exit gates are thus unable to mediate sister chromatid cohesion.

Conclusion

It has long been postulated that cohesin forms rings that can be opened to mediate entry and exit of DNA. Here, we used electron microscopy to demonstrate the existence of such open forms, generated either by proteolytic cleavage of Sccl (mimicking the effect of separase at the metaphase-to-anaphase transition) or by weakening the interaction between Sccl’s NHD and the coiled coil of Smc3 (mimicking the opening of cohesin’s DNA exit gate). Because the latter is thought to be achieved by Wapl, our exit gate mutant may resemble an otherwise transient intermediate in the ring opening and closing cycle (Fig. 5D). We identified residues at the outside of the solenoid-like Pds5B that reside in direct proximity to Wapl and the Smc3-Sccl interaction (fig. S13), implying that Wapl and Pds5 control the exit gate through direct interactions. However, it remains to be addressed at a mechanistic level how Wapl promotes ring opening and how this is coordinated by Pds5, antagonized by sororin, and regulated by phosphorylation events.

REFERENCES AND NOTES


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SUPPLEMENTARY MATERIALS

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REPORTS

OPTICS

Single-mode laser by parity-time symmetry breaking

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Effective manipulation of cavity resonant modes is crucial for emission control in laser physics and applications. Using the concept of parity-time symmetry to exploit the interplay between gain and loss (i.e., light amplification and absorption), we demonstrate a parity-time symmetry–breaking laser with resonant modes that can be controlled at will. In contrast to conventional ring cavity lasers with multiple competing modes, our parity-time microring laser exhibits intrinsic single-mode lasing regardless of the gain spectral bandwidth. Thresholdless parity-time symmetry breaking due to the rotationally symmetric structure leads to stable single-mode operation with the selective whispering-gallery mode order. Exploration of parity-time symmetry in laser physics may open a door to next-generation optoelectronic devices for optical communications and computing.

Lasers support a large number of closely spaced modes because their dimensions are typically much larger than an optical wavelength. As a result, the outputs from such lasers are subject to random fluctuations and instabilities because of mode competition for limited gain. During recent decades, effective mode manipulation and selection strategies have been intensively explored to achieve single-mode operation with both spatial and spectral controllability—a requirement for enhanced laser performance with higher monochromaticity, less mode competition, and better beam quality. Obtaining single-mode operation depends on sufficiently modulated gain and loss, but such modulation is impeded by factors such as inhomogeneous gain saturation. Several approaches have been developed that make use of an additional cavity for the intracavity feedback (7), distributed feedback gratings (2), an enlarged free spectral range through mode size reduction (3, 4), or spatially varied optical pumping (5). However, these approaches are applicable to specific configurations; what is desired is a general design concept with flexible control of cavity modes.

Recent explorations of parity-time (PT) symmetry offer an opportunity to advance laser science by strategically manipulating gain and loss in order to control light transport. PT symmetry was initially proposed in quantum mechanics as an alternative criterion for non-Hermitian Hamiltonians \( H \neq H^\dagger \) that possesses a real eigenspectrum (6). Because of the equivalence between the Schrödinger equation in quantum mechanics and the electromagnetic wave equation, optics has become an ideal platform for studying the fundamentals of PT symmetry (7–16), with non-Hermiticity conferred by optical gain and loss. An intriguing PT phase transition has been demonstrated (17, 12), enabling unique optical phenomena such as unidirectional light transport (13–15) and novel devices including low-power optical diodes (16). The strategic modulation of gain and loss in the PT symmetry–breaking condition can fundamentally broaden optical science at both semiclassical and quantum levels (17–23).

Using the PT symmetry–breaking concept, we delicately manipulated the gain and loss of a microring resonator and observed single-mode laser oscillation of a whispering-gallery mode (WGM). We exploited the continuous rotational symmetry of the microring structure to facilitate unique
thresholdless PT symmetry breaking. This thresholdless PT symmetry breaking was valid only for the desired WGM order and enabled two energy-degenerate modes—the non-oscillating loss mode and the oscillating gain mode—whereas all other WGM modes experienced balanced gain/loss modulation and thus remained below the lasing threshold, leading to single-mode lasing.

The PT-synthetic microring resonator was designed with 500-nm-thick InGaAsP multiple quantum wells (MQWs) on an InP substrate (Fig. 1A). InGaAsP MQWs have a high material gain coefficient (>1000 cm⁻¹) around 1500 nm (24). The gain/loss modulation, satisfying an exact PT symmetry operation, was periodically introduced using additional Cr-Ge structures on top of the InGaAsP/InP microring resonator to mimic a pure gain/loss modulation. The diameter and width of the microring resonator are 8.9 μm and 900 nm, respectively. The microring also extends 1.5 λ around 1500 nm (see supplementary text). Evolution of PT symmetry (Fig. 1, B and C) and complex conjugate modal gain/loss coefficients: effective gain of 268 cm⁻¹ [Im(β)] = −134 cm⁻¹ for the lasing mode (A) and effective loss of −268 cm⁻¹ [Im(β) = 134 cm⁻¹] for the absorption mode (B). (C and D) Eigen-electric field intensity distributions of paired lasing and absorption modes at m = 53. The two modes share the same eigenfrequency of 200.9 THz and a similar modal loss coefficient of −8 cm⁻¹ [Im(β) = 4/cm].

Fig. 1. Design of PT microring lasers. (A) Schematic of the PT microring laser, which consists of Cr/Ge bilayer structures arranged periodically in the azimuthal direction on top of the InGaAsP/InP microring resonator to mimic a pure gain/loss modulation. The diameter and width of the microring resonator are 8.9 μm and 900 nm, respectively. The microring also extends 1 μm deeper into the InP substrate. Here, the designed azimuthal order is m = 53 to achieve the resonant wavelength around 1500 nm. (B and C) The same eigenfrequency (197.6 THz) and complex conjugate imaginary eigenspectra for the two modes at m = 53 determined by numerical simulations (circles and dots) and theoretical calculations (solid lines). The onset in (C) indicates thresholdless PT symmetry breaking.

Fig. 2. WGMs of different azimuthal orders in the PT microring laser. (A and B) Eigen-electric field intensity distributions of paired lasing and absorption modes at m = 53. Fields are confined in the gain (A) and loss (B) sections, resulting in conjugate modal gain/loss coefficients: effective gain of 268 cm⁻¹ [Im(β)] = −134 cm⁻¹ for the lasing mode (A) and effective loss of −268 cm⁻¹ [Im(β) = 134 cm⁻¹] for the absorption mode (B). (C and D) Eigen-electric field intensity distributions of paired lasing WGMs at m = 54. The two modes share the same eigenfrequency of 200.9 THz and a similar modal loss coefficient of −8 cm⁻¹ [Im(β) = 4/cm].
selects the desired lasing mode. This confirms that our PT microring laser does not alter original WGMs but efficiently...

is possible, but the thresholdless PT symmetry-breaking feature is still preserved (see supplementary text and fig. S2).

The PT microring laser with Cr/Ge modulations (Fig. 3A) was fabricated using overlay electron beam lithography and plasma etching. Under optical pumping with a femtosecond laser (see supplementary text and fig. S3), a broad photoluminescence emission around 1500 nm was first observed at low pump power densities. As the pump power was increased, the transition to amplified spontaneous emission and full laser oscillation was clearly observed from the rapidly increasing spectral purity of the cavity mode (Fig. 3B). At higher pumping intensities well above the lasing threshold, the single-mode lasing peak is seen at the wavelength of 1513 nm, confirming our theoretical prediction of the single WGM lasing operation of the PT microring laser. The lasing linewidth is about 1.7 nm around the transparency pump power, corresponding to a quality factor of about 890 that is limited by the surface roughness of the sample. In Fig. 3C, the light-light curve corresponding to single-mode emission and full laser oscillation shows the power relationship between the lasing emission and the pump light. A clear onset of the intrinsic single-mode lasing appears at a threshold slightly larger than 600 MW cm⁻².

For comparison, a control sample of a WGM laser was fabricated consisting of the same-sized InGaAsP/InP microring resonator without additional Cr/Ge index modulation. As expected, we observed a typical multimode lasing spectrum with different WGM azimuthal orders distributed over the gain spectral region (Fig. 4A). Relative to the PT microring laser, it can be seen that...
under a similar pumping condition, the resonance peak for the same azimuthal order of $m = 53$ well matches the single-mode lasing of the PT ring resonator at a wavelength of $1513$ nm (Fig. 4B). The power efficiency and the lasing threshold are also similar because the introduced loss in the PT microring laser minimally affects the desired lasing mode. We also fabricated an additional PT microring laser with a different azimuthal PT modulation for the order of $m = 55$. Its lasing emission at $1467$ nm (Fig. 4B) also agrees well with the multimode lasing spectrum of the conventional WGM laser for the same azimuthal order (Fig. 4A). It is evident that instead of altering the WGM in the microring resonator, the introduced PT gain/loss modulation selects the lasing WGM in the PT-broken phase over a broad spectral band. By changing the desired azimuthal order of the structured PT modulation, the single-mode lasing frequency can be efficiently selected. Although we demonstrated lasing for only two WGM orders, this mode selection concept is general and in principle valid for arbitrary gain spectra. In applications, the demonstrated stable single-mode lasing can be efficiently routed, using a bus waveguide through the evanescent ring-waveguide coupling, to photonic integrated circuits for on-chip signal amplification and processing.

We have demonstrated a PT microring laser by delicate exploitation of optical loss and gain.

Such a microring laser is intrinsically single-mode regardless of the gain spectral bandwidth. This is because the continuous rotational symmetry of PT modulation enables the thresholdless PT symmetry breaking only for the desired mode. More important, our PT laser demonstration is a major step toward unique photonic devices such as a PT-symmetric laser-absorber that coincides lasing and anti-lasing (i.e., coherent perfect absorption (29, 30)) simultaneously.

REFERENCES AND NOTES


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Supplementary Text

Figs. S1 to S3

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OPTICS

Parity-time-symmetric microring lasers

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The ability to control the modes oscillating within a laser resonator is of fundamental importance. In general, the presence of competing modes can be detrimental to beam quality and spectral purity, thus leading to spatial as well as temporal fluctuations in the emitted radiation. We show that by harnessing notions from parity-time (PT) symmetry, stable single-longitudinal mode operation can be readily achieved in a system of coupled microring lasers. The selective breaking of PT symmetry can be used to systematically enhance the maximum attainable output power in the desired mode. This versatile concept is inherently self-adapting and facilitates mode selectivity over a broad bandwidth without the need for other additional intricate components. Our experimental findings provide the possibility to develop synthetic optical devices and structures with enhanced functionality.

S
ince the early days of the laser, enforcing single-mode operation in a given arrangement has been one of the primary goals of cavity design (1). At first glance, one might expect these challenges to become less acute in the course of miniaturization, as the separation of resonances, or free spectral range, scales inversely with size. However, despite their smaller size, mode management in semiconductor lasers is still demanding because of their large inhomogeneously broadened gain bandwidth (2). In such broadband gain environments, the lasing of the desired mode does not prevent the neighboring resonances from also experiencing amplification. Consequently, additional steps must be taken to suppress the competing parasitic modes. This can be accomplished in a number of ways, as, for example, coupling to detuned external cavities (3), by including intracavity dispersive elements such as distributed feedback gratings or distributed Bragg mirrors (4–6), by spatially modulating the pump (7), or more recently by extreme confinement of light in subwavelength structures using metallic cavities (8–10). However, not all of these schemes are practically compatible with every type of resonator, and each of them introduces further demands in terms of design complexity and fabrication tolerances. Clearly, of importance will be to identify alternative strategies through which mode selection can be established not only in a versatile manner, but also without any negative impact on the overall efficiency.

A prominent class of integrated laser arrangements is based on microring resonators (11, 12). By virtue of their high refractive index contrast, such configurations can support whispering gallery modes that exhibit high quality factors and small footprints, thus making them excellent candidates for on-chip integrated photonic applications. However, like many other microscale resonators, these cavities tend to support multiple longitudinal modes with almost similar quality factors throughout their gain bandwidth, while offering little control in terms of mode discrimination with conventional techniques.

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