Supporting Information

Generating and Manipulating Higher Order Fano Resonances in Dual-Disk Ring Plasmonic Nanostructures

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The spectra as a function of the thickness of the SDDR

Figure S1 shows the extinction (Figure S1a) and absorption (Figure S1b) spectra as a function of the thickness h of the symmetric dual-disk ring (SDDR) nanostructure with $a_1 = a_2 = 40$ nm. A resonance peak appears when the thickness of the nanostructure increases to 50 nm, which is pointed by the arrow. The resonance peak is red shift with the increasing of the thickness of the nanostructure and overlaps the Fano resonance.

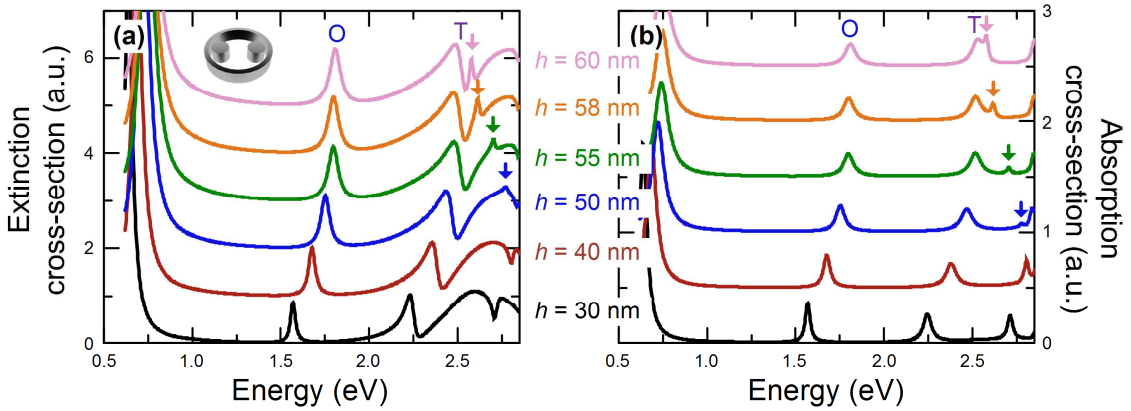

Figure S1. (a) Extinction and (b) absorption spectra as a function of the thickness h of the symmetric dual-disk ring (SDDR) nanostructure with $a_1 = a_2 = 40$ nm. The arrow indicates that a resonance peak appears when the thickness increases to 50 nm. The letters "O" and "T" represent octupolar and triakontadipolar Fano resonances, respectively.

The similar calculations of values of the FOM and the CR for various SDDR and ADDRs

Figure S2 shows the similar calculations of the figure of merit (FOM) and the contrast ratio (CR) for the symmetric dual-disk ring (SDDR) nanostructure with the larger size of the disks (a_1 = a_2 = 50 nm) and the asymmetric dual-disk ring (ADDR) nanostructures with a_1 = 40 nm and various a_2 = 50 nm and 100 nm respectively. The sensitivities of the octupolar Fano resonance (O mode, at 1.81 eV) and the triakontadipolar Fano resonance (T mode, at 2.53 eV) are 0.84 eV RIU^{-1} and 1.06 eV RIU^{-1}. According to the Fano line-shapes, the calculated values of the FOM and the CR are showed in each plot respectively.

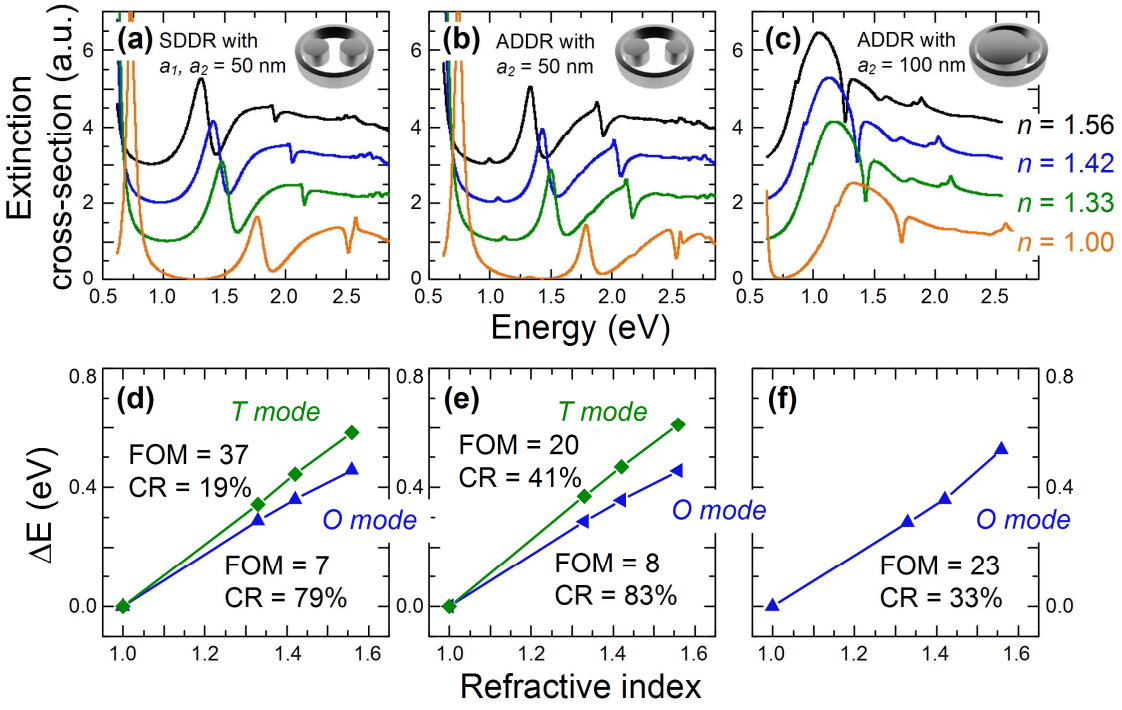

Figure S2. (a-c) Extinction spectra and (d-f) energy shifts of the resonances of (a,d) a symmetric dual-disk ring (SDDR) structure with a_1 = a_2 = 50 nm, (b,e) an asymmetric dual-disk ring (ADDR) structure with a_1 = 40 nm and a_2 = 50 nm, and (c,f) an ADDR structure with a_1 = 40 nm and a_2 = 100 nm for the surrounding media with refractive index at n = 1.00, 1.33, 1.42 and 1.56, respectively. The O mode and T mode are the octupolar Fano resonances (at 1.81 eV in a-c) and the triakontadipolar Fano resonance (at 2.53 eV in a-b) respectively. The corresponding values of the figure of merit (FOM) and contrast ratio (CR) are shown in the plots.

The spectra of NCSDRs and SDDRs of using gold

Figure S3 shows the extinction (dark blue curve), scattering (green curve) and absorption (light red curve) spectra of disk-ring plasmonic nanostructures with gold (Au). Figure S3a and S3b are a NCSDR and a SDDR plasmonic nanostructure with the same size of using silver (Ag) respectively. It also shows that the quadrupolar and the hexadecapolar Fano resonances are suppressed, while the octupolar and the triakontadipolar Fano resonances are enhanced in SDDR with gold. However, the robustness of the triakontadipolar Fano resonance is week due to the highly dissipating of gold in the spectrum ranges above 2 eV. In Figure S3c to S3g, we optimize some parameters of the Au SDDR nanostructures. The radii of the disks, the gaps and the width of the ring are fixed ($a_1 = a_2 = 60$ nm, $g_1 = g_2 = 10$ nm, $r_o - r_i = 20$ nm), and inner radius of the ring r_i is varied. The triakontadipolar Fano resonance appears on the right shoulder of the disk mode's resonance as shown in Figure S3c, and shifts to the left shoulder in Figure S3d to S3g; meanwhile the bandwidth increase and robustness become strong. In the case of Figure S3f, the bandwidth of the triakontadipolar Fano resonance is as narrow as the bandwidth by using silver. Figure S3i and S3j are the extinction spectra of the Au NCSDR and the Au SDDR nanostructures with the same parameters in Figure S3f respectively. Figure S3j is the extinction spectrum of the Ag SDDR with $r_i = 130$ nm, $r_o = 150$ nm, $a_1 = a_2 = 40$ nm and $g_1 = g_2 = 10$ nm. As a result we can see that in spite of higher dissipation of gold compare to silver it is possible to generate some higher order resonances almost with the same efficiency (see Figure S3h, S3i and S3j).

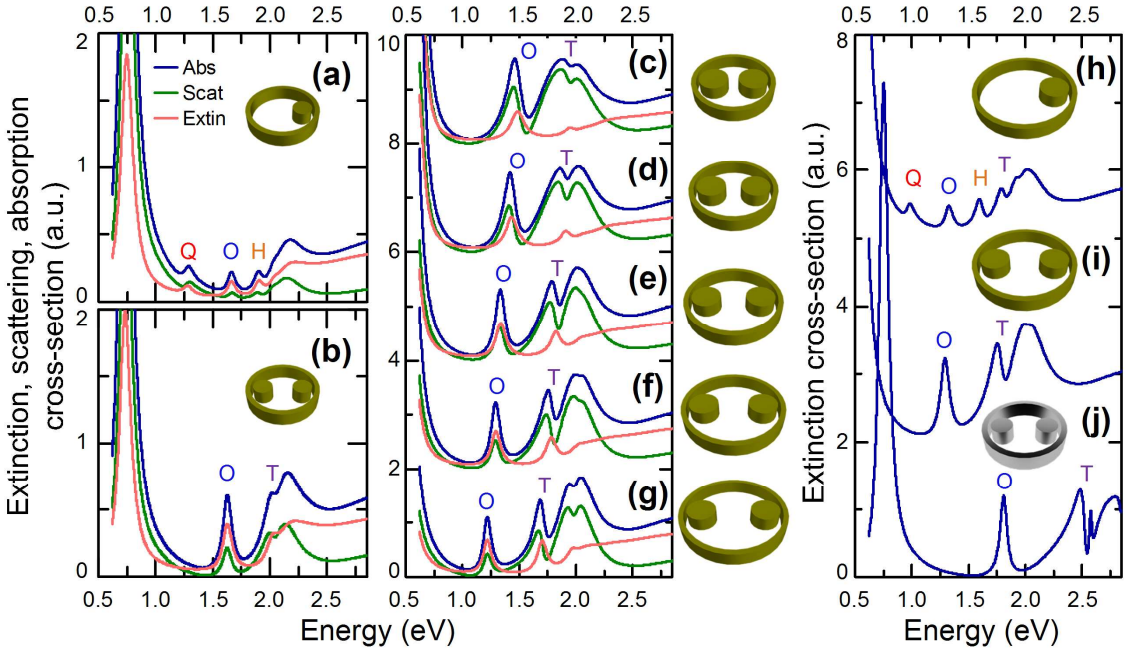

Figure S3. Extinction (dark blue curve), scattering (green curve) and absorption (light red curve) spectra of disk-ring plasmonic nanostructures with gold (Au), (a) a nonconcentric single-disk ring (NCSDR) nanostructure with r_i = 130 nm, r_o = 150 nm, a_1 = 40 nm and g_1 = 10 nm, (b) a symmetric dual-disk ring (SDDR) nanostructure with same parameters in (a). (c-g) Au SDDR nanostructures with fixed $a_1 = a_2$ = 60 nm, $g_1 = g_2$ = 10 nm, r_o - r_i = 20 nm and various r_i, where (c) r_i = 150 nm, (d) r_i = 160 nm , (e) r_i = 180 nm, (f) r_i = 190 nm and (g) r_i = 210 nm. (h,i) Extinction spectra of the Au NCSDR and the Au SDDR nanostructures with the same parameters in (f), respectively. (j) Extinction spectrum of the Ag SDDR with r_i = 130 nm, r_o = 150 nm, $a_1 = a_2$ = 40 nm and $g_1 = g_2$ =10 nm. The letters “Q”, “O”, “H”, and “T” represent quadrupolar, octupolar, hexadecapolar, and triakontadipolar Fano resonances, respectively.