PT-Symmetric Microring Laser Gyroscope

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Abstract: A new scheme for ultrasensitive micro-ring laser gyroscopes based on the physics of exceptional points is proposed. In such systems, the sensitivity to low rotation rates can be enhanced by several orders of magnitude.

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For measuring rotation rate, ring laser gyroscopes (RLGs) are among the most sensitive instruments developed to date. Such devices work based on converting the induced Sagnac phase difference between two counter-propagating beams within an active loop into a splitting in the corresponding resonant frequencies. Since they rely on a Sagnac shift that is proportional to the area of the ring, the sensitivity of RLGs quickly drops as they are scaled down to chip-scale dimensions. In many consumer and industrial applications, it is imperative to detect angular velocities in the range of ~0.1−100 °/hour. Unfortunately, such sensitivity levels have so far remained practically out-of-reach in fully integrated optical platforms, where the area of the loop is inevitably small. In addition, in on-chip settings, light scattering from the cavity walls may cause unwanted coupling between the two counter-propagating modes. This can lead to the lock-in effect, rendering the RLG ineffective for measuring speeds below a certain rotation rate [1]. Here, we propose a novel type of ring laser gyroscope based on the physics of non-Hermitian degeneracies at the exceptional point (EP) that provides a pathway towards miniaturization and lock-in free operation.

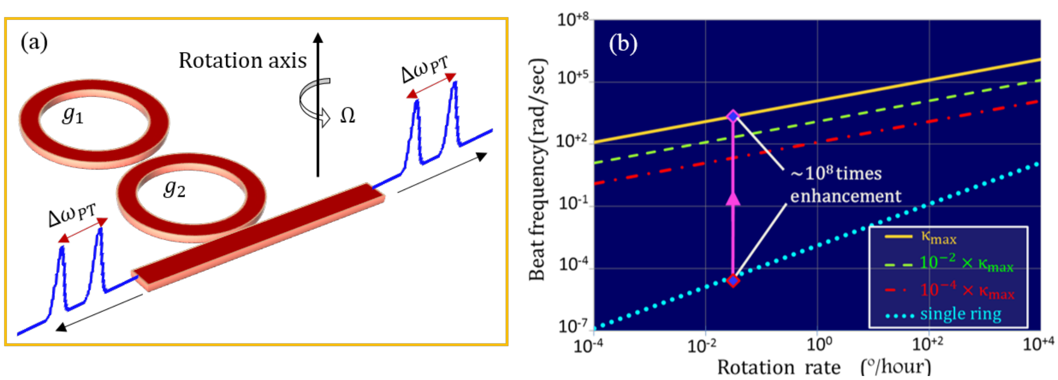

Figure 1 PT-symmetric laser gyroscope. (a) Schematic of a PT-symmetric microring laser gyroscope system. (b) The beat frequency as a function of the rotation rate for a single ring (dotted line) and PT-symmetric coupled ring systems with various coupling strength levels.

Figure 1(a) depicts a schematic of the proposed non-Hermitian gyroscope, comprised of two coupled ring resonators (of radius R, coupling strength κ). The rings are identical in every respect but are subject to different levels of gain and/or loss. This system becomes PT symmetric once it is gauged by a constant gain/loss bias [2,3], which can be introduced through preferential pumping. A bus waveguide can be incorporated on the side of one (or both) ring(s) to direct the lasing emission into a photodiode in order to measure the resulting beat frequency.

In this system, the interplay between the electric modal fields in the two identical rings can be described through a set of time dependent coupled equations:

$$\begin{aligned} i\dot{a}_1 + \omega_1 a_1 - ig_1 a_1 + \kappa a_2 = 0 \\ i\dot{a}_2 + \omega_2 a_2 - ig_2 a_2 + \kappa a_1 = 0. \end{aligned} \qquad (1)$$

where a_1, a_2 represent the modal amplitudes in the two resonators. The angular frequencies, ω_1 and ω_2, are independently determined by the resonance conditions for each resonator in the absence of coupling. The gain (loss) in each ring is denoted by g_1 and g_2, respectively. Without loss of generality, here we limited our analysis to a single longitudinal mode propagating in one direction [3]. The unidirectional operation can also be enforced by incorporating S-bends with opposite chirality in the two ring resonators [4].

For two identical cavities at rest, at the exceptional point ($2\kappa=|g_1-g_2|$), the dimensionality of the system abruptly collapses [5,6]. As a result, the system, if pumped appropriately, will lase in only one frequency ω_0. At a gyration rate of Ω, the resonance frequency of a single ring resonator is expected to shift by an amount of $\Delta\omega_s=\omega_0 nR\Omega/c$. For the above coupled PT system, however, if at rest it was biased at the exceptional point, once it is perturbed at the same rotation rate (Ω), it will support two supermodes with a beat frequency $\Delta\omega_{PT}=2\sqrt{\kappa^2-(g_1-g_2+2i\Delta\omega_s)^2/4}$. For small perturbations where $\Delta\omega_s \ll |g_1-g_2|$, the splitting between the real components of these two eigenfrequencies is $\Delta\omega_{PTreal}\cong 2\sqrt{|\Delta\omega_s\kappa|}$.

Clearly, the above square-root behavior can result in a substantially increased frequency separation for small rotation rates. Figure 1(b) shows the beat frequency as a function of rotation rate in the log-log scale. In this example, the radii of the rings are taken to be R=100 µm, and the operating wavelength is centered at λ_0=1.55 µm. In contrast to standard Hermitian RLGs, in a non-Hermitian PT-symmetric system, the slope of the line drops to one half – indicating a superior square-root behavior. Under the weak-coupling approximation, the coupling factor can in principle be as large as a quarter of the free spectral range. One can then show that, unlike standard ring laser gyroscopes, in such PT-symmetric systems, the maximum frequency splitting is entirely independent of the radius of the rings involved ($\Delta\omega_{PT\,max}=\sqrt{n\omega_0\Omega/2\pi n_g}$). In this regard, one can envision a micro-scale ring laser gyroscope that can exhibit a sensitivity similar to that obtained in free-space centimeter-scale systems [7].

A preliminary error analysis indicates that the above proposed device can reach its full potential for sensing purposes if it operates at a close vicinity of an exceptional point. If biased precisely at the exceptional point, the uncertainties in coupling/gain-contrast can at most generate the same degree of error in the rotation rate ($\delta\Omega/\Omega=\delta\kappa/\kappa=\delta g/g$). This aspect is shown in Fig. 2(a). Since the exceptional point represents an abrupt phase transition, even if the system's bias moved from the exceptional point, the EP can be readily identified through monitoring the variation of the observable ($\delta\Delta\omega_{PT}$) with respect to a scanning parameter (Δg or κ). Figure 2(b) shows that regardless of the rotation velocity, $\delta\Delta\omega_{PT}$ reaches its extremum at the exceptional point. One can then choose the measurement result performed at this point as the most accurate representation of the rotation rate.

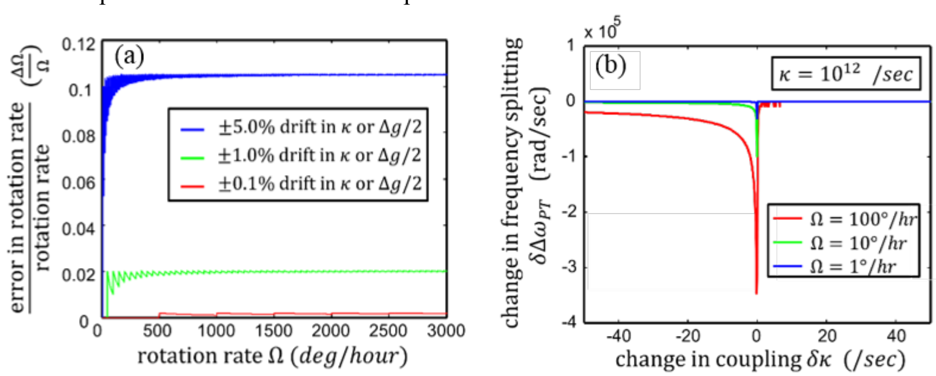

Figure 2 effects of parameter drifts (coupling/gain-contrast) on the performance of gyros. (a) The ratio of error in rotation rate to rotation rate itself as a result of different levels of drift. (b) Change in frequency splitting ($\delta\Delta\omega_{PT}$) with respect to drift in coupling.

In conclusion, we have proposed a new physical principle to enhance the Sagnac effect. The enhanced sensitivity is attributed to the intriguing properties of exceptional points. At such a point, the system responds to external perturbations in a square-root fashion. For small rotation rates, this could result in orders of magnitude enhancement in sensitivity. When this effect is fully utilized, the frequency splitting becomes independent of the size of the rings – hence, our approach can be used to realize micro-scale ring laser gyroscopes with the same sensitivities as those at centimeter-scale. The proposed approach may open new directions towards the realization of highly sensitive, and miniature size ring laser gyroscopes.

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