

Reporting Summary

Nature Portfolio wishes to improve the reproducibility of the work that we publish. This form provides structure for consistency and transparency in reporting. For further information on Nature Portfolio policies, see our [Editorial Policies](#) and the [Editorial Policy Checklist](#).

Statistics

For all statistical analyses, confirm that the following items are present in the figure legend, table legend, main text, or Methods section.

n/a Confirmed

- | | | |
|-------------------------------------|-------------------------------------|--|
| ☐ | ☒ | The exact sample size (n) for each experimental group/condition, given as a discrete number and unit of measurement |
| ☐ | ☒ | A statement on whether measurements were taken from distinct samples or whether the same sample was measured repeatedly |
| ☒ | ☐ | The statistical test(s) used AND whether they are one- or two-sided
<i>Only common tests should be described solely by name; describe more complex techniques in the Methods section.</i> |
| ☐ | ☒ | A description of all covariates tested |
| ☐ | ☒ | A description of any assumptions or corrections, such as tests of normality and adjustment for multiple comparisons |
| ☒ | ☐ | A full description of the statistical parameters including central tendency (e.g. means) or other basic estimates (e.g. regression coefficient) AND variation (e.g. standard deviation) or associated estimates of uncertainty (e.g. confidence intervals) |
| ☒ | ☐ | For null hypothesis testing, the test statistic (e.g. F , t , r) with confidence intervals, effect sizes, degrees of freedom and P value noted
<i>Give P values as exact values whenever suitable.</i> |
| ☒ | ☐ | For Bayesian analysis, information on the choice of priors and Markov chain Monte Carlo settings |
| ☐ | ☒ | For hierarchical and complex designs, identification of the appropriate level for tests and full reporting of outcomes |
| ☒ | ☐ | Estimates of effect sizes (e.g. Cohen's d , Pearson's r), indicating how they were calculated |

Our web collection on [statistics for biologists](#) contains articles on many of the points above.

Software and code

Policy information about [availability of computer code](#)

Data collection DFT calculations were performed using Materials Studio with GGA/PBE functional. Micromagnetic simulations were performed using Mumax3 (v3.10). RCS simulations were performed using CST Studio Suite 2024.

Data analysis OriginPro 2021 and Peakfit 4.12 were used for XPS data analysis and fitting.

For manuscripts utilizing custom algorithms or software that are central to the research but not yet described in published literature, software must be made available to editors and reviewers. We strongly encourage code deposition in a community repository (e.g. GitHub). See the Nature Portfolio [guidelines for submitting code & software](#) for further information.

Data

Policy information about [availability of data](#)

All manuscripts must include a [data availability statement](#). This statement should provide the following information, where applicable:

- Accession codes, unique identifiers, or web links for publicly available datasets
- A description of any restrictions on data availability
- For clinical datasets or third party data, please ensure that the statement adheres to our [policy](#)

The data supporting the findings of this study are available within the article and the Supplementary Information. Source data are provided with this paper.

Research involving human participants, their data, or biological material

Policy information about studies with [human participants or human data](#). See also policy information about [sex, gender \(identity/presentation\), and sexual orientation](#) and [race, ethnicity and racism](#).

Reporting on sex and gender

Reporting on race, ethnicity, or other socially relevant groupings

Population characteristics

Recruitment

Ethics oversight

Note that full information on the approval of the study protocol must also be provided in the manuscript.

Field-specific reporting

Please select the one below that is the best fit for your research. If you are not sure, read the appropriate sections before making your selection.

☐ Life sciences ☐ Behavioural & social sciences ☒ Ecological, evolutionary & environmental sciences

For a reference copy of the document with all sections, see nature.com/documents/nr-reporting-summary-flat.pdf

Ecological, evolutionary & environmental sciences study design

All studies must disclose on these points even when the disclosure is negative.

Study description

This study does not employ an empirical research design nor incorporate quantitative experimental data. Consequently, concepts such as treatment factors, factor interactions, and experimental units are not applicable and therefore not reported. In this work, single-phase Zr⁴⁺-doped high-entropy M-type ferrites have been successfully synthesized for the first time via an iron-deficient strategy. It is found that iron vacancies are beneficial for eliminating the impurities in the high-entropy ferrites, which ascribes to the enhanced entropy value and a more adaptable local structural environment. The synergistic effect of high entropy and iron vacancies amplifies the dielectric loss capacity, while adeptly modulating the magnetic resonance behavior to broaden the magnetic loss range of M-type ferrite through Zr⁴⁺ doping. This intricate optimization of electromagnetic parameters consequently elevates the absorbing performance characteristics within the millimeter-wave atmospheric window around 35 GHz, achieving an extensive effective absorption bandwidth of 12.18 GHz and a remarkable reflection loss of -45.98 dB under a thin matching thickness of less than 1 mm.

Research sample

Our work does not involve any empirical study, nor does it include biological samples, organisms, or existing datasets of that nature. Therefore, the requested information regarding sample description, organism taxa, sex, age range, manipulations, population representativeness, or data sources is not applicable to our study.

Sampling strategy

There is no sampling procedure, no sample size calculation, and no statistical predetermination of sample size applicable to this study.

Data collection

Material Characterizations
X-ray diffraction (XRD, model Bruker D8 ADVANCE) was utilized to identify the crystal structure and X-ray photoelectron spectroscopy (XPS, PHI 5000 Versa probe) was performed to analyze the element states. Fe L_{2,3} edge XAS/XMCD spectra were collected in total-electron-yield mode, which were carried out on SINS beamline at the Hefei Light Source. The morphologies were characterized by scanning electron microscope (SEM, Hitachi S-4800), transmission electron microscope (TEM, JEOL ARM200F). The magnetic domain structures were analyzed by magnetic force microscope (AFM, Shimadzu SPM-9700HT). Hysteresis loops were measured by a magnetic property measurement system (MPMS-XL-5). The electromagnetic parameters in the range of 26.5-40 GHz (Ka band) were carried out using a vector network analyzer (Ceyear 3672C), wherein the test samples are made by high-entropy M type ferrite and paraffin wax with mass ratio of 8:2. These mixtures were subsequently pressed into toroidal-shaped specimens for measuring electromagnetic parameters with an inner diameter of 3.04 mm, an outer diameter of 7.00 mm, and a thickness ranging from 2.0 mm to 3.0 mm.

Differential Charge Density and Electronic Band Structure Calculations

The differential charge density maps and electronic band structures of the various M-type ferrites were calculated based on density functional theory (DFT) by using Materials Studio software. The DFT calculations in this work were performed using the experimentally determined room-temperature crystal structure, which aim to elucidate the intrinsic electronic-structure-based mechanisms relevant to the observed macroscopic properties. The electron-ion interaction and the exchange-correlation function were based on the Generalized-Gradient-Approximation (GGA) with the Perdew-Burke-Ernzerhof (PBE) generalized gradient approximation. On the basis of the experimental results, different types of M-type ferrite were applied as calculated models using their single cells. A Monkhorst-Pack grid size of 5×5×1 was employed for surface calculations. The cut-off energy for plane wave expansions was set at 571.40 eV. Convergence tolerance optimization was performed for energy with values set at 1.0×10⁻⁶ eV.

Gibbs Free Energy Calculations

Gibbs free energy values of the various M-type ferrites were calculated by a combination of DFT calculation and manual calculation through the following Eq. 4, where formation enthalpy was obtained by DFT calculation while configurational entropy was manually calculated on the basis of Eq. 5.

$$\Delta G = \Delta H - T\Delta S \quad (4)$$

$$\Delta S = -R \left(\sum_{i=1}^N x_i \ln x_i \right) \quad (5)$$

where R , $N(M)$, and x_i refer to the gas constant, atomic species, and contents at the cation sites, respectively. For the Fe deficient systems, the vacancy is also treated as a distinct species on the cation sublattice.

Micromagnetic Simulations

Micromagnetic simulations were executed by Mumax3 software, aimed to evaluate the dynamic evolution process of magnetic vortices and analyze their behaviors by construction of material spheres with a radius of 200 nm. The damping factor of spin precession was 0.01, and the external magnetic field frequency was 30 GHz. The attached software Muvview was applied to visualize the results calculated by Mumax3.

RCS Simulations

RCS simulations of the PEC plate with size of 110 mm×110 mm×0.07 mm were carried out using CST Studio Suite 2018 software package with and without the high-entropy M type ferrite coatings. The electric boundary was established as an open boundary condition, while the excitation frequency was meticulously selected at 32, 35 and 38 GHz. The Z-axis represents the incident direction of the electromagnetic wave, and the detection angle was taken within the range from -90° to 90°.

C.Y.L., Y.J.Z. and G.B.J. conceived, designed and supervised the project. C.Y.L., Y.F. and X.Y.X carried out most of the experiments/ calculations, analyzed the data and co-wrote the manuscript. E.L., Y.Y.S., P.Y. and D.H.K. conducted data curation and reviewed & edited the manuscript. All the authors contributed to the analysis and interpretation of the data.

Timing and spatial scale	As our work does not involve any empirical datasets, the requested information regarding data collection dates, sampling frequency, cohort gaps, or spatial scale is not applicable to our manuscript.
Data exclusions	No data were excluded from the analyses.
Reproducibility	All attempts to repeat the experiment were successful.
Randomization	Data obtained under the same testing conditions were allocated into the same group.
Blinding	Blinding procedures are not used because the study is not a clinical trial or any human-subject experiment.
Did the study involve field work?	☐ Yes ☒ No

Reporting for specific materials, systems and methods

We require information from authors about some types of materials, experimental systems and methods used in many studies. Here, indicate whether each material, system or method listed is relevant to your study. If you are not sure if a list item applies to your research, read the appropriate section before selecting a response.

Materials & experimental systems

n/a	Involved in the study
☒	☐ Antibodies
☒	☐ Eukaryotic cell lines
☒	☐ Palaeontology and archaeology
☒	☐ Animals and other organisms
☒	☐ Clinical data
☒	☐ Dual use research of concern
☒	☐ Plants

Methods

n/a	Involved in the study
☒	☐ ChIP-seq
☒	☐ Flow cytometry
☒	☐ MRI-based neuroimaging

Plants

Seed stocks	Not applicable
Novel plant genotypes	Not applicable
Authentication	Not applicable