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Abstract: A generic model of two dissimilar antenna-type resonators coupled both via near-field and far-field and embedded in active gain and/or loss medium is considered. Conditions required for hitting the superscattering regime corresponding to the threshold of lasing emission operation are established. It is shown that modulation of the medium gain and losses level within realistic parameters is an efficient approach for implementation of tunability. This two-antenna set-up can serve as an inspiration for the implementation of high-contrast tunable metasurfaces.

Keywords: metasurface, Parity-Time symmetry, coupled-mode theory

I. INTRODUCTION

The advent of metasurfaces, with their ability to manipulate reflection and refraction beyond the limits of classical optics [1,2], or to control the orbital angular momentum of light beams and their polarization state [3], has led to the emergence of a plethora of applications of flat optics ranging from microwave and THz to near-infrared and optical spectral domains [4-9]. However, despite these spectacular advances, current metasurfaces are mostly limited to static applications. Once manufactured, it is generally not possible to modify their optical properties unless special strategies for the implementation of a tunability mechanism are deployed.

The most currently studied tunability mechanisms are aimed at modifying either the real part of the refractive index of the very resonator material or that of its surrounding environment. Typical means encompass electric gates, photoexcitation, use of phase change materials, magneto-optical control, optical non-linearity, beam shaping, mechanical actuators or a deformation system to affect the geometrical parameters of the resonators. Progress in each of the listed tunability mechanisms is presented in [10]. The ultimate goal would be to independently address each pixel of the metasurface to control at a sub-wavelength scale the phase, intensity and polarization of transmitted or reflected waves. Such reconfigurable active metasurfaces would be highly desirable for a range of applications including beam steering modulators, varifocal lenses, dynamic holograms and other adaptive optics metadevices [10].

In the meantime, despite massive efforts from numerous teams worldwide, there is currently no clear strategy on the optimal technological solution to bring this breakthrough. In this landscape, the dawn of Parity-Time symmetry optics has heralded the advent of a new challenger into the arena. Here, the paradigm shift comes from the idea of primarily manipulating the imaginary part of the refractive index of the resonator or its surrounding environment by introducing losses and/or gain into the system. Following this approach, experimental observation of the transition through exceptional point (EP) [11-13] has been reported, followed by theoretical and modeling results predicting the ability to design optical devices for the control of light at the nanometer scale [14-16] and to obtain spectral singularities in active hybrid metamaterials [17-20]. The exceptional point is not the whole story, however. When systems interact with more degrees of freedom (external for scattering and their own degrees of freedom), subtleties that are reminiscent of those of Fano resonances open avenues that do not rely on the EP, all the more if the gain value to operate at this EP is large. The interplay of other degrees of freedom then leads to other interesting working points, with the hope of requesting much less gain than would be needed in a restricted system, with only its own degrees of freedom, including gain and loss, but no scattering channel. Ref.20 can serve as a realistic implementation of the principle that we nevertheless want to discuss with some generality.

The objective of this paper is to further consolidate this research direction by addressing the problem of optimal metasurface design in terms of ensuring an affordable level of gain to achieve the required spectral singularity that corresponds to the laser emission threshold. As is well known, an abrupt variation in intensity and phase is obtained for a small stimulus close to the lasing threshold, representing a “sweet spot” much desired for active tunable metasurfaces.

Special attention is given to explicitly taking into account the open nature of a system due not only to the presence of losses and/or gain but also to the antenna radiation properties, typical of plasmonic resonators. To better grasp this specific context, a first section is devoted to the relevance of the various concepts: parity-time symmetry, spectral singularity, and to their phenomenological modeling. In particular, it is stressed that radiative loss engineering is an important factor in diminishing the gain level required to reach the laser emission threshold condition. On the basis of the analysis performed, an optimized design of coupled resonators is proposed.

II. CONCEPTS AND MODELS

In the last decades, the ability to carve wavelength of sub-wavelength scale resonators supporting few modes or a single mode has prompted a large application of coupled mode theory. The flavor most used in this endeavor is a frequency domain version [21-26], at variance with the spatial coupled mode theory of holograms, distributed feedback (DFB) lasers and waveguide-type structures with dielectric or metallic periodicity (e.g. photonic crystals and plasmonic systems). The focus on small or mesoscale systems has ben more prone to bring the consideration of openness as a characteristic. In a classical laser, openness is treated primarily through the threshold condition and as an edge boundary condition. For the typical elements of metasurfaces, conversely, radiation to open space or to the outside must be a built-in feature to describe the local energy flow. Periodic higher-order DFB lasers indeed also feature radiation and feedback altogether, and their initial in-depth depiction, over 30 years ago, [27] has regained popularity in recent times, e.g. to discuss bound-states-in-continuum and similar remarkable resonances [28].

The focus on parity-time symmetry has further strengthened the popularity of a frequency(time) approach, even though guided optics was a cornerstone of the PTS studies [29-31]. Thus, starting from a closed conservative system and adding gain/loss on the one hand and openness (radiation losses) on the other hand, we must expect an interplay of two kinds of singularities: (i) The gain-loss parameter and the coupling parameter are expected to produce the exceptional point (EP), whereby the eigenvalues of the evolution equation merge and change nature (from real to imaginary, with adequate conventions). (ii) the spectral singularity, which can be assimilated to the lasing threshold at first order, although the examination of the coherence of the system under the various noises (pump, spontaneous emission) should be investigated in detail to provide an exact picture.

Due to this complexity, and to the many systems described in the literature, we choose to focus on the generic coupled mode (frequency/temporal) description, without specifying a material basis. The reader can refer to the various works on nanoresonator-based metasurfaces and related devices [4,32,33] to assess how the correspondence is done based on the response of subsystems, not yet routinely nowadays, but in a reasonably established manner.

The overall framework is linear scattering, with two degrees of freedom in the local system, each able to radiate in the far-field.

Thus the equation (1) applies

$$S=C+iV\left[\omega I-H_{eff}\right]^{-1}V^{\dagger} \tag{1}$$

where C is the background scattering which does not interact with the resonator and V is the radiation-resonator coupling, relating impinging wave to eigenmode weights.

For a closed system, the effective Hamiltonian [26] H_{eff} would comprise only

$$H_{eff}=\begin{bmatrix}\omega_1 & \kappa\\ \kappa^* & \omega_2\end{bmatrix}+i\begin{bmatrix}\chi_1 & 0\\ 0 & \chi_2\end{bmatrix} \tag{2}$$

with frequencies $\omega_{1,2}$, coupling κ, and where χ_1 and χ_2 define either absorption losses (χ_i>0) or gain (χ_i<0) experienced by the isolated resonator mode.

Thus the exceptional point of PTS would arise when $\chi_1-\chi_2=\kappa$, as is well-known. For strongly coupled systems such as a close pair of antenna, the values of gain and loss involved are substantial (more exactly their difference $\chi_1-\chi_2$).

For an open system, there is an extra coupling that comes from the interaction of the radiated field with the resonators. Under the essential assumptions of an identical symmetry of both resonator mores [23,24], the result is that the extra coupling and the decay rates must be strongly related so that one must add the middle matrix of eq. (3) below

$$H_{eff}=\begin{bmatrix}\omega_1 & \kappa\\ \kappa^* & \omega_2\end{bmatrix}+i\begin{bmatrix}\gamma_1 & \sqrt{\gamma_1\gamma_2}\\ \sqrt{\gamma_1\gamma_2} & \gamma_2\end{bmatrix}+i\begin{bmatrix}\chi_1 & 0\\ 0 & \chi_2\end{bmatrix} \tag{2}$$

i.e. the nondiagonal terms are not free. The off-diagonal elements $\sqrt{\gamma_1\gamma_2}$ describe the indirect coupling, or in other terms the radiative coupling, between the resonances induced by the interaction between each resonator and the free space. We stick to this established description rather than modifying κ by a complex addition i $\sqrt{\gamma_1\gamma_2}$.

We also note that many numerical and practical examples were given in [26], based on cylindrical inclusion in waveguides, in the microwave domain. The high dielectric constant achievable in this domain makes the separation of individual resonator modes better defined than for lower dielectric constants (and low Q) resonators. We thus wish to focus on the main finding without such explicit examples. We will only add hints to what it means it terms of relevant examples of references [24,26].

We finally distinguish between features of the resonator and features of the scattering: on the one hand, parity-time symmetry (PTS) as defined here involves only the first and third matrix, it is defined as independent of coupling and scattering. On the other hand, characteristic configurations of scattering are (i) the spectral singularity, akin to the laser threshold, which is a pole in the response and (ii) the dark-mode feature, which is based on the sole absence of radiative decay even in the absence of resonator's own gain and loss. We intend here to discuss findings that point to the possibility of obtainment of the latter features at much lower gain and losses than the PTS feature.

III. MODELING AND DISCUSSION

1. Temporal Coupled Mode Theory model

The first point of our analysis concerns examination of the requirements for attaining the superscattering regime with its characteristic spectral singularity. To this end we consider a system of two coupled antenna-type resonators. Let us note for convenience $\delta=(\omega_2-\omega_1)/2$, $\sigma=(\gamma_1+\gamma_2+\chi_1+\chi_2)/2$, $\eta=(\gamma_2-\gamma_1)/2$, $\xi=(\chi_2-\chi_1)/2$ and $\gamma_0=\sqrt{\gamma_1\gamma_2}$.

The eigenmodes of H_{eff} are complex-frequency poles of the transmission matrix and correspond to sharp features in the spectral response. They can be classified as even ω_+ or odd ω_- (symmetric or antisymmetric, while the individual modes have the same symmetry, as stressed above, the symmetry or antisymmetry relates here to the field's similar or opposite phases in both resonator). As follows directly from Eqs. (1,3)[8-10] and using above notations we get:

$$\omega_\pm=\frac{\omega_1+\omega_2}{2}+i\sigma\pm\sqrt{\left(\delta+i\left(\eta+\xi\right)\right)^2+\left(\kappa+i\gamma_0\right)^2} \tag{4}$$

The lasing threshold condition occurs when the imaginary part of the antisymmetric mode eigenfrequency in Eq. (3) vanishes. Note that condition $\mathrm{Im}\left(\omega_-\right)=0$ can be also satisfied in the case of a totally passive system without the presence of losses and gain, i.e. when $\chi_i=0$. In this case it corresponds to the operation in the dark-mode (DM) regime [34]. By direct calculation this simpler DM condition is then as follows:

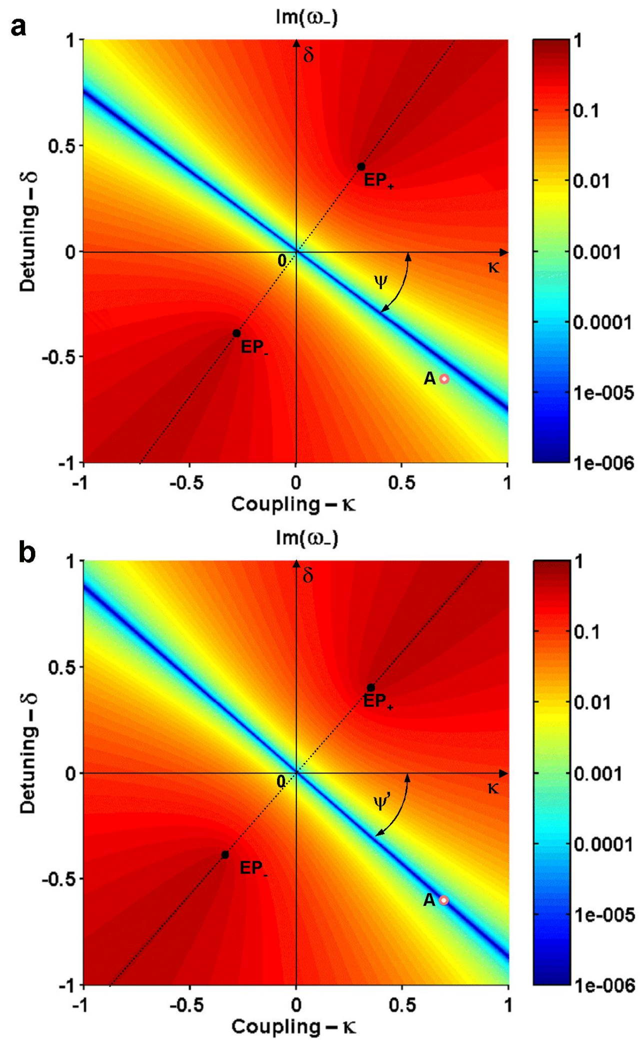
$$\frac{\delta}{\kappa}=\frac{\eta}{\gamma_0}=\frac{\gamma_2-\gamma_1}{2\sqrt{\gamma_1\gamma_2}} \tag{5a}$$

It corresponds to the blue diagonal wedge in Fig. 1a forming an angle $\psi=\mathrm{atan}(\eta/\gamma_0)$ with the ordinate axis. It says how coupling and detuning must be re-balanced for the DM condition to cope with the difference in radiative coefficient of the individual resonator, essentially to produce the proper resonator amplitude algebraic ratio. Note that it has only a distant relation to PTS, as argued above. Moreover, exceptional points arise here in a detuned system, due to the complex coupling [34,35]. From this consideration, for a given particular choice of γ_1 and γ_2 determining the angle ψ, either the detuning δ or coupling coefficient κ could be adjusted to satisfy condition given by Eq. (5a). An obvious exception is the point of origin (δ=0, κ=0) where DM operation is fulfilled independently of the values γ_1 and γ_2.

A similar situation still holds in the presence of losses and gain. The $\mathrm{Im}(\omega_-)=0$ condition for superscattering is then given by the expression:

$$\frac{\delta}{\kappa}=\frac{\eta+\chi}{\gamma_0}=\frac{\gamma_2+\chi_2-\gamma_1-\chi_1}{2\sqrt{\gamma_1\gamma_2}} \tag{5b}$$

In the presence of losses and gain the $\mathrm{Im}(\omega_-)=0$ line is now forming an angle $\psi'=\mathrm{atan}((\eta+\xi))/\gamma_0)$ with the ordinate axis, larger in absolute terms if $\eta > 0$ and $\xi > 0$. Thus, as shown in Fig. 1, the given point A in the $\kappa-\delta$ plane, which was not originally on the DM line (the present example was chosen to lie in the greenish area, the middle of the logarithmic range), can be made to satisfy the exact DM condition when losses and gain are introduced into the system to tilt the DM line to the appropriate angle. We will see below that this evolution is accompanied by a radical change in the spectral response.



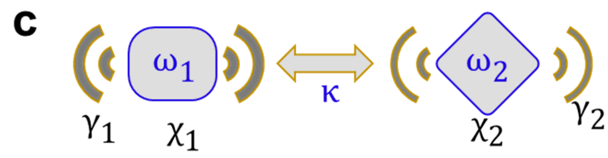


Fig. 1: Behavior of two coupled systems also coupled with scattering channels. The main panels a),b) are colormaps of the behavior while a sketch of the system is given in c). a),b) Logarithmic scale colormap representations of the imaginary part of the antisymmetric mode eigenfrequency Im(ω_-). The dotted line corresponds to the PT-symmetric path. Bold black dots indicate exceptional points. Void magenta dot indicates superscattering operation point in the $\kappa-\delta$ plane. Parameters of the coupled resonators system used in numerical modeling: $\omega_1=10$, $\gamma_1 = 0.8$, $\gamma_2 = 0.2$, $\gamma_0 = 0.4$, $\eta = -0.3$. All values are given in normalized frequency units. The two plotted cases are a) Lossless case ($\chi_1 = \chi_2 = 0$); b) System with losses and gain ($\chi_1 = 0.08$, $\chi_2 = -0.0182$. The values of χ_1 and χ_2 are bounded by the Eq. (11); c) Sketch of the coupled system with radiative channels. The coupling κ is direct, not radiative. The radiative coupling $\sqrt{\gamma_1\gamma_2}$ results from the radiative channels.

2. Single-layer metasurface

To assert this point, we calculate the transmission and reflection coefficients of a single-layer metasurface using the temporal coupled mode theory approach [22-26]. Since there is no general theory for lossy and gainy systems yet, we use formulas from lossless theory [24] with transition to the complex plane in terms of the dielectric permeability and frequencies i.e., we use the analytical extension of the results [24] (a very favorable element is that the algebra does not raise any Riemann sheet or similar issue). The scattering matrix is then:

$$\mathbf{S}=\begin{pmatrix} r & it \\ it & r \end{pmatrix}+\left[\frac{\left(i\left(\omega-\omega_1\right)+\gamma_1+\chi_1\right)\gamma_2+\left(i\left(\omega-\omega_2\right)+\gamma_2+\chi_2\right)\gamma_1-2\gamma_0\left(\gamma_0-i\kappa\right)}{\left(i\left(\omega-\omega_1\right)+\gamma_1+\chi_1\right)\left(i\left(\omega-\omega_2\right)+\gamma_2+\chi_2\right)-\left(\gamma_0-i\kappa\right)\left(\gamma_0-i\kappa\right)}\right]\begin{pmatrix} -\left(r+it\right) & -\left(r+it\right) \\ -\left(r+it\right) & -\left(r+it\right) \end{pmatrix} \tag{6}$$

where r and t describe non-resonant, real reflection and transmission coefficients ($\mathbf{r}^2+\mathbf{t}^2=\mathbf{1}$). For what follows, we consider that the reflection of the substrate is negligible and we set r = 0 and t = 1.

Figures 2a and 2b show the spectral response in intensity and phase variation, respectively, of an ideal lossless passive plasmonic metasurface operated near the DM condition given by Eq. (5a). The intensity variation shows, beside the main broad line, a sharp characteristic asymmetrical resonance of the Fano type, in a very narrow range (around 8.46 n.u.) due to operation near the DM (asymmetry can only be seen in magnified plots but brings no novel data per se). A Fano type characteristic is also observed for the phase response which shows a variation of 2π for the transmitted wave and a back-and-forth jump of $-\pi$ to $+\pi$ for the reflected wave (see inset of Fig.2b).

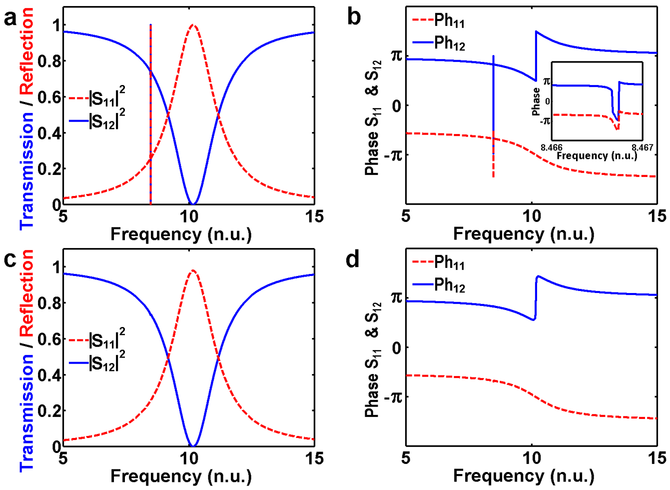


Fig. 2: Scattering matrix Intensity (a) & (c) and phase (b) & (d) spectral responses, respectively. a) & b) Operation in the near vicinity of DM regime. Parameters of the lossless ($\chi_1=\chi_2=0$) coupled resonators system used in numerical modeling: $\omega_1=10$, $\omega_2=8.63$, $\gamma_1=0.9$, $\gamma_2=0.1$. All values are given in normalized radial frequency units. Inset in (b) shows transmitted and reflected waves phase variation at the Fano resonance frequency; c) & d) Same resonators parameters as in (a) & (b) except $\chi_1=\chi_2=0.01$.

The introduction of losses into the system leads to a radical change in the complex spectral response. As can be seen in Figs. 2c and 2d, the Fano resonance features in intensity and phase have almost completely disappeared, while for the rest of the spectral response the changes are barely noticeable. Based on a similar approach, an active control of electromagnetically induced transparency (EIT) analogue in terahertz metamaterials was demonstrated in [36]. As expected in these resonant phenomena, the bandwidth is reduced when the tuning sensitivity increases.

Further avenues are opened with the introduction of the gain into the system. Firstly, such an introduction can obviously restore the DM singularity, albeit in a modified form. Whereas for the initial "Off" state in the absence of absorption, the normalized sum of the reflected and transmitted intensities is equal to unity, it becomes unbounded (Fig. 3a, semilog scale) in the "On" super-scattering state occurring in the presence of losses and gain. The resonant frequency can be determined by explicitly solving equation $\mathrm{Im}(\omega_-)=0$. Using a straightforward calculation, the following expression can be obtained:

$$\delta=\frac{\kappa\gamma_0(\gamma_2+\chi_2-\gamma_1-\chi_1)}{2(\gamma_1\gamma_2+\chi_1\chi_2+\gamma_1\chi_2+\gamma_2\chi_1)}\pm\sqrt{\Delta} \qquad (7)$$

where the discriminant Δ is:

$$\Delta=64\sigma^2\left(\kappa^2+\sigma^2-(\eta+\xi)^2\right)\left(\gamma_0^2+(\eta+\xi)^2-\sigma^2\right) \qquad (8)$$

The gain level required to reach the superscattering threshold corresponds to the condition $\Delta=0$, which is fulfilled when one of the three elements of the product given by Eq. (8) vanishes. The first term $\sigma=0$ means operation at the EP represented in the κ-δ plane by black dots in Fig. 1. As evidently appears and as the large distance between EP and DM line in Fig.1 suggests, operation at the EP is a poor option in terms of the large gain it requires:

$$\chi_2=-(\gamma_1+\gamma_2+\chi_1) \qquad (9)$$

The physical meaning is clear: the level of gain required in the second resonator should fully compensate for the radiative losses in both resonators as well as possible absorption losses in the first resonator. Note that despite the fact that loss and gain are not balanced, the system still has PT-symmetric and PT-symmetry-broken phases, but PT-symmetric phase no longer exhibit real spectra.

Neither is the condition given by the second term in product decomposition given by Eq. (8) is a good option:

$$\chi_2=-\frac{\kappa^2+\gamma_1\gamma_2+\gamma_2\chi_1}{\gamma_1+\chi_1} \qquad (10)$$

In the limit $\kappa\to0$ and $\chi_1\to0$ the lowest "threshold" gain for reaching DM is $\chi_2=-\gamma_2$. It corresponds to the compensation by gain of the radiative losses in the second resonator. Note also that the same lowest gain $\chi_2=-\gamma_2$ can be achieved when $\chi_1>>\gamma_1$ while $\kappa\to0$. Though this operation regime in terms of gain requirement is less demanding compared to the operation at the EP, it is still much less favorable than the demand when the last factor in the product decomposition given by Eq. (8) vanishes:

$$\chi_2=-\frac{\gamma_2\chi_1}{\gamma_1+\chi_1} \qquad (11)$$

In the limit of $\chi_1<<\gamma_1$, $\chi_2\to-\chi_1(\gamma_2/\gamma_1)$. This means that in theory the required gain level χ_2 can be arbitrary small, and notably much lower than the loss χ_1, provided that $\gamma_2<<\gamma_1$.

This can lower the gain requirement to only 1% for instance of the loss compensation, essentially at the expenses of a narrower bandwidth. In other words, the resonant character of the system is optimally utilized, accumulating amplitude and phase changes for degrees of freedom that most easily compensate the losses. Another remarkable feature is that the gain condition given by Eq.(11) is independent of the coupling strength κ. Also note that when the lasing threshold condition given by Eq. (11) is satisfied, Eq. (7) becomes identical to Eq. (5b).

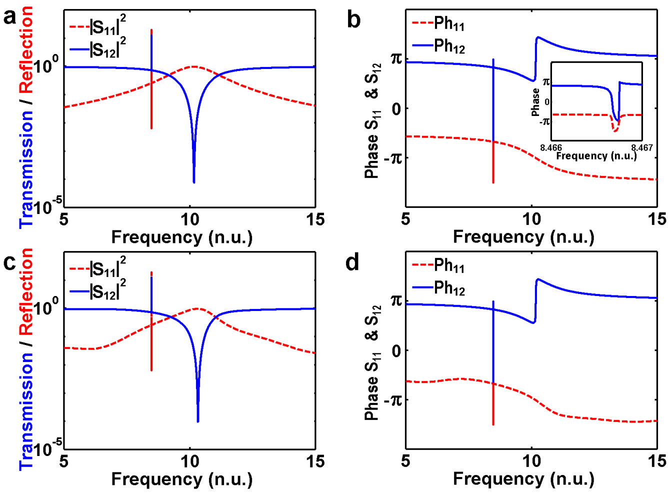


Fig. 3: Scattering matrix Intensity (a) & (c) and phase (b) & (d) spectral response, respectively. a) & b) Single-layer metasurface operation in the vicinity of superscattering regime. Parameters of the coupled resonators system used in numerical modeling: ω_1=10, ω_2=8.63, γ_1=0.9, γ_2=0.1, χ_1=0.01, χ_2=-0.0011. All values are given in normalized radial frequency units. Inset in (b) shows transmitted and reflected waves phase variation at the Fano resonance frequency; c) & d) Double-layer metasurface with dielectric spacer thickness $d=1.18\times2\pi c/\omega_1$ Same resonators parameters as in (a) & (b).

A practical implementation of such dark mode metasurface design may be akin that shown in Fig. 4. It consists of a dolmen type structure with a bright dipole element and a dark quadripole element embedded in gain medium. Full-wave simulations of such type of structure was reported in [20]. For the operation wavelength around 1μm it was found that the gain level to required to achieve the superscattering condition is about 1760cm^{-1}. Such a gain level is attainable by using either organic dyes [37] or semiconductor materials [38].

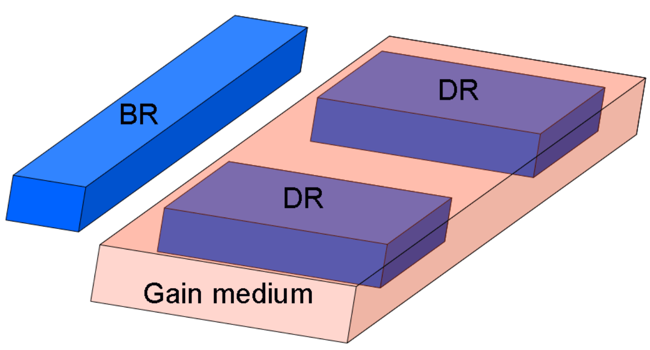


Fig. 4: Schematic diagram of the hybridized metamaterials consisting of a bright resonator (BR) dipole nanoantenna and a dark resonator (DR) quadrupole antenna embedded in a gain medium.

3. **Double-layer metasurface**

Though detuning δ between resonators expressed by Eq. (7) is sensitive to κ, its deviation from nominal value can be adjusted through either variation of the gain level χ_2 or loss level χ_1. It is clear that the ability to independently adjust the losses level χ_1 as well as the gain level χ_2 in controlling the phase and intensity of the transmitted and reflected waves and fine-tuning the superscattering frequency. The technological implementation of such an independent control of χ_1 and χ_2 with a single metasurface is, however, not trivial. The solution to this problem is to use a double-layer metasurface. In this case, one metasurface can support only gain elements consisting, for example, of III-V semiconductor resonators and another metasurface supports resonators either based on III-V heterostructures where absorption is controlled by the quantum-confined Stark effect (QCSE), or consisting of metal-type resonators.

The intensity and phase spectral response of a double layer metasurface calculated using the same approach as in [25] is shown in Figs. 3c and 3d, respectively. As can be seen, it is very similar to that of single-layer metasurface (the broad peak is only slightly sharper) and, importantly, presents the same divergence of intensity when approaching the superscattering threshold condition.

IV. SUMMARY AND CONCLUSIONS

Tunability mechanisms based on gain or loss variation in a system of two coupled antenna-type resonators were considered. The primary interest of the study is to focus on operation condition other than those implying the EP of the bare resonators. In a spirit similar to Fano resonances, we found that when the scattering channel are included, new operation conditions for switching effects with much smaller gain excursion can be realized. In some sense, focusing on the “traditional” EP could obscure more advantageous working points. According to our study of two coupled nanoantenna-type systems with proper phenomenological addition of scattering channels, there is room for such working points, in relation with the dark mode condition. It also gives rise to the superscattering regime with strong response for small parameter modulation. There is logically a price to pay in terms of limited bandwidth. However, in the telecom context for instance, the plasmonic nanoantenna-related bandwidths are way too broad compared to telecom optical switching requirements for narrow channels, thus it does make sense to put such features to good use.

In our study, conditions corresponding to the operation in the adequate superscattering regime were identified. It was found that the optimal configuration in terms of lowest gain to be supplied corresponds to a system composed of gain and loss resonators with highly asymmetric radiative rates (γ_2/γ_1) and detuned resonance frequencies. We emphasize here that this is obtained in a regime of very limited gain i.e. with $\chi_2 << \chi_1$, i.e. a very small gain level, according to the rationale exposed above. The proposed approach can be exploited for the implementation of tunable metasurfaces with high-contrast. It can be used to further improve the enhancement of quantum emission phenomena, such as superradiance [39,40], the enhancement of optical nonlinearities [19,41], and could be extended to the study of strong coupling between resonant cavity and localized emitters modes. The obtained results are fully consistent with previously numerical modeling results with realistic gain parameters reported in [17,18,20].

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