magnetic quadrupole Q_{m}, are smaller in strength by 3-4 orders than that scattered by the dipoles.

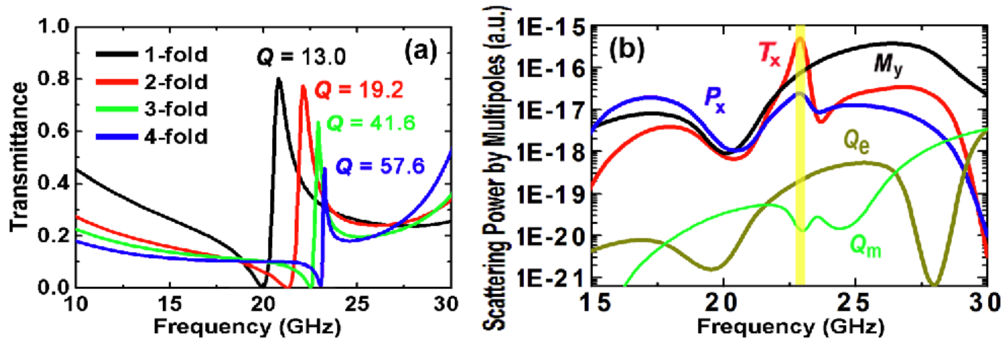

Fig. 4. (a) Transmittance spectra for multifold double-ring metamaterials, where a high quality factor (Q) is obtained for the well-shaped torus-like metamolecule (4-fold case). The incident wave propagates along the z-direction with polarized electric-field component in the x-direction, as specified in Fig. 1. (b) The scattering powers of toroidal dipole (T_x), electric dipole (P_x), electric quadrupole (Q_{e}), magnetic dipole (M_y), and magnetic quadrupole (Q_m) calculated from the 4-fold structure. The yellow shadow is for eye guide.

4. Summary

In summary, we numerically investigate the toroidal dipole response, represented by the closed distribution of head-to-tail magnetic dipoles, in a torus-like metamaterial composed of multifold double-ring resonators, by virtue of the antibonding magnetic-dipole mode. In essence, the subradiant-mode excitation in symmetry-broken configurations, induced by the nonuniform near-field environment, is responsible for the formation of the intriguing toroidal dipole response. As a consequence, a high quality factor for the resonance spectrum is observed in the well-shaped toroidal metamaterial with 4-fold double rings. Such a metamaterial analogue of the toroidal dipole moment should be helpful in further understandings of the underlying mechanism related to the elusive toroidal electromagnetic response, which will contribute to potential applications regarding to sensing, magnetoelectric effect, and polarization controllability.

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