Supplementary Materials

Donor-Acceptor Modified Ixiolite Structural Ceramic for Millimeter-wave Broadband Metamaterial Devices

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Multipole Decomposition Process

In multipole decomposition process for our mode-coupling, I was the radiating power of multipoles, P was the electric dipole moment, M was the magnetic dipole moment, T was the toroidal dipole moment and $Q_{\alpha\beta}$ was the electric quadrupole moment. The distribution of the multipoles upon could be expressed as followed.

$$P = \frac{1}{i\omega}\int j d^3 r \tag{S1.1}$$

$$M = \frac{1}{2c}\int (r \times j) d^3 r \tag{S1.2}$$

$$T = \frac{1}{10c}\int \left[(r \cdot j) r - 2r^2 j\right] d^3 r \tag{S1.3}$$

$$Q_{\alpha\beta} = \frac{1}{i\omega}\int \left[r_\alpha j_\beta + r_\beta j_\alpha - \frac{2}{3}(r \cdot j)\right] d^3 r \tag{S1.4}$$

…

Moreover, j was current density and c was the speed of light .

Geometric Design

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In mode-coupling process here, the influence of geometry was important, which mainly affected the distribution of coupling field in the metamaterial unit cell, showing varied S-parameters. Here, we studied the change of mode-coupling by adjusting the x-axis dimension (electric field direction), the rest simulation and normalized multipole decomposition results calibrated by ED scattering under different geometries (... , 2.4×2×1.1 mm^3, 2.5×2×1.1 mm^3, ... , 2.7×2×1.1 mm^3, 2.8×2×1.1 mm^3, ...) were exhibited in Figure.S1.

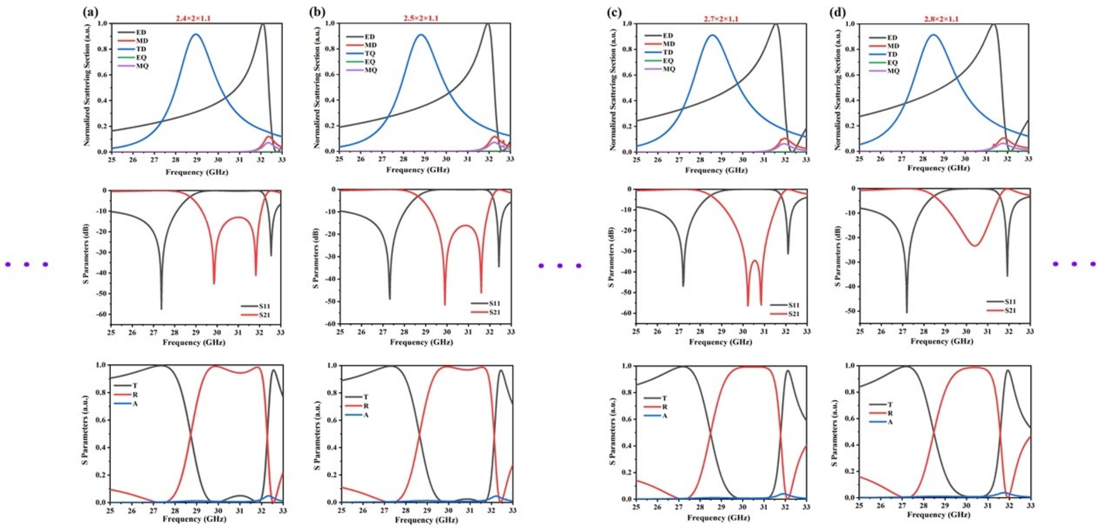

Fig. S1 Simulation and normalized multipole decomposition results calibrated by ED scattering under different geometries (a) 2.4×2×1.1 mm^3, (b) 2.5×2×1.1 mm^3, (c) 2.7×2×1.1 mm^3, and (d) 2.8×2×1.1 mm^3.

With the increase of length in x-axis direction, the coupling of ED and MD gradually enhanced. Obviously, in the results of S parameters, weak coupling meant that the insertion loss of broadband reflectors was large. On the contrary, strong coupling hindered the realization of broadband characteristic here. Thus, we chose 2.6×2×1.1 mm^3 for appropriate coupling of ED and MD, achieving low insertion loss and broadband characteristic simultaneously.