter of 10 µm, two bus waveguides with a width of 600 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 200 nm. The temperature of the MDR is controlled by using a temperature controller (ILX Lightwave LTD-5910B). The optical spectra of the generated optical signal are measured through an optical spectrum analyzer (Ando AQ6317B). The lasing mode and the linewidth of the output are analyzed through a delayed self-heterodyne system with a 10-km fiber delay line, and 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.

Figure 2(a) shows the measured optical spectrum of the PT-symmetric laser at a temperature of 24 ℃. A single-mode lasing with a sidemode suppression ratio of 42.6 dB is achieved. By thermally tuning the dual-waveguide MDR from 17 to 32 ℃, the wavelength is tuned. Fig. 2(b) shows the optical spectra of the proposed transverse PT-symmetric laser. A continuous wavelength tuning range from 1552.953 to 1554.147 nm is achieved.

To verify that the single-mode lasing of the PT-symmetric laser is really achieved, the self-heterodyne RF spectrums by using the delayed self-heterodyne method is measured. The results are shown in Fig. 3(a) and (b). As can be seen from Fig. 3(a), the RF beating spectrums without PT-symmetry have a series of closely spaced beating signals, which means multi-mode lasing occurs in the laser. This is caused due to the long time-delay in the loops. 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. 3(b). Clearly, single-mode lasing is achieved.

The linewidth of the proposed PT-symmetric laser is evaluated in Fig. 3(c). The measured RF beating spectrum and its Lorentz fitting curve of the proposed traverse PT-symmetric laser are plotted. Excellent agreement is found between the measured data and the fitted curve with an adjusted R-Squares of 0.9913. Considering the unavoidable $1/f$ noise at the center frequency caused by the long delay line, the linewidth of the laser is evaluated from the 20-dB spectrum width of the Lorentz fitting curve. The measured 20-dB Lorentz linewidth of the proposed optical fiber laser is 12.8 kHz, corresponding to a 3-dB linewidth of 640 Hz.

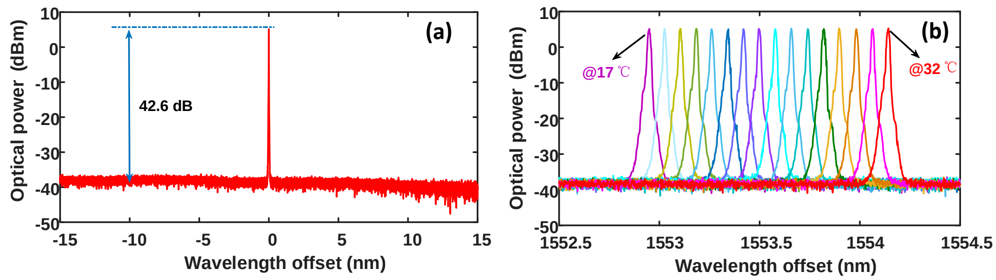

Fig. 2. The measured spectra of the proposed PT-symmetric fiber laser at (a) a temperature of 24 °C and (b) a temperature tuning range from 17 to 32 °C with a tuning step of 1 °C.

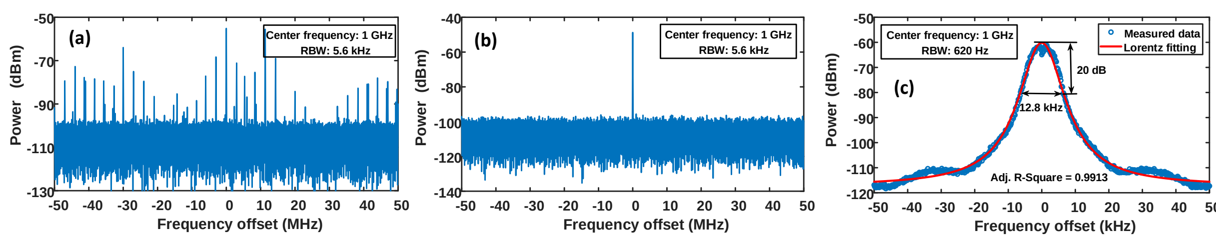

Fig. 3. The measured self-heterodyne RF beating spectrums (a) without PT-symmetry and (b) with PT-symmetry. (c) Linewidth measurement.

4. Conclusion

We have proposed and experimentally demonstrated a single physical loop parity-time symmetric sub-kHz laser based on an integrated MDR. Thanks to the hybrid use of a Sagnac loop and a thermally tunable integrated MDR, a single physical loop PT-symmetric laser was achieved. The key advantage of using a single physical loop structure is that the implementation is greatly simplified. In the experiment, a continuously tunable single-mode laser was implemented, with a sub-kHz linewidth of 640 Hz and a tunable wavelength range from 1552.953 to 1554.147 nm. The demonstration opens new avenues to reduce the complexity of non-Hermitian systems based on PT symmetry for potential applications in photonics and microwave photonics.

Acknowledgments

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