Supporting Information

Dual control of multi-band resonances with a metal-halide perovskite-integrated terahertz metasurface

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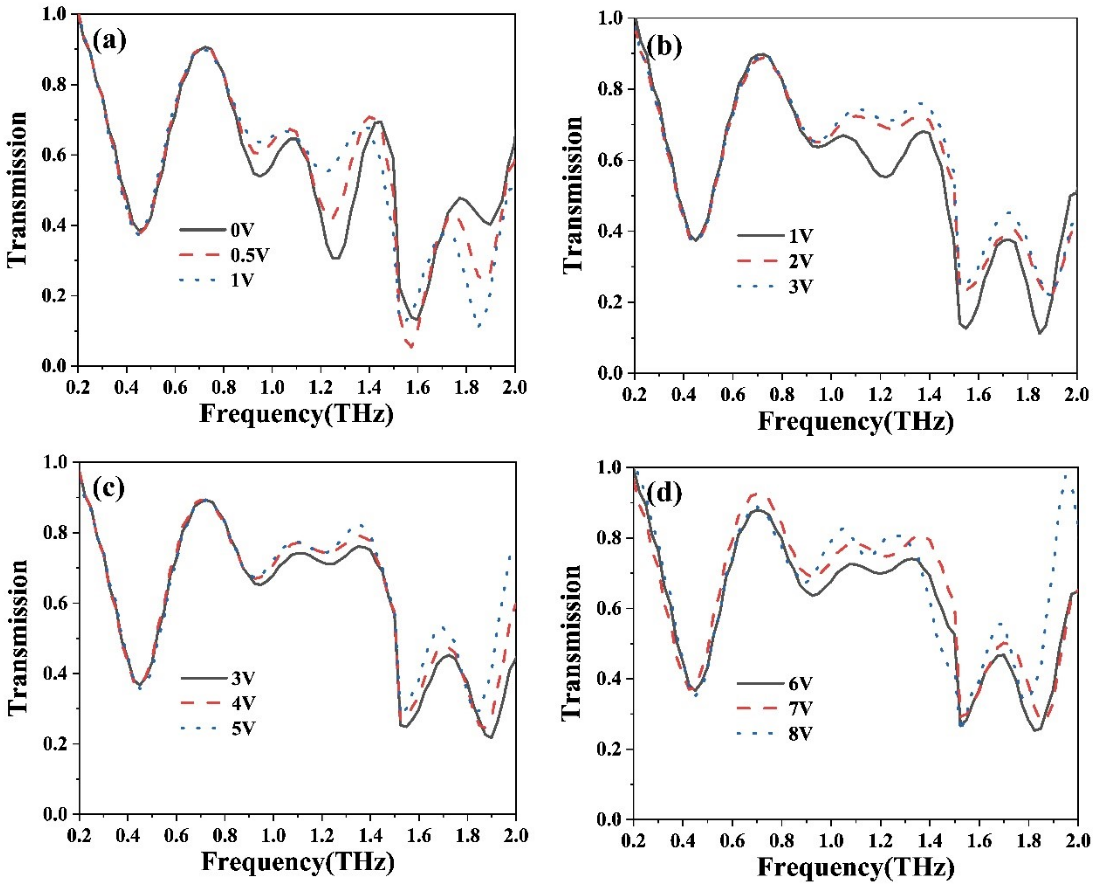


Fig. S1. Transmission modulation of higher-order Fano resonances by the electronic method: (a)- (d) Y-polarized electrical modulation, also by tuning the bias voltage from 0 to 8 V.

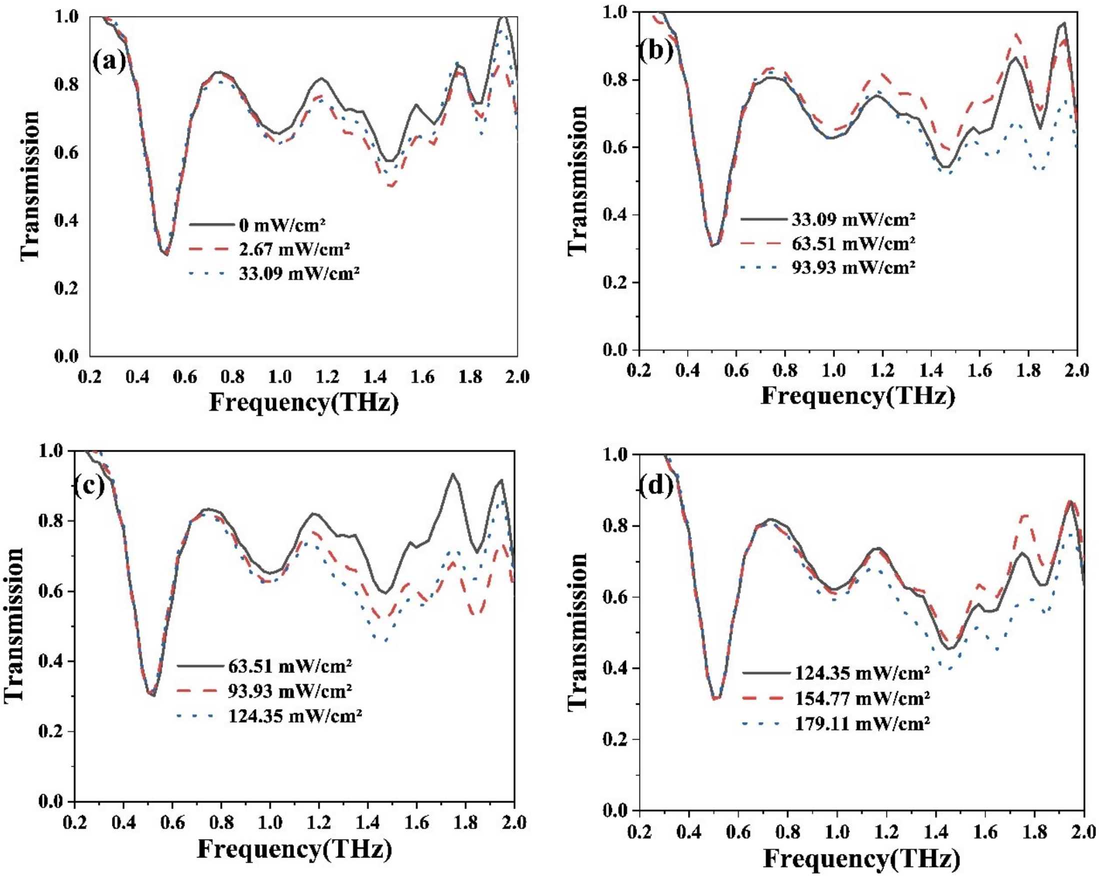


Fig.S2. Transmission modulation of higher-order Fano resonances via the optical method: (a)-(d) Y-polarized optical modulation for the optical pump powers from 0 to 179.11 mW/cm^2.

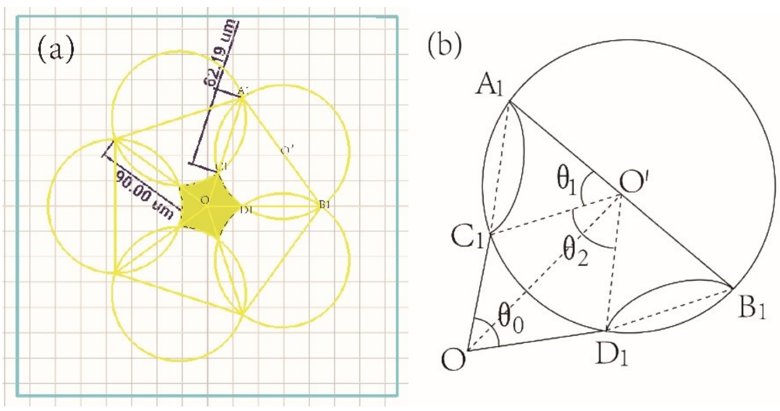


Fig. S3. The calculation process of the arcs (a) the macroscopic schematic diagram of the arc A_1C_1 and C_1D_1 (b) the microscopic schematic diagram of the arc A_1C_1 and C_1D_1.

The coordinate point of O is (0, 0) and the coordinate point of O' is $(x0, y0)$.

Also, $\mathrm{OO'}=\mathrm{R}=90\mu\mathrm{m}$.

In this picture, $x0 = R * cos(rot\_phi) \approx 27.81\mu\mathrm{m}$

Here, $y0 = R * sin(rot\_phi) \approx 85.59\mu m$.

For n=5, $rot\_\deg = 360 / n = 72°$.

And, $rot\_phi = rot\_\deg * 2 * \pi / 360$.

We set $R" = \frac{A_1B_1}{2} = D_1O' = A_1O'$ and $R" = \sqrt{(R - x0)^2 + y0^2}$,

After calculation, we can gain $R" \approx 53.91\mu m$,

By measuring the length of the model of CST software, $A_1C_1 = 62.19\mu m$

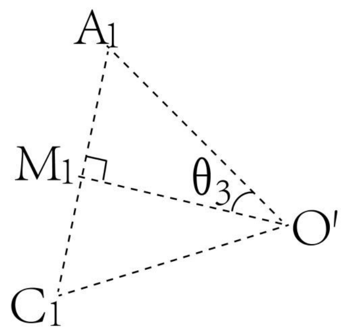


Fig.S4. The calculation process of the center angle corresponding to the arcs

For $\theta_0 = 72°$, we set $\theta_1 = 2 * \theta_3 = \angle A_1O'C_1$,

And, we also set $\theta_2 = \angle C_1O'D_1$; $\theta_2 + 2\theta_1 = \pi(rad)$,

$\theta_3 = \frac{1}{2} * \theta_1$ and $A_1M_1 = \frac{1}{2} A_1C_1 \approx 31.095\mu m$.

$$\sin\theta_3 = \frac{A_1M_1}{A_1O'} = \frac{A_1M_1}{R"} \approx \frac{31.095}{53.91} = 0.57679$$

$$\theta_3 \approx \arcsin(0.57679) \approx 0.6148(rad)$$

$$\theta_1 = 2 * \theta_3 = 1.2296(rad)$$

$$\theta_2 = \pi - \theta_1 * 2 = 0.6824(rad)$$

Thus, the center angle and radius corresponding to the arc A_1C_1 are 53.91μm and 1.2296(rad). While, the center angle and radius corresponding to the arc C_1D_1 are 53.91μm and 0.6824(rad). The curvature of these arcs can be more clearly described by arc lengths and radius.

Table 1. X-polarized electrical dynamic amplitude and its corresponding frequencies

Freq/Voltage	F_{0x}(THz)/Amp	F_{1x}(THz)/Amp	F_{2x}(THz)/Amp	F_{3x}(THz)/Amp	F_{4x}(THz)/Amp
0 V	0.4495/0.3789	0.9490/0.5928	1.2237/0.2964	1.5734/0.1959	1.7732/0.3027
0.5 V	0.4495/0.3859	0.9490/0.5725	1.2487/0.2248	1.5734/0.3598	1.7482/0.3976
1 V	0.4495/0.3826	0.9740/0.6209	1.2237/0.4259	1.5234/0.1420	1.8231/0.1305
2 V	0.4495/0.3730	0.9740/0.6514	1.2237/0.5916	1.5484/0.3701	1.8481/0.2573
3 V	0.4495/0.3657	0.9240/0.6939	1.1988/0.6913	1.5234/0.4561	1.8231/0.3097
4 V	0.4495/0.3712	0.9240/0.6699	1.1988/0.6450	1.4985/0.4168	1.8231/0.2555
5 V	0.4495/0.3673	0.9240/0.6982	1.1738/0.6928	1.4985/0.4829	1.7982/0.2732
7 V	0.4495/0.3617	0.8991/0.7147	1.1238/0.7237	1.4485/0.5751	1.7482/0.3371
8 V	0.4495/0.3601	0.8991/0.7229	1.0989/0.7427	1.4485/0.5826	1.7482/0.3644

Table 2. X-polarized optical dynamic amplitude and its corresponding frequencies

Power/mW/cm^2	**G_{0x}(THz)/Amp**	**G_{1x}(THz)/Amp**	**G_{2x}(THz)/Amp**	**G_{3x}(THz)/Amp**	**G_{4x}(THz)/Amp**
0	0.5244/0.3207	0.9990/0.6198	1.4235/0.4959	1.5984/0.5648	1.7982/0.6841
2.67	0.4995/0.3224	0.9990/0.5735	1.4485/0.4580	1.5984/0.5224	1.8231/0.6054
33.09	0.4995/0.3172	0.9990/0.6161	1.4485/0.4953	1.5984/0.5582	1.7982/0.6346
63.51	0.5244/0.3235	0.9990/0.6648	1.4485/0.5881	1.5984/0.6219	1.7982/0.6582
93.93	0.4995/0.3147	0.9990/0.6554	1.4485/0.5920	1.5984/0.6489	1.7982/0.7193
124.35	0.4995/0.3228	0.9990/0.6324	1.4485/0.5196	1.5984/0.5709	1.7982/0.6422
154.77	0.4995/0.3222	0.9990/0.6408	1.4485/0.5106	1.5984/0.5795	1.7982/0.6652
179.11	0.5244/0.3187	0.9990/0.6628	1.4485/0.5926	1.5984/0.6635	1.7982/0.7132

Table 3. X-polarized electrical dynamic calculated MD and its corresponding frequencies

Freq/Voltage	F_{0x}(THz)/MD(%)	F_{1x}(THz)/ MD(%)	F_{2x}(THz)/ MD(%)	F_{3x}(THz)/ MD(%)	F_{4x}(THz)/ MD(%)
0 V	0.4495/0	0.9490/0	1.2237/0	1.5734/0	1.7732/0
0.5 V	0.4495/1.847	0.9490/-3.42	1.2487/-24.15	1.5734/83.66	1.7482/31.35
1 V	0.4495/0.976	0.9740/4.74	1.2237/43.69	1.5234/-27.51	1.8231/-56.88
2 V	0.4495/-1.55	0.9740/9.88	1.2237/99.59	1.5484/88.92	1.8481/-14.99
3 V	0.4495/-3.48	0.9240/17.05	1.1988/133.23	1.5234/132.82	1.8231/2.31
4 V	0.4495/-2.03	0.9240/13	1.1988/117.61	1.4985/112.76	1.8232/-15.59
5 V	0.4495/-3.061	0.9240/17.78	1.1738/133.73	1.4985/146.50	1.7982/-9.74
7 V	0.4495/-4.53	0.8991/20.56	1.1238/144.16	1.4485/193.56	1.7482/11.36
8 V	0.4495/-4.96	0.8991/21.94	1.0989/150.57	1.4485/197.39	1.7482/20.38
MD range(%)	6.807	25.36	174.72	224.9	77.26

Table 4. X-polarized optical dynamic calculated MD and its corresponding frequencies

Freq/Power	G_{0x}(THz)/MD(%)	G_{1x}(THz)/ MD(%)	G_{2x}(THz)/ MD(%)	G_{3x}(THz)/ MD(%)	G_{4x}(THz)/ MD(%)
0 mW/cm^2	0.5244/0	0.9990/0	1.4235/0	1.5984/0	1.7982/0
2.67 mW/cm^2	0.4995/0.53	0.9990/-7.47	1.4485/-7.64	1.5984/-7.50	1.8231/-11.50
33.09 mW/cm^2	0.4995/-1.09	0.9990/-0.59	1.4485/-0.12	1.5984/-1.168	1.7982/-7.23
63.51 mW/cm^2	0.5244/0.87	0.9990/7.26	1.4485/18.59	1.5984/10.10	1.7982/-3.78
93.93 mW/cm^2	0.4995/-1.87	0.9990/5.74	1.4485/19.37	1.5984/14.89	1.7982/0.7193
124.35 mW/cm^2	0.4995/0.65	0.9990/2.03	1.4485/4.77	1.5984/1.08	1.7982/5.14
154.77 mW/cm^2	0.4995/0.46	0.9990/3.38	1.4485/2.96	1.5984/2.60	1.7982/-2.76
179.11 mW/cm^2	0.5244/-0.62	0.9990/6.93	1.4485/19.49	1.5984/17.47	1.7982/4.25
MD range(%)	2.74	14.73	27.13	24.97	16.64

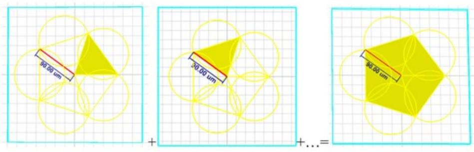
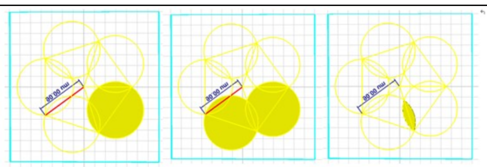
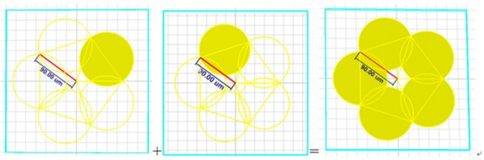
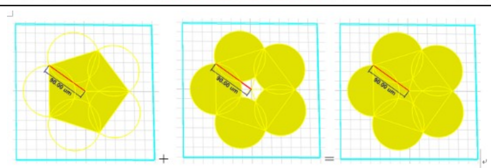
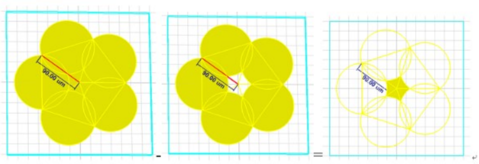
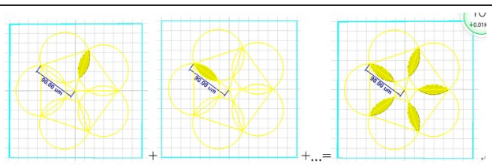
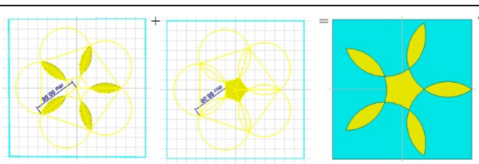
Table 5. X-polarized electrical dynamic calculated frequency shifts and their corresponding frequencies

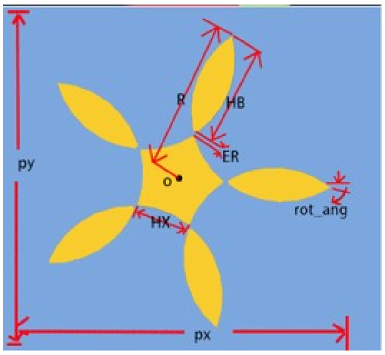
Freq/Voltage	F_{0x}(THz)/frequency shift(GHz)	F_{1x}(THz)/frequency shift(GHz)	F_{2x}(THz)/frequency shift(GHz)	F_{3x}(THz)/frequency shift(GHz)	F_{4x}(THz)/ frequency shift(GHz)
0 V	0.4495/0	0.9490/0	1.2237/0	1.5734/0	1.7732/0
0.5 V	0.4495/0	0.9490/0	1.2487/25	1.5734/0	1.7482/-25
1 V	0.4495/0	0.9740/25	1.2237/0	1.5234/-50	1.8231/49.9
2 V	0.4495/0	0.9740/25	1.2237/0	1.5484/-25	1.8481/74.9
3 V	0.4495/0	0.9240/-25	1.1988/-24.9	1.5234/-50	1.8231/49.9
4 V	0.4495/0	0.9240/-25	1.1988/-24.9	1.4985/-74.9	1.8231/49.9
5 V	0.4495/0	0.9240/-25	1.1738/-49.9	1.4985/-74.9	1.7982/25
7 V	0.4495/0	0.8991/-49.9	1.1238/-99.9	1.4485/-124.9	1.7482/-25
8 V	0.4495/0	0.8991/-49.9	1.0989/-124.8	1.4485/-124.9	1.7482/-25
Shift Range (GHz)	0	74.9	149.8	124.9	99.9

Table 6. X-polarized optical dynamic calculated frequency shifts and their corresponding frequencies

Freq/Opitcal	G_{0x}(THz) /frequency shift(GHz)	G_{1x}(THz) /frequency shift(GHz)	G_{2x}(THz) /frequency shift(GHz)	G_{3x}(THz) /frequency shift(GHz)	G_{4x}(THz)/ /frequency shift(GHz)
0 mW/cm^2	0.5244/0	0.9990/0	1.4235/0	1.5984/0	1.7982/0
2.67 mW/cm^2	0.4995/-24.9	0.9990/0	1.4485/25	1.5984/0	1.8231/24.9
33.09 mW/cm^2	0.4995/-24.9	0.9990/0	1.4485/25	1.5984/0	1.7982/0
63.51 mW/cm^2	0.5244/0	0.9990/0	1.4485/25	1.5984/0	1.7982/0
93.93 mW/cm^2	0.4995/-24.9	0.9990/0	1.4485/25	1.5984/0	1.7982/0
124.35 mW/cm^2	0.4995/-24.9	0.9990/0	1.4485/25	1.5984/0	1.7982/0
154.77 mW/cm^2	0.4995/-24.9	0.9990/0	1.4485/25	1.5984/0	1.7982/0
179.11 mW/cm^2	0.5244/0	0.9990/0	1.4485/25	1.5984/0	1.7982/0
Shift Range (GHz)	24.9	0	25	0	24.9

Table 7. The drawing process of the unit cell for the metasurface

Step1		First, we make a triangle with R=90 um as the radius and the center angle of 360/n=360/5=72°. Then, we rotate the triangle five times with the Z axis to obtain a regular pentagon. One side of the triangle is parallel to the X axis. Five triangles are combined by Boolean operation (ADD) to obtain Part 1.
Step2		We toke the midpoint of the hypotenuse of the triangle as the center of the circle. Its coordinate point is (x0,y0). We also toke the half of the hypotenuse of the triangle as the radius to draw a single circle. The intersection between the two adjacent circles is named as part 2. $x0 = R * cos(rot\_phi) \approx 27.81 \mu m$ $y0 = R * sin(rot\_phi) \approx 85.59 \mu m$
Step3		Rotate the single circle in the previous step for five times with the z-axis to obtain Part 3.
Step4		Add Part 1 and part 3 by Boolean operation to obtain Part 4.
Step5		Subtract Part 4 and part 3 by Boolean operation to obtain Part 5.
Step6		An intersection between two adjacent circles can be obtained as part 2. Add all the Boolean operations of part 2 to obtain part 6.
Step7		Part 5 and part 6 are added by Boolean operation to form part 7.

Step 8		We rotate the obtained metasurface in the counterclockwise direction, In order to achieve the sharpest S-parameters curves at all the resonant frequencies, the rotated angle of the unit cell can be achieved by the scanning function in the CST software. By a lot of simulation process, the optimization goal was achieved when the rot_angle equals to π/60(rad) in Figure 1.

The videos for the electric fields of the five resonant frequencies are attached as follows,

0.61THz.mp4 0.8025THz.mp4 1.03THz.mp4 1.4175THz.mp4 1.5875THz.mp4