Review article

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Plasmon-induced transparency effect for ultracompact on-chip devices

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Abstract: On-chip plasmon-induced transparency (PIT) possessing the unique properties of controlling light propagation states is a promising way to on-chip ultrafast optical connection networks as well as integrated optical processing chips. On-chip PIT has attracted enormous research interests, the latest developments of which have also yield progress in nanophotonics, material science, nonlinear optics, and so on. This review summarizes the realization methods, novel configurations, diversiform materials, and the improved performance indexes. Finally, a brief outlook on the remaining challenges and possible development direction in the pursuit of the application of a practical on-chip photonic processor based on PIT is also afforded.

1 Introduction

Photons have many advantages, including large bandwidth and strong stability, and can be used as information carriers on integrated computing chips. The most essential requirement is the acquisition of different propagation states of signal light by designing different device configuration, which lays the entire foundations of mesoscopic optical field, including communication networks, optical computing systems, and quantum information processing chips [1, 2]. Nanostructures with plasmon-induced transparency (PIT) can provide diversiform transmission properties at different wavelengths. Therefore, PIT nanostructures, which is the subject of this review, can be regarded as a basic element, playing a crucial and essential role in constructing on-chip all-optical logic computing networks and photonic central processing units as well [3, 4].

PIT was developed as an analog of electromagnetically induced transparency (EIT) phenomenon in an atomic system, leading the traditional quantum phenomena into the realm of classical optics [5]. In the EIT medium, a destructive interference occurs due to the coupling between a metastable level pumped by a laser beam and an energy level with a dipole-allowed transition [6]. Therefore, a narrowband transparent window can be observed within a broad absorption band. In the surface plasmonic system, a resonant cavity can support either radiative (bright) mode or subradiant (dark) mode, which depends on how strong the pump light can be coupled into [7, 8]. To mimic the EIT phenomenon, by designing cavity structures, the bright and dark modes with different quality factors (Q-factors) can exist simultaneously and destructively interfere with each other strongly, and a narrowband transparent window appears in the wideband transmission forbidden band. Apart from the high

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transmission, the large group refractive index and slow-light effects are also demonstrated at the narrowband transparent window [9]. With the help of the slow light, some nonlinear effects can be highly enhanced, which opens up the possibilities for constructing active all-optical logic devices and the large-scale optical circuit with signal processing capabilities [10].

Recently, to use PIT effect on optical on-chip devices practically, plenty of configurations have been proposed and experimentally demonstrated, most of which are physically based on the nanocavities and waveguides coupling mechanism, paving the way for on-chip integration [11, 12]. In contrast, as metals have intrinsic ohmic dissipation due to their ultrahigh carrier concentration, other materials with low loss have been also introduced into the PIT system, including transparent conducting oxides (TCOs), a new type of plasmonic materials, conventional dielectric and novel low-dimensional materials such as graphene and quantum dots (QDs) [13–16]. Simultaneously, using these materials, photons, phonons, and excitons are introduced in the coupling system, making PIT effects realized in more spectral range and obtained more applications.

Based on the development of the PIT field, the research community has witnessed the rise of device applications. Many all-optical device configurations have been proposed and experimentally demonstrated. These applications include optical logic gates, active tunable optical switching, and optical interconnects, which are all the footstone of the optical circuit. Since the beginning of 2011, our group has been dedicated for device applications in PIT systems. Using the PIT configuration combined with nonlinear materials, we realized switching, all-optical diodes, logic adders, and the all-optical exchangers.

Here, we review the PIT effects and recent progress toward chip integration applications as introduced above. With this article, we hope to provide a comprehensive overview of the past development in this field while simultaneously offer our perspectives on its future potentials. The rest of the review is organized as follows. In Section 2, we review the basic realizing mechanism of PIT nanostructures, and the most important properties of PIT configurations, such as the spectrally sharp transparent windows at the dark mode's resonant frequency and the large group refractive index at this frequency point, are also discussed. In Section 3, diversiform configurations for the PIT effect are described in detail. Section 4 reviews the unique PIT microstructures with novel materials introduced. Section 5 reviews the device applications in the PIT system, especially the on-chip utilization for signal

processing. Finally, the summary and future outlook are presented in Section 6.

2 Realization principle of PIT optical configurations

As the resonance of plasmonic nanostructures can be regarded as an electromagnetic analog of molecular orbital theory [17], there could be analogs in plasmonic nanocavities of many quantum phenomena in the atom systems. The physical mechanism of PIT, which is analogous with the classical EIT effect in quantum fields, are based on the strong destructive interference coupling between wideband bright mode (or so-called superradiant mode) and narrowband dark mode (or so-called sub-radiant mode). In this way, PIT is physically related to the Fano resonance, which can be mathematically described with the framework of temporal coupled mode theory that describes the interaction of two coupled nanocavities' resonant modes [18, 19]. Specifically, PIT can be understood as a particular case of the Fano interference, in which the two resonators are spectrally matched [20]. Therefore, the temporal coupled mode equations can be written as

$$\frac{\partial b}{\partial t} - \left(j\omega_{\text{PIT}} - \frac{1}{\tau_b} \right) b + j\kappa d = \alpha_{\text{in}} S_{\text{in}} e^{j\omega t} \quad (1)$$

$$\frac{\partial d}{\partial t} - \left(j\omega_{\text{PIT}} - \frac{1}{\tau_d} \right) d = -j\kappa b \quad (2)$$

where b and d represent the normalized field amplitudes of the bright and dark modes respectively. Also, τ and κ indicate the decay rate of each resonators and the coupling strength between two resonators, respectively, whereas the right side of Eq. (1) describes the coupling between incident light and bright mode. The reflection and transmission coefficients can be derived as

$$r = \frac{-|\alpha_{\text{in}}|^2 j \left(\omega - \omega_{\text{PIT}} - j\frac{1}{\tau_d} \right)}{\left(\omega - \omega_{\text{PIT}} - j\frac{1}{\tau_b} \right) \left(\omega - \omega_{\text{PIT}} - j\frac{1}{\tau_d} \right) - \kappa^2} \quad (3)$$

$$t = 1 + r \quad (4)$$

Based on the quantitative description, the corresponding transmission spectrum (i.e. $T = |t|^2$) is indicated as a narrowband transparent window located in the center of the wide forbidden band (i.e. ω_{PIT}). The

typical properties of bright modes are shown as directly excited by external incident light and wideband resonant spectrum, whereas, for the dark modes, they have to be indirectly excited through the near-field coupling (i.e. by the scattering or reflection) of the bright mode instead of being excited directly by the incident light due to the momentum mismatch. The Q-factor of the PIT spectrum is determined by the full-width at half-maximum of the transparent window. Based on Eqs. (3) and (4), this factor is mainly related to the decay rate of the dark mode $\frac{1}{\tau_d}$ and the coupling strength κ . Given a fixed decay rate, the slope of the transmission/reflection curves is inversely proportional to κ^2 . Therefore, the reduction of κ (i.e. weakening the coupling between two resonators) will result in a monotonic increase of the Q-factor to infinity until $\kappa=0$ is reached, whereas the PIT phenomenon will vanish at the same point. In specific PIT structures, κ is determined by both the geometric configuration and the material parameters. Therefore, this parameter is generally numerically fitted based on the experimental results instead of the results calculated analytically. In a PIT structure with a given κ , the linewidth of the dark mode and the Q-factor are primarily determined by the dark mode decay rate $\frac{1}{\tau_d}$. Owing to the momentum mismatch of the dark mode, the radiation loss can be neglected, and it is primarily the intrinsic losses of the materials that determine the maximum Q-factors of the PIT system. In plasmonic systems, the Drude damping limit of conventional noble metals is about 10 THz at optical frequency range, indicating that the maximum Q-factor that can be achieved in realistic all-metal PIT systems cannot be extended to 100 [21, 22]. Besides the unique transparent window, another important benefit of the PIT is that the group refractive index is greatly enlarged at the frequency point of the destructive interference peak (i.e. transparent window), which indicates that the incident light with this frequency can be “slowed down” when transmitted through a PIT structure [23]. Therefore, the PIT structure can store enhanced optical energy and realize near-field enhancement when illuminated by incident light with transparency frequency ω_{PIT} . Further, the enhanced field intensity can reinforce the light-matter interaction, offering the possibility of combining the PIT structures with nonlinear materials to construct all-optical integrated devices.

In plasmonic systems, another type of transparent windows was first experimentally observed when visible light is transmitted through periodically perforated silver film, which is named as the extraordinary optical

transmission effect [7]. Remarkable differences exist between the extraordinary optical transmission and PIT effects. First, the configurations of the nanostructure etched in the noble metal film are different. Simple and uniform air holes (or short grooves) were etched through the silver (or gold) film for the case of extraordinary optical transmission, whereas composite nanostructure units providing radiative and irradiative plasmonic modes were adopted for the case of PIT. Second, the physics process is different. The excitation and conversion process of (incident light)-to-(plasmonic modes)-to-(output light) was included in the case of the extraordinary optical transmission effect, whereas the complicated physics process of (incident light)-to-(radiative plasmonic modes)-to-(interference coupling between plasmonic radiative and irradiative modes)-to-(output light) was included in the case of PIT. There exists an energy transfer between plasmonic radiative and irradiative modes.

In PIT systems, as the radiative mode can be acquired in the majority of nanocavities, the key to observe the PIT effect is to choose proper nanocavities supporting irradiative modes and build up the coupling channels between these two types of modes. In general, a practical PIT effect can be observed in such plasmonic microstructure constructions, including nanorod metal resonators, periodic metal split-ring resonator (SRR) arrays, nanoparticle clusters, plasmonic nanocavities side coupled with bus plasmonic waveguides, and gold nanowire gratings coupled with dielectric waveguides, all of which can support the bright and dark modes simultaneously. A metal nanorod might be the simplest surface plasmon polariton (SPP) resonators; therefore, the pioneer study in the PIT field was based on the combination of three nanorod metal resonators to form π -shaped metallic nanorod arrays [24]. In this nanostructure, the vertical single nanorod can support bright dipole resonant mode with relatively large bandwidth, while at the same time the horizontal dual nanorods can support dark quadrupole modes that can be excited by the near-field coupling of the bright mode and the PIT effect can be formed in this nanostructure through the interference of the two modes, which is schematically shown in Figure 1A. Also, large group refractive index and slow-light effect can be appeared near the transparent window. SRR can also exhibit a strong resonant response to external incident light [28] and thus is also suitable for constructing a PIT system. To perform the PIT phenomenon, two identical SRRs are placed with structural 90° rotation asymmetry in a single unit. The bright mode is provided by one of the two constituents when excited by the external incident light, whereas the other constituent supports the dark mode excited through magnetoinductive or electroinductive coupling, and the near-field

Figure 1: Transmission spectrum and near-field distribution of the PIT effect.

(A) A π -shaped structure containing metal nanorods as building blocks. The real and imaginary parts of the electric field spectra indicate that PIT phenomena can be tuned by changing the gap distance between bright and dark resonators. The 2D field plot of electric field distribution indicates the bright and dark modes [24]. (B) Asymmetric SRRs supporting magnetoinductive or electroinductive coupling. Simulated transmittance and reflectance spectra of the asymmetric SRRs indicate a PIT transparent window at 93 THz. The electric field distributions at resonances ω_1 and ω_2 of the PIT structure are also provided [25]. (C) Schematic illustration of the hybrid PIT structure illuminated by a light with an incident angle of θ . The simulated field distributions at PIT range indicate the metallic nanogratings and the dielectric cover layer provide the bright and dark modes, respectively [26]. (D) Schematic of an in-plane coupling PIT structure composed of double-sided teeth-shaped nanocavities and plasmonic waveguide. By optimizing the length of the two nanocavities d_1 and d_2 , the PIT window can be shown at about 1000 nm [27]. (a) Reproduced with permission from Ref. [24]. Copyright 2008 American Physical Society. (b) Reproduced with permission from Ref. [25]. Copyright 2008 Wiley. (c) Reproduced with permission from Ref. [26]. Copyright 2011 AIP. (d) Reproduced with permission from Ref. [27]. Copyright 2010 OSA.

distribution is shown in Figure 1B [25]. Similar to SRR pairs, closely packed nanoparticle clusters are also potential building blocks for the PIT system. In these systems, a strong near-field coupling emerges among individual gold nanospheres and the formed hybridized mode with different decay rate can be used to realize the PIT effect [29].

Apart from conventional metals, dielectric materials are also suitable for constructing dark mode nanocavities due to their low intrinsic loss properties. The decrease of the material absorptions in these nanocavities can further improve the Q-factors of the irradiative dark modes, which in turn enhance the PIT effect greatly. A simple dielectric

layer can behave as a dark mode resonator in which the supported waveguide mode cannot be excited by incident light due to phase mismatch [30, 31]. When combined with metallic nanogratings, it can be used to construct PIT structures [32]. The resonant modes of each metallic nanowire can be easily excited by incident light and work as bright modes, as indicated in Figure 1C [26]. Also, the scattering of gratings can effectively compensate the momentum mismatch of the waveguide mode and build up the coupling tunnel between the plasmonic (bright) mode and low-loss dielectric (dark) mode [33]. Besides, as described by the Mie theory, dielectric nanoparticles can also support localized resonant mode and build up the PIT response. Similar to metallic nanocavities, a silicon nanobar can be regarded as an electric dipole antenna and provide bright mode coupling with external field; also, a ring nanocavity with two gaps can support magnetic dipole modes, which is used as dark mode [34]. The all-dielectric PIT-like system can provide a sharper transparent window.

The above-mentioned PIT configurations are designed to be excited by external field in the vertical direction, which might have potential to be used in three-dimensional (3D) optical chips for layer-to-layer interconnections. In contrast, the PIT effect can also be realized when the incident light is injected from the horizontal direction. In this situation, a metallic air slot is generally used to guide the transmission of the incident light with high confinement [35]. Nanocavities are side coupled with the slot waveguides for energy harvesting to excite resonant mode, as indicated in Figure 1D. Generally, a single stub slot can be directly excited and provide bright mode with large bandwidth [27], whereas another Fabry-Pérot (FP) resonance can be formed between two cavities, which behaves as dark modes in the PIT system. Also, the energy coupling between these two modes can be controlled by tuning the phase mismatch of the two nanocavities [36].

To conclude, in this section, we review the physical mechanism of the PIT effect, which is the resonant mode destructive interference. As the resonance and coupling of nanocavity modes in the optical field are mostly determined by the structures, we also involved the classical nanocavity designs that are widely used for constructing the PIT device in this section.

3 Typical configurations of PIT structures

The previous section reviews the physical principle of the PIT effect and gives a brief introduction of the structures

with PIT effects. In this section, we review the diversiform PIT configurations in detail, which provide broader ideas and thoughts for integration and miniaturization.

3.1 Out-of-plane coupling configurations

π -shaped metallic nanorod arrays might be the most classical PIT construction consisting of three nanorods. One of the three nanorods is placed horizontally to provide bright mode, and the other two are placed vertically on both sides of the horizontal one to provide quadrupole resonant interfering with the bright mode, and all these rods are made of metal, such as gold and silver. Inspired by this basic configuration, some other structures have been proposed and demonstrated. Cetin et al. experimentally demonstrated a cascaded π -shaped PIT planar metamaterials with the characteristic of asymmetric position [37]. Compared to the PIT behavior in individual π -structures, the PIT spectral position and the intensity enhancement location of the cascaded structure can be tuned in great precision by adjusting the distance of the elements in such asymmetric structures. Apart from gold nanobars, nanoslots, which can be fabricated by etching rectangular air holes on gold films, can also work as antennas to construct the PIT effect with π -shaped configuration, which was indicated by Liu et al. [38]. The π -shaped structure is also developed for multispectral PIT. Artar et al. fabricated a planar slot antenna system-based metal-dielectric-metal multilayered metamaterial [39]. Two transparent windows emerge simultaneously in the double-layered structures. Therefore, this design can enhance nonlinear processes at multiple frequency domains synchronously, which might open up new possibilities in optical information processing with high bandwidth. Moreover, the active tunability of the transparent window shown in the π -structure is also experimentally studied. Zhu et al. demonstrated an ultralow power and ultrafast all-optical tunable PIT metamaterials working at the optical communication wavelength range [40]. In this structure, the π -shaped gold nanoparticle was fabricated on a polycrystalline indium-tin oxide (ITO) layer with high conductivity, which was chosen as the optical tunable materials with third-order nonlinearity. At the threshold pump light intensity of about 0.1 MW/cm² order, the transparent window shows a maximum shift of 86 nm with an ultrafast response time of 51 ps, indicating the possibility of building up quantum solid chips and integrated all-optical photonic devices based on PIT metamaterials. By combining the asymmetric cascaded π -structure with nanocomposite nonlinear substrate, Zhu et al. demonstrated pumping with

femtosecond laser, two PIT windows in a single structure could be optically tuned simultaneously with a response time of 34.9 ps [41]. Furthermore, the π -structure has also inspired some deformed configurations. Liu et al. theoretically investigated a resonant PIT system in which the π -structure was replaced by a nanorod and a triangle nanocavity [42]. It is the resonant cavity mode supported by the triangle cavity that worked as a dark mode. To avoid the disadvantage of the polarization sensitivity of such π -structure, in 2014, our group designed and fabricated a generalized π -structure PIT system. Rather than the straight bars, three triangle gold nanocavities served as the basic element [43], the scanning electron microscopy (SEM) image of which is shown in Figure 2A. Owing to the rotational symmetry, the PIT response remains almost unchanged under the linear polarized incident light with different polarization angle. We further experimentally demonstrated the giant slow-light effect in the gold nanoprism PIT structure with multilayer nonlinear material. In this structure, the PIT resonance was provided by the nanoprism dimer, whereas the transparent window is located at about 1300 nm [47]. At this frequency point, a group index of more than 4×10^3 was obtained. In addition, combined with the nanocomposite nonlinear material (i.e. multilayer graphene microsheet/ZnO layer/a monolayer graphene/polycrystalline ITO layer), a 120 nm wavelength shift of the PIT window was achieved under 1.5 kW/cm² light pumping.

In addition to the most common π -type configuration, there are many other different periodic structures for the PIT effect, which might have an enlarged operation frequency range or improved parameters. As metallic ring resonators are widely used as plasmonic nanocavities to provide resonant modes [48], they could also be appropriate building blocks for constructing PIT configurations. Wu et al. proposed and fabricated planar metamaterials consisting of SRRs coupled with a straight metal stripe, in which the PIT phenomenon shows up in terahertz (THz) frequency range [49]. Specifically, in this structure, the straight metal stripe behaved as the radiative resonator coupling the electromagnetic field with the external illumination, whereas the double-gap SRR provides the electric quadrupole mode, in which counterpropagating current flows along each side arm. In this structure, the length of the gap between the two cavities is precisely tuned, which has a strong influence on the performance of the transparent window. In addition to a three-level PIT, this structure is also used for four-level PIT when the SRR is placed asymmetrically between the straight stripes. In this situation, the bright mode can be coupled with the two dark mode simultaneously and consequently

two transparent windows emerge in the operation frequency band. Also, some similar configurations have also been widely adopted and experimentally demonstrated [50, 51]. Furthermore, based on the similar structure, Zhu et al. designed a PIT structure containing two SRRs with enlarged gap and experimentally demonstrated a broadband PIT effect in which the bandwidth of the transparent window is greater than 0.40 THz [52]. Such broadband PIT configurations are promising candidates to construct slow-light devices and the highly nonlinear elements. For practical utilization in an optical signal processing regime, polarization-independent properties are necessary as the polarization of the signal could be changed when propagating, whereas most of the PIT structures mentioned above are sensitive to the polarization of the incident light. Therefore, once the polarization of the illumination light is altered, the bright resonant mode may not be strong enough to excite the dark mode, and the PIT phenomenon may be weakened or not be formed [53]. To overcome this limitation, Zhang et al. proposed a PIT nanostructure in which a cross bar resonator and four identical SRRs with different gap positions were chosen to provide bright and dark modes, respectively [54]. They experimentally demonstrated that this sample had the same response with the two orthometric polarized incident waves and realized the polarization-independent property, which originated from the fourfold symmetry of the structure. The tunability of these SRR PIT configurations has also been investigated. As the PIT phenomenon is strongly related to the mode coupling between different resonators, the relative distance of each nanocavities can affect not only the transmission coefficient but also the spectra position of the window, which is illustrated in Ref. [55] in detail. In addition to the coupling distance, Ma et al. demonstrated that changing the twisting properties between cavities was also an effective way to manipulate the PIT effect [56]. From the perspective of practical integrations, active tunability is needed so that the transmission properties can be changed dynamically under different external stimulus. Gu et al. skillfully incorporating amorphous Si islands into the PIT metamaterial unit cell to build up an optical reconfigurable PIT structure [44]. Specifically, the structure contains a straight metal bar and two SRRs, and Si particle is filled into the gap of each SRRs. Pumped by infrared (IR) laser, the silicon island became photoconductive and the dark mode was no longer supported by the ring. Therefore, the PIT spectrum was optically tuned into the signal resonant dip, and the group velocity of the signal pulse was controlled synchronously, which is determined by using the THz time-domain spectroscopy, as indicated in Figure 2B. Besides, Xu et al. also integrated

Figure 2: Schematic of typical out-of-plane coupling configurations for PIT structures.

(A) Schematic and the SEM image of a polarization-insensitive PIT structures composed of gold triangle nanoprisms on ITO substrate. The measured transmission spectra indicate that the structure is insensitive to the incident light polarization states. The simulated field distributions at the transparent window is also provided [43]. (B) Active all-optical tunable PIT structures containing SRRs with silicon nanoislands embedded in the gaps. With IR pump excitations, the refractive index of silicon islands can be changed and the PIT effect at the THz range can be tuned [44]. (C) Plasmonic quasicrystal arrays with disordered gold nanodisks. The thickness of the PIT metasurface is 10 nm. The period of the unit cell is 266 nm. The unit cell consists of four gold nanodisks, each with different radii arranged in a square lattice. Tuning the radius of nanodisks can influence the disorder state of the structure, resulting in tuning the PIT response in the optical frequency range. The blue lines correspond to the polarization-independent case, whereas red/green lines correspond to x/y polarization cases, respectively [45]. (D) Chiral PIT structures with dichroic coupling mechanism. Reflectivity spectra for RH and LH shuriken nanostructures in water are also provided, including for linearly polarized input light, LCP input light, and RCP input [46]. (a) Reproduced with permission from Ref. [43]. Copyright 2014 Wiley. (b) Reproduced with permission from Ref. [44]. Copyright 2012 Macmillan Publishers. (c) Reproduced with permission from Ref. [45]. Copyright 2015 ACS. (d) Reproduced with permission from Ref. [46]. Copyright 2018 ACS.

silicon nanoparticle into each end of the metallic resonant bars in PIT unit cells and spectrally tuned the transparent window from 0.82 to 0.74 THz under the optical pump [57].

There are also some deformation structures designed for PIT effect by adopting ring resonators [58–60]. Huang et al. both experimentally and theoretically introduced localized asymmetric SRRs inserted into the periodic hole arrays [61]. The different sizes of SRRs possess different Q-values and resonance wavelengths. By adjusting the gap between them, the coupling configuration can realize the PIT. Liu et al. replaced the straight metal bars with closed-ring resonators to provide bright mode in PIT unit cells [62]. Therefore, the coupling between individual resonant elements can be tuned more freely, and both the polarization-independent and polarization-dependent PIT responses can be acquired in this configuration. As the metamaterials have potentials to be applied as layer-to-layer connecting elements in constructing 3D optical chips, the 3D PIT configurations have also been studied in addition to the conventional planar structures. Pitchappa et al. introduced the microelectromechanical systems (MEMS) into an SRR PIT system and realized the dynamic tunable PIT phenomenon, in which the shape of the unit cells can be physically changed under the applied electrical field [63].

To overcome the absorption loss, which in turn can improve the performance of the PIT phenomena, dielectric layers were introduced into the PIT system to provide the waveguide resonant mode with narrow bandwidth. Dong et al. studied a PIT structure in which a set of dipole-like bar gratings with slightly reduced symmetry was covered by a dielectric waveguide layer [64]. Owing to the reduction of the metal grating symmetry, the dipole plasmon resonance mode can be completely coupled into the dielectric waveguide mode with low loss and the PIT is formed in a way of destructive interference. Chai et al. experimentally demonstrated the optical tunability of the transparent window by adopting the polycrystalline LiNbO_3 as dielectric layers with nonlinearity caused by the quantum size confinement effect [65]. The transparent window in this well-designed structure is located at 600 nm and can be blue shifted about 50 nm at the pump power density of 7 MW/cm².

Recently, some other types of out-of-plane coupling configurations are also proposed to realize the PIT effect. As most of the out-of-plane coupling PIT structures are periodically arranged, the quasi-crystal configurations can also be used to develop PIT. Amin and Khan reported a quasicrystal structure formed by a planar array of thin gold nanodisks arranged in a square lattice with different diameters, where PIT windows were shown in the visible

spectrum [45]. Compared to the periodic structures, the essential aspect of this quasi-crystal is the periodic disorder that couples higher-order modes to the broadband background resonant mode; therefore, it can support multitransparent windows in the operation band, as shown in Figure 2C. Besides, the gap resonant mode formed between the gold nanotubes by chemical synthesis can also be used as dark mode to form PIT, which was experimentally demonstrated in 2016 [66]. In addition, the PIT-like response was also built up by the resonant mode in pure dielectric photonic crystals [67].

Moreover, the chiral PIT phenomena has gradually become a research hotspot. Kelly et al. designed a chiral structure contains “shuriken”-shaped indentations with sixfold rotational symmetry arranged in a square lattice [46], as illustrated in Figure 2D. They analyzed that the coupling between optically bright and dark chiral modes could be controlled by manipulating the chiral asymmetries of the near fields; thus, the chiral PIT windows could be applied at near-IR windows.

3.2 In-plane coupling configurations

In the previous section, we reviewed the diversiform out-of-plane coupling configurations to realize the PIT effect. Based on these nanostructures, the incident signal can be modulated with high efficiency, including the transmission and the group velocity. Moreover, the geometric dimensions of these integrated nanocavities are usually at the scale of 100 nm, indicating that these configurations are potential candidates to build up layer-to-layer optical interconnection in 3D photonic integration and optical processing chips [68]. In contrast, to make a direct planar integration with the developed plasmonic circuit, some in-plane coupling two-dimensional (2D) PIT configurations (i.e. light signal propagating through the PIT structure on the chip plane) have also been studied, which are reviewed in this section. Most of these configurations are designed based on the coupled mode theory of resonant nanocavities [69].

To realize the in-plane coupling PIT effect, an intuitionist manner is to combine the resonant antennas with waveguides for signal injection. He et al. used symmetric single-mode slab waveguide and embedded silver nanoparticles to realize PIT, as shown in Figure 3A [70]. The waveguide is a slab waveguide with i_3N_4 as the core layer. The two silver elliptical nanoparticles serve as the bright and dark modes, respectively. Owing to the polarization state of the waveguide mode, the resonant mode of the vertically placed nanoparticle can be easily excited and

Figure 3: In-plane coupling PIT structures with incident light injected through waveguide.

(A) A symmetric single-mode slab waveguide with embedded silver nanoparticles providing bright and dark modes, respectively. The PIT window appears at 800 nm and the simulated near-field distributions are also provided [70]. (B) A dielectric loaded plasmonic waveguide side coupled with two racetrack ring microcavities. According to the microscope image and experimental CCD image, energy in the plasmonic waveguide can be effectively coupled into the two nanocavities to form on-chip PIT responses [71]. (C) A metallic air-slot waveguide with two aperture coupled FP nanocavities for acquiring on-chip PIT responses. Optimizing the length of the upper nanocavities, both the spectral position of the transparent window and the Q-factor of the PIT response can be changed [72]. (D) Four stub nanocavities are attached to a single slot waveguide, and three transparent windows appear in the forbidden band. According to the field distributions at the transparent windows, PIT responses occur between two adjacent stub resonators with detuned resonant wavelengths [73]. (E) A cross-shaped composite nanocavity combined with slot waveguide forms an ultracompact PIT structure. The measured transmission spectrum indicates that the transparent window is located at 850 nm [74]. (F) SEM images of the hybrid PIT system based on the photon-plasmon composite nanocavities coupling. The gap between the dielectric photonic crystal and gold films forms a hybrid bus waveguide. The gold stub nanocavity and photonic crystal microcavity provide the bright and dark modes, respectively [75]. (a) Reproduced with permission from Ref. [70]. Copyright 2011 AIP. (b) Reproduced with permission from Ref. [71]. Copyright 2013 OSA. (c) Reproduced with permission from Ref. [72]. Copyright 2011 OSA. (d) Reproduced with permission from Ref. [73]. Copyright 2012 OSA. (e) Reproduced with permission from Ref. [74]. Copyright 2014 Wiley. (f) Reproduced with permission from Ref. [75]. Copyright 2016 ACS.

acts like a bright mode. The dark mode can be excited not by the waveguide mode but by the bright resonator. The bright mode has a broadband transmission dip, whereas the dark mode processes a narrow band, owing to the indirect coupling. Such two resonators coupled together cause extreme destructive interference, and the PIT can be realized in the waveguide configuration. Instead of nanoparticle resonators, the ring cavities were also proven to be alternatives to realize the waveguide-loaded PIT effect. Han et al. built a structure consisting of a dielectric loaded plasmonic waveguide and two cavities, as shown in Figure 3B [71]. The radii of the two racetrack cavities are slightly different. Because of optical path difference in the two detuned resonators, the resonant modes destructively interfere with each other when coupling back into the output waveguide. Besides, by increasing the radius difference, the peak of PIT can be changed and shifted.

In the integrated SPP circuits, air-slot waveguides are widely adopted for its strong field confinement and smaller geometric dimension compared to the dielectric loaded waveguides. Therefore, some on-chip PIT configurations have also been proposed based on the metal air-slot waveguide and cavities. Figure 3C shows a PIT structure based on slot waveguides theoretically proposed by Han and Sergey and the yellow background in the figure represents silver with dielectric embedded [72]. In this structure, the slot waveguide uses the gap surface plasmon mode, which allows extreme field confinement, whereas two detuned FP nanocavities are side coupled. They first studied the property when the waveguide is only coupled with a single FP nanocavity. By changing the geometric cavity length, the central peak can be changed. Therefore, when the two FP nanocavities, which are equally spaced but with opposite signs of detuning of the eigenfrequency from incident light, are set to be side coupled to the waveguide simultaneously, the cancelation of two detuned resonances can result in a PIT phenomenon. They also demonstrated that the central position of the PIT spectra can be shifted by alternating the length of FP cavity. In addition, the two FP nanocavities can also be placed at the same side of the bus waveguide to realize PIT phenomenon, as the two cavities have different coupling distance with the bus waveguide [76].

The stub nanocavity is also widely used in the in-plane coupling PIT system because it is convenient to be excited by the bus waveguide. The single stub nanocavity can be regarded as a bright-mode resonator with a broadband spectrum as it is directly connected to the bus waveguide. Chen et al. designed a multiple coupled resonator structure containing two stub nanocavities attached to a single slot waveguide to realize multiple PIT phenomena [73].

On the one hand, the single resonance of each stub can be considered as a synthetic bright mode with a large bandwidth; on the other hand, these two resonators can couple with each other through the slot waveguide. In the frequency range of the bright mode, both stubs can reflect SPP as it is near resonance frequency, constructing an FP cavity serving as dark mode, resulting in a narrowband transparent window. Based on this mechanism, multiwindows can also be realized when introducing more stubs. As indicated in Figure 3D, four stubs are attached to the same waveguide. Each two adjacent stubs of the four construct an FP cavity, and it is clear that there are three transmission peaks and the window's spectral positions can be controlled by carefully choosing the length of the stub. This PIT structure was experimentally demonstrated by Yang et al. [77]. The measured transmitted spectrum clearly indicated three transparent windows located at about 800 nm. In this structure, the nanocavities can not only couple with each other indirectly (i.e. through the bus waveguide) but also couple directly with each other when these nanocavities are placed close enough. In this situation, it is the distance and the length difference between the two nanocavities that influence the coupling strength strongly. The PIT as well as slow-light effect can be more pronounced by decreasing the length difference between the two stub nanocavities with fixed coupling distance, which is theoretically investigated by Cao et al. [11, 78]. The experimental results provided by Zhu et al. indicate that this direct coupling mechanism also works when two stubs are placed on different sides of the waveguide [79]. Besides, combined with other types of cavities, the stub nanocavity can also be used to realize bright-dark mode interference in which the stub works as a bright "atom", owing to the strong coupling and the broadband resonant bandwidth. Cui and Zeng built a nanostructure and used the stub combined with a nanoring resonator [80]. The injected SPP signal transmits through the slot waveguide. The stub can be excited by the waveguide directly, but as the ring is relatively far from the waveguide the injected SPP field in the waveguide is hard to excite the ring resonator. These two resonators act as the bright and dark modes, respectively. Also, as the ring resonator is close to the stub, the modes in them can be coupled together through near field. The simulated field distribution clearly indicates the difference between the two resonant modes and the interference between them. Similarly, Zhang et al. designed another PIT structure composed of a stub nanocavity coupling with a rectangular cavity [81]. The rectangular cavity is placed parallel to the bus waveguide. The stub cavity can be regarded as a branch of the waveguide and can be directly excited, providing bright mode. By

varying the distance between the rectangular cavity and the waveguide, the excitation property of this cavity can be controlled. By increasing the coupling distance, the direct coupling is prohibited and only dark mode exists in the rectangular nanocavity, ensuring the emergence of the PIT effect.

A single composite nanocavity can also be adopted to realize the PIT effect through the destructive interference of the different resonant modes in the composite nanocavity. Lu et al. might first theoretically investigated the PIT in the composite nanocavity [82]. A T-shaped composite cavity supports the bright and dark modes in the vertical and horizontal parts, respectively. The transmission characteristics depend on the phase matching condition (i.e. the length and the refractive index) and coupling distance between the two parts of the nanocavity. A similar configuration was also theoretically analyzed by He et al. [83]. The experimental demonstration of this type of on-chip PIT configuration was provided by Chai et al. [74]. The focused ion beam etching system was adopted to fabricate the sample in a 300-nm-thick gold film, which contains an air-slot bus waveguide combined with a cross-shaped nanocavity. Using confocal microscopic measurement, the transparent window is located at 780 nm, as shown in Figure 3E. More importantly, as only one cavity is involved in this system, the feature size of these configurations is at the scale of 100 nm, paving the way to large-scale integration on a single chip.

In the metal-only on-chip PIT system mentioned above, the bandwidth of transparent windows is relatively large, owing to the absorption loss of the metal; therefore, the group indexes are usually less than 100, which might limit the practical utilization in the slow-light devices. Consequently, some traditional dielectric cavities, including microring cavities, photonic crystal microcavities, and self-coupled optical waveguide resonators, are used to obtain PIT lineshapes in coupled resonator systems [84–90]. As for the low intrinsic loss of dielectrics, such all-dielectric PIT systems can obtain a strong slow-light effect with a larger group refractive index compared to the conventional metal PIT system [91]. However, the large feature size, which is usually dozens of micrometers, restricts the compact on-chip integration. To overcome the tradeoff between the large group refractive and the small feature size, Chai et al. designed a hybrid on-chip system based on the photon-plasmon composite nanocavities coupling [75], as schematically shown in Figure 3F. The proposed structure consists of a plasmonic nanocavity coupled with a 2D silicon photonic crystal nanocavity connected to a hybrid waveguide, which is formed by an air slot between a gold film and a silicon photonic

crystal slab. The destructive interference can be obtained between the broadband plasmonic nanocavity mode and photonic crystal nanocavity modes with high Q-factors. In such hybrid system, a significant group refractive index and a small feature size can be acquired simultaneously, and the multitransparent windows emerge due to the multimode resonance features of the photonic crystal nanocavity.

4 Novel materials for PIT

Besides conventional noble metals, many novel materials, including 2D materials, superconducting materials, low-loss transparent dielectric materials [including TCOs (ITO and AZO)], phase-changed materials [including chalcogenides (GST)], alternative plasmonic materials (including TiN, SiC, and diamond metamaterials/metasurfaces), and QDs, have also been proposed to realize the PIT effect in compact optical systems. These novel materials provide new mechanisms and pathways for designing active tunable integrated devices, including slow-light devices, ultrasensitive sensors, and nonlinear devices.

Graphene has shown various interesting properties in mechanical, electric, and optical applications. More importantly, graphene is also a promising candidate of plasmonic material from THz to mid-IR spectral range, and the graphene plasmons (GPs) have been extensively investigated both theoretically and experimentally [92, 93]. Compared to metal plasmonics, GPs possess higher confinement, longer relative propagating distances, and better electrostatic tunability. The wavelengths of the GPs are about two orders of magnitude smaller than the wavelength in free space [94]. Besides propagating GPs, localized GPs and the coupling between the two plasmons have also attracted considerable attention in recent years. Xia et al. proposed an easily implemented and dynamically tunable PIT system that was composed of sinusoidal curved and planar graphene layers separated by a dielectric sinusoidal layer [95], as indicated in Figure 4A. The design of this PIT system can be easily realized as it avoids any of the pattern of the graphene sheet. The induced transparent window can be drastically tuned by changing the coupling strength between the two layers through the various grating amplitudes and the interlayer spacing. Chen and Fan proposed a multilayer graphene-dielectric structure, which also has PIT features according to the calculated transmission spectrum. Moreover, owing to the symmetry, the PIT response is polarization insensitive [16]. The multi-PIT can also be constructed by adding

Figure 4: Graphene layers work as building blocks for constructing PIT structures.

(A) Sinusoidal curved and planar graphene layers separated by a dielectric spacer. The height of the dielectric spacer determines the coupling strength between the two graphene layers [95]. (B) An active PIT system based on graphene grating sheet near-field coupling mechanism. The PIT effect is based on the near-field coupling between localized plasmon resonances of graphene nanostructures. The thickness of dielectric spacer can be optimized to more than 100 nm [96]. (C) Graphene waveguide side coupled with two graphene nanoribbons working as FP nanocavities. This structure is based on the graphene surface plasmon at the IR region. The graphene nanosheets with different lengths can be worked as bus waveguide and FP resonant nanocavities, respectively [97]. (D) SRR PIT structures with graphene covering the gaps as tunable materials. The device can be reconfigured by tuning the Fermi level of graphene. The SEM image of the structure is also shown [98]. (a) Reproduced with permission from Ref. [95]. Copyright 2016 OSA. (b) Reproduced with permission from Ref. [96]. Copyright 2016 OSA. (c) Reproduced with permission from Ref. [97]. Copyright 2016 IOP. (d) Reproduced with permission from Ref. [98]. Copyright 2018 Wiley.

multiple graphene layers [99]. The patterned graphene nanoribbons are also widely investigated and introduced into PIT system. Luo et al. investigated the performance of an active PIT system based on graphene grating sheet with near-field coupling distance of more than 100 nm in mid-IR [96], as shown in Figure 4B. As it is well known, the Fermi level of graphene and the related GPs can be efficiently tuned by external voltages or chemical doping.

They also theoretically demonstrated that the frequency of the transparent window of the proposed PIT system can be tuned by external electricity. The multispectral PIT responses with wavelength tunability were investigated by Sun et al. in the THz frequency range in periodically patterned graphene double layers separated by a dielectric layer [100]. Each graphene layer was patterned with three rectangular holes as resonators, and the coupled

Lorentz oscillator model was introduced to explain the multispectral PIT phenomena resulting from the near-field coupling in different graphene layers and the dark-bright mode coupling in graphene single layer. Also, the resonance coupling between two graphene nanoribbons was also analyzed and adopted in the PIT system. Tang et al. reported a graphene-based ultrasensitive specific THz sensor using the PIT resonance [101]. The unit cell of the proposed graphene microribbon array structure consists of two kinds of graphene ribbons with different widths. The interference between the plasmonic resonances of the narrow graphene microribbon and the wide graphene microribbon gives rise to a narrow linewidth high-Q PIT resonance. The specific sensing of a trace amount of benzoic acid using this PIT sensor is realized with detection limit smaller than $6.35 \mu\text{g}/\text{cm}^2$. Moreover, this coupling system can be combined with graphene waveguide for on-chip configuration. The on-chip structure designed by Li et al. consists of a waveguide and two short graphene nanoribbons as cavities coupled to the waveguide, which is shown in Figure 4C [97]. Due to the unique behavior of the edge mode, the short graphene nanoribbons act like FP cavities. The short nanoribbon close to the waveguide behaves as bright mode, whereas the short nanoribbon farther away acts as dark mode. Such two cavities can generate extreme destructive interference, which gives rise to the PIT response. In addition, the central wavelength can be tuned by the chemical potential of graphene, which avoids to design new structures [102–106]. In short, graphene is a potential candidate in constructing nanocavities for the PIT system due to its ultracompact size and ultrastrong field confinement. Moreover, the dynamic electrical tunability of its Fermi energy level and the dielectric constant also make it suitable for working as a cover layer in tunable PIT systems [107–111]. In the THz region, Kindness et al. put graphene layers on the gap of the SRRs that provide dark mode in PIT system, as shown in Figure 4D [98]. The external direct current (DC) bias can not only shift transparent windows but also change the transmission of the window. Chai et al. experimentally demonstrated such tunable property maintained in the near-IR region [75].

As the intrinsic loss of the PIT system mainly originates from the ohmic dissipation of metals, superconductors are considered to be involved in the PIT system to breakthrough the bottleneck. Wu et al. designed and fabricated planar superconducting NbN THz metamaterials to realize a typical PIT over a temperature range from 8 to 300 K [49]. The resonator unit can be viewed as consisting of a dipole antenna and a two-gap SRRs. Unlike metal PIT, when tuning the ambient temperature, the coupling

and damping of the superconducting state also changed, leading to the formation of transparent window. Cao et al. combined the high-temperature superconductor YBCO closed-ring resonator as the bright mode with metal SRR as the dark mode to realize the PIT in the THz region. The wavelength range extension greatly promotes their applications in the optical and THz communication devices, light storage, and delay lines [112]. Apart from superconductors, in the optical frequency region, the introduction of dielectric materials is also effective for constructing low-loss PIT systems with high Q-factor. Yang et al. realized a silicon PIT structure where the transparent window is located at 1348 nm with a Q-factor of 466 [113]. Combined with the strong field confinement and optical nonlinearity of silicon, they also demonstrated an ultrafast modulation with a pump intensity of $3.2 \text{ GW}/\text{cm}^2$. In the visible region, diamonds and SiC are promising materials for constructing PIT metasurfaces [114, 115]. Compared to silicon, they are transparent in the whole visible region, and the moderate refractive index can make them more easily fabricated into functional metasurfaces while maintaining strong field confinement [116].

Recently, chalcogenides have also widely been explored in plasmonic metamaterial systems, especially for the germanium antimony telluride ($\text{Ge}_2\text{Sb}_2\text{Te}_5$ or GST) with optically induced phase switching properties [117]. Generally, the amorphous-crystalline transitions of the GST thin film with different refractive indexes can be reversible optically induced by pulsed lasers. Therefore, combining this phase-changed medium with plasmonic nanostructures can realize all-optical and nonvolatile modulated PIT structures. Gholipour et al. experimentally demonstrated an all-optical switching based on structured gold films with arrays of asymmetric split-ring slots covered with a subwavelength GST film accompanied with dielectric buffer layers, as indicated in Figure 5A [118]. The pump laser is operated at 660 nm with a relatively low power consumption, and the laser-induced phase transitions in the GST layer can bring about dramatic changes on the device's transmission and reflection characteristics at the IR region, realizing the active ON/OFF switching properties. Moreover, the nonvolatile, all-optical modulation can be expanded to a broad wavelength range within the transparent range of the GST material by modifying the plasmonic metamaterial design. Apart from working as cover layers, the GST material itself can also work as a building block for realizing tunable PIT resonances. Chu et al. theoretically designed a π -shaped PIT structure using GST nanorods, where the transparent window is centered at 1483 nm with a Q-factor of about 30 [120]. With a phase transition from amorphous to crystalline

Figure 5: Other novel materials for constructing PIT structures.

(A) Schematic of a multilayer structures with all-optical and nonvolatile tunability. The SEM image indicates that the structure owns a subwavelength unit cell and the GST is introduced as a phase-changed material. By changing the GST from amorphous to crystalline phase, the transparent window can be tuned with a high contrast ratio [118]. (B) SEM images of an artificial metamaterial nanostructure comprising arrays of subwavelength nanowires made of ITO on silicon. Under the application of an applied electric field, the structure can be reversibly structurally deformed due to electrostriction [119]. (a) Reproduced with permission from Ref. [118]. Copyright 2013 Wiley. (b) Reproduced with permission from Ref. [119]. Copyright 2019 Wiley.

state, both the refractive index and the extinction coefficient of the material can be changed, resulting in a drastically changed transmission and reflection coefficients. Besides, as the PIT effect is originated from the near-field coupling and interference of resonant modes, different compositions of rod-phase states can also result in different coupling states in this three-rod metamolecule, thus indicating different transmission spectra. Therefore, this PIT structure can provide a flexible all-optical modulation in the near-IR region. The phase-changed GST material is also explored for tunable plasmonic metasurfaces in the ultraviolet to the visible region. In this region, the GST materials can work as an optically active material with a transition between a plasmonic material and a dielectric [121]. Therefore, it is an ideal alternative material for

designing reconfigurable metasurfaces with large tunability. Gholipour et al. reported phase change-driven GST metasurfaces operating at the visible region [122]. The structure is composed of subwavelength nanogratings, in which the thin layer is formed by a 70-nm-thick GST film sandwiched by low-loss dielectric ZnS/SiO₂. They experimentally demonstrated that the phase transition can change the sign of the real part of the epsilon for GST material below 660 nm; thus, the spectral response of the metasurface can be greatly changed for both TE and TM modes, indicating that the GST can be explored to design reconfigurable PIT structures in this spectral region.

TCO is also a type of plasmonic semiconductor composed of metal oxides doped with metallic elements, including the widely used ITO, Al:ZnO, Ga:ZnO, and

In: CdO. Owing to the intraband transition of free carriers, these materials can be chosen as cover layers with large third-order optical nonlinearity for all-optical tunable PIT structures [123, 124]. As reviewed in the previous section, the gold nanoparticle-doped ITO thin films can be used as efficient nonlinear cover layers to realize all-optical modulations of the PIT response, which is demonstrated by Zhu et al. and Lu et al., respectively [40, 43]. Apart from third-order nonlinearities, the electric field tunability of TCO thin films is also used for realizing the on-chip PIT modulators. Tao et al. theoretically reported an ITO-filled plasmonic modulator, where the on-chip PIT structure is composed of stub resonators side coupled with bus waveguide [125]. With an applied voltage bias, a thin accumulation layer can be established at the boundary of ITO layer with high carrier concentrations and subsequently modulate the transmission spectrum in this on-chip PIT structures. Moreover, the TCO material itself can also be used as building blocks for realizing Fano and PIT resonances. Karvounis et al. experimentally demonstrated a Fano nanostructure at the telecom wavelength range comprising arrays of subwavelength nanowires, which are made of ITO and silicon [119]. In this structure, the ITO layer is patterned at each end of the nanowires for realizing that neighboring pairs can be electrically isolated from each other and connected to opposing terminals of the device, as indicated in Figure 5B. Under the application of an electric field, the structure is reversibly structurally deformed, owing to the electrostriction effect. Therefore, this structure can provide electro-optic modulations with an effective electro-optic coefficient of order 10^{-6} mV^{-1} . Similar to TCOs, titanium nitride (TiN) is also an alternative plasmonic material to noble metals for constructing plasmonic metamaterials. Specially, the dielectric constants of both TCOs and TiN can be mathematically described by the Drude model, whereas the plasma frequencies are located at the near-IR and visible regions, respectively [126, 127]. Consequently, the nanostructures of these materials can show pronounced localized surface plasmon resonances at the IR region; moreover, compared to the conventional metals, these structures own larger nonlinearities [128]. Therefore, these materials can be considered for PIT structures working at the IR region.

Another novel material used to realize the PIT effect is QD [129]. Recently, significant attention has been paid to the investigation of the hybrid nanostructures combining different types of nanoparticles such as nanowires, semiconductor QDs, and metal nanoparticles (MPs) [130]. A significant amount of this kind of researches has been focused on hybrid QD-MP systems. It is well understood

that, when the plasmon resonances in MPs match the excitonic transitions of QDs, diverse optical effects appear. Hatef et al. theoretically investigated the MP energy absorption rate of a hybrid QD-MP system when the system is embedded in a 3D photonic crystal [131]. They found that the amplitudes of the absorption peaks can be tuned by varying the interparticle distance between the QD and the MP. The quantum optical and the nonlinear optical responses in such active media are noticeably altered from their behavior in free space. This modification manifests as an inhibition or strong alteration of spontaneous emission of the excited states in such systems. These abilities have led to the design of novel photonic devices such as nano-optical switching elements, laser systems with very low thresholds, and quantum buffers.

5 Device applications of PIT effects

PIT, as an intriguing phenomenon in plasmonic realm, provides a new path to high-performance photonic devices. In this section, we focus on the recent progress in the applications of PIT effects in integrated photonic devices mainly in the following four aspects: slow-light devices, optical switching devices, optical signal processing devices, and optical sensors, which are all essential components in the field of integrated optical circuits. Significant device functions and significant performance parameters will be presented clearly.

5.1 Slow-light devices

Slow-light devices have harvested enormous interests in optical society as it can effectively “slow down” the group velocity of the transmitted signals, which is vital in the region of optical storage, optical buffers, and the environment sensors [132]. For realizing the slow-light effect, the device should provide a large group refractive index, which is investigated in different photonic nanostructures [133, 134]. In PIT structures, owing to the destructive interference coupling between the bright and dark modes, the transparent window is accompanied by steep dispersion, providing a large group refractive index and the related slow-light effect [135].

Zhang et al. proposed the well-known π -shaped PIT structures operating at the visible spectrum. They also analyzed that the width of the resonance is controlled by changing the gap distance and subsequently the coupling strength of the two parts of the metamolecule. Eventually,

they theoretically demonstrated that the group refractive index can be optimized to 40 in the suggested structure [22]. By introducing the gain materials for loss compensation, the group index of the PIT slow-light device can be optimized to more than 400 [136]. Subsequently, by optimizing the geometrical dimensions of the PIT metamolecule, the slow-light effect can be enhanced further. Lu et al. experimentally demonstrated a PIT metasurface composed of arrays of metamolecules made of gold nanoprism dimers [42]. In this structure, a group index of more than 4000 is achieved, and the pass time of signal light propagating through this device can be delayed by 500 fs compared to that through the air. The PIT slow-light devices can also be constructed by graphene metasurfaces. Xu et al. proposed a simulated THz slow-light device based on planar monolayer graphene ribbons [137]. In this device, monolayer graphene sheets are designed to be periodically sandwiched in silicon dielectrics. In a unit cell, the graphene presents an asymmetrical crisscross design, which can provide dual transparent windows simultaneously. The numerical calculation of this structure indicates that this system has a group index of about 800, indicating that the 2D materials are also efficient for designing slow-light devices. Apart from the out-of-plane coupling configurations, the in-plane coupling PIT devices can also acquire a large group index at the transparent windows. Chai et al. experimentally demonstrated a slow-light device with a group index of about 4000 [90]. The device is composed of a plasmon-photon hybrid nanocavity, and the transparent window is formed by the interference between the plasmon resonance mode and the dielectric cavity mode. The introduction of dielectrics can greatly improve the slow-light effect of these PIT devices.

From the perspective of practical utilizations, slow-light devices should be polarization insensitive and own active tunability. Yang et al. designed a polarization-independent PIT slow-light device with silver nanoprism periodic tetramers [138]. Owing to the high structural symmetry of the device, the PIT response in this structure is polarization insensitive and the group index can reach up to 225. The all-optical tunability of the slow-light devices can be realized by the introduction of nonlinear materials. Gu et al. incorporated Si islands into the PIT metamolecules, and they are optically excited by IR pump laser. Based on the experimental transmission measurement, they retrieved that the group index can be actively tuned from 91 to 10.5 with a 500 mW photoexcitation at 0.74 THz [55]. In the visible region, the group index tunability of slow-light devices is also studied in a metal-dielectric-metal waveguide PIT system [139]. In this device, a monolayer graphene is chosen as a nonlinear cover layer and

the corresponding group index is controlled from 14.5 to 2.0 with a pump intensity of 4.4 MW cm^{-2} .

Furthermore, a large group index over a narrow bandwidth will result in strong pulse distortions during the light propagating through the designed structures, which conflicts with the wide bandwidth requirements of practical slow-light applications. In PIT slow-light devices, this restriction can be well alleviated, and the bandwidth of operation can be significantly broadened. Papasimakis et al. designed a PIT device based on the continuous fish-scale metallic patterns [140]. The transparent window is centered at 5.5 GHz. They also explored that, by the stacking of metamaterial slabs, the coupling between adjacent layers results in multiple closely spaced trapped-mode resonances with continuously normal dispersion. Therefore, the operation bandwidth of this slow-light device can be significantly enhanced. Song et al. designed a dispersionless PIT slow-light devices, which consist of a long metal strip and an I-section part, operating at optical frequency [141]. This structure supports two magnetic resonance modes and both of them are served as bright modes. Owing to the hybridization of the two bright modes, this device owns a nearly constant group index of 5 over a broad frequency width of 15 THz.

5.2 Optical switching

Optical switching is an essential component of ultrafast optical interconnection and integrated signal computing chips, which are generally cascaded to realize diversiform functions in the optical signal processing region [142]. Basically, optical switching possesses the ON/OFF conversion function of injected light signal by external control parameters [143]. Recently, many researches have revealed the possibility of realizing optical switching using the PIT effect due to its narrowband transparent window.

The operation principle of the PIT optical switching is to tune or deform the transmission spectrum of the PIT device by changing the surrounding refractive index or break the near-field coupling between nanocavities; therefore, the transmission at the wavelength located in the transparent window can be changed drastically. In general, many types of external stimuli are adopted to realize the switching function. Pitchappa et al. introduced the MEMS system into a conventional PIT system composed of two coupled SRR nanocavities [144]. This structure can be actively reconfigured through the mechanical deformation of the dark SRR cantilevers. When the microcantilevers of the dark SRR are released from the silicon

substrate, the optical coupling between the bright and dark resonators is broken. The PIT lineshape transforms into a single dip and the normalized signal transmission decreases from 80% to 30%, which is defined as the OFF state, as illustrated in Figure 6A. In the same year, a similar switching device is also experimentally realized, which is composed of triatomic metamolecules, and the dual

excitation pathways for dark mode can be controlled independently [147]. Li et al. also proposed and experimentally demonstrated another switching configuration based on the mechanical deformation of the coupled nanocavities [148]. In this device, the gap distance of the two silica ring nanocavities can be controlled by an optical force through an optomechanic effect. Thus, the coupling strength, as

Figure 6: Device configurations of optical switching based on PIT effects.

(A) MEM PIT optical switching based on two coupled ring resonators. The transition of the ON/OFF state can be realized through the physical deformation of the nanocavities [144]. (B) All-optical switching containing Kerr nonlinear nanocavities. The Ag-BaO material is filled into one plasmonic nanocavity for conducting all-optical modulations. With an increased incident light intensity, the transmission spectrum can be effectively shifted. The pump intensity is determined at about 670 MW/cm² [145]. (C) An SEM image of an on-chip-triggered all-optical switching consisting of a 2 × 2 matrix of plasmon-photon-hybrid nanocavity PIT system. Four plasmon-photon nanocavities are labeled as A1–A4 as indicated in the SEM image. The response time of each switching unit is measured to be 63 ps according to a pump-probe measurement [146]. (a) Reproduced with permission from Ref. [144]. Copyright 2016 AIP. (b) Reproduced with permission from Ref. [145]. Copyright 2015 Macmillan Publishers. (c) Reproduced with permission from Ref. [146]. Copyright 2016 Wiley.

well as the transmission of the signal at telecom C-band, can be actively changed.

In addition to mechanical force, electric field can also be chosen as external triggers for PIT optical switching. Just in 2018, Wang et al. proposed a PIT switching that worked in the THz region containing liquid crystal as tunable materials to realize the modulation properties [149]. Owing to the electro-optical effect of liquid crystals, the dielectric constant of them can be greatly changed with external DC bias. Under a certain applied voltage, the PIT window disappears due to the destruction of the nanocavities coupling and the modulation depth is calculated to be larger than 90% but with an insertion loss of smaller than 0.5 dB.

From the perspective of practical utilization and integration of optical circuits, the response time of optical switching is a primary parameter as it determines the operating bandwidth of the device. Therefore, the all-optical PIT switching are also widely investigated in which the pump light worked as a trigger of switching. In this type of device, nonlinear materials are needed to cover the PIT structures and the excitation of pump light causes the refractive index change of them, which in turn can shift the transmission spectrum. Therefore, nanocomposite materials are adopted widely in all-optical PIT switching system because of their ultrafast response time [150]. Meanwhile, the needed pump power for nonlinear response can also be lowered owing to the giant near-field enhancement of plasmonic nanocavities [151]. Han et al. numerically investigated an all-optical ultrafast and low-power PIT switching, which contained two ultracompact rectangular nanocavities, aperture-coupled air-slot SPP waveguide with monolayer graphene embedded as a nonlinear medium [152]. They theoretically determined that such device owns an ultrafast response time at the order of 1 ps with a pump intensity of 7.5 MW/cm². A similar device was also proposed in the same year in which two stub nanocavities are introduced to realize PIT phenomenon [153]. Subsequently, He et al. proposed an all-optical switching with Kerr nonlinear nanocavities, which owns multiple operating wavelength [145]. This cavity coupling system contains a SPP slot waveguide side coupled with bright-dark-dark resonators, and one of which nanocavities is filled with nonlinear material Ag-BaO, as shown in Figure 6B. Using the finite-difference time domain method, they determined the multiswitch property of this device under the pump intensity of 670 MW/cm². Based on the dielectric-metal PIT configuration, Chai et al. experimentally demonstrated ultrafast on-chip triggered all-optical switching with ultralow energy consumption, high switching efficiency, and multiple

operating wavelengths simultaneously [146]. The device is schematically illustrated in Figure 6C, which consists of a 2×2 matrix of plasmon-photon-hybrid nanocavity PIT system interconnected by ultralow-loss Si₃N₄ slot optical waveguides and covered by a nonlinear nanocomposite layer. The coexistence of excited-state intermolecular energy transfers and resonant excitation of the adopted nonlinear cover layer ensures that the large nonlinearity and ultrafast response time can be realized in this device simultaneously. Measured with a pump-probe experiment, this switching shows a fast response of 63 ps with a pump intensity of 450 kW/cm².

5.3 All-optical logic devices

Apart from optical switching, the PIT effect is also explored to build other signal processing devices, including diodes, logic gates, and optical adders, which are all essential components in integrated optical circuits.

Chai et al. combined two multicomponent PIT nanocavities, C1 and C2, coupled to a single SPP slot waveguide with a nonlinear cover layer to build a chip-integrated all-optical diode, and the SEM image of the device is shown in Figure 7 [154]. The two cavities show similar PIT responses, whereas the spectral position of the transparent windows are slightly different. The working principle is a 795 nm signal light-induced transmission spectrum shift. For the C1-C2 propagation case, the signal light reaches nanocavity C1 first and results in a remarkable blue shift in the spectral position of the transparent window of C1. As a result, limited by the low transmission of nanocavity C1, the signal light power reduces greatly when reaching nanocavity C2 and results in a much smaller blue shift for the transparent window of nanocavity C2 and the device processes a low transmittance. On the contrary, for the C2-C1 propagation case, the power signal can be maintained when traveling through C2 and induce the transparent window shifted to the operation frequency point in nanocavity C1; finally, the system owns a high total transmission.

Logic gates and optical adders, which can do binary computations in optical nanocircuits, are also realized based on integrated PIT nanocavities combined with nonlinear materials. Yang et al. experimentally realized a logic operation of XOR gate in a plasmonic system with two stub cavities side coupled to a same waveguide [155]. Based on FP resonances, the two coupled stubs process a PIT linear transmission lineshape and the operation wavelength of the device is chosen to be located at the center of the transparent window (i.e. 815 nm). The logic

Figure 7: Schematic and experimental results of the all-optical diode based on PIT nanocavities system combined with nonlinear materials. The device is composed of two cross-shaped plasmonic nanocavities with a slight difference. The operating wavelength is 795 nm and the measured all-optical diode performance is also shown [154]. Reproduced with permission from Ref. [154]. Copyright 2017 De Gruyter.

gate owns two branched input ports, and when only one port is excited, corresponding to the operation “1 XOR 0=1”, the relatively low injected intensity can only shift the spectrum slightly and the high transmittance can be sustained. In contrast, when two ports are both excited, the injected power is doubled and the transmission minimum is shifted to 815 nm, realizing the operation of “1 XOR 1=0”. Also, when introducing X-shaped branched waveguides and multicomponent nanocavities, an all-optical full-adder can also be constructed with three input ports and two output ports [156].

5.4 Ultrasensitive sensors

Compact sensors with high sensitivity are very important in the on-chip signal processing region and for practical applications. Due to the strong field confinement and narrow bandwidth of the transparent window, PIT structures are ideal platform for integrated sensors [157–161]. In these devices, only a small amount of chemical molecules or cells can greatly influence the field distribution of nanoresonators; further, the coupling among nanocavities can also be changed, which finally results in the deformation of the PIT lineshape. Liu et al. theoretically and experimentally demonstrated a 3D plasmonic nanorulers using the PIT effect in which the measured spectra can be used to estimate the geometrical dimension of analyses [162]. Subsequently, an analytical model was also developed for

such PIT nanorulers [163]. Zhang et al. also developed an optical biosensor based on waveguide metallic photonic crystals [164]. In this device, PIT resonance was formed by the interference of the incident light scattered by the particle plasmon and the waveguide mode provided by photonic crystal, leading to an appearance of a narrow dip within the optical extinction spectrum. By observing the dynamic change of this dip, they can resolve p24 antigens at a concentration lower than 20 ng/ml, which promotes the development of the early diagnosis of HIV infection.

6 Conclusions and future outlook

Recent years have witnessed profound achievements in the whole field of PIT photonics, including the working principles, specific structure configurations, diversiform experimental realizations, and practical applications in functional devices. The PIT effect is formed by the destructive interference between two resonant modes, which are supported by nanocavities. By properly designing the structures, the incident electromagnetic energy can be coupled into PIT structures through both out-of-plane and in-plane directions. Two major properties of PIT effects, their sharp transparent windows and large group refractive indexes, have been widely combined with nonlinear materials to enhance light-matter interactions for on-chip light control with high efficiency and

low energy consumption. Beyond the conventional noble metals, some novel materials such as low-loss dielectrics and monolayer graphene are also explored to be introduced into PIT systems for performance promotion. Based on this platform, lots of functional nanophotonic devices have been demonstrated including slow-light devices, optical switching, logical gates, and sensors, which have prominent performances.

There still exist some challenges, and in the next few years, we will still witness development in the on-chip PIT field, which most likely involve novel materials, more flexible tunability, and the practical chip-scale integration. Thus far, the majority of the materials used in PIT systems are conventional noble metals such as gold and silver. Although they have prominent plasmonic properties from visible to IR regions, the large intrinsic losses limit the improvement of device performances greatly. Besides, these materials are usually with relatively small third-order nonlinearities, indicating that large pump light intensity is needed to realize all-optical tunable PIT transparent windows. Therefore, it is necessary to find alternative materials with low loss and large nonlinearities for realizing PIT devices. The TCOs and the TiN, as types of wide bandgap semiconductors with high carrier concentrations, might be proper materials for PIT devices. Specifically, they can behave as low-loss plasmonic materials in the IR region while are also transparent in the visible range. The nonlinear coefficients and the damage threshold of these materials are also orders of magnitude larger than that of metals, indicating that, in PIT structures made of these materials, additional nonlinear materials are not necessary for all-optical tunability. Another type of alternative materials is dielectric. Owing to the natural low-loss properties, PIT devices composed of these materials can easily acquire high Q-factors and large group indexes. Diamond and SiC might be the suitable dielectrics as they have moderate refractive indexes and high transparency in a broad wavelength range. In addition, the high hardness of the two materials is also helpful for fabricating high-quality PIT structures. As the PIT effect is physically originated from the interference of resonant modes, it is naturally sensitive to the nanocavity refractive indexes. Thus, some phase-changed materials such as widely used chalcogenides and vanadium oxide can also be considered as building blocks for PIT devices. Based on the pump excitations, they can provide nonvolatile tunability, which is vital for the applications in optical memory and buffers [165, 166]. The 2D materials also have potentials for designing PIT structures. Although graphene is widely explored in PIT systems, limited works are involved in other types of 2D materials for PIT structures, including transition metal chalcogenides and black phosphorus. As experimental

results have demonstrated that they can support surface plasmons, it is feasible to use them as building blocks for PIT devices [167, 168].

Apart from material exploration, the tunability of switchable PIT structures is also needed to be systematically developed. By introducing nonlinear Kerr materials, the PIT device can provide all-optical modulations with response time at the scale of femtoseconds. Also, the electro-optic modulation can also be considered to introduce into PIT systems. With applied electric fields, the carrier concentrations in some materials such as TCOs can be effectively modulated, which can be used to change the PIT responses. Furthermore, the PIT responses are sensitive to the coupling strength between resonant modes; thus, changing the geometrical parameters of PIT structures is also an effective modulating method. Specifically, it can be achieved by introducing MEMS systems or choosing flexible substrates in PIT structures.

PIT systems are also needed to be explored for chip-scale integrations and practical utilizations. It is the advantage of PIT systems that the transmission spectrum is more diverse with transparent windows and dips at different positions. Therefore, based on PIT structures, a lot of PIT functional operations can be realized, which illustrates that PIT structures are suitable as building blocks to construct all-optical nanocircuits and optical signal processing chips. In contrast, as it is sensitive to both surrounding environment and geometrical parameters simultaneously, a PIT structure with a flexible substrate is also suitable for working as wearable sensors used in life sciences field.

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