Supplementary of the: Significant enhancement of magnetic shielding effect by using the composite metamaterial composed of mu-near-zero media and ferrite

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1. Simplified circuit diagram of metamaterial unit.

The elements of the unit shown in figure S1 are connected in series and the lumped capacitance value is 8.2nf, and the inductance of the coil is 0.55mH. The coil provides inductance and combines with lumped capacitance and a small amount of distributed capacitance to form a resonance. No matter in the high or low power system, the energy absorbed by the structure itself can be ignored, and no heat phenomenon will occur. Due to the weak skin effect of the Litz line at low frequencies, the resistance value of the structure is extremely low and can be ignored.

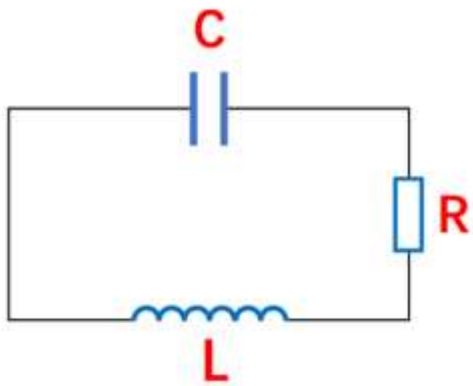

Fig S1. The circuit diagram of metamaterial unit

2. Parameter data of the ferrite material.

We chose a ferrite material with high permeability at low frequencies. In all experimental samples with ferrite, commercial MnZn ferrite was used. The initial permeability is shown in Fig S2. It has a high initial permeability of about 3000 at low frequencies (<1MHz). The same parameters were also set in the simulation.

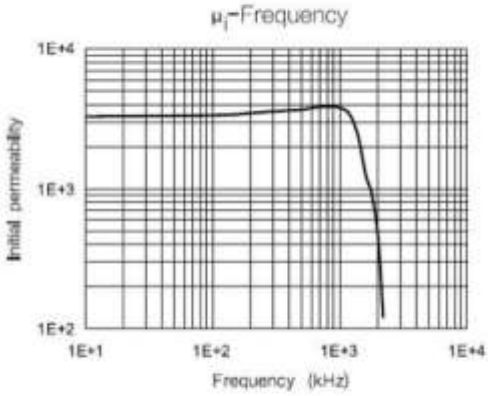

Fig S2. The permeability of the MnZn ferrite material.

3. Modeling diagram in simulation.

The model established in the commercial CST studio suite software.

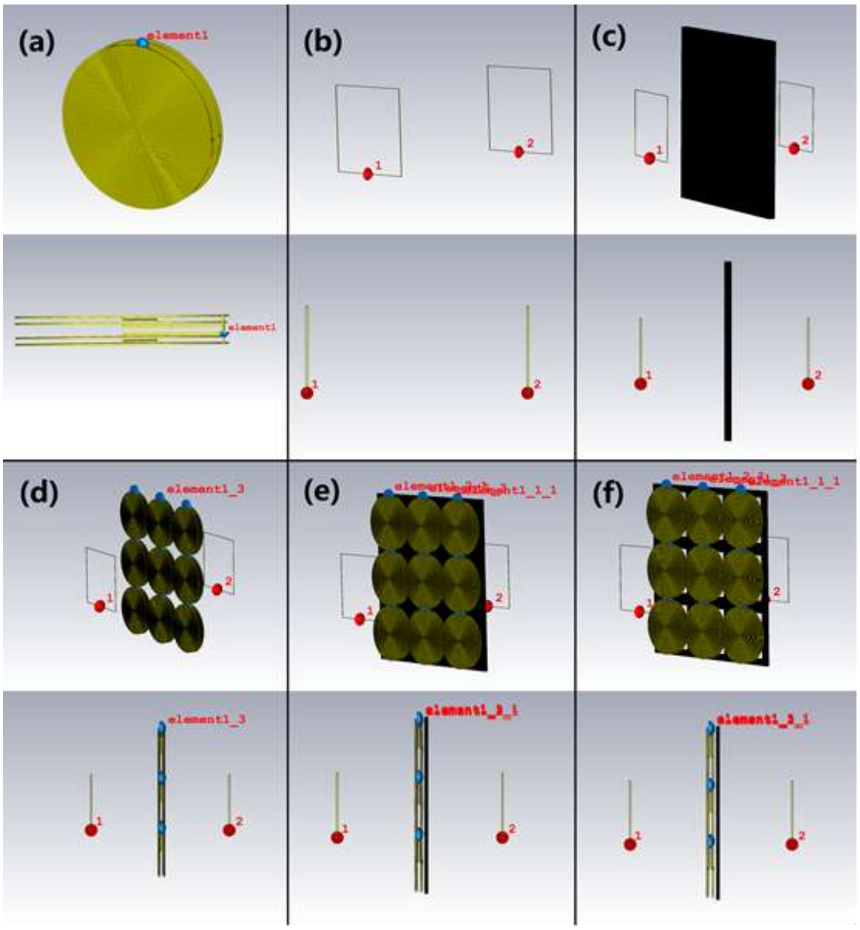

Fig S3. Model diagrams of various schemes used in simulation.

Fig.S3 (a) shows the unit structure of the metamaterial. Use copper wires instead of litz wires and increase the gap between them to ensure insulation between wires and between disks. Fig.S3 (b) shows a non-resonant near-field system. Use a simplified single-turn copper coil model with a side length of 53mm and a copper wire diameter of 1mm. Fig.S3 (c) is a model of a single ferrite slab solution. Fig.S3 (d) is the model of MNZ metamaterial. Fig.S3 (e) shows the composite metamaterial with a bulk ferrite model. Fig.S3 (f) is the model of composite metamaterial with a patterned ferrite material.

4. The shielding effectiveness (SE) of each scheme when the distance between Tx coil and Rx coil is 120mm.

We have added a set of comparative experiments. Change the distance between the Tx coil and the Rx coil in the non-resonant system to 120 mm. Then, the same as the previous measurement method, the SE of the four scenarios were obtained.

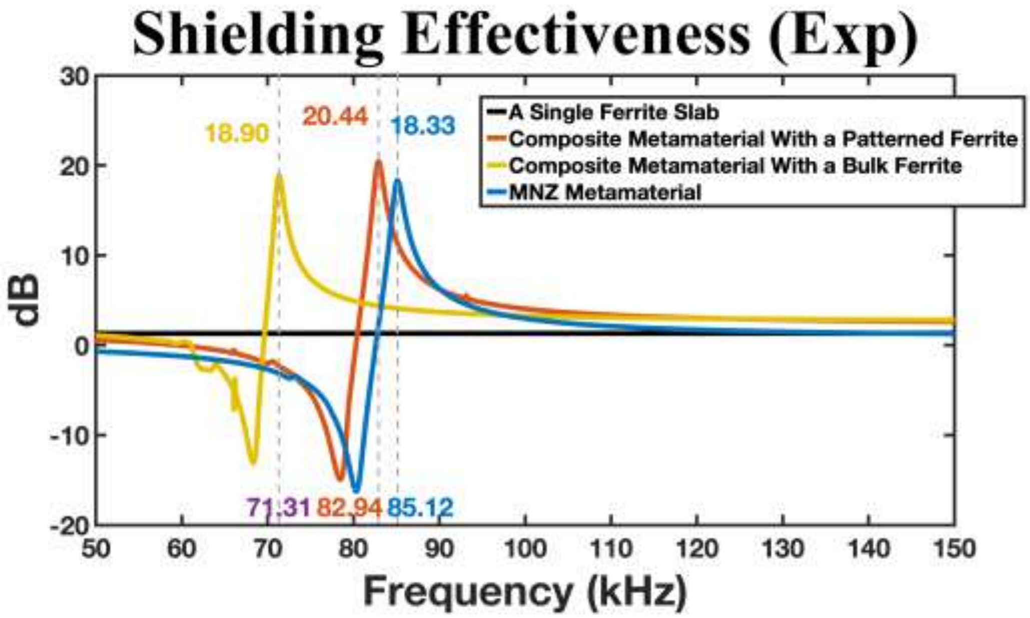

Fig S4. Shielding effectiveness (SE) measured in the experiment. The distance between TX and RX is 120mm.

As shown in Figure S4, when the distance between Tx coil and Rx coil is 120mm, the maximum SE of composite metamaterial with a patterned ferrite is 20.44dB at 82.94kHz, and the maximum SE of composite metamaterial with a bulk ferrite is 18.90dB at 71.37kHz. The maximum SE of MNZ metamaterial is 18.33dB at 85.12 kHz, and the SE of a single ferrite slab is only 1.4dB.

5. Shielding effectiveness (SE) of a single ferrite slab of different thickness.

The SE of a single ferrite slab measured in the experiment. When the distance between the Tx coil and the Rx coil is 120mm, we gradually increase the thickness of the ferrite slab without changing the area of the slab. The measured frequency is 82.94 kHz (the same as the frequency at the maximum SE of the composite metamaterial with a patterned ferrite under the same conditions).

As shown in Table 1, when the thickness of a single ferrite slab is increased to 20mm, its shielding effect is only 4.793dB. At this time, the quality of the ferrite material is already quite high. However, its SE value is still much smaller than that of a composite magnetic shielding metamaterial with the same area but only 4mm thick.

Serial number	The thickness of the Ferrite Board scheme	Shielding effectiveness
1	6mm	3.324
2	8mm	3.541
3	10mm	3.759
4	12mm	3.966
5	14mm	4.175
6	16mm	4.373
7	18mm	4.573
8	20mm	4.793

Table 1. The measured SE of a single ferrite slab when the distance between the Tx and Rx coils is 60mm and the selected frequency is 82.94kHz.

As with the previous method, the distance between the Tx coil and the Rx coil was increased to 150mm. We still keep the area of a single ferrite slab unchanged (the area is the same as the composite metamaterial), gradually increase the thickness of the ferrite plate and test its SE value. The measured frequency is 82.25 kHz (the same as the frequency at the maximum SE of the composite metamaterial with a patterned ferrite under the same conditions).

Serial number	The thickness of the Ferrite Board scheme	Shielding effectiveness
1	6mm	1.570
2	8mm	1.693
3	10mm	1.876

4	12mm	2.021
5	14mm	2.183
6	16mm	2.326
7	18mm	2.470
8	20mm	2.612

Table 2. The measured SE of a single ferrite slab when the distance between the Tx and Rx coils is 150 mm and the selected frequency is 82.25 kHz.

As shown in Table 2, we have observed a situation similar to Table 1. Increasing the thickness of a single ferrite slab does not significantly increase its SE. When the thickness of a single ferrite slab is increased to 20mm (the mass of the ferrite at this time is already quite large), its SE is only 4.793dB. This is much smaller than the SE of a composite magnetic shielding metamaterial with the same area but only a thickness of only 4mm.