PAPER

Unidirectional reflectionless propagation of near-infrared light in resonator-assisted non-parity-time symmetric waveguides

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Abstract

The unidirectional reflectionless (UR) light propagation is investigated in the waveguide coupled to gain and loss resonators by using a developed coupled mode-scattering matrix theory. The results show that there is almost no reflection in the case of the backward incidence, but total reflection in the case of the forward incidence under the condition of balancing gain and loss in the gain resonator for the proposed waveguide when the indirect coupling phase $\theta$ ranges from 0.8 rad to 2.3 rad and from 4 rad to 5.5 rad. Moreover, the coherent perfect absorption (CPA) can be observed at the same time. Especially, the UR light propagation appears when the absolute value of detuning $\delta$ is smaller than $1 \times 10^{13}$ rad s$^{-1}$. Based on the findings above, we propose a metal–insulator–metal non-parity-time symmetric plasmonic waveguide and obtain the UR plasmonic propagation and CPA. The theoretical results are in excellent agreement with the finite-difference time-domain simulations. These results will provide a new pathway for the realization of unidirectional propagation and absorption of light at the nanoscale.

1. Introduction

Hermitian Hamiltonians have great significances for observable physical variables due to its real eigenvalues. However, non-Hermitian Hamiltonians exist more universally in physical systems, and thus it is crucial to explore the non-Hermitian Hamiltonian with real eigenvalues. Until 1998, Bender et al had proposed non-Hermitian Hamiltonians with parity-time symmetry (PT-symmetry), which exhibit real eigenvalues [1]. Subsequently, the PT-symmetry was studied in various systems, such as quantum fields [2], acoustics [3, 4], non-Hermitian Anderson models [5], electronics [6], Lie algebras [7], and so on. Based on the similarity between the dispersion equation and the Schrödinger equation, Ganainy et al constructed optical gain and loss regions and achieved the PT-symmetric optical system [8]. The optical system presented real eigenvalues when the gain-loss ratio was less than the PT-symmetric threshold. The threshold could be regarded as the PT-symmetric phase transition point or exceptional point (EP). At the EP, a number of novel optical phenomena were reported, such as optical isolation [9–11], nonlinear effect [12, 13], unidirectional reflectionless (UR) [14, 15], coherent perfect absorption (CPA) [16, 17], loss induced transparency [18, 19]. Especially, the UR and CPA were widely studied in both the PT-symmetric and non-PT-symmetric systems [17, 20–29]. Feng et al experimentally demonstrated the UR near the PT-symmetric EP, providing the feasibility for optical PT-based unidirectional devices [20], the demonstrated UR at EP on chip confirms the feasibility of creating complicated on-chip parity-time
metamaterials and optical devices. Zhang et al achieved a dual-band UR in the ultracompact non-Hermitian plasmonic waveguide [21], there was no need to dope with any gain or loss, which allowed for simpler fabrication of the waveguide structure. Jin et al achieved the UR in the non-PT-symmetric metasurfaces based on the far field coupling [17], they achieved the polarization independent UR and CPA due to the two-ring structure. Rivolta et al analyzed the UR in the dual- and quadruple-resonator coupled waveguides through the coupled mode theory and transfer matrix theory [22], they could achieve a broadband unidirectional invisibility with only two resonators and observed tunable rich dispersions for these anisotropic transmission resonances with four resonators. Sakhdari et al achieved the low-threshold lasing and CPA in the generalized PT-symmetric optical structures [26], they showed that the concept of generalized PT-symmetry may help to reduce the threshold gain in achieving newly discovered PT-enabled applications. Sarısaman et al reported the broadband CPA in the PT-symmetric two-dimensional materials [27], they showed that a two-dimensional Weyl semimetal is more effective than graphene in obtaining the optimal conditions. Huang et al demonstrated broadband total light absorption in the non-PT-symmetric waveguide systems by cascading multiple unit cell structures, they realized the absorption of ~100% in a wide range of frequencies [28]. Jin et al found that the time-reversal symmetry, pseudo-Hermiticity, and generalized inversion symmetry can protect the symmetric transmission and/or reflection, but the particle–hole symmetry, chiral symmetry, and sublattice symmetry do not [29]. These previous results show that UR could be only observed in the case of resonant detuning \( \delta \neq 0 \) when the indirect coupling phase \( \theta \) is equal to single value. The results are not conducive to designing reliable unidirectional devices. Therefore, it is of great significance to realize UR in the case of a continuously varying phase when the resonant detuning \( \delta \neq 0 \).

Here, we study the UR in a metal–insulator–metal PT-symmetric plasmonic waveguide by using the coupled mode-scattering matrix theory and finite-difference time-domain simulation. We can see that UR can be realized under the condition of a continuously varying phase \( \theta \) when the absolute value of resonant detuning \( \delta < 1 \times 10^{13} \text{ rad s}^{-1} \). Especially, the CPA can be observed in the non-PT symmetric resonator-coupled waveguide.

2. Model and theory

As shown in figure 1, the proposed waveguide consists of an optical waveguide side-coupled with gain and loss resonators. The dissipation in the left resonator is caused by the intrinsic and coupling losses, and the gain in the right cavity is attributed to the gain medium. The coupled mode-scattering matrix theory can be used to analyze the spectral responses in the proposed waveguide [17, 30, 31]. Here, \( L \) is the indirect coupling distance between the gain and loss resonators. \( \kappa_0 \) \((\kappa_1)\) is the coupling coefficient between the loss (gain) resonator and the bus waveguide. The incoming and outgoing waves are depicted by \( S_{n\pm} (n = 1, 2, 3, 4) \). The subscripts ‘±’ represent the forward and backward propagating directions of light, respectively.

Based on the coupled waveguide model mentioned above, the corresponding coupled mode equations can be described as [32–40]

\[
-j\omega a_1 = \left( -j\omega_1 - \frac{1}{\tau_{1l}} - \frac{1}{\tau_{1w1}} \right) a_1 + S_{1+} \sqrt{\frac{1}{\tau_{w1}} + S_{2+}} - \sqrt{\frac{1}{\tau_{w1}}},
\]

\[
-j\omega a_2 = \left( -j\omega_2 - \frac{1}{\tau_{2l}} - \frac{1}{\tau_{2w2}} + \Gamma \right) a_2 + S_{3+} \sqrt{\frac{1}{\tau_{w2}} + S_{4+}} - \sqrt{\frac{1}{\tau_{w2}}},
\]

Where, \( a_1 \) and \( a_2 \) are complex amplitudes of the resonant modes in the loss and gain cavities, \( \omega \) is the angular frequency of the incident light wave, \( \omega_1 \) and \( \omega_2 \) are angular frequencies of the loss and gain resonant modes, \( \Gamma \) is the gain coefficient of the gain resonator, \( 1/\tau_{1l} \) and \( 1/\tau_{2l} \) are decay rates of the loss and gain resonant modes due to the intrinsic loss, \( 1/\tau_{w1} \) and \( 1/\tau_{w2} \) are decay rates of the loss and gain resonant modes due to the intrinsic loss.

![Figure 1. Schematic diagram of the proposed waveguide coupled to gain and loss resonators.](image-url)
modes due to the energy escaping into the waveguide from the resonators, respectively. Here, we assume that the bus waveguide is lossless, according to the energy conservation law, the relationships among \( S_{n\pm} \) could be written as

\[
S_{2+} = S_{1+} - a_1 \sqrt{\frac{1}{\tau_{w1}}}, \quad S_{4+} = S_{3+} - a_1 \sqrt{\frac{1}{\tau_{w2}}},
\]

\[
S_{1-} = S_{2-} - a_1 \sqrt{\frac{1}{\tau_{w1}}}, \quad S_{3-} = S_{4-} - a_1 \sqrt{\frac{1}{\tau_{w2}}},
\]

\[
S_{4+} = e^{i\theta} S_{2+}, \quad S_{3-} = e^{-i\theta} S_{2-}.
\]

Where, \( \theta \) is the indirect coupling phase between the loss and gain resonators. According to the scattering matrix theory, the scattering matrix equation can be expressed as

\[
\frac{S_{4+}}{S_{1+}} = s \begin{pmatrix} t \rho \tau \end{pmatrix} \frac{S_{2+}}{S_{4-}},
\]

where, \( t \) is the transmission coefficient of the proposed waveguide system, \( \rho \) is the reflection coefficient in the case of the forward (backward) incidence, respectively. Here, the scattering matrix \( s \) can be described as

\[
s = \begin{pmatrix}
(1 + \chi_1)(1 + \chi_2) & -\chi_1 \chi_2 e^{i\theta} \\
(1 + \chi_1)(1 + \chi_2) & (1 + \chi_1)(1 + \chi_2) - \chi_1 \chi_2 e^{i\theta}
\end{pmatrix} \begin{pmatrix}
1 + \chi_1 \chi_2 e^{i\theta} + (1 + \chi_2) \chi_1 \\
(1 + \chi_1)(1 + \chi_2) & (1 + \chi_1)(1 + \chi_2) - \chi_1 \chi_2 e^{i\theta}
\end{pmatrix},
\]

with

\[
\chi_1 = \frac{1}{\tau_{w1} \cdot [j(\omega - \omega_1) - 1/\tau_1 - 1/\tau_{w1}]},
\]

\[
\chi_2 = \frac{1}{\tau_{w2} \cdot [j(\omega - \omega_2) - 1/\tau_2 - 1/\tau_{w2} + \Gamma]}.
\]

Thus, the transmission \( (T) \), reflection \( (R) \) and absorption \( (A) \) in the case of the forward incidence, reflection \( (R_f) \) and absorption \( (A_b) \) in the case of the backward incidence can be expressed as \( T = |t|^2, R_f = |\rho|^2, A_f = 1 - T - R_f, R_b = |\rho|^2, \) and \( A_b = 1 - T - R_b \), respectively.

### 3. Results and analysis

#### 3.1. UR on resonant

Firstly, we investigate the dependence of the indirect coupling phase \( \theta \) on spectral responses of \( R_f, R_b, A_f, \) and \( A_b \) when \( \Gamma = 2 \times 10^{13} \text{ s}^{-1} \). Here, the angular frequencies are assumed as \( \omega_1 = \omega_2 = 1.86 \times 10^{15} \text{ rad s}^{-1} \) meaning on resonant in the proposed waveguide. For simplification, the intrinsic losses are set as \( 1/\tau_{u1} = 1/\tau_{u2} = 1 \times 10^{13} \text{ s}^{-1} \), the coupling losses are set as \( 1/\tau_{w1} = 1/\tau_{w2} = 1 \times 10^{13} \text{ s}^{-1} \), respectively. \( \Gamma = 1/\tau_{u1} + 1/\tau_{w2} \), representing the gain and loss in the gain resonator are completely balanced. From figure 2, we can see that spectral responses show the periodic evolution with increasing the indirect coupling phase \( \theta \). As shown in figures 2(a) and (b), the spectra of \( R_f \) is obviously different from that of \( R_b \). Meanwhile, the spectrum of \( A_f \) is also different from that of \( A_b \), as depicted in figures 2(c) and (d). Notably, from figure 2(b), we can see that an obvious UR appears as \( \theta \) ranges from 0.8 rad to 2.3 rad and from 4 rad to 5.5 rad. This continuously varying phase \( \theta \) for UR is of great significance for designing reliable unidirectional devices. We also can see that there are two asymmetric absorption peaks as shown in figure 2(c), which is caused by the asymmetric dissipation in the two resonators. Especially, from figure 2(d), we can see that the perfect absorption effect appears in the case of the backward incidence, and the largest absorption can be observed at \( \omega = 1.86 \times 10^{15} \text{ rad s}^{-1} \) when \( \theta = 1.57 \text{ rad} \) and 4.76 rad. To describe the index of UR, we introduce the contrast ratio of UR as \( \eta = |r_f - r_b|/|r_0 + r_b| \) [20, 41]. The contrast ratio \( \eta \) can be approximately equal to 1 at \( \omega = 1.86 \times 10^{15} \text{ rad s}^{-1} \) when \( \theta = 1.57 \text{ rad} \) and 4.76 rad, respectively.

Then, we also investigate the spectral responses of \( R_f, R_b, A_f, \) and \( A_b \) as a function of the gain coefficient \( \Gamma \) in the gain resonator. Here, the relative parameters are set as \( \omega_1 = \omega_2 = 1.86 \times 10^{15} \text{ rad s}^{-1}, \theta = 1.57 \text{ rad}, 1/\tau_{u1} = 1/\tau_{u2} = 1 \times 10^{13} \text{ s}^{-1}, \) and \( 1/\tau_{w1} = 1/\tau_{w2} = 1 \times 10^{13} \text{ s}^{-1} \). In figure 3(a), it is shown that the \( R_f \) increases continuously as \( \Gamma \) increases. However, the \( R_b \) always keeps low values, as shown in figure 3(b), and the largest contrast ratio \( \eta \) of UR can be realized when \( \Gamma = 2 \times 10^{13} \text{ s}^{-1} \). From figures 3(c) and (d), we can see that the \( A_b \) can approach to 1, which means the perfect absorption phenomenon in the proposed non-PT symmetric waveguide when \( \Gamma \) increases to \( 2 \times 10^{13} \text{ s}^{-1} \). What’s more, the negative
Figure 2. Spectral responses of (a) $R_f$, (b) $R_b$, (c) $A_f$, and (d) $A_b$ as a function of the indirect coupling phases $\theta$ when $\omega_1 = \omega_2 = 1.86 \times 10^{15}$ rad s$^{-1}$, $\Gamma = 2 \times 10^{13}$ s$^{-1}$, $1/\tau_{i1} = 1 \times 10^{13}$ s$^{-1}$, and $1/\tau_{i2} = 1 \times 10^{13}$ s$^{-1}$.

Figure 3. Spectral responses of (a) $R_f$, (b) $R_b$, (c) $A_f$, and (d) $A_b$ as a function of the gain coefficient $\Gamma$ when $\omega_1 = \omega_2 = 1.86 \times 10^{15}$ rad s$^{-1}$, $\theta = 1.57$ rad, $1/\tau_{i1} = 1 \times 10^{13}$ s$^{-1}$, and $1/\tau_{i2} = 1 \times 10^{13}$ s$^{-1}$.

absorption can be observed in figure 3(c) when $\Gamma > 1/\tau_{i2} + 1/\tau_{i1}$, which is caused by the over gain in the gain resonator [42].

To clarify the physical mechanism of UR and CPA, we analyze eigenvalues of the scattering matrix $s$. Generally, the matrix $s$ is non-Hermitian, whose corresponding complex eigenvalues can be expressed as $s_{\pm} = t \pm (r_f \times r_b)^{1/2}$. The scattering matrix is in analogy to the Hamiltonian matrix in quantum systems [41, 42]. The EPs can be formed by selecting proper elements for the scattering matrix leading to the generation of UR and CPA. In figure 4, we plot real and imaginary parts of the eigenvalues $s_{\pm}$ with $\theta = 1.57$ rad and $\omega_1 = \omega_2 = 1.86 \times 10^{15}$ rad s$^{-1}$ when $\Gamma = 0$, $1 \times 10^{13}$ s$^{-1}$, and $2 \times 10^{13}$ s$^{-1}$, respectively. From figures 4(a) and (b), we can see that the eigenvalues $s_{\pm}$ are complex numbers meaning the inexistence of EPs when $\Gamma = 0$ and $1 \times 10^{13}$ s$^{-1}$. As shown in figure 4(c), both the real and imaginary parts of eigenvalues $s_{\pm}$ are equal to
Figure 4. Real and imaginary parts of eigenvalues $s_\pm$ with $\theta = 1.57$ rad, $\omega_1 = 1.86 \times 10^{15}$ rad s$^{-1}$, $1/\tau_{i1} = 1/\tau_{i2} = 1 \times 10^{13}$ s$^{-1}$, and $1/\tau_{w1} = 1/\tau_{w2} = 1 \times 10^{13}$ s$^{-1}$, when (a) $\Gamma = 0$, (b) $1 \times 10^{13}$ s$^{-1}$, and (c) $2 \times 10^{13}$ s$^{-1}$, respectively.

Figure 5. Spectral responses of (a) $R_R$, (b) $R_b$, (c) $A_f$, and (d) $A_b$ as a function of the resonant detuning $\delta$ when $\theta = 1.57$ rad, $\omega_1 = 1.86 \times 10^{15}$ rad s$^{-1}$, $1/\tau_{i1} = 1/\tau_{i2} = 1 \times 10^{13}$ s$^{-1}$, $1/\tau_{w1} = 1/\tau_{w2} = 1 \times 10^{13}$ s$^{-1}$, and $\Gamma = 2 \times 10^{13}$ s$^{-1}$. Real and imaginary parts of the eigenvalues $s_\pm$ when the resonant detuning (e) $\delta = 0$ and (f) $1 \times 10^{13}$ rad s$^{-1}$, respectively.

zero at $\omega = 1.86 \times 10^{15}$ rad s$^{-1}$ when $\Gamma = 2 \times 10^{13}$ s$^{-1}$ and $\theta = 1.57$ rad. This point is regarded as EP, and UR and CPA appear near the EP.

3.2. UR in the presence of detuning

In this section, we study spectral responses of $R_R$, $R_b$, $A_f$, and $A_b$ as a function of the resonant detuning ($\delta = \omega_2 - \omega_1$) for the indirectly coupled resonators. The relative parameters are set as $\omega_1 = 1.86 \times 10^{15}$ rad s$^{-1}$, $1/\tau_{i1} = 1/\tau_{i2} = 1 \times 10^{13}$ s$^{-1}$, $1/\tau_{w1} = 1/\tau_{w2} = 1 \times 10^{13}$ s$^{-1}$, and $\Gamma = 2 \times 10^{13}$ s$^{-1}$. From figures 5(a) and (b), we can see that UR appears distinctly when the resonant detuning $\delta$ ranges from $-1 \times 10^{13}$ rad s$^{-1}$ to $1 \times 10^{13}$ rad s$^{-1}$, which is of great significance for realizing the reliable unidirectional devices. In addition, the CPA also can be observed when $\delta = 0$, as shown in figure 5(d). The light absorption decreases with increasing the $|\delta|$, as depicted in figure 5(d). Therefore, the resonant detuning $\delta$ plays an important role for UR and CPA in the proposed non-PT symmetric waveguide. In figures 5(e) and (f), we give the analysis on the corresponding eigenvalues of the scattering matrix $s$. Both the real and imaginary parts of eigenvalues $s_\pm$ are equal to zero when $\delta = 0$, as shown in figure 5(e). However, when
\( \delta = 1 \times 10^{13} \text{ rad s}^{-1} \), the eigenvalues \( s_+ \) turn into complex, which means that the typical EP disappears, and thus there are no CPA phenomena in the coupled waveguide system.

### 3.3. UR in a non-PT symmetric plasmonic waveguide

As an example, we design a non-PT symmetric plasmonic waveguide for verifying the generation of UR. Figure 6(a) shows the schematic diagram of the plasmonic waveguide, which is composed of a metal–insulator–metal plasmonic bus waveguide side-coupled with a gain ring-shaped resonator and a loss ring-shaped resonator. Here, the metal is set as silver, whose permittivity \( \varepsilon_m \) can be defined by the Drude model

\[
\varepsilon_m(\omega) = \varepsilon_\infty - \frac{\omega_p}{\omega^2 + j\omega\gamma_p}.
\]

In the model, \( \varepsilon_\infty = 3.7 \) is the relative permittivity at the infinite frequency, \( \omega_p = 1.38 \times 10^{16} \text{ rad s}^{-1} \) is the bulk plasmon frequency, and \( \gamma_p = 2.73 \times 10^{13} \text{ rad s}^{-1} \) stands for the damping rate [32]. The bus waveguide is assumed as air. The left and right ring-shaped resonators are filled with CdSe quantum dots (\( \varepsilon_1 = 4.0804 - j0.6 \)) and InGaAsP (\( \varepsilon_2 = 11.38 + j0.41 \)), respectively [28, 43]. As shown in figure 6(a), \( r_{Li} \) and \( r_{Lo} \) stand for the inside and outside radii of the loss ring-shaped resonator, respectively. \( r_{Gi} \) and \( r_{Go} \) are the inside and outside radii of the gain ring-shaped resonator, respectively. \( l \) is the distance between the loss and gain resonators. The structural parameters are set as \( w = 50 \text{ nm}, r_{Gi} = 40 \text{ nm}, r_{Go} = 65 \text{ nm}, r_{Li} = 75 \text{ nm}, r_{Lo} = 125 \text{ nm}, l = 280 \text{ nm} \). The spectral responses in the waveguide structure can be simulated by using the finite-difference time-domain simulation. In the simulations, the effective area is divided into uniform Yee cells with \( \Delta x = \Delta y = 2 \text{ nm} \) and \( \Delta t = \Delta x/2c \) (\( c \) is the velocity of light in vacuum) [44, 45]. The perfectly matched layer can be set for the boundary conditions in the simulation [46].

In figures 6(b)–(d), we plot the transmission spectrum exhibits a distinct dip at the wavelength of 1410 nm when \( \delta = 0 \). Meanwhile, the reflection \( R_f \) reaches the maximum at the wavelength. However, the reflection \( R_f \) is equal to zero, and CPA appears at 1410 nm in the case of the backward incidence. In figure 6(c), the UR also can be observed, but the quality factors of spectra decrease when \( \delta = 0.8 \times 10^{13} \text{ rad s}^{-1} \) (\( r_{Li} = 74 \text{ nm} \) and \( r_{Lo} = 124 \text{ nm} \)). The spectra of \( T, R_f, R_b, \) and \( A_f \) show asymmetry when \( \delta = 4.4 \times 10^{13} \text{ rad s}^{-1} \) (\( r_{Li} = 70 \text{ nm} \) and \( r_{Lo} = 120 \text{ nm} \)) as depicted in figure 6(d). Compared with the case when \( \delta = 0 \), the \( R_f \) shows an obvious reflection peak when \( \delta = 4.4 \times 10^{13} \text{ rad s}^{-1} \), denoting the disappearance of UR.

### 4. Conclusions

In summary, we have studied the dependences of the indirect coupling phase \( \theta_g \), gain coefficient \( \Gamma \), and resonant detuning \( \delta \) on \( T, R_f, R_b, A_f, \) and \( A_b \) in the waveguide side-coupled with gain and loss resonators by
using the developed coupled mode-scattering matrix theory and finite-difference time-domain simulation. It is shown that the UR light propagation can be realized in the case of the backward incidence under the condition of balancing gain and loss in the gain resonator when the indirect coupling phase $\theta$ ranges from $0.8$ rad to $2.3$ rad and from $4$ rad to $5.5$ rad. However, the total reflection appears in the case of the forward incidence at the same time. Moreover, the CPA can be observed in the non-PT symmetric case for the proposed waveguide. And we find that the negative absorption appears when $\Gamma > 1/\tau_{12} + 1/\tau_{21}$. Especially, the reflection in the case of the backward incidence is approximately equal to zero when the absolute value of the detuning $\delta$ between the two resonant modes is smaller than $1 \times 10^{13}$ rad s$^{-1}$. At last, we have also proposed a metal–insulator–metal PT-symmetric plasmonic waveguide and obtained UR and CPA phenomena. These results may be of great significance for the realization of reliable unidirectional devices.

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Data availability statement

No new data were created or analysed in this study.

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References

[1] Bender C MBoettcher S 1998 Real spectra in non-Hermitian Hamiltonians having PT symmetry Phys. Rev. Lett. 80 5243
[2] Bender C MBrody D CJones H F 2004 Extension of PT-symmetric quantum mechanics to quantum field theory with cubic interaction Phys. Rev. D 70 025001
[3] Aurégan YPagneux V 2017 PT-symmetric scattering in flow duct acoustics Phys. Rev. Lett. 118 174301
[4] Zhu XRamezani HShi CZhu X 2014 PT-symmetric acoustics Phys. Rev. X 4 031042
[5] Goldsheid I YKhoruzhenko B A 1998 Distribution of eigenvalues in non-Hermitian Anderson models Phys. Rev. Lett. 80 2897
[6] Ramezani HSchindler JEllis F MGunther UKottos T 2012 Bypassing the bandwidth theorem with PT symmetry Phys. Rev. A 85 062122
[7] Bagchi BQuesne C 2002 Non-Hermitian Hamiltonians with real and complex eigenvalues in a Lie-algebraic framework Phys. Lett. A 300 13–26
[8] El-Ganainy RMakris K GChristodoulides D NMusslimani Z H 2007 Theory of coupled optical PT-symmetric structures Opt. Lett. 32 2633–4
[9] Chang LIjiang XHua SYang CWen JLi GWang GXiao M 2014 Parity-time symmetry and variable optical isolation in active-passive-coupled microresonators Nat. Photon. 8 524
[10] Regensburger ABorders CMiró MAOnishchukov GChristodoulides D NPeschel U 2012 Parity-time synthetic photonic lattices Nature 488 167
[11] Liu XGupta SAgarwal G 2014 Regularization of the spectral singularity in PT-symmetric systems by all-order nonlinearities: Nonreciprocity and optical isolation Phys. Rev. A 89 013824
[12] Ramezani HChristodoulides D NKovanis VVitebskiy IKottos T 2012 PT-symmetric Talbot effects Phys. Rev. Lett. 109 033902
[13] Lazarides NTsironis G P 2013 Gain-driven discrete breathers in PT-symmetric nonlinear metamaterials Phys. Rev. Lett. 110 035301
[14] Sarısaman MTas M 2018 Unidirectional invisibility and PT symmetry with graphene Phys. Rev. B 97 045409
[15] Yin XZhang X 2013 Experimental demonstration of a unidirectional light propagation at exceptional points Nat. Mater. 12 175
[16] Zezyulin D AOtt HKonotop V V 2018 Coherent perfect absorber and laser for nonlinear waves in optical waveguide arrays Opt. Lett. 43 5901–4
[17] Sun YTian WLi HLi JChen H 2014 Experimental perfect absorption of a coherent perfect absorber with PT phase transition Phys. Rev. Lett. 112 143902
[18] Kang MBli J 2013 Effective spontaneous PT-symmetry breaking in hybridized metamaterials Phys. Rev. A 87 053824
[19] Rüer C EMakris K GEl-Ganainy R EChristodoulides D NZezyulin D AOtt H 2010 Observation of parity-time symmetry in optics Nat. Phys. 6 192–5
[20] Feng LXu YLFegadolli W SLu M HOliveira J E BAmaide V RChe n YF Scherer A 2013 Experimental demonstration of a unidirectional reflectionless parity-time metamaterial at optical frequencies Nat. Mater. 12 108
[21] Zhang CB, Gu XJ, Xin X, RZhang Y, QLee Y 2017 Dual-band unidirectional reflectionless phenomena in a ultracompact non-Hermitian plasmonic waveguide system based on near-field coupling Opt. Express 25 24281–9
[22] Rivolta NM, Ass B 2016 Side-coupled resonators with parity-time symmetry for broadband unidirectional invisibility Phys. Rev. A 94 053854
[23] Huang Y, Shen Y, Fan C, Veronis G 2017 Unidirectional reflectionless light propagation at exceptional points Nanophotonics 6 977–96
[24] Sarsamam M 2017 Unidirectional reflectionlessness and invisibility in the TE and TM modes of a PT-symmetric slab system Phys. Rev. A 95 013806
[25] Jin LS, Song Z 2018 Incident direction independent wave propagation and unidirectional lasing Phys. Rev. Lett. 121 073901
[26] Sakhdari ME, Stalhri N, Bagci H, Chen P 2018 Low-threshold lasing and coherent perfect absorption in generalized PT-symmetric optical structures Phys. Rev. Appl. 10 024030
[27] Sarsamam M, Tan M 2019 Broadband coherent perfect absorber with PT-symmetric 2D-materials Ann. Phys., NY 401 139–48
[28] Huang Y, Min C, Veronis G 2016 Broadband near total light absorption in non-PT-symmetric waveguide-cavity systems Opt. Express 24 22219–31
[29] Jin LS, Song Z 2021 Symmetry-protected scattering in non-Hermitian linear systems Chin. Phys. Lett. 38 024202
[30] Gu X, Bai R, Zhang Y, Jin X, RZhang Y, QLee Y 2017 Unidirectional reflectionless propagation in a non-ideal parity-time metasurface based on far field coupling Opt. Express 25 11778–87
[31] Huang Y, Shen Y, Min C, Veronis G 2017 Switching of the direction of reflectionless light propagation at exceptional points in non-PT-symmetric structures using phase-change materials Opt. Express 25 27283–97
[32] He Z, Li H, Li X, Chen Z, Zheng M 2016 Theoretical analysis of ultrahigh figure of merit sensing in plasmonic waveguides with a multimode stub Opt. Lett. 41 5206–9
[33] Lu H, Liu X, Mao D 2012 Plasmonic analog of electromagnetically induced transparency in multianoreresonator-coupled waveguide systems Phys. Rev. A 85 053803
[34] Lu H, Gan X, Jia B, Mao D, Zhao J 2016 Tunable high-efficiency light absorption of monolayer graphene via Tamm plasmon polaritons Opt. Lett. 41 4743–6
[35] Xu H, Li H, He Z, Chen Z, Zheng M, Zhao M 2017 Dual tunable plasmon-induced transparency based on silicon-air grating coupled graphene structure in terahertz metamaterial Opt. Express 25 20780–90
[36] Zhan SL, Li H, He Z, Chen Z, Xu H 2015 Sensing analysis based on plasmon induced transparency in nanocavity-coupled waveguide Opt. Express 23 20313–20
[37] Lu H, Liu X, Wang G, Mao D 2012 Tunable high-channel-count bandpass plasmonic filters based on an analogue of electromagnetically induced transparency Nanotechnology 23 444003
[38] Cao GL, HZhan SX, HLiu ZHe Z, Wang Y 2013 Formation and evolution mechanisms of plasmon-induced transparency in MDM waveguide with two stub resonators Opt. Express 21 9198–205
[39] Cao GL, HZhan SX, He Z, Gu X, ZHuo Z, Yang H 2014 Uniform theoretical description of plasmon-induced transparency in plasmonic stub waveguide Opt. Lett. 39 216–9
[40] He ZZ, Zhao J, Li H 2020 Tunable nonreciprocal reflection and its stability in a non-PT-symmetric plasmonic resonators coupled waveguide systems Appl. Phys. Express 13 012009
[41] Huang Y, Veronis G, Min C 2015 Unidirectional reflectionless propagation in plasmonic waveguide-cavity systems at exceptional points Opt. Express 23 29882–95
[42] Li YY, Du G, Wu Y 2016 PT-symmetry-induced evolution of sharp asymmetric line shapes and high-sensitivity refractive index sensors in a three-cavity array Phys. Rev. A 93 023814
[43] Yu Z, Veronis G, Fan S, Brongersma M, L 2008 Gain-induced switching in metal-dielectric-metal plasmonic waveguides Appl. Phys. Lett. 92 041117
[44] He Z, Li M, Pu L, Xu H, Yi Z, Cao X, Cui W 2020 Graphene-based metasurface sensing applications in terahertz band, results in physics Results Phys. 21 103795
[45] He Z et al 2020 Tunable Fano resonance and enhanced sensing in a simple Au/TiO2 hybrid metasurface Nanomaterials 10 687
[46] Zhan SL, Cao GL, He Z, Li H, Yang H 2014 Slow light based on plasmon-induced transparency in dual-ring resonator-coupled MDM waveguide system J. Phys. D: Appl. Phys. 47 205101