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**Deterministic relation between thermal-phonon dressings and non-Hermitian multi-Fano interferences router in ion-doped microcrystals**

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We report the multi-Fano interference obtained through the simultaneous acquisition of bright and dark states in different phase transitions of Eu3+: BiPO4 (7:1, 6:1, 1:1, and 0.5:1) and Eu3+:

NaYF4 (1:1/4) crystals. We employ multi-dressed spontaneous four-wave mixing and multi- dressed fluorescence (multi-order) to optimize the strong photon-phonon nested dressing

effect resulting in more obvious multi-Fano interference. Firstly, the multi-Fano is produced through interference in continuous and multi- bound states. Secondly, five multi-Fano dips originate from nested five dressings (one photon and four phonons) under symmetrical splitting of 7F1 energy level. We depict that the pure H-phase (0.5:1) sample exhibits the strongest photon- phonon dressed effect (five Fano dips). Further, we investigate high-order non-Hermitian exceptional points in multi-Fano interference by adjusting the ratio of Rabi-frequency to de-phase rate through nested photon and phonon dressing. Our experimental results are validated by theoretical simulations, which may be applied to designing optoelectronic devices such as non- Hermitian multi-Fano interferences (multi- channel) router.

**Keywords**: Multi-Fano interferences, Thermal- phonon dressings, Non-Hermitian, Router

# INTRODUCTION

In recent times, there has been a notable surge in research efforts on Fano resonance, primarily driven by its extensive range of material applications within the realms of physical, chemical, and biological sciences. 1–7. There is significant potential for the application of structures with Fano resonance that we can expect in the field of hybrid photonics and nano- photonics related to the coupling of light with various particles and quasi-particles such as phonons, electrons, spins, excitons, and mechanical degrees of freedom8. In Fano interference, interference of a discrete quantum state with a continuum of states sharing the same energy leads to the appearance of asymmetric line shapes in the measured excitation spectra, which can be characterized by

a Fano ‘shape’ parameter, which was first observed in experiments exciting rare gas atoms to Rydberg states9,10. Fano lineshapes serve as essential spectroscopic indicators that provide quantitatively insights into the structural and dynamic properties of physical objects, spanning from nuclei to three-dimensional solids and liquids.

In recent studies, there has been a special emphasis on exploring higher-order Exceptional points (EP)11-13 and Parity Time (PT) symmetric systems that involve alternating Gain and Loss 14-

18. These systems have shown potential for effectively controlling non-Hermitian multi-Fano interference. The applications of Fano resonance encompass various domains, including the utilization of linear and nonlinear dielectric nano resonators, 2D materials19-21, slow light optomechanical nanocavities22, Dirac

semiconductors with ultrafast dynamics of phase and topology23, Fano-lasers and spacers24,25, Fano devices26,27. Being so sensitive to changes in geometry and surroundings, Fano-based devices provide major implementation hurdles despite being an essential component of effective sensors.

In a bid to address this challenge, there has been significant recognition of the merits of exploiting rare-earth ion-doped crystals for the advancement of integrated quantum circuits. The lifetime, coherence time, and spectral resolution of doped crystals such as Eu3+: YPO4, Pr3+: Y2SiO5, and Eu3+: BiPO4 can be precisely controlled through the nonlinear process28,29. But, among them Eu3+: BiPO4 is the best candidate due to the longest coherence among other doped crystals owing to photon-phonon dressing30-33. The functional crystal of BiPO4 has three different crystal structures, namely, hexagonal phase (HP, space group: Po3121), low- temperature monoclinic phase (LTMP, space group: P21/n), and high-temperature monoclinic phase (HTMP, space group: P21/m)34,35. The phase transition of BiPO4 from LTMP or HTMP to HP occurs by continuously doping Ln3+ ions. Our research investigates the effective manipulation of the phase transition, which results in the identification of the novel phenomena of multi- Fano resonances controlled through photon- phonon interaction and multi-dressing effect. However, all of the spectral Fano interferences that have been previously reported involved a single Fano interference arising from the interaction between one continuous state and one bound state, solely caused by external photon dressing.

In this paper, we report the complex

relationship between novel multi-Fano interference and phase transitions of ion-doped microcrystals (Eu3+: BiPO4/Eu3+: NaYF4). Our results show that each BiPO4 fine structure energy level exhibits distinct lattice vibrations, which result in different phonon frequencies. As

a consequence, the number of dressing levels varies, leading to the observation of multi-Fano interferences. The evolution of five Fano interferences from a single Fano interference was observed by precisely controlling the interaction between a continuous state and multi-bound states using laser power, temperature, and gate position (GP). In our experiment, single laser excitation results in a single Fano dip caused by the self-dressing effect, whereas multi-dressing is generated from photon-phonon multi-Fano interference. We realize the non-Hermitian controlled higher- order exceptional points (EPs), which can be defined by real and imaginary quantization alignment. We apply our outcomes to suggests a non-Hermitian multi-channel router and show that broadband peak input fluorescence (FL) to multi-Fano output can be achieved. This study explores extensively into the correlation between thermal-phonon dressings and multi- Fano interference in ion-doped microcrystals, with potential applications in the development of optoelectronic devices.

# EXPERIMENTAL SETUP

In our experiment the molar ratio (PO43-: [Bi3+ + Eu3+]) of doped ions is adjusted with different concentrations of Hexagonal- (H) and monoclinic (M) phase to obtain different phase transitions of BiPO4 nanocrystals (7:1, 6:1, 1:1, 0.5:1) as shown in Fig. S1(a-f) (See Supply Information for detailed physical images of the samples). The (7:1, 6:1, 1:1) BiPO4 crystals with C1 point group site-symmetry has a proportion of M-phase whereas the concentration of H-phase is high in (0.5:1) BiPO4 sample (C2 symmetry) resulting in more lattice vibrating phonon36,37. The Eu3+: NaYF4 (YF43-: [Na3+ + Eu3+] =1:1/4) has

pure H-phase with Cs symmetry. The transition between H-phase to M-phase has been achieved by increasing the phosphate ion (PO43−) concentration in the Eu3+: BiPO4 system while

different crystal phases are synthesized by adjusting the pH values38-42.

In our experiment, samples were held in a cryostat (CFM-102) with temperatures varying from 300K (strong phonon dressing) to 77K (weak phonon dressing) by flowing liquid nitrogen. Figures 1a1 and 1a2 show crystal field (CF) splitting levels of Eu3+: BPO4 and Eu3+: NaYF4, respectively. Figure 1a3 shows photon-assisted crystal field splitting in Eu3+: BPO4/NaYF4. The 7F1 fine structure (J = 1) splits into three levels 7F1, MJ=-

1 (587.3nm), 7F1, MJ=0 (592.3nm), and 7F1, MJ=+1

(597.3nm) under the dressing and crystal field effect of BiPO4. Figure 1b illustrates the sub- energy levels that corresponds to Figure 1a3. Two dye lasers (narrow scan with a 0.04 cm−1 linewidth and broad scan with a 0.08 cm−1 linewidth, R610 dye) pumped by an injection- locked single-mode Nd: YAG laser (Continuum Powerlite DLS 9010, 10Hz repetition rate, 5ns pulse width) were used to generate the two

spectral optical outputs are obtained by scanning laser frequency, while the time-resolved OS obtains temporal optical outputs by fixing DL frequency. The grating motor of DL1 and DL2 is scanned by computer to form the x-axis (wavelength), and the intensity of the excitation spectrum is the average of ten shots from the gated integrator appearing on the y-axis. The optical signal generated is detected at photomultiplier tubes (PMT) via confocal lenses (CL) in Fig. S1(g) (See Supply Information for detailed experimental setup). While PMT2 is positioned close to the sample to detect hybrid signal (FL + ***E*S/AS**) with dominant FL emission, PMT1 (near detector position) and PMT3 (far detector position) are precisely positioned to detect the generated in-phase spontaneous four-wave mixing (SFWM) (Fig. 1b). By adjusting the gate position, one can obtain output signals from different energy levels with different lifetimes. The ratio of FL to

pumping fields

***E***1 ( 1 ) and

***E***2 ( 2 ). By

***E*S/AS** in a hybrid signal is controlled by gate

exciting Eu3+: BiPO4 crystal with ***E*1** and ***E*** (reflection of ***E*1**) (Fig. 1d), the output Stokes (***E*S**)/anti-Stokes (***E*AS**) signals are generated

1

under phase-matched condition ( ***k***1***+k***1***= k***S***+k***AS ) due to interaction with Eu3+: BiPO4 energy levels. The out-of-phase FL1 and FL2 are generated through ***E*1** (broadband laser) and ***E*2** (narrowband laser), respectively. The pulse generated from Nd3+: YAG laser is used to simultaneously trigger a boxcar gated integrator (G) and oscilloscope (OS). The input

laser beams are along the [010] axis of the crystal, which is perpendicular to the optical axis. The

position. Due to the distinct decay rates exhibited by the FL and SFWM, they can be easily differentiated at the PMT by employing a boxcar gate position. Furthermore, Fano resonance strongly depends upon point group site symmetry of different phases of Eu3+: BiPO4. Figure 1c shows the proposed model of a non- Hermitian multi-channel optical router. Figure 1d shows the dressing-like-Zeeman splitting of 7F1 energy level. For the 7F1 energy level by dressing field quantized rotation, we can get splitting energy levels 7F1, MJ=-1, 7F1, MJ= 0, and 7F1, MJ=+1.

|  |  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- | --- |
| **Eu3+: BiPO4**  5D0 **(a1)**  ***Ei***  7F1,MJ=0  7F1,MJ=**±**1  **|3>** | **Eu3+: NaYF4**  5D0 **(a2)**  ***Ei***  7F1,MJ=0  7F1,MJ=+1  7F1,MJ=-1 | | **Eu3+: BiPO4/ NaYF4**  **(a3)**  5D0 **|2>**  ***Ei***  7F1,MJ=+1 **|0>**  7F1,MJ=0  7F1,MJ=-1 **— — |1>** | | **(b)** + ++    **—**  + **—**    +  **—**    + **—** +  **—** | | |  |
| **(c)** |  | **Output** | | **MJ Z** | | **(d)** |  |  |
| **Input** |  | **y1** | | **1** | |  | **MJ=+1** |  |
|  | **multi- channel** | **y3** | | **0** | |  | **MJ=0** |  |
| x | **Router** | **y5** | | **-1** | |  | **MJ=-1** |  |

**Fig. 1 a1** and **a2** Crystal field splitting of 7F1 energy level for Eu3+: BiPO4 and Eu3+: NaYF4, respectively. **a3** Photon assistance crystal filed splitting in Eu3+: BiPO4/NaYF4. **b** Enlarged view of 7F1 energy levels corresponding to **a**. **c** Model of a non-Hermitian multi- channel router. **d** Dressing like-Zeeman splitting (7F1, MJ=-1, 7F1, MJ= 0 and 7F1, MJ=+1) in Eu3+: BiPO4.

# THEORETICAL MODEL

Our proposed model shows that more phonons can couple more energy levels as shown in Fig. 1a3. The excitation from single- and two-lasers shows single Fano dip (self-dressing) and multi-Fano dips (external dressing**),** respectively. It is worth mentioning that multi- dressing can only be generated from photon- phonon multi-Fano interference, not through

Therefore, more phonon results in effective

dressing36. Our findings reveal the five sharp dips which can only be explained by the combined effect of photon dressing and phonon.

# The non-Hermitian multi-Fano of one laser

By opening field ***E*1**, the dressed third-order density matrix element for ***E*S** ( ρ(3) ) and ***E*AS** ( ρ(3) ) via perturbation chains

*S AS*

one or two lasers’ excitations. For Eu3+: BiPO4

(0) *E*1 (1) *EAS* (2) *E*1 (3)

00 20 00 20(*S* )

ρ ρ ρ ρ

and

sample, unique lattice vibrations can produce phonons with different frequencies which are coupled to different crystal field splitting levels 5D1 →7F1, 5D0 →7F1 and 5D0 →7F3 in the ion Eu3+.

(0) *E*1 (1) *ES* (2) *E*1 (3)

ρ ρ ρ ρ

00 20 00 20( *AS* )

written as

, respectively can be

ρ(3)

 *iG*1 *GASG*1 =ρ(3) +ρ(5) +ρ(7) , (1)

*S* (2)

(  *i* )(  *i*  *i*

+*d* )(    *i*  *i* )

*S* (2)

*S* (2)

*S* (2)

20 1 00 1

*AS* 1 20 1

*AS* 1

ρ(3)

 *iG*1 *GSG*1 =ρ(3)

+ρ(5)

+ρ(7)

, (2)

*AS* (2)

(  *i*)( +*i*  *i* +*d* )( +*i*  *i* +*i* ))

*AS* (2)

*AS*(2)

*AS*(2)

20 1 00 1 *S* 2 20 1 *S* 1

Where

*d* | *G* |2 /(  *i*  *i*  *d* ) , *d* | *G*

|2 /(  *i*  *i*  *i* ) ,

1 1 20 1

*AS* 3 3

*p*1 10 1

*AS p*1

*d* | *G* |2 /(  *i*  *i*  *d* ) , *d*

| *G*

|2 /(  *i*  *i*  *i* ) ,

2 1 20 1

*S* 4 4

*p*1 10 1

*S p*1

(3)

| ρ

*S* / *AS*

| ( *A*2  *B*2  *C* 2  2 *AB* cos(φ ) 

. The linewidth

*i*/ *j*  *pop*  *ion**spin*  *ion**ion*  *phonon*  *dres* sin *g*

, where

2 *AC* cos(φ )  2*BC* cos(φ ))1/2  is related to the sample temperature and

1

2 3

*phonon*

of the *E*S/AS signal is

*S*/ *AS*  20  00  20 . The

*dres* sin *g*

is associated with dressing. Here, two

transverse de-phase rate

*ij*  (*i*   *j* ) / 2 ,

Fano interferences are controlled by three phases ( φ1  π , φ2  π , φ3  0 ). The above

equations show nested double dressing suggesting two-Fano interference originates

excitation arises from the interaction of the doped ion with a source of phonons (crystal

from one continuous state ρ(3)

*S* / *AS*

and two bound

lattice vibration), which are vibrations in the

states (photon1 ρ(5)

*S* / *AS*

photon1-phonon1 ρ(7) ).

crystal lattice. The phonon Rabi frequency is

*Gi*  μ*H H* /

*S* / *AS*

is the photon Rabi frequency,

described as the phonon Rabi frequency

where . *H* is the magnetic field for Rabi

*Gpi*  μ*kl Epi* /

, μ*kl*

which is the dipole moment

frequency, μ*H*

is the magnetic dipole matrix

between *k* and *l* of crystal field energy levels

elements levels *m* and *n* and *m* and *n*

in 7F1.

ω *pi* is the phonon frequency of phonon

are the crystal field splitting energy levels of 5D0

field *Epi* , which is determined by the vibration

and 7F1, respectively.

*mn* is the transverse decay

frequency of crystal lattice state mode. The

*kl*

rate between levels *m* and *n* . The frequency is the transverse decay rate between *k* and

detuning

*i*  *mn* ω*i*

, where

*kl*

is the

*l * . *Gi*  μ*kl Ei* /

is the frequency detuning,

corresponding atomic transition frequency

where

*kl* is the resonant frequency between

between levels *m* and *n* . of the laser field ***Ei*** .

ω*i* is the frequency

*k * and *l * . ω*i* is the frequency of photon field *Ei*

, which is determined by the vibration frequency

Photon excitation results from the interaction of laser light with the host material (Eu3+: BiPO4). On the other hand, phonon

of crystal lattice state mode. For the three dark states of nested three dressing, the expression (figure 5e) can be written as

ρ(3)

 *iG*1 *GASG*1  ρ(3)  ρ(5)  ρ(7) +ρ(9) , (3)

*S* (3)

(  *i* + *d* )(  *i*  *i* )(  *i*  *i*  *i*

)))

*S* (3)

*S* (3)

*S* (3)

*S* (3)

20 1 00 00 1 *AS* 20 1 1 *AS*

ρ(3)

 *iG*1 *GSG*1 =ρ(3)

+ρ(5)

+ρ(7)

+ρ(9)

, (4)

*AS* (3)

(  *i* +*d* )( +*i*  *i* )( +*i*+*i*  *i* )

*AS* (3)

*AS* (3)

*AS* (3)

*AS* (3)

20 1 00 00 1 *S* 20 1 1 *S*

where,

*d* | *G* |2 /(  *i*  | *G* |2 /( 

*i*  *i*  | *G* |2 /(  *i*  *i*  *i* ))

00 1 20 1

*p*1 10

1

*p*1

*p* 2 13 1

*p*1

*p* 2

, resulting in three-Fano interference, which originates from an imperfect continuous state

*d* | *G* |2 /(  *i*  | *G*

00 1 20 1

|2 /(  *i* 

.

*p*1 10 1

(3)

*S* / *AS*

ρ

(

) and three bound (photon1

(5)

*S* / *AS*

ρ

*i*  | *G* |2 /(  *i*  *i*  *i*

)))

photon1-phonon1

ρ(7)

photon1-phonon1-

*p*1 *p* 2 13 1

*p*1 *p* 2

*S* / *AS*

(3) (5) (7) (9)

| ρ  ρ  ρ  ρ |

*S* / *AS S* / *AS S* / *AS S* / *AS*

phonon2

(9)

*S* / *AS*

ρ

) states. The three Fano

( *A*2  *B*2  *C* 2  *D*2  2 *AB* cos(φ ) 

1

2 *AC* cos(φ2 )  2 *AD* cos(φ3 ) 

2*BC* cos(φ )  2*BD* cos(φ )  2*CD* cos(φ ))1/2

4 5 6

Equations (3-4) represent nested three dressing

interferences are governed by six phases ( φ1  π ,

φ2  π , φ3  π , φ4  0 , φ5  0 , φ6  0 ). For the four dark states of nested four dressing, the expression can be written as

ρ(3)

 *iG*1 *GASG*1 1 =ρ(3) +ρ(5) +ρ(7) +ρ(9) +ρ(11) , (5)

*S* (4)

(  *i* +*d* ) (  *i*  *i* )(  *i*  *i*  *i* )))

*S* (4)

*S* (4)

*S* (4)

*S* (4)

*S* (4)

20 1 3 00 1 *S* 20 1 1 *S*

ρ(3)

 *iG*1 *GSG*1 1 =ρ(3)

+ρ(5)

+ρ(7)

+ρ(9)

+ρ(11)

. (6)

*AS* (4)

(  *i* +*d* ) (  *i*  *i* )(  *i*  *i*  *i* )))

*AS* (4)

*AS* (4)

*AS* (4)

*AS* (4)

*AS* (4)

20 1 4 00 1 *S* 20 1 1 *S*

*d* | *G* |2 /  *i*  | *G*

|2 /(  *i*  *i* 

ρ(3) (5) (7) (9) (11)

3 1 20 1

*p* 2 30 1 *p*1 *p*2

*p*1 10 1 *p*1

| *S* / *AS* +ρ*S* / *AS* +ρ*S* / *AS* +ρ*S* / *AS* +ρ*S* / *AS* |

where

| *G* |2 /(  *i*  *i* +*i* 

( *A*2  *B*2  *C* 2  *D*2  *E*2  2 *AB* cos(φ ) 

| *G* |2 /(  *i*  *i*

*p*3 31 1

*p*1+*i* *p*2  *i*

*p*3 ))))

2 *AC* cos(φ2 )  2 *AD* cos(φ3 )  2 *AE* cos(φ4 ) 

The

*d* | *G* |2 /  *i*  *i*  | *G*

1

4 1 20 1 1

|2 /(  *i*  *i* 

2*BC* cos(φ5 )  2*BD* cos(φ6 )  2*BE* cos(φ7 ) 

2  2*CD* cos(φ )  2*CE* cos(φ )  2*DE* cos(φ

*p*1 10 1 1

)))1/2

*i* *p*1  | *Gp*2 | /(13  *i*1  *i*1  *i* *p*1  *i* *p*2 

. By

8 9 10

| *G* |2 /(  *i*  *i*  *i*  *i*  *i* ))))

*p*3 03 1 1 *p*1 *p*2 *p*3

using equations (1-2), we can write the interference terms as

dressed third-order density matrix can be

approximated as the sum of the third-order, fifth-order, and seventh, ninth, and eleventh- order ***E*S/AS**, governed by dressed SFWM multi-

Fano phase φ

=φ( *L*)

 φ( *K* )

(*L<K*). The total

Fano interference, which originates from an

phase

( *j*)

φ

*S* / *AS*

*S* / *AS S* / *AS S* / *AS*

of generated ***E*S/AS** is a sum of the

approximate continuous state ρ(3)

, photon1

initial phase

φ *I* ( *j*) , cross-Kerr non-linear phase

(5)

*S* / *AS*

ρ

, photon1-phonon1

(7)

*S* / *AS*

*S* / *AS*

ρ

, photon1-

*x*( *j*)

*S* / *AS*

φ

*S* / *AS*

, and self-Kerr non-linear phase φ *s*( *j*) (

phonon1-phonon2

(9)

*S* / *AS*

ρ

, photon1-phonon1-

φ( *j*)

 φ *I* ( *j*)

 φ*s*( *j*)

 φ *x*( *j*)

). Therefore, multi-

phonon2-phonon3

ρ(11)

states. The

*S* / *AS S* / *AS S* / *AS S* / *AS*

*S* / *AS*

Fano interference could be constructive or destructive depending upon the total phase.

*S* / *AS*

interference between continuous and multi- bound states of SFWM multi-Fano interference

When the condition is set as

φ*S*/*AS*  0

(*i*  1 to

when the 1 is scanned.

10), which results in 10 bright states. However, at 0 or π (*i*  1 to 10), the result shows 10 dark

# The non-Hermitian multi-Fano of two lasers

In -type three-level system, third order

states. For the four dark states, the expression

(3)

1. *E*
2. *E*
3. *E*

can be written as

ρ*S* / *AS*

via

ρ00 1 ρ20 *AS* ρ00 1 ρ20(*S* )

and

| ρ(3)

 ρ(5)

 ρ(7)

 ρ(9)

 ρ(11) | . The four-Fano

*S* / *AS S*/ *AS S*/ *AS S*/ *AS S*/ *AS*

ρ ρ ρ ρ

is controlled by ten phases ( φ  π , φ  π ,

(0) *E*1 (1) *ES* (2) *E*1 (3)

00 20 00 20( *AS* )

, respectively, can be

1 2

φ3  π , φ4  π , φ5  0 , φ6  0 , φ7  0 , φ8  0 ,

φ9  0 , φ10  0 )). Equations (1-2) show four-

written as

ρ *x*(3)  *iG*1 *GASG*1 1  ρ*x*(3)  ρ*x*(5)  ρ*x*(7)  ρ*x*(9) , (7)

*S* (3)

(20  *i*1 +*d*5 ) (00  *i*1  *i**AS*

)(20  *i*1  *i*1  *i* *AS*

)))

*S* (3)

*S* (3)

*S* (3)

*S* (3)

ρ *x*(3)

 *iG*1 *GSG*1 1  ρ*x*(3)  ρ*x*(5)  ρ*x*(7)  ρ*x*(9) . (8)

*AS* (3)

(  *i* +*d* ) (  *i*  *i* )(  *i*  *i*  *i* )))

*AS* (3)

*AS* (3)

*AS* (3)

*AS* (3)

20 1 6 00 1 *S* 20 1 1 *S*

*d*  |G |2 / (  *i*  *i* +|G |2 / (  *i* 

dipole transition), and 5D0 →7F3 (induced electric

Where

*p*1

*p* 2

5 2 20 1 2

*p*1 10 1

*i*  *i* |G |2 / (  *i*  *i* -*i*

2

*p*1

*p* 2 13 1 2

-*i*

)))

dipole transition) at the crystal field of about 106

*d*  |G |2 / (  *i*  *i* +|G |2 / (  *i*  volts/cm. The spectral signal recorded at PMT1

6 2 20 1 2

*p*1 10 1

. The

*i*  *i* |G |2 / (  *i*  *i* -*i*

2

*p*1

*p* 2 13 1 2

*p*1

-*i*

)))

(Fig. 2a11) shows three Fano interference

equations represent three-Fano interference, which originates from the photon1-photon2

*p* 2

resulting from the coexistence of dressing and fine structure energy levels splitting (5D0 →7F1 in

continuum state

*x*(3)

*S* /*AS*

ρ

and three bound states

Fig. 5g1) whereas three Fano dips (three dark

(photon1

(5)

*S* /*AS*

ρ

, photon1-phononon1

(7)

*S* /*AS*

ρ

,

states) come from destructive interference

photon1-phonon1-phonon2

*AS* (3)

(9)

*S* /*AS*

ρ

). Three-Fano

between approximate continuous state ( ρ (3) )

has six phases ( φ1  π , φ2  π , φ3  π φ4  0 ,

φ5  0 ,

*AS* (3)

φ6  0 ). The interference between

and three bound states ( ρ (5)

(7)

*AS* (3)

, ρ 

(9)

*AS* (3)

, ρ 

) and

continuous and multi-bound states of SFWM

multi-Fano appears when the 2 is scanned.

is controlled by Fano phase ( φ1  π , φ2  π ,

# RESULTS AND DISCUSSIONS:

φ3  π

) modeled through Eqs. (3-4). It is

Through the Eu3+: BiPO4 crystal lattice vibrations, the phonon dressing can control multi-Fano interference. Figure 2a shows the spectral evolution of hybrid signal (FL+SFWM) from single Fano to triple Fano obtained from

noteworthy that the magnitudes of the two Fano peaks are greater than those of the three Fano dips because of more pronounced splitting of energy levels within the 7F1 state compared to the nested three dressing.

(0.5:1) Eu3+: BiPO4 sample by changing GP (5μs,

| *G* |2 /(  *i*  | *G*

|2 /(  *i*  *i* 

1 20 1

*p*1 10 1 *p*1

from Eqs.

500μs, 1ms) when ***E***

is scanned at 300K. The

| *G* |2 /(  *i*  *i*  *i*

)))

**1** *p* 2 13 1 *p*1 *p* 2

(0.5:1) Eu3+: BiPO4 crystal exhibits three distinct fine structure energy levels named as 5D1 →7F1 (magnetic dipole transition), 5D0 →7F1 (magnetic

(3-4). The validation of this is supported by our theoretical findings as illustrated in Figure 2h3 at

1 =-50. When the gate position approaches 1ms,

the three suppression Fano dips (Fig. 2a31) become more prominent compared to the enhancement Fano peaks. This observation can be attributed to the dominance of nested three dressing in the completion between energy

Fano interference (Fig. 2a13), occurs due to the coexistence of single dressing and energy level splitting. In contrast, a single Fano dip emerges from the interference between dark states and bright states, a phenomenon regulated by the

levels splitting and dressing. In Fig. 2a21, the first Fano dip is stronger than the third Fano dip

Fano phase ( φ  π ) and modeled by ρ(3)

(5)

+ρ

.

*AS* (1)

*AS* (1)

which can be attributed to the greater influence of the linear polarization dipole moment in energy level 7F1, MJ =0 in comparison to the circular partial dipole moment in energy level ( μ*L*  μ*C* ). Our theoretical results (Figs. 2g and 2h) validate the multi-Fano evolution (Fig. 2a). In Fig. 2a12, two Fano interference results from the coexistence of double dressing and energy levels splitting (5D0 →7F1), where two Fano dips come from interference in an approximate continuous

When GP is at, single Fano dip increases in comparison to two Fano peaks due to photon dressing ( |*G* |2 ) dominance.

The spectral evolution of two sharp peaks to five Fano interference, recorded at PMT2 by adjusting GP, is displayed in Fig. 2b. The two sharp peaks observed in Figs. 2b11, 2b12, and 2b13 can be attributed to the splitting of energy levels during the transitions 5D1 → 7F1, 5D0 → 7F1, and 5D1 → 7F3, respectively. Multi-Fano

1

state

ρ (3)

and two bound states

ρ (5) , ρ (7)

interference seen at PMT2 (Fig. 2b) is stronger

*S* (2)

*S* (2)

*S* (2)

than at PMT1 (Fig. 2a) because of the strong

controlled by Fano phase ( φ1  π , φ2  π ). The practical results obtained align precisely with the theoretical results depicted in Fig. 2h2. (Simulated at 1 =-50). When the GP increases to 500μs (Fig. 2a22), the two Fano dips evolve into three Fano dips due to sensitive phonon dressing

SFWM at the near detector. The Spectral evolution observed at PMT3 (Fig. 2c) exhibits behavior that is identical to that shows similar behavior as observed at PMT1. The Fano interference in Figs. 2d-2f, resulting from the interaction of two lasers, is stronger compared to

( |*Gp*1

|2 ,

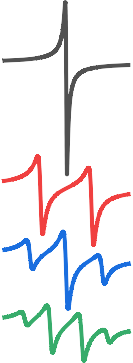
|*Gp* 2

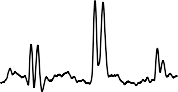
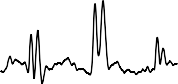
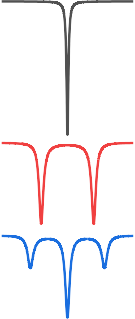
|2 ) and easy distinction for in-phase

that of a single laser (Figs. 2a-2c), mostly due to two lasers dressing enhancement. However, the

SFWM. When GP is at 1ms (Fig. 2a23), the right first Fano dip is strongest due to more dressing interaction of 7F1, MJ =0 and 7F1, MJ =+1. The single

left first Fano dip is stronger than the left third Fano dip in Fig. 2d, f due to more dressing interaction effect between 7F1, MJ =+1and 7F1, MJ =0.

**)**



**Int**

|  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- |
| 5D1-7F1 5D0-7F1 5D0-7F3 | | | | | | |
| **Intensity** | **(a1) (a) (a13)**  **(a2) (a11) (a23) (a3)**  **(a12)**  **(a21) (a22)**  **(a31) (a32) (a33)** | **(b1) (b12) (b) (b2)**  **(b3) (b13)**  **(b11) (b22)**  **(b21) (b23)**  **(b31) (b32) (b33)** | **(c) (c12)**  **(c (c11) (c13) 1)**  **(c23) (c2) (c21) (c22)**  **(c3) (c31) (c32)**  **(c33)** | **ensity** | **(g1)**  **(g2)**  **(g3)**  **(g4)** | **(h1)**  **(h2)**  **(h3)**  **(h4)** |
| **510 650 wavelength(nm)** | | | | |
| **Intensity** | **(d) (d12)**  **(d1) (d11) (d13)**  **(d21)**  **(d2) (d22) (d23)**    **(d3) (d31) (d32) (d33)** | **(e) (e (e12)(e13) 11)**  **(e1)**  **(e2)(e21) (e22) (e23)**  **(e3)(e31) (e32) (e33)** | **(f) (f12)**  **(f1) (f13)**  **(f11)**  **(f2) (f22)**  **(f3) (f21) (f23)**  **(f31) (f32) (f33)** |  |
| **510 650 wavelength(nm) 570** -- **615 wavelength(nm** | | | | | | |

**Fig. 2** Spectral intensity signal measured from Eu3+: BiPO4 crystal with molar ratio (0.5:1) by scanning ***E*1**; **a** PMT1; **b** PMT2 and **c** PMT3. **a1-a3** the spectral signal intensity measured at different gate positions (5μs, 500μs, and 1ms). **b1-b3, c1-c3** are the same GP as **a1-a3**. **d**, **e** and **f** Spectral intensity from (0.5:1) Eu3+: BiPO4 measured at PMT1, PMT2, and PMT3, respectively, when ***E*1** is scanned while ***E*2** is fixed at 588nm (Laser power=7mW, temperature=300k, gate width = 200ns). **g** and **h** Theoretical results for dressing evolution corresponding to **2a** at 1= 0 and corresponding **3a** at 1 =-50, respectively.

Figure 3a shows the spectral evolution of multi- Fano interference from three Fano dips to a single Fano dip in (7:1) Eu3+: BiPO4 crystal when ***E*1** is scanned. In Fig. 3a11, two Fano peaks and

7F1) dominance and dressing which can be further explained by two lasers interaction and

low-intensity phonon dressing ( | *Gp*1 | , | *G* | ) at

*p* 2

2 2

three Fano dips come from nested three dressing low temperatures. Moreover, the spectral

| *G* |2 /  *i*  | *G*

|2 /(  *i*  *i* 

linewidth of the peak is sharp (Fig. 3b1). The four

( 1 20 1 *p*1 10 1

*p*1 ) and can be

| *G* |2 /(  *i*  *i*  *i* ))

*p* 2 30 1

*p*1

*p* 2

Fano dips (Fig. 3b2) come from destructive

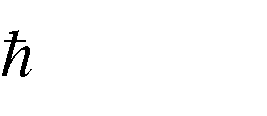
controlled through the Fano phase ( φ1=π ,

interference (

(3) (5) (7) (9) (11)

*S* / *AS S* / *AS S* / *AS S* / *AS S* / *AS*

ρ +ρ +ρ +ρ +ρ from

φ2 =π , φ3 =π ), corresponding to the simulation in Fig. 2g3. The Hamiltonian ( *H*  *i* κ α †α † α †

1 1 *p*1 *p* 2

Eqs. (5-6)). The control of Fano dips and peaks can be achieved by manipulating the Fano phase where the dips are attributed to the presence of

where

κ  *i*ϖχ (9)*E E E E*3 /2

) shows strong

four dark states that are observed at

1 1 *S p*1 *p* 2 1

φ1=φ2 =φ3=φ4 =π . Such four dressing dips

dressing coupling between photon1 (

α

*p* 2

*p*3

† ),

come from photon1 dressing

| *G* |2

and three

sample phonon1 ( α †

1

*p*1

1

), and sample phonon2

phonons dressing ( | *Gp*1

|2 , | *G*

|2 , | *G*

|2 ) with

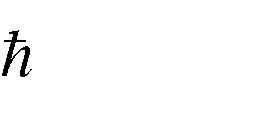
( α †

). The energy level splitting (5D0-7F3) and

Hamiltonian

*H*  *i* κ α †α † α † α †  *H*.*c*.

where

*p* 2 1 1 *p*1 *p* 2 *p*3

dressing coexistence lead to two Fano interferences in Fig. 3a12, where two Fano dips

(11) 3

1 1 *AS S p*1 1 *p* 2 *p*3

κ  -*i*ϖχ *E E E E E E*

/ 2 . It shows the strong

can be explained by nested two dressing dressing coupling among photon1 ( *G*† )-phonon1

1

( | *G* |2 /  *i*  | *G*

|2 /(  *i*  *i*

) ) controlled by

( *G* † )-phonon2 ( *G*† )-phonon3 ( *G*† ). In Fig. 3b2,

1 20 1

*p*1 10 1 *p*1

*p*1 *p* 2 *p* 3

Fano phase ( φ1=π , φ2 =π ) mentioned in Eqs. (1- 2). The amplitude of three Fano dips (Fig. 3a11) reduces as a consequence of the weak dressing

broad profile linewidth is caused by three phonons dressing in (0.5:1) BiPO4. The Fano phase for four dark states and six bright states

resulting from the interaction of two lasers,

can be written as

φ1=φ2 =φ3=φ4 =π

and

when compared to Fano dips illustrated in Figure 3a11. Similarly, the two Fano interference becomes weak in Fig. 3a22 which aligns with the simulation results depicted in Fig. 2g2. When compared to the Fano interference in Fig. 3a11, the Fano interference seen in Fig. 3a3 is weak.

φ5 =φ6 =φ7 =φ8 =φ9 =φ10 =0 , respectively. The presence of six bright states surpasses the number of four dark states due to the additional bright state being integrated into the existing five bright states. The left first Fano dip is stronger than the left fourth Fano dip in Fig. 3b2

This difference can be attributed to the influence

due to

μ*C*  μ*L* . These results correspond to our

of a narrower excitation band, which controls the extent of crystal vibration phonons in the system. In Fig. 3b1, two sharp peaks result from competition between energy level splitting (5D0-

theoretical results obtained for nested four dressing at 1 =50.

In Fig. 3b3, the signal observed by scanning

***E*1** while fixing ***E*2** (588nm) shows multi-Fano

interference with three Fano dips resulting from nested three dressings

*p*1 10 2

Fig. 3b3 to those in Fig. 3b4, it is evident that the latter exhibit three consecutive Fano dips. This

| *G* |2 /(  *i*  | *G*

2 20 2

(

|2 /(  *i*  *i*

*p*1 ) in Eqs. (7-8)

can be attributed to an more phonon dressing.

 | *G*

*p* 2 30 2

|2 /(  *i*  *i*  *i*

)))

As gate width increases from 200μs (Fig. 3b3) to

and four Fano peaks from energy level splitting and Autler–Townes (AT) splitting. In addition, it is observed that single laser excitation (Fig. 3b2) exhibits a greater number of dressing dips compared to two lasers excitation (Fig. 3b3). This can be attributed to the interaction between the two lasers within the crystal, which reduces the dressing effect, as illustrated in Fig. 2e. The observed outcome is consistent with the findings obtained from the nested three-dressing simulation. at 1 =50. The spectral signal

*p*1

*p* 2

500ns (Fig. 3b4), the increasing ratio of SFWM in hybrid signal causes high spectral resolution. The bright and dark states can be controlled by adjusting the phase between zero and π . As the gate width expands, the number of bright states

rises, as illustrated in Fig. 3b4.The three Fano dips and four Fano peaks originate from two laser excitation with a Fano phase of three dark states ( φ1=φ2 =φ3=π ) and three bright states ( φ4 =φ5 =φ6 =0 ), respectively. The additional peak comes from pure constructive states at

depicted in Fig. 3b4 exhibits strong three Fano

Fano phases φ*i* =0

( *i* =1,2,3,4,5,6). When the GP

interference at 15μs gate width for (0.5:1) Eu3+: BiPO4 sample mostly attributed to the dominance of SFWM dominance. The three multi-Fano dips can be explained by photon2 and

reaches to 1ms, Fig. 3b5 depicts clearly defined sharp peaks that can be attributed to the dominance of crystal field splitting, as illustrated in Fig. 1a2. Based on the findings obtained from

two phonons nested dressing ( | *G* |2 , | *G*

2 *p*1

|2 ,

our research, it can be concluded that the (0.5:1) H-phase Eu3+: BiPO4 exhibits strong dressing

| *Gp* 2

**Intensity**

**Intensity**

**Intensity**

**Intensity**

|2 ). By comparing the Fano dips observed in

Fano interference as compared to (7:1) M-phase Eu3+: BiPO4 due to more phonon dressing.

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
| **(b1)** | **(b2)** | **(b3)** | **(b4)** | **(b5)** |

**Fig. 3 a** Measured spectral intensity of the hybrid signal from (7:1) phase Eu3+: BiPO4 at PMT1 by fixing GP (30μs), gate width (500ns), and temperature (300K). **a1** Scan ***E*2** only, **a2** Scan ***E*1** while ***E*2** is fixed at 588nm; **a3** Scan ***E*2** only. **b** Measured Spectral from (0.5:1) Eu3+: BiPO4 at PMT2 and 9mW power. **b** GP (500μs), and gate width (200ns). **b1** Scanning ***E*1** while fixing ***E*2** (588nm) and low temperature (77K); **b2** Scanning ***E*1** only at 300K; **b3** Scan ***E*1** is scanned while ***E*2** is fixed at 588nm at room temperature (300K). **b4** Scan ***E*1** is scanned and ***E*2** (588nm), GP (500μs), gate width (15μs) and 300K temperature; **b5** Scanning ***E*1** at GP (1ms), gate width (200ns) and 300K temperature.



**(a1)**

**(a11)**

**(a12)**

**(a21)**

**(a2)(a22)**

**570**

**610**

**650 560**

**605**

**650 560**

**605 650**

**wavelength(nm) wavelength(nm) wavelength(nm)**

**0 1 2 3 4 5**

**Time (ms)**

**565 590 615 565**

**590 615 565 590 615 565**

**wavelength(nm)**

**590 615 565 590 615**

**wavelength(nm)**

**wavelength(nm)**

**Eu:BiPO4**

**(c)**

**(a3)**

**Intensity**

Figures 4a and 4b discusses the evolution of SFWM from FL in a hybrid signal for (6:1) and (1:1) Eu3+: BiPO4, respectively. At near GP, the dressing effect is weak, leading to a spectral peak characterized by low resolution and a broad linewidth, as shown in Fig. 4a1. Upon increasing the GP (20μs), an emergence of three Fano dips and two Fano peaks is apparent, (Fig. 4a2), resembling the pattern depicted in Fig. 2a22. The observed phenomenon can be attributed to the reduced impact of dressing detuning, resulting in a decreased photon dressing effect and high SFWM resolution. By further increasing GP (200μs), the three Fano dips become stronger in Fig. 4a3 due to one photon dressing ( | *G* |2 ) and

1

two phonon dressings ( | *G* |2 , | *G* |2 ) as modeled

*p*1 *p* 2

from Eqs (3-4). As the GP reaches 500μs, the five Fano-dips in Fig. 4a4 originate from energy levels 7F1 symmetrical splitting of one laser excitation.

Figure 4b shows the evolution from a single broad dip to sharp multi-dips for (1:1) Eu3+: BiPO4 under the same experimental conditions as described in Fig. 4a. In comparison to Fig. 4a1, the broad dip is shown in Fig. 4(b1) due to higher

to the FL signal, the SFWM signal exhibits higher resolution. The presence of multiple Fano dips can be readily observed in the signal generated by SFWM).

From our results, we have realized the wavelength division multiplexing of both classical and coherent channels. The non- classical SFWM may be effectively multiplexed with divided Fano dip across a range of 1μs to 500μs. This multiplexing technique enables the routing of identical information across many channels, ranging from one channel (Fig. 4b1) to five channels (Fig. 4b4). A non-Hermitian multi- channel router can be realized by non-Hermitian control real part quantization (Fig. 1c), and the routing process can be achieved by changing the boxcar gate position. Similarly, when GP is at 500μs, the coherent channel output can be multiplexed to five divided Fano dips for routing the same information to different channels. Fig. 4b shows two adjacent dips with relative distance between many dips. Such a phenomenon (pure dip to five Fano dip) is analogous to routing. Such results are used for routing. Here we use, channel equalization ratio

frequency ( *wpi* ) phonon for (1:1) than (6:1) Eu3+:



*N* -1

(*s*  *a*) / *a*

2

1

*i*

BiPO4, which results in strong phase transition

( *P* 1

) to measure de-

phonon dressing ( | *G* |2 /(*i*  *iw* ) ) with

*pi mn pi*

1   *p*1 ,

multiplexing, where *a* is the area of one dip and

*s*i is the area of each dip or gap between dips.

1   *p*1   *p*2 ,

1   *p*1   *p*2   *p*3 , which is close to

When *si*  *a P* is maximum (100%) and we get

resonance compared with (6:1) sample in Fig. 4a. As GP reaches 500 μs, the five Fano dips are shown in Fig. 4b4. So, the phase transition phonon dressing is stronger in the (1:1) sample than in the (6:1) sample. In summary, in contrast

more balanced and stable spatial channels. From Fig. 4b, the channel equalization ratio P has the potential to reach values ranging from 60% to 80%.

|  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- |
| **572.4 612.4 Wavelength (nm)**    **572.4 612.4 Wavelength (nm)** | | | | | **(e1)** |
| **(e2)** |
| **(e3)** |
| **(c1)** | **(c2)** | **(c3)** | **(c4)** | **(c5)** |
| **(e4)** |
| **572.4 612.4 Wavelength (nm)** | | | | |
| **(d1)** | **(d2)** | **(d3)** | **(d4)** | **(d5)** |  |
| **(e5)** |

**Fig. 4 a** and **b** Spectral intensity of hybrid signal measured at PMT1 from (6:1) and (1:1) Eu3+: BiPO4 crystal, respectively, by scanning Δ1 with gate position being 1μs, 20μs, 200μs, and 500μs. **c** and **d** Spectral intensity of (0.5:1) and (1:1) Eu3+: BiPO4 crystal versus Δ1 by increasing power of ***E*1** from 9mW to 1mW, respectively. **e** Theoretical results corresponding to **c**.

**572.4 612.4**

**Wavelength (nm)**

**572.4 612.4**

**Intensity**

**Intensity**

Next, Figs. 4c and 4d represent the spectrum evolution from multi-Fano interference to two sharp peaks for (0.5:1, 1:1) BiPO4 respectively, versus changing power. In Fig. 4c, the spectral intensity for the (0.5:1) Eu3+: BiPO4 sample is shown at the near detector (PMT2). The laser power was changed from 9mW to 1mW at 300K. When the power is high, strong

|*G* |2 results in five dressing dips (Figs. 4c1, 4c2)

1

from 7F1 symmetrical splitting (similar to Fig. 4a4),

The nested dressing multi-Fano dips observed in our studies can be associated with third-order quantization, as depicted in Figure 1d [20-22]. Herein, we discuss exceptional points (EP) or non-Hermitian control originating from real and imaginary quantization alignment as shown in Fig. 1d. The non-Hermitian exceptional point (EP) manifests itself via crystal field splitting independently of any dressing effects. Figures 4a,b and 4c,d exhibits full- and half-EP

correspond to the simulation result at

1 =0 in

control, respectively. The multi-Fano real part

Figs. 4e1-4e2, respectively. Also, the left first to third Fano dip for energy level 7F1, MJ =±1 in Figs.

quantization channels can be defined as

*N*  *Nm* / *NEP* , where *Nm* represents the number of

4c1-4c2 come from nested three dressings,

dressing dips in SFWM signal,

*NEP*

is the

where the left fourth to fifth Fano dips come for energy level 7F1, MJ =±1 in Figs. 4c1-4c2 owing to nested double dressing. Fig. 4d shows the spectral intensity for (1:1) Eu3+: BiPO4 at PMT2 by changing power (9mW, 7mW, 5mW, 3mW,

number of peaks at EP control (two CF peaks), where each peak represents one level (7F1, MJ =±1, or 7F1, MJ=0). The SFWM multi-Fano quantization exhibits owing channel N=3 (fourth-order) at 7F1, 7F1, MJ =±1 for the left EP peak (Fig. 4a4 to Fig. 4a2

1mW). When the power of ***E*1** decreases to 1mW,

and

*N*  2

(third-order) at 7F1, MJ =0 for the right

the two sharp peaks are shown in Fig. 4c5 and EP peak (Fig. 4c5 to Fig. 4c1). Similarly, N=1

4d5 due to weak dressing ( |*G* |2  0 ) at low power.

**Intensity**

**Intensity**

1

|  |  |  |  |
| --- | --- | --- | --- |
| **(a1)** | **(a2)** | **(a3)** | **(a4)** |

|  |  |  |  |
| --- | --- | --- | --- |
| **(b1)** | **(b2)** | **(b3)** | **(b4)** |

(second-order) at 7F

1, MJ =0,

and third-order N=2 at

7F1, MJ =±1 exhibited from each level in Fig. 4b and N=2 (third-order) exhibited in each level from Fig. 4d.

Figure 5 shows the evolution from multiple dips to two peaks when the laser of ***E*1** is kept high. Figures 5a and b show five Fano dips resulting from five nested dressings (three dressing in 7F1, MJ =±1 and two dressing in 7F1, MJ =0) in a similar manner to that described in Fig. 4c1. When the laser power is lowered, there is a reduction in photon dressing, which leads to the diminishing of three Fano dips resulting from three distinct fine structure energy levels (7F1, MJ =-1, 7F1, MJ =0, 7F1, MJ =1). This reduction in photon dressing causes the phenomenon illustrated in Fig. 4c4 to also

center of the peak remains unchanged due to strong phonon dressing. When comparing the signal measurements of PMT2 with PMT1 and PMT3, it is observed that the signal measured at PMT2 exhibits a stronger dressing effect. This can be attributed to its proximity to the sample, allowing it to detect fluorescence with a higher amplitude, resulting in a more significant dressing dip. Theoretical results are displayed in Figure 5d in accordance with experimental results (Fig. 5b).

Owing to the above explanations, figure 5 shows similar EP control for SFWM multi-Fano quantization (half-EP control). Figure 5b1 shows channel N=3 (fourth-order) at 7F1, MJ =±1 for the left

decrease. When the power reaches 1mW, only

EP peak 5b4 and exhibit

*N*  2

(third-order) at

two sharp peaks appear in Fig. 5a4, b4, c4 due to weak photon dressing. From Figs. 5a1 to 5a4, the



5D1 **1**

**5D 7F**

**1**

**Eu:BPO**

**(g2)**

5D

0

**(g1)**

***E***

***E***1

1

7F 1,MJ=0

7F1,MJ=1

7F

7F3,MJ=0

7F

1,MJ=-1

F3,MJ=**±**2

7

7 3,MJ=**±**1

F3,MJ=**±**3

**(e)**

**|2>**

**Δ1**

**(f)**

***E*S *E*1**

***E*AS**

**Δ1**

**|0>**

**|1>**

**|1>**

**|2>**

**|3>**

**|4>**

***E*** Δp2

**p2**

**|1> *E*p1Δp1**

**|5>**

**|0>**

**572.4**

**612.4**

**Wavelength (nm)**

**572.4**

**612.4**

**Intensity**

7F1, MJ =0 in 5b1 for the right EP peak (5b4). Similar results were observed for Figs. 5a, c .

|  |  |  |  |
| --- | --- | --- | --- |
| **(a1)**  **(a2)**  **(a3)**  **(a4)** | **(b1)**  **(b2)**  **(b3)**  **(b4)** | **(c1)**  **(c2)**  **(c3)**  **(c4)** | **(d1)**  **(d2)**  **(d3)**  **(d4)** |

**Fig. 5 a-c** Spectral intensity of the hybrid signal from (0.5:1) Eu3+: BiPO4 plotted versus  by increasing ***E*1** power measured at PMT1, PMT2, and PMT3, respectively, at fixed gate width (200ns), gate position (500μs) and temperature (300K). **d** Theoretical results by scanning 2 from -50 to 50 and fixing 1 at -500, -250, 0, 250 to 500. **e** SFWM dressing energy level. **f** Five nested

1

dressing energy levels. **g1-g2** Fine structure energy level diagram of Eu3+: BiPO4 for transition 7F1→5D1 and 7F3→5D0, respectively.

Figure 6a shows the EP evolution vs the ratio (*G*p1/Γ20) between photon-phonon dressing Rabi-frequency and transverse de-phase rate between level |2> and |0>. The theoretical results correspond to nested double dressing. At *G*p1/Γ20=0.5, one energy level splits into a real part and an imaginary part, respectively. At internal dressing *G*1/Γ20=0.5, the real and imaginary parts are split in Figs. 6a3, a4, respectively. The splitting of the real part and the

imaginary part of the nested double dressing does not occur simultaneously. When the third- order splitting (*G*1/Γ20) occurs in the real part (Fig. 6a3), the corresponding imaginary part (Fig. 6a4) will have the second-order splitting (*G*p1/Γ20). Thus, the real part splitting is larger than the imaginary part splitting. The imaginary part is nonlocal, more degenerate and non-Abelian, and highly symmetric. The real part is local, less degenerate and Abelian, and low symmetric.

More importantly, the real part is changed from local, Abelian, and more degenerate to non-local,

|*Gp* 2

|2 , |*G* 2

in Eqs. (5-6)). The left first and

non-Abelian, and less degenerate in third-order systems. The dominance of real part splitting (G>Г) shows high-order router, however, the dominance of imaginary part splitting (Г>G) shows low-order router. The non-Hermitian Exception Point (EP) is a point without dressing. Such exceptional point can be achieved by varying various external parameters. Such EP can be achieved by changing different external parameters. The GP is the primary parameter. When the GP is changed from middle (hybrid) to far (SFWM), there is an existence of the EP between hybrid and SFWM. For the nested double dressing, the dressing term is already solved, and it is converted into a univariate cubic equation to be solved, so three eigenvalues are obtained. But in our model, the photon dressing like Zeeman splits three energy levels in Fig. 1a4. The 7F1, MJ =-1 and 7F1, MJ =+1 energy levels are nested dressed by two phonons (phonon1 and phonon2) and the other two phonons (phonon3 and phonon4), respectively. One photon (photon1) dressed 7F1, MJ =0 energy level. So, eight eigenvalues can be obtained by solving the equations of two nested double dressing and one single dressing. Moreover, our experimental results are a subset of the theoretical simulation.

|

*p*3

Figures 6c, d show the spectral intensity

signal obtained from (0.5:1) Eu3+: BiPO4 (*C*2 symmetry) and H-phase Eu3+: NaYF4 (*C*s symmetry), respectively. In this experiment, the competition between real *a* and imaginary *ib* eigenvalues based on nested photon-phonon dressing is discussed. The detailed model of EPs control based on different laser dressing are depicted in Table S1 to S4 (supplementary file). It is worth mentioning that the GP affects the de- phase rate (Γ) at the spectral signal. In other words, the ratio of *G* and Γ can be tuned by changing the GP. In Figs. 4c, Fig. 5b1, and Fig. 6c1, one can observe the visible five Fano dips due to

the dominance of the nested dressing ( |*G* |2 , |*G* 2

1

| ,

*p*1

second Fano dips come from phonon1 and phonon2 dressing. The central Fano dip results from photon1 dressing. The fourth and fifth Fano dips can be explained by phonon3 and phonon4 dressing. Compared to the other four Fano dips, the fifth Fano dip is the strongest (Figs. 4a4) due to photon dressing (similar to Figs. 4c1, c2 and 5a1, b1).

|  |  |
| --- | --- |
| **(a3)** |  |
|  |
|  |  |
| **0 G** | **/Γ20 1** |
|  |  |
|  |
| **(a4)** |  |

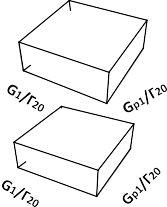
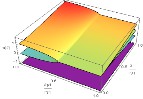
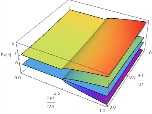
|  |  |  |  |
| --- | --- | --- | --- |
| **(c1)** | **(c2)** | **(c3)** | **(c4)** |

|  |  |  |  |
| --- | --- | --- | --- |
| **(d1)** | **(d2)** | **(d3)** | **(d4)** |

**Fig. 6 a1, a3** Real and **a2, a4** imaginary parts of the eigenvalues as a function of the dressing Rabi-frequency (*G*) and transverse de-phase rate (Γ) with a Gaussian-like envelope. **b1, b2** show 3D simulation corresponding to 2D simulation **a1-a2, a3-a4**, respectively. The spectral signal measured at PMT2 obtained from **c, d**; (0.5:1) sample of Eu3+: BiPO4 and Eu3+: NaYF4 when ***E*1** is scanned from 572.4 nm to

**(b2**

**)**



**1**

**1**

**(b1)**

**(a1)**

**-1**

**0**

**1**

**-1**

**Gp1/Γ20**

**1**

**1**

**1**

**0**

**-1**

**0**

**(b2)**

**1**

**0**

**-10**

**1**

**0.5**

**0.5**

**1**

**1 0**

**1**

**0.5**

**-1**

**0**

**(a2)**

**Gp1/Γ20**

**-1**

**0.5**

**1**

**0**

**G1/Γ20**

**1**

**1 0**

**570 590 615**

**Wavelength(nm)**

**570 590 615**

**Wavelength(nm)**

**Intensity**

**Intensity**

**Im(δ)**

**Re(δ)**

**Re(δ)**

**Im(δ)**

**Im(δ)**

**Re(δ)**

612.4nm and GP is changed (**c** (500μs, 2ms, 5ms, 20ms) and

**d** (1ms, 6ms,10ms, 25ms)) at 200ns gate width and 300 K temperature at power= 9mW, respectively.

When the GP reaches 5ms, one can observe

the two sharp peaks in Fig. 6c3 corresponding to EP where G and Γ are equal due to the dominance of crystal field splitting (Fig. 1a2), validated by theoretical results in Fig. 6(a). The visible three Fano dips observed in Fig. 2a12, Figs. 4a2, b2 and Fig. 6c3 are attributed to the stronger nested three dressing (photon1- phonon1-phonon2 atomic coherence coupling in Fig. 1a4) than crystal field splitting. The evolution from three Fano dips to two sharp EP peaks, to five Fano dips corresponds to Figs. 1a2, a4. Figures 6b1 and b2 are the 3D simulation results

corresponding to the real and imaginary parts of 2D simulations (Fig. 6a and b), respectively.

Lastly, Fig. 6c exhibits fourth-order (N=3) at 7F1, MJ=±1, which corresponds to four eigenvalues in a univariate quartic equation (S4 Galois group)

[38] with three dressing, and one third-order (N=2) EP control at 7F1, MJ =±1 corresponding to four eigenvalues in a univariate cubic equation (S3 Galois group) with two dressing for left and right peak, respectively. Figure 6d1-d4 exhibits one third-order (N=2) EP control for each peak.

# CONCLUSION

In summary, this research examined the phenomenon of multi-Fano dips and demonstrated that their behavior can be regulated by higher-order exceptional points control in non-Hermitian systems. Additionally, we demonstrated the relationship between multi-Fano interference and the photon-phonon nested dressing effect for various Eu3+: BiPO4 samples. This research establishes the categorization of the multi-Fano resonance between discrete and continuous states into three distinct types (dressed MFL, hybrid, and dressed SFWM Fano interference), which can be controlled through the gate position (ratio of MFL and Stokes). Moreover, our experimental results suggest a scheme to achieve a higher channel equalization ratio of about 80%.

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**Data Availability.** All data generated or analyzed during this study are included in this published article.

**Declarations.** The authors declare that they have no conflict of interest.

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**Declaration of interests**

☒ The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

* + The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: