Unidirectional Perfect Absorber

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(Invited Paper)

***Abstract*—We show an interplay between Fano resonances and a judicious absorption mechanism leads to a unidirectional perfect absorber, which can be controlled in both direction and frequency. Critical coupling phenomenon created by interference, separates the left- and right-side of the system. At the same time, Fano resonance causes a divergence in the delay time of photons traveling through the loss part of the system, which results in full absorption of the photons from one side. Moreover, we depict that coincidence of the two unidirectional perfect absorber modes from opposite directions results in a perfect absorber mode, which is distinct from the CPA modes. Furthermore, we show that the unidirectional perfect absorber mode is at the same time a spectral singularity and an exceptional point, which makes this point ultrasensitive to any changes in the system. Our results open a direction for designing new type of absorbers, sensors, and switches.**

***Index Terms*—critical coupling, exceptional point, metrology, Parity time symmetry, perfect absorber, spectral singularity, unidirectional perfect absorber.**

I. Introduction

AMONG non-Hermitian systems, parity-time (PT) symmetric systems have recently attracted tremendous attention. This is due to their fascinating feature to generate unidirectional transport such as unidirectional invisibility [1], unidirectional reflectionless [2]–[5] unidirectional lasing [6], [7], nonlinear assisted asymmetric transport [8]–[11], unidirectional excitation [12], asymmetric solitons [13], to name a few. While study of PT symmetric system started in quantum mechanics [14], later the concept of PT symmetry brought to optics [15]–[17], [43], electronics [18], [19] and acoustics [4], [5]. In the realm of optics, a PT symmetric system is defined by index of refraction $n(x)$ that is symmetric in its real part and anti-symmetric in its imaginary part. Although this ensures that there is a balanced amplification and absorption mechanism in the system, it does not guarantee the realness of the spectrum of the system. More specifically, depending on the degree of non-Hermiticity, PT symmetric systems might encounter a phase transition from exact phase with real spectrum to broken phase with complex spectrum. Transition point, also named exceptional point, is a topological singularity where the Hamiltonian of the corresponding system becomes defective and the eigenvalues and their associated eigenstates coalesce. Therefore, there are amplifying or decaying modes in the broken phase and despite the presence of the loss mechanism, by accommodating the amplifying modes in a feedback system one can attain a lasing threshold. Consequently, new lasing schemes such as coherent perfect absorber-laser [2], [20], [21], lasing shutdown via asymmetric gain [22]–[25], single mode lasing [26], [27], and loss induced lasing [28] has been proposed. Recently, we have proposed new types of lasing modes which are distinct from the conventional aforementioned ones [7]. At these modes, only one of the reflection coefficients tends to infinity while the rest of the elements of the scattering matrix remain finite. We call these modes unidirectional lasing modes.

Time reversed counter part of lasers are known as coherent perfect absorbers (CPA) [29] and support purely ingoing fields. More specifically, in a CPA one can achieve complete absorption at a single frequency by illuminating two counter propagating fields to a Fabry–Perot cavity that possess a lossy slab. CPA has a vast application in interferometric procedures in the optical circuits and the technologies related to light harvesting. In last few years the CPA concept has been investigated in many areas spanning from optics to acoustics [29]–[35]. While CPA needs coherent illumination of two beams; in many practical applications it is desirable to have perfect absorption under single beam illumination. In previous absorption study, it has been shown that we can obtain perfect absorption using critical coupling phenomenon [36], [37] under single coherent source illumination.

In this paper, we show that there is a time-reversed counterpart for a unidirectional laser, which we call it unidirectional perfect absorber (UPA). In a UPA at a specific frequency, reflection, and transmission to one side tend to zero [38]. Thus, we can conclude that in a reciprocal UPA only one element of the scattering matrix, or in other words one reflection, is not zero. This implies that a UPA mode is at the same time a spectral singularity and an exceptional point. To obtain a UPA mode we couple a discrete element to a PT symmetric continuum. This generates a Fano resonance, which leads to photon trapping in the loss element. As a result, there exists reflection only from the passive site (with

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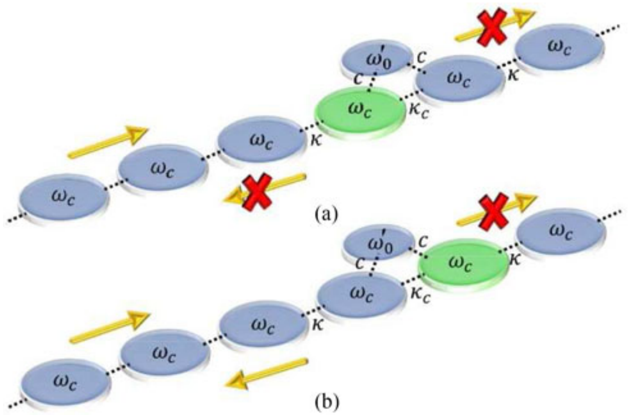

Fig. 1. Main panel: Schematic of the PT symmetric Fano coupled disk resonators defined in Eq. (5). The PT dimer composed of a passive (purple) disk with no gain or loss and a lossy (green) disk. This dimer is coupled to the passive micro-disk with resonance frequency ω_0'. This triangle is embedded in a chain of passive disk resonators. (a) At the critical value of the loss $\gamma^\star$ given in Eq. (13), transmission and reflection from loss side tends to zero resulting in UPA mode while (b) there is a perfect reflection from the opposite side.

no net gain or loss) while transmission and reflection from the opposite side become zero. Using similar structure, but with no loss, we show that the zero transmission is a result of the critical coupling phenomenon. An abrupt phase shift occurs at the zero transmission wavevector. Furthermore, we construct a perfect absorber mode by combining two UPA singularities. In a perfect absorber, the structure fully absorbs the incoming fields. Our proposal provides freedom to have a controllable perfect absorber for the left and/or right illumination with independent frequencies.

In order to demonstrate the UPA modes, let us consider a one-dimensional (1-D) chain of evanescently coupled microcavities with resonance frequencies ω_c. Without loss of generality, we set all the couplings in the chain to one. In the middle of the chain, we embed a PT symmetric defect, which is coupled to the chain with a coupling strength κ to the chain. The PT defect is composed of two coupled microcavities with resonance frequencies ω_c. One of them possess loss. The other one is a passive microcavity with no net gain or loss. It has been shown that by a transformation this passive-loss dimer can be mapped to a PT symmetric dimer [39]. The inter dimer coupling strength between the passive and loss microcavities is denoted as κ_c. The cavity chain including the PT dimer corresponds to a continuum with a spectrum given by

$$\omega = \omega_c - 2\cos(q), \quad -\pi < q < \pi \tag{1}$$

where q is the wavevector.

Fano resonances are generated in multi-path scattering events due to an interaction between a discrete state coupled to the continuum. Therefore, we couple a passive cavity with resonance frequency $\omega_0' = \omega_0 + \omega_c$ to the PT dimer. Coupling strength between each microcavities in the PT dimer and discrete state is given by c. This construction gives different choices to the photons to propagate through the scattering region. For instance, an obvious choice for the photons is a direct path through the PT dimer while another option is an indirect path through the passive cavity. An interference between the photons taking different paths leads to a delay in *time flight* of the photons and a mechanism to trap them. A delicate design of the interference process results in a tremendous delay for traveling photons and consequently causes annihilation of photons residing in the loss part of the dimer.

Transfer matrix M relates amplitude of the forward $F_{L,R}$ and backward $B_{L,R}$ propagating waves on the left (L) and right (R) side of the scattering region

$$\begin{pmatrix} F_R \\ B_R \end{pmatrix} = M \begin{pmatrix} F_L \\ B_L \end{pmatrix} \tag{2}$$

where

$$M = \begin{pmatrix} M_{11} & M_{12} \\ M_{21} & M_{22} \end{pmatrix}. \tag{3}$$

Equivalently, we can describe the same scattering problem using the scattering matrix S. Scattering matrix relates the ingoing and outgoing fields. Elements of the scattering matrix are the transmission and reflection amplitudes.

In a reciprocal system, elements of the transfer matrix are related to the elements of the scattering matrix through the following relations:

$$t_L = t_R \equiv t = \frac{1}{M_{22}} \quad r_L = -\frac{M_{21}}{M_{22}} \quad r_R = \frac{M_{12}}{M_{22}}. \tag{4}$$

We can use the aforementioned scattering formalism to describe the dynamics of our PT Fano setup. More specifically, let us assume an elastic scattering process, namely $\phi_n = \psi_n e^{-i\omega t}$ for the total field amplitude at disk n. In this case the stationary modal amplitudes of the system has the asymptotic behavior $\psi_n = F_L e^{\mathrm{i}q(n+1)} + B_L e^{-\mathrm{i}q(n+1)}$ for $n \leq -1$, and $\psi_n = F_R e^{\mathrm{i}q(n-1)} + B_R e^{-\mathrm{i}q(n-1)}$ for $n \geq 1$, respectively.

Moreover, the dynamics of the total field amplitudes ϕ for each cavity can be expressed using the coupled mode theory[1] [40], [41] with the following equations:

$$\begin{aligned}
\frac{id\phi_1}{dt} &= -\phi_2 - \kappa\phi_p + \omega_c\phi_1 \\
\frac{id\phi_{-1}}{dt} &= -\phi_{-2} - \kappa\phi_l + \omega_c\phi_{-1} \\
\frac{id\phi_n}{dt} &= -\phi_{n-1} - \phi_{n+1} + \omega_c\phi_n; \quad (|n| > 2) \\
\frac{id\phi_0}{dt} &= -c(\phi_p + \phi_l) + (\omega_0 + \omega_c)\phi_0 \\
\frac{id\phi_l}{dt} &= -\kappa\phi_{-1} - \kappa_c\phi_p - c\phi_0 - i\gamma\phi_l + \omega_c\phi_l \\
\frac{id\phi_p}{dt} &= -\kappa\phi_1 - \kappa_c\phi_l - c\phi_0 + \omega_c\phi_p.
\end{aligned} \tag{5}$$

Above, we denoted the field amplitude, composed of clockwise and counterclockwise modes, at the microcavities in the PT dimer by $\phi_{l,p}$ where l, p stand for the loss and passive disks,

[1]One can write the same set of equations for the subtraction of the clockwise and counterclockwise modes where all the couplings change their sign and the dispersion relation becomes .We carried on the same analysis and obtain the same results.

respectively. Total field amplitude at the disk n and passive discrete cavity are given by ϕ_n, ϕ_0, respectively. The coupling terms κ, $\kappa_c$and c are normalized with respect to the coupling strength in the chain.

A reciprocal unidirectional laser cavity emits field only to one side without any injection [7]. In a 1-D system, this is equivalent to

$$\begin{array}{l} F_L = B_R = F_R = 0, \quad B_L \neq 0 \\ \text{or} \\ F_L = B_R = B_L = 0, \quad F_R \neq 0 \end{array} \tag{6}$$

where the first one is associated with a left lasing condition and second one is a right lasing condition. According to Eqs. (4) and (6), we should have $M_{21(12)}\left(q^{\star}\right) \to \infty$ and $M_{22}\left(q^{\star}\right) \neq 0$. In this case, the left (right) reflection coefficient diverges to infinity for a real wavevector $q^{\star} \in \Re$. Notice that $M_{22}\left(q^{\star}\right) \neq 0$ makes sure that the transmission remains finite.

In a UPA we are looking for the time reversed counterpart of the unidirectional laser with boundary conditions

$$\begin{array}{l} B_L = F_R = 0, \quad F_L \neq 0 \\ \text{or} \\ F_R = B_L = 0, \quad B_R \neq 0 \end{array} \tag{7}$$

which can be obtain if we have

$$M_{22} \to \infty, \;\; M_{21(12)} \to 0, M_{12(21)} \neq 0. \tag{8}$$

The elements of the transfer matrix M associated with the system described by Eq. (5) can be expressed as

$$M_{22} = \frac{Y}{2i\Gamma\kappa^2 \sin q} \quad M_{21(12)} = \frac{(-)\, X_{L(R)}}{2i\Gamma\kappa^2 \sin q} \tag{9}$$

where

$$\begin{aligned} \Gamma \equiv&\ \kappa_c - c^2\left(2\cos\left(q\right) - \omega_0\right)^{-1} \\ Y =&\ e^{-2\mathrm{i}q}[\Gamma^2 - (\alpha + \xi_p)(\alpha + \xi_l)] \\ X_{L(R)} =&\ \Gamma^2 - (\alpha^* + \xi_{l(p)})(\alpha + \xi_{p(l)}) \end{aligned} \tag{10}$$

with $\xi_p \equiv -2\cos q + \frac{c^2}{2\cos q + \omega_0}$, $\xi_l \equiv \xi_p + i\gamma$, and $\alpha \equiv \kappa^2 e^{\mathrm{i}q}$.

In order to satisfy the UPA conditions given by Eq. (8) from Eq. (10) we have

$$\Gamma \to 0 X_{L(R)} \to 0 \quad X_{R(L)} \neq 0. \tag{11}$$

To satisfy the first condition in Eq. (11), obviously, we need to have $\kappa_c^{\star} = -c^2/(2\cos q^{\star} + \omega_0)$. In addition, this relation together with the condition $X_L \to 0$ (assuming left UPA), lead to the critical value of loss, namely

$$\gamma^{\star} = \kappa^2 \sin q^{\star}. \tag{12}$$

The critical value of loss simplifies the critical coupling $\kappa_c^{\star}$

$$\kappa_c^{\star} = \left(\kappa^2 - 2\right)\cos q^{\star}. \tag{13}$$

Moreover, the critical coupling $\kappa_c^{\star}$ yields the critical resonance frequency of the passive discrete state

$$\omega_0'^{\star} = \omega_c - 2\cos - c^2/\kappa_c^{\star}. \tag{14}$$

One can show that in the first order approximation in $\delta q = q - q^{\star}$ and $\delta\gamma = \gamma - \gamma^{\star}$ and for the above critical values we have

$$\begin{aligned} Y \cong&\ 2\kappa^4 e^{-2\mathrm{i}q^{\star}} \sin^2 q^{\star} \\ X_R \cong&\ -2\kappa^4 \sin^2 q^{\star} \\ X_L \cong&\ 0. \end{aligned} \tag{15}$$

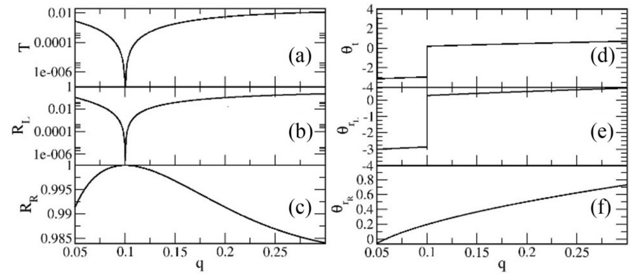

Fig. 2. (a) Transmission, (b) reflection from the left side, and (c) reflection coefficient from the right side for $\kappa = 1.45$, $c = 0.1$, and $\gamma^{\star} \simeq 0.21$ versus wavevector q. Right panel shows the corresponding phases of (d) the transmission, (e) the left reflection, and (f) the right reflection amplitudes versus the wavevector q. The abrupt phase change in (d), (e) at the UPA, $q = 0.1$, results in the resonance trapping and large delay time for the photons being reflected from the structure. This resonance trapping annihilates the reflection of the system from the left (loss side).

It is clear from the Eqs. (15), (9) and Eq. (4) that

$$\begin{aligned} t =&\ \frac{2i\Gamma k^2 \sin q^{\star}}{Y} = 0 \\ r_L =&\ \frac{X_L}{Y} = 0 \\ r_R =&\ \frac{-X_R}{Y} = e^{2\mathrm{i}q^{\star}}. \end{aligned} \tag{16}$$

Fig. 2(a)–(c) depicts transmission and reflections of our setup versus wavevector. We observe that at $q = 0.1$ transmission and reflection from the loss side are zero while the reflection from the right side is perfect. Thus, one can conclude that at the UPA wavevector the setup is a perfect mirror from one side and a perfect absorber from the opposite side.

The perfect reflective behavior of the system is due to the critical coupling phenomenon, $\Gamma \to 0$. For such an arrangement, because of interferences, left and right side of the system become decouple from each other. Notice that for $\gamma = 0$, due to the symmetry $X_R = X_L$. In this case, $Y, X_{L,R}$ functions to the first order approximation in δq are given by

$$\begin{aligned} Y \cong&\ \kappa^4 e^{-2\mathrm{i}q^{\star}} \sin^2 q^{\star} \\ X_L =&\ X_R \cong -\kappa^4 \sin^2 q^{\star}. \end{aligned} \tag{17}$$

Therefore, for the passive system with no loss we expect to have perfect reflection from both sides of the system. In Fig. 3, we have plotted a schematic (main panel) and the generic response (3(a), (b)) of the passive structure.

Considering the above discussions, we expect to have perfect absorber for a dimer consisting of two lossy microresonators (double loss dimer depicted in the main panel of Fig. 4). Construction of the perfect absorber is due to the coexistence of the two independent spectral singularities associated with two separate UPA modes. In this case, light gets absorbed from both

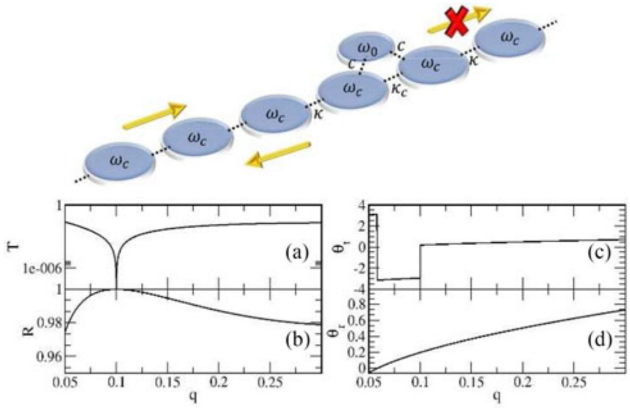

Fig. 3. Schematic of the passive Fano coupled disk resonators in Eq.(5) with $\gamma = 0$. (a) At the critical couplings and resonances, left and right of the system decouple from each other (critical coupling) and transmission tends to zero resulting (b) a perfect reflection from the both sides at $q = 0.1$. (c), (d) Phase of the transmission and reflection amplitudes. The abrupt π phase shift at $q = 0.1$ in the transmission amplitude is responsible for critical coupling phenomenon.

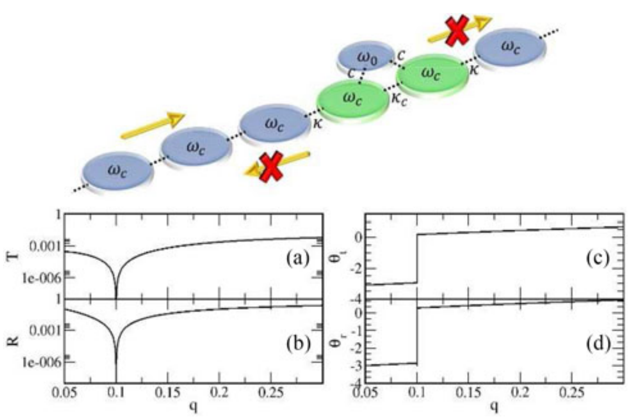

Fig. 4. Schematic of the double loss Fano coupled disk resonators with coincidence of two UPA modes from left and right generating a perfect absorber. (a) Transmission and (b) reflections from the both sides tends to zero at $q = 0.1$. (c), (d) Phase of the transmission and reflection amplitudes. The abrupt π phase shift is responsible for the perfect absorption.

left and right. This is distinct from the coherent perfect absorber, where one needs to design the phase and amplitude of the incoming fields in order to observe the complete absorption. However, while in our setup there is no need to design the incoming fields, one needs to set couplings and resonance frequency of the passive discrete state. Notice that by setting the coupling κ on the left and right side to different values, and consequently γ, we can have perfect absorption at two different frequencies for the left and right. This gives the possibility to design the UPA for different directions independently.

As we mentioned earlier, to have a perfect absorber one needs to have a divergence in the delay time τ of the photons in the lossy microcavity. Delay time of the transmitted and reflected photons is proportional to the derivative of the phase of the transmission or reflection amplitude versus the wavevector, namely

$$\tau \sim \frac{d\theta_{t,r}}{dq}. \tag{18}$$

We plotted the phase of the reflected and transmitted signals for the PT symmetric case in the right panel of the Fig. 2. At the UPA wavevector, $q = 0.1$, the phase of the transmission and left reflections, θ_t, θ_{r_L}, undergoes an abrupt π phase shift. This implies the existence of the divergence of their derivative with respect to the wavevector resulting in the diverging delay time of the reflected or transmitted photons. The huge delay time increases the interaction of the photons with the loss element, causes UPA behavior.

It is beneficial to consider the phases for the passive and double loss structure. In the passive case, as depicted in Fig. 3(c) and (d), only transmission phase θ_t undergoes an abrupt π-phase shift due to the critical coupling phenomenon while phases of the reflections are smooth functions. In the double loss case, as depicted in the Fig. 4(c) and (d), all the phases experience the π-phase shift and due to the loss elements we have a perfect absorber with zero transmission and reflection to both sides.

It is interesting that the UPA is a spectral singularity and an exceptional point, simultaneously. At the exceptional point eigenvalues of the corresponding scattering matrix

$$S = \begin{pmatrix} t & r_R \\ r_L & t \end{pmatrix} \tag{19}$$

given by

$$s_{\pm} = t \pm \sqrt{r_L r_R} \tag{20}$$

become degenerate and the eigenvectors,

$$|s\rangle = \begin{pmatrix} 1 \\ \pm\sqrt{\dfrac{r_L}{r_R}} \end{pmatrix} \tag{21}$$

coalesce. However, existence of exceptional point induced unidirectional reflectionless mode (see for example Ref. [3]) does not imply necessarily zero transmission. This is in contrast to our UPA mode, which makes it a distinct feature of our proposal.

An interesting feature of the UPA as a spectral singularity is the sensitivity of the mode to the changes in the environment, which potentially can be used in metrology [42], and sensing. In Fig. 5, we present the changes in the reflection from the loss side of the PT system depicted in Fig. 1. We change (see Fig. 5(a)) the loss, $\Delta = \gamma - \gamma^\star$, (see Fig. 5(b)) resonance frequency of the discrete state $\Delta = \omega_0' - \omega_0'^\star$, and (see Fig. 5(c)) the coupling $\Delta = c - c^\star$.[2] We observe that a small change in any of the critical parameters of the system in the scattering domain causes a noticeable change in the intensity of the reflected field. The sensitivity of the system is pronounced for the wavevectors near to zero or π. This is expected as, to the first order, in all the above three cases the reflection from the loss side is proportional to $\csc(q)$.

In conclusion, we discussed a unique way to generate a controllable unidirectional perfect absorber mode; a time reversed counterpart of a unidirectional laser. At the UPA mode, transmission and one side reflection tend to zero. We showed that

[2]The parameter Δ has the same units in all the three cases. This makes the changes in the reflection to be in the same magnitude.

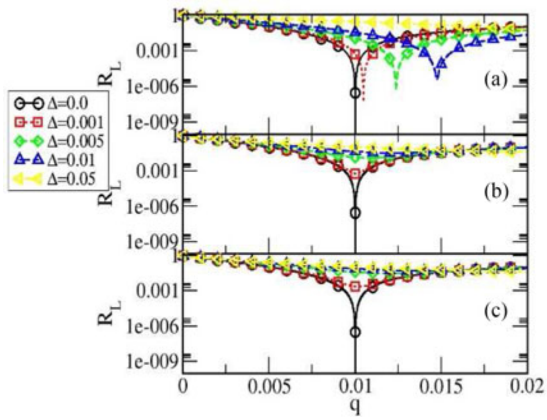

Fig. 5. Sensitivity of the amplitude of the reflection from the loss side at the UPA mode. (a) Deviation in the loss parameter $\Delta = \gamma - \gamma^{*}$, (b) deviation in the resonance of the discrete element $\Delta = \omega_0' - \omega_0'^{*}$, and (c) deviation the coupling between the PT dimer and the discrete element $\Delta = c - c^{\star}$. We used $q^{\star} = 0.1,\ c = 0.1,\ \kappa = 1.45$.

the critical coupling phenomenon guarantees the zero transmission while the zero reflection is due to the divergence of the time flight of the photon trapped in the loss element by the Fano resonance. Furthermore, we discussed how to implement a perfect absorber mode by combining two UPA modes. The perfect absorber mode is distinct from the CPA mode as there is no need to design the incoming field. Moreover, the left and right UPA modes are independent of each other, which provides the opportunity to have UPA modes at the left and right side of the system independently. Finally, we discussed that the UPA mode is simultaneously a spectral singularity and an exceptional point of the system. This feature makes the mode ultra-sensitive to the changes in the environment. This sensitivity might have application in sensing and metrology. Of great interest will be the extension the notion of UPA to two and three dimensions and incorporating the UPA in such lattices.

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