# High-Q fano resonances via direct excitation of an antisymmetric dark mode

Bochkova, Elena; Han, Song; De Lustrac, André; Singh, Ranjan; Burokur, Shah Nawaz; Lupu, Anatole

2018

Bochkova, E., Han, S., De Lustrac, A., Singh, R., Burokur, S. N., & Lupu, A. (2018). High-Q fano resonances via direct excitation of an antisymmetric dark mode. Optics Letters, 43(16), 3818-3821. doi:10.1364/OL.43.003818

https://hdl.handle.net/10356/137436

https://doi.org/10.1364/OL.43.003818

# High-*Q* Fano resonances via direct excitation of antisymmetric dark mode


**Elena Bochkova,[1] Song Han,[2] Andre de Lustrac,[1,3] Ranjan Singh,[2] Shah Nawaz Burokur,[4] Anatole Lupu[1,*]**

[1]*Centre de Nanosciences et de Nanotechnologies, CNRS, Univ. Paris-Sud, Université Paris-Saclay, C2N – Orsay, 91405 Orsay cedex, France*
[2]*Division of Physics and Applied Physics, School of Physical and Mathematical Sciences, Nanyang Technological University, Singapore 637371, Singapore*
[3]*UPL, Univ Paris Nanterre, 92410 Ville d'Avray, France*
[4]*LEME, UPL, Univ Paris Nanterre, F92410 Ville d'Avray, France*
**Corresponding author: anatole.lupu@c2n.upsaclay.fr*



Received XX Month XXXX; revised XX Month, XXXX; accepted XX Month XXXX; posted XX Month XXXX (Doc. ID XXXXX); published XX Month XXXX



**We revisit the engineering of metasurfaces displaying sharp spectral features based on Fano-type interference between symmetric bright mode and antisymmetric dark mode. The proposed mechanism for direct excitation of antisymmetric mode avoids the necessity of mode hybridization through near field coupling. We bring modeling and experimental evidence in the microwave domain that such excitation mechanism provides greater flexibility for high quality factor metasurface engineering and results in a large improvement of their performances. We also show that Fano interference is related to the broken eigenmodes orthogonality in open systems and is independent of hybridization mechanism.**





***OCIS codes:*** (160.3918) Metamaterials; (260.5430) Polarization; (350.4010) Microwaves; (260.2110) Electromagnetic optics.

http://dx.doi.org/10.1364/OL.99.099999


Frequency selective metasurfaces (MSs) displaying sharp spectral features are highly valuable for a range of applications as for instance chipless radio frequency identification (RFID) in wireless microwaves technology [1,2] or biochemical sensing in the THz [3,4] and optical domains [5,6]. According to the mechanism used for achieving a narrow bandwidth spectral response in transmission or reflection, the numerous studies reported in the literature can be broadly classified into three categories: i) Fano type interference in a system of coupled resonant elements [7-9]; ii) high finesse factor Fabry-Perot resonator cavity formed by two MSs [10-12]; iii) direct symmetry-based resonance coupling to higher order modes of metallic resonators [13-15].

Given that discussion on *pro et contra* of each method is deserving a dedicated analysis, this contribution is focused on achieving both high quality factor and contrast of resonant intensity variation using Fano resonance interference in a system composed of interacting resonant elements. This problem is particularly acute since generally in such systems high resonance quality factor is achieved at the expense of the intensity variation contrast and a search for an optimal tradeoff between these two parameters is then required [16].

The conventional approach to the problem is to consider a system associating a superradiant element bearing an electric dipolar momentum and acting as a radiative (bright) mode, with a subradiant element bearing an electric quadrupolar or magnetic dipolar momentum and playing the role of a trapped (dark) mode [7,8,16,17]. The mode hybridization induced by the strong near-field coupling between resonant elements leads to the excitation of antisymmetric currents in the near vicinity of the resonance frequency. The radiation emitted by oppositely directed electric dipoles is strongly suppressed, leading thus to the opening of a narrow electromagnetically induced transparency (EIT) window inside the absorption band. Despite a great variety of demonstrations based on such a scheme, the issue is that the control of the antisymmetric mode resulting from mode hybridization through near field coupling is challenging, especially when considering operation in the THz or optical domains.

An important point that should be underlined is that the break of orthogonality that renders the possibility of the excitation of antisymmetric mode is not caused by mode hybridization. It is rather the consequence of the *non-Hermiticity of eigenmodes* due the open character of the system [18-22]. In such situation it is natural to wonder whether it is possible to bypass the critical for the control through near field coupling hybridization step by finding a mechanism for the direct excitation of the antisymmetric mode.

In this letter we pursue a twofold objective i) demonstration of a direct antisymmetric mode excitation mechanism providing both high contrast and quality factor Fano resonance and ii) bring evidence that Fano resonance interference relying on the broken eigenmodes orthogonality is accompanied by a resonant increase of higher order components in the scattered field multipolar decomposition.

To hit these objectives, we consider a bi-layered metasurface intended for operation in microwave domain and composed of identically dimensioned copper Z-shaped resonators printed in an enantiomeric arrangement on the two sides of a dielectric substrate. The design of the considered MSs unit cell is represented in Fig. 1(a). The dielectric substrate separating the upper and lower MSs has permittivity of $\varepsilon_r$ =2.2, tangential losses tan$\delta$=0.0009 and thickness $h$ =0.4 mm. One advantage of such a design is to minimize the overlap between the upper and lower MSs resonant elements and by this reduce almost completely hybridization through near field coupling. Another advantage is that negligible metal and dielectric substrate absorption losses in the GHz frequency domain greatly facilitate the observation of higher order scattered terms in multipolar decomposition, which are expected to display a resonant enhancement at Fano frequency as a consequence of broken eigenmode orthogonality.

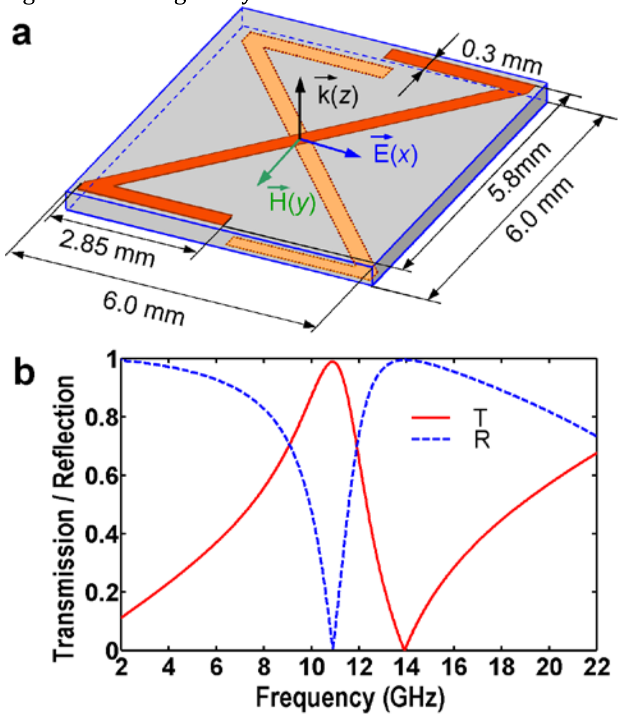


Fig. 1. a) Enantiomeric Z-shaped meta-atoms MSs unit cell design; b) Normal incidence transmission and reflection amplitudes (solid and dashed lines, respectively).

The MSs spectral response was numerically calculated by using the finite element method (FEM) Maxwell's equations solver of high frequency structure simulator (HFSS) commercial code by ANSYS [23]. The electric field component of the normally incident plane wave is oriented along the $x$-axis. The amplitude of x-polarization transmission and reflection coefficients is shown in Fig. 1(b). A marked Fano resonance effect with reflection maximum at $f_0$ = 10.9 GHz and minimum at $f_1$ = 13.9 GHz can be observed. Note that in contrast to the conventional arrangements of coupled resonant elements based on symmetry breaking [7-9], here the observed Fano resonance is obtained in a system of identical resonant elements where near field coupling between them is strongly reduced.

To exemplify the reduced influence of near field coupling on Fano resonance additional modeling results where either the thickness of the dielectric substrate was increased from 0.4 to 1.6mm, or the size of the unit cell from 6×6mm to 9×9mm while keeping same dimensions for resonant elements, are shown in Figs. 2(a) and 2(b), respectively. As it can be seen, aside a shift toward lower frequencies, the increase of the unit cell size doesn't produce fundamental changes on Fano resonance shape or amplitude. Similar trend, albeit a small decrease of Fano resonance amplitude caused by the dielectric material absorption is observed when the substrate thickness is increased.

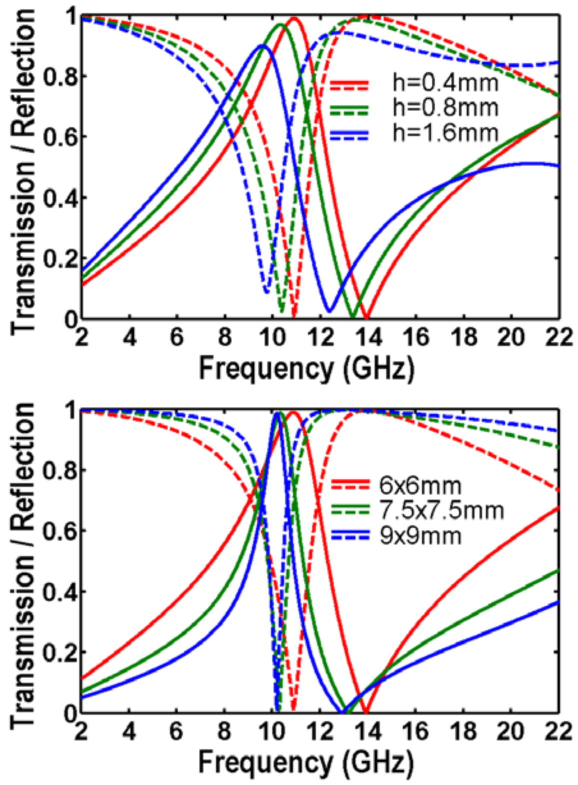


Fig. 2. Normal incidence transmission and reflection amplitudes (solid and dashed lines, respectively). a) Dielectric substrate thickness variation; b) MSs unit cell size variation.

To explain the origin of the occurring Fano resonance it is insightful to have a close look on the instantaneous charge distribution at 10.9GHz frequency, which is shown in Fig. 3. As it can be seen, for the upper metasurface labeled as (1), the electric field oriented along the x-axis is inducing a dipolar polarization momentum $P_{xx1}$. However, because of the Z-shaped meta-atom geometry electric charges are also spatially separated along the y-axis, leading thus to dipolar polarization momentum $P_{xy1}$ perpendicular to the orientation of external electric field. Similar situation is observed for the lower metasurface - (2), but cross-polarization momentum $P_{xy2}$ is now oriented in the opposite direction with respect to $P_{xy1}$. It is easy to observe that the two oppositely oriented cross polarization momentums $P_{xy1}$ and $P_{xy2}$ on the upper and lower MSs, respectively, are forming an antisymmetric mode that is directly excited by the external field. The observed Fano resonance results from the interference of bright symmetric mode ($P_{xx1}$ & $P_{xx2}$) and antisymmetric dark mode ($P_{xy1}$ & $P_{xy2}$).

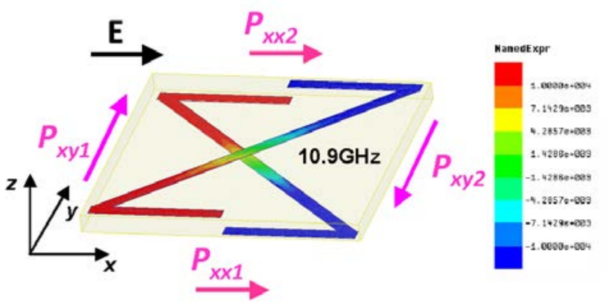


Fig. 3. Instantaneous charge distribution corresponding to Fano resonance maximum reflection at 10.9GHz. Direction of incident field electric component and resonant elements polarizations indicated by arrows.

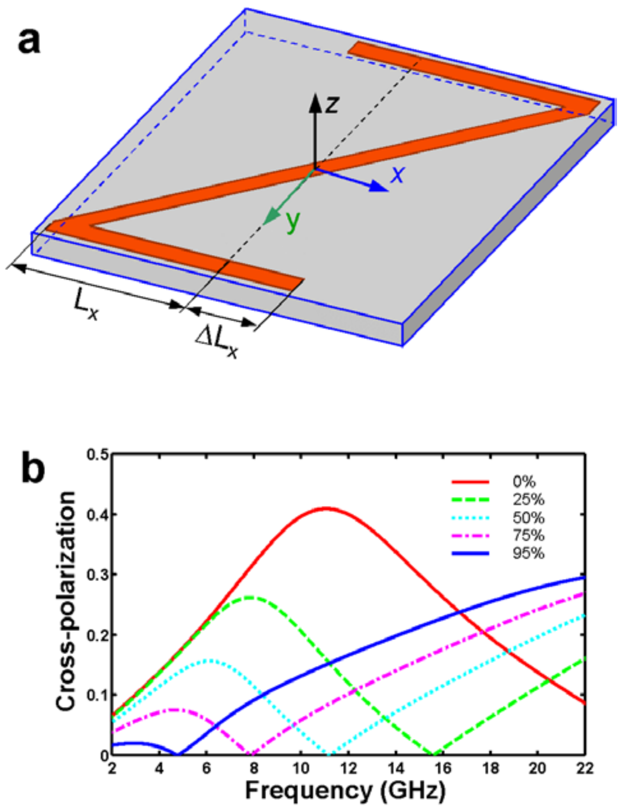


Fig. 4. a) Schematic of Z-atom design with variation of horizontal arms length; b) Cross-polarization conversion of single layered Z-atom metasurface as function of relative horizontal arms length variation defined by ρ parameter.

The degree of coupling of the antisymmetric mode to the external field can be controlled through the engineering of the anisotropy properties of Z-shaped meta-atom. The reduction of cross polarization momentum could result in a smaller coupling of antisymmetric mode to the external field and respectively increase of resonance quality factor. This can be achieved through a mere change of Z-shaped element geometry, which consists of increasing the length of Z-element horizontal arms, as it is represented in Fig. 4(a). We define by $\rho=\Delta L_x/L_x$ the ratio of the horizontal arm length variation $\Delta L_x$ with respect to its nominal value $L_x$=2.85mm used in non-overlaping enantiomeric Z-MSs design shown in Fig. 1(a). In the case of bi-layered enantiomeric Z-MSs shown in Fig. 5(a), same value of parameter ρ corresponds to the overlap ratio between the horizontal arms of the upper and lower MSs.

The cross-polarization conversion can be readily determined through the numerical modeling of single layered Z-atom metasurface. The calculated cross-polarization reflection amplitude as function of ρ parameter variation is shown in Fig. 4(b). As it can be seen, the amplitude of the cross-polarization term is indeed reduced by more that order of magnitude as ρ varies from 0 to 95%. Obviously, this variation is even more striking (more than two orders of magnitude) when considering the intensity of cross-polarized terms, which finally are important for the quality factor of antisymmetric mode. Note also that the increased length of the Z-resonant element causes the shift toward lower frequencies of the local maximum in cross-polarization spectra.

The spectral responses of direct and cross-polarized reflection calculated for the bi-layered enantiomeric Z-MSs at different values of overlapping ratio ρ are shown in Fig. 5(b) and 5(c), respectively. The shift toward lower frequencies of the marked resonance in the spectral response is due to the increased length of the Z-shaped element. As expected, the reduction of cross-polarization terms related to the increase of the horizontal arms length translates in a drastic increase of Fano resonance quality factor. For instance, the quality (*Q*) factor for 0% overlapping Z equals to 3.8, while for 75% *Q* factor is as high as 117, reaching extremely high value of 720 for 95% overlapping configuration. This result is directly related to the enhancement of the quality factor of the antisymmetric dark mode, which can be readily observed in cross-polarization reflection data shown in Fig. 5(c). The resonant enhancement of cross-polarization conversion at Fano frequency attests thus that the orthogonality of eigenmodes is broken.

Further evidence for the broken eigenmodes orthogonality can be obtained by considering multipole decomposition of the scattered field. Results of such analysis for 0% and 75% overlapping ratio cases are displayed in Fig. 6. The multipole decomposition consists in calculation of the relative strength of induced multipole moments contributing to the far-field response of the metasurface [24-28]. This method is based on expressing the total radiated power through three families of multipoles such as electric, magnetic and toroidal type of excitations [26]. The total scattering includes contributions of electric, magnetic and toroidal dipoles, electric and magnetic quadrupoles. With the multipole components, electric field (Es) emitted by the array can be calculated [28], and the radiation reflected and transmitted by the 2D array can also be determined, as shown in Fig. 6.

According to computed intensity of multipole terms for the bi-layered enantiomeric Z-MSs illuminated by a plane wave with electric field orientated along *x*-axis, the strongest contribution to radiation is provided by the electric dipole, particularly its *x*-component, for both 0 and 75% overlapping ratio structures. However, the contribution of all *y*-polarized higher order terms is also considerable (≈15%). The resonant enhancement of these higher order terms in the vicinity of Fano frequency is manifest. The multipolar decomposition results are thus globally in agreement with resonant cross-polarization-conversion results presented in Fig. 5(c).

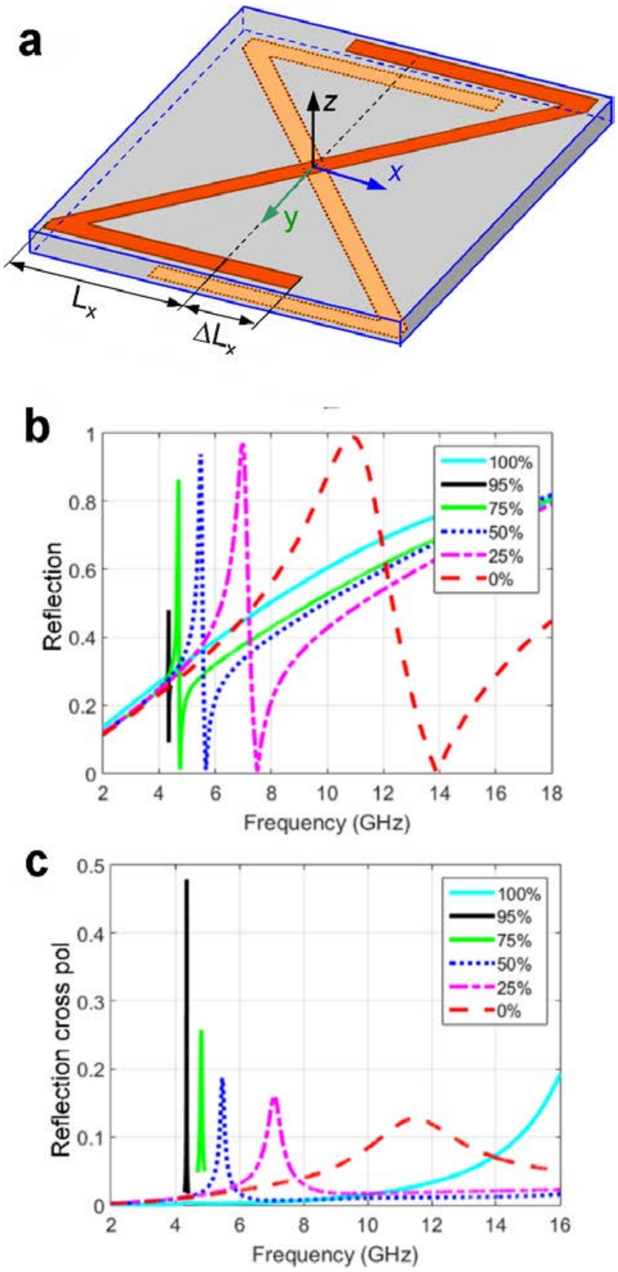


Fig. 5. a) Schematic of bi-layered Z-MSs unit cell design with partially overlapping enantiomeric elements; b) X-polarization reflection spectra for different values of overlapping ratio; c) Cross polarization reflection for different values of overlapping ratio.

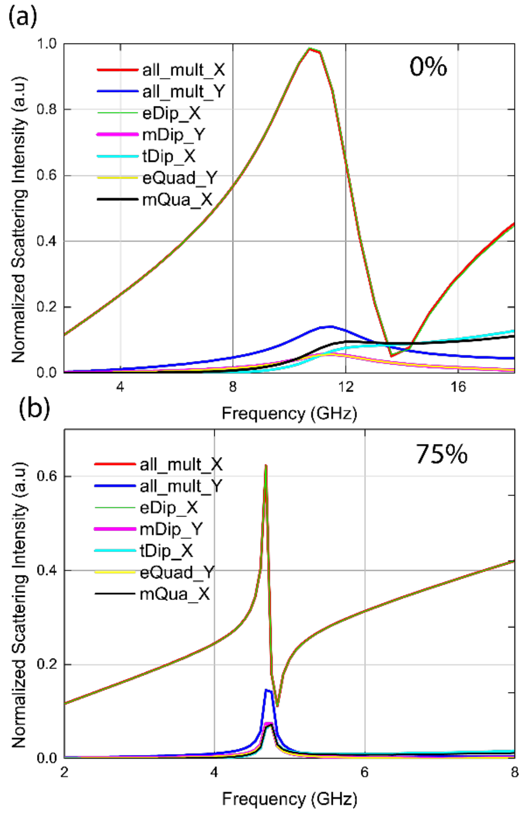


Fig. 6. Multipole decomposition including scattering intensity of electric (Edip), magnetic (Mdip) and toroidal dipoles (Tdip), electric (Qe) and magnetic quadrupoles (Qm), interference between electric and toroidal dipoles (etdip) and the contribution of higher order terms (mrad) for enantiomeric Z-shaped metasurface. (a) 0% and (b) 75% overlapping ratio configurations.

To validate modeling results, prototypes of bi-layered Z-MSs with partially overlapping enantiomeric elements were fabricated using classical printed circuit board technology. Each metasurface comprises 35 × 35 unit cells on a 210 mm × 210 mm dielectric substrate. The material parameters of the substrate and the geometrical dimensions used for the experimental validation are the same as those used in numerical simulations. Microwave transmission measurements based on the experimental setup described in [29] are done in an anechoic chamber using an Agilent 8722ES network analyzer and two [2-18 GHz] wideband horn antennas. Phase referencing and normalization are performed in transmission by removing the sample from the signal path. As it can be clearly observed in Fig. 7, measured transmission characteristics for the different Z-MSs designs show a very good qualitative agreement with simulation results. The noisy features appearing in the measurement data are caused by Fabry-Perot interferences in the parallel-plate cavity system formed by the emission antenna and the metasurface.

As follows from modeling and experimental results presented in Fig. 7 the quality factor of Fano resonance increases with the overlap ratio ρ. The $Q$ factor of measured Fano resonance for enantiomeric Z-MSs with 75% overlapping ratio equals to 62 and the contrast of intensity variation is ≈52%. As compared to simulation results the lower $Q$ factor and intensity variation contrast is due to the metal related absorption losses that are not taken into account in the numerical model. The further improvement of performances related to the increase of overlap ratio is prevented by the saturation of the resonance quality factor caused by losses. Fano resonance almost vanishes as the feeding rate of the antisymmetric dark mode by the external field becomes comparable or lower than losses. This is what is observed in modeling results shown in Fig. 5(b) when ρ>95%.

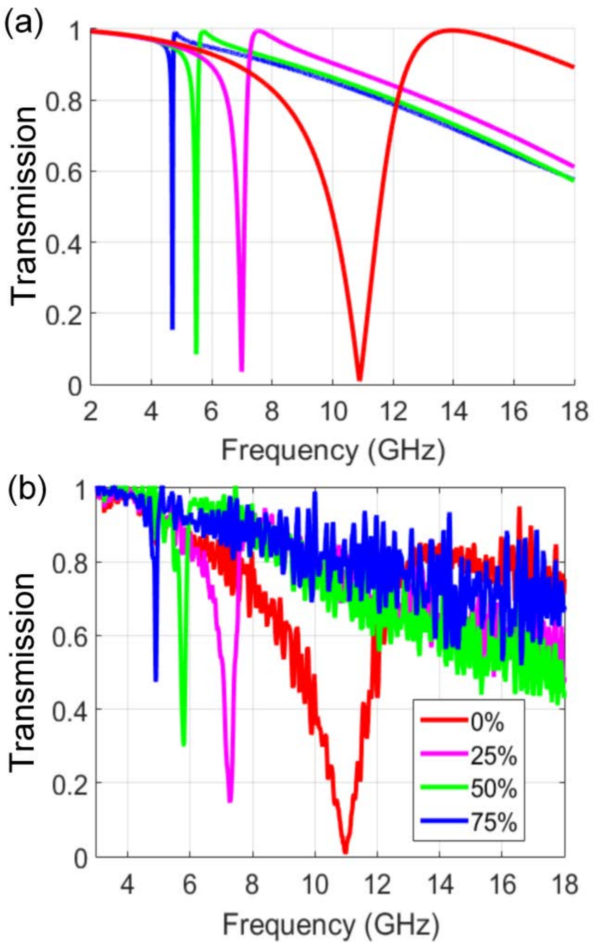


Fig. 7. Transmission coefficients of bi-layered Z-MSs with partially overlapping enantiomeric elements. a) Modeling results; b) Experimental data.

In conclusion, we demonstrated numerically and experimentally the possibility for the realization of high contrast and Q-factor Fano resonance MSs through direct excitation of antisymmetric dark mode by the external field. The advantage of such solution is to avoid the necessity of mode hybridization through near field coupling. The obtained results unambiguously show that Fano resonance interference is related to the broken eigenmodes orthogonality in open systems and is independent of hybridization mechanism.

## References

1. S. Preradovic, I. Balbin, N. C. Karmakar, and G. F. Swiegers, “Multiresonator-based chipless RFID system for low-cost item tracking,” IEEE Trans. Microwave Theory Tech. 57, 1411-1419 (2009).
2. A. Vena, E. Perret, and S. Tedjini, “Chipless RFID tag using hybrid coding technique,” IEEE Trans. Microwave Theory Tech. 59, 3356-3364. (2011).
3. JF O’Hara, R Singh, I Brener, E Smirnova, J Han, AJ Taylor, W Zhang, “Thin-film sensing with planar terahertz metamaterials: sensitivity and limitations,” Opt. Express 16 (3), 1786-1795 (2008).
4. R Singh, W Cao, I Al-Naib, L Cong, W Withayachumnankul, W Zhang, “Ultrasensitive terahertz sensing with high-Q Fano resonances in metasurfaces,” Appl. Phys. Lett. 105 (17), 171101 (2014).
5. B. Gallinet and O. J. F. Martin, “Refractive index sensing with subradiant modes: a framework to reduce losses in plasmonic nanostructures,” ACS Nano 7, 6978 (2013).
6. A. Sereda, J. Moreau, M. Canva, and E. Maillart, “High performance multi-spectral interrogation for surface plasmon resonance imaging sensors,” Biosens. Bioelectron. 54, 175 – 180 (2014).
7. V. A. Fedotov, M. Rose, S. L. Prosvirnin, N. Papasimakis, and N. I. Zheludev, “Sharp trapped-mode resonances in planar metamaterials with a broken structural symmetry,” Phys. Rev. Lett. 99, 147401 (2007).
8. S. Zhang, D. A. Genov, Y. Wang, M. Liu, and X. Zhang, “Plasmon-induced transparency in metamaterials,” Phys. Rev. Lett. 101, 047401 (2008).
9. N. Liu, L. Langguth, T. Weiss, J. Kästel, M. Fleischhauer, T. Pfau, and H. Giessen, “Plasmonic analogue of electromagnetically induced transparency at the Drude damping limit,” Nat. Mater. 8, 758 (2009).
10. R. Ameling and H. Giessen, “Cavity Plasmonics: Large Normal Mode Splitting of Electric and Magnetic Particle Plasmons Induced by a Photonic Microcavity,” Nano Lett. 10, 4394–4398 (2010).
11. R. Ameling, and H. Giessen, “Microcavity plasmonics: strong coupling of photonic cavities and plasmons,” Laser Photonics Rev. 7(2), 141-169 (2013).
12. K. Kanjanasit and C.H. Wang,. “Fano resonance in a metamaterial consisting of two identical arrays of square metallic patch elements separated by a dielectric spacer,” Appl. Phys. Lett. 102, 251108 (2013).
13. N. Verellen, F. López-Tejeira, R. Paniagua-Domínguez, D. Vercruysse, D. Denkova, L. Lagae, and J. Sánchez-Gil, “Mode parity-controlled Fano-and Lorentz-like line shapes arising in plasmonic nanorods,” Nano Lett. 14(5), 2322-2329 (2014).
14. S.N. Burokur, A. Lupu and A. de Lustrac, “Direct dark mode excitation by symmetry matching of a single-particle-based metasurface,” Phys. Rev. B 91, 035104 (2015).
15. E. Bochkova, S.N. Burokur, A. de Lustrac, and A. Lupu, “Direct dark modes excitation in bi-layered enantiomeric atoms-based metasurface through symmetry matching,” Opt. Lett. 41(2), 412-415 (2016).
16. W. Cao, R. Singh, I.. A.. Al-Naib, M. He, A.. J. Taylor, and W. Zhang, "Low-loss ultra-high-Q dark mode plasmonic Fano metamaterials," Opt. Lett. 37, 3366-3368 (2012)
17. B. Luk’yanchuk, N. I. Zheludev, S. A. Maier, N. J. Halas, P. Nordlander, H. Giessen, and T. C. Chong, “The Fano resonance in plasmonic nanostructures and metamaterials,” Nat. Mater. 9, 707 (2010).
18. J. Wiersig, “Formation of Long-Lived, “Scarlike Modes near Avoided Resonance Crossings in Optical Microcavities,” Phys. Rev. Lett. 97, 253901 (2006).
19. O. Merchiers, F. Moreno, F. Gonzalez, and J.M. Saiz, “Light scattering by an ensemble of interacting dipolar particles with both electric and magnetic polarizabilities,” Phys. Rev. A 76, 043834 (2007).
20. C. Forestiere, L. Dal Negro, and G. Miano, “Theory of coupled plasmon modes and Fano-like resonances in subwavelength metal structures,” Phys. Rev. B 88, 155411 (2013).
21. B. Hopkins, A. N. Poddubny, A. E. Miroshnichenko, and Y. S. Kivshar, “Revisiting the physics of Fano resonances for nanoparticle oligomers,” Phys. Rev. A 88, 053819 (2013).
22. A. Lovera, B. Gallinet, P. Nordlander, and O. J. F. Martin, “Mechanisms of Fano resonances in coupled plasmonic systems,” ACS Nano 7, 4527 (2013).
23. High Frequency Structure Simulator v. 15, Ansys Ltd
24. V. Savinov, V. A. Fedotov and N. I. Zheludev, “Toroidal dipolar excitation and macroscopic electromagnetic properties of metamaterials,” Phys. Rev. B 89, 205112 (2014).
25. E. E. Radescu and G. Vaman, “Exact calculation of the angular momentum loss, recoil force, and radiation intensity for an arbitrary source in terms of electric, magnetic, and toroid multipoles,” Phys. Rev. E 65, 046609 (2002).

26. V. A. Fedotov, A. V. Rogacheva, V. Savinov, D. P. Tsai, and N. I. Zheludev "Resonant transparency and non-trivial non-radiating excitations in toroidal metamaterials," Scientific Reports 3, 2967 (2013).
27. M. Gupta, V. Savinov, N. Xu, L. Cong, G. Dayal, S. Wang, W. Zhang, N. I. Zheludev, and R. Singh, "Sharp toroidal resonances in planar terahertz metasurfaces," Adv. Mater. 28, 8206 (2016).
28. L. Cong, Y. K. Srivastava, and R. Singh, "Tailoring the multipoles in THz toroidal metamaterials," Appl. Phys. Lett. 111, 081108 (2017).
29. A. Dhouibi, S. N. Burokur, A. Lupu, A. de Lustrac, and A. Priou, "Excitation of trapped modes in single element planar metamaterial composed of Z-shaped meta-atom," Appl. Phys. Lett., 103, 184103 (2013).