Reconfigurable, zero-energy, and wide-temperature loss-assisted thermal non-reciprocal metamaterials

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Abstract. Thermal non-reciprocity plays a vital role in chip heat dissipation, energy-saving design, and high-temperature hyperthermia, typically realized through the use of advanced metamaterials with nonlinear [1, 2], advective [3], spatiotemporal [4, 5], or gradient properties [6]. However, challenges such as fixed structural designs with limited adjustability, high energy consumption, and a narrow operational temperature range remain prevalent. Here, a systematic framework is introduced to achieve reconfigurable, zero-energy, and wide-temperature thermal non-reciprocity by transforming wasteful heat loss into a valuable regulatory tool. This research presents a different approach to achieving non-reciprocity, broadening the potential for non-reciprocal devices such as thermal diodes and topological edge states, and inspiring further exploration of non-reciprocity in other loss-based systems.

Loss-assisted thermal non-reciprocity.

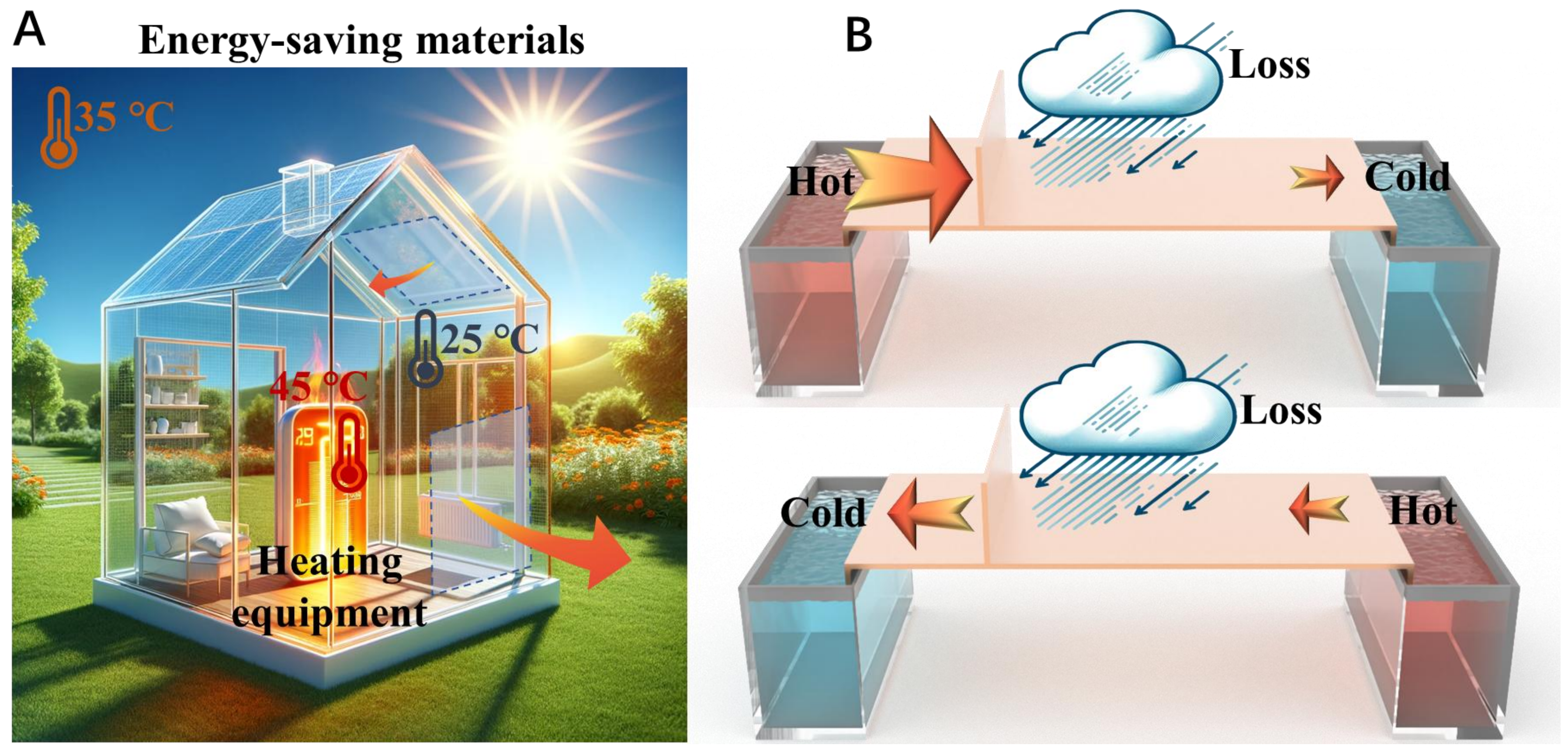

Fig.1. (A) Application of general thermal non-reciprocity. Asymmetric heat transfer achieved through thermal non-reciprocity enables effective thermal management in enclosed spaces, reducing external heat flow into the interior and precisely dissipating heat from internal sources. (B) Schematic of the loss-assisted non-reciprocal metamaterials. In asymmetric structures made from natural bulk materials, natural convection-induced asymmetric thermal losses disrupt the inherent spatial symmetry of thermal conduction.

Multi-parameter control of thermal nonreciprocity.

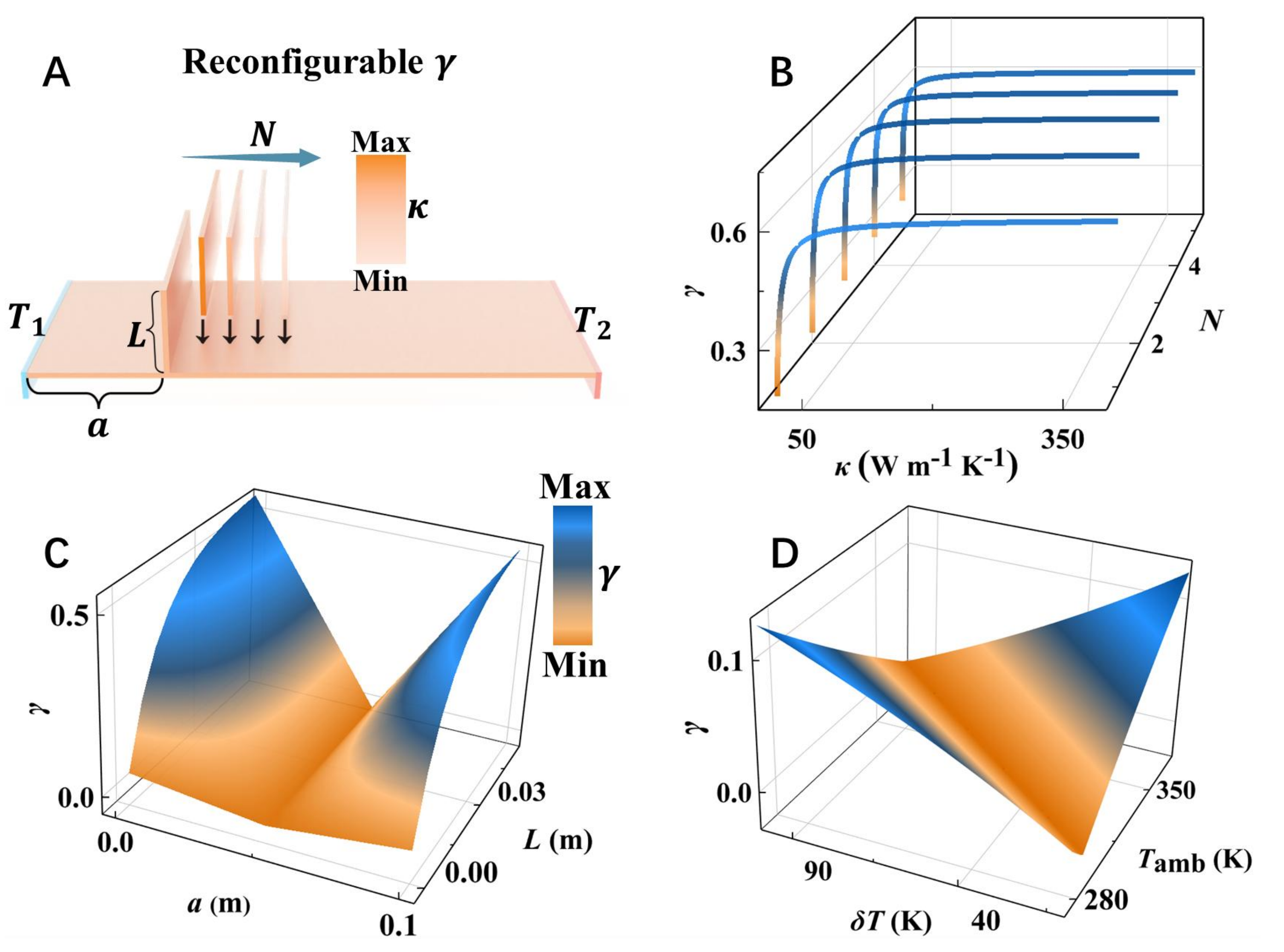

Fig. 2. (A) The asymmetric structure made of natural materials has multi-parameter control characteristics. The reconfigurable rectification ratio γ changes with the thermal conductivity κ and number N of vertical plates (B), the position a and height L of the vertical plates (C), the ambient temperature T_{amb} and the temperature difference $\delta T=|T_1-T_2|$ between hot and cold sources (D).

Numerical and experimental verification.

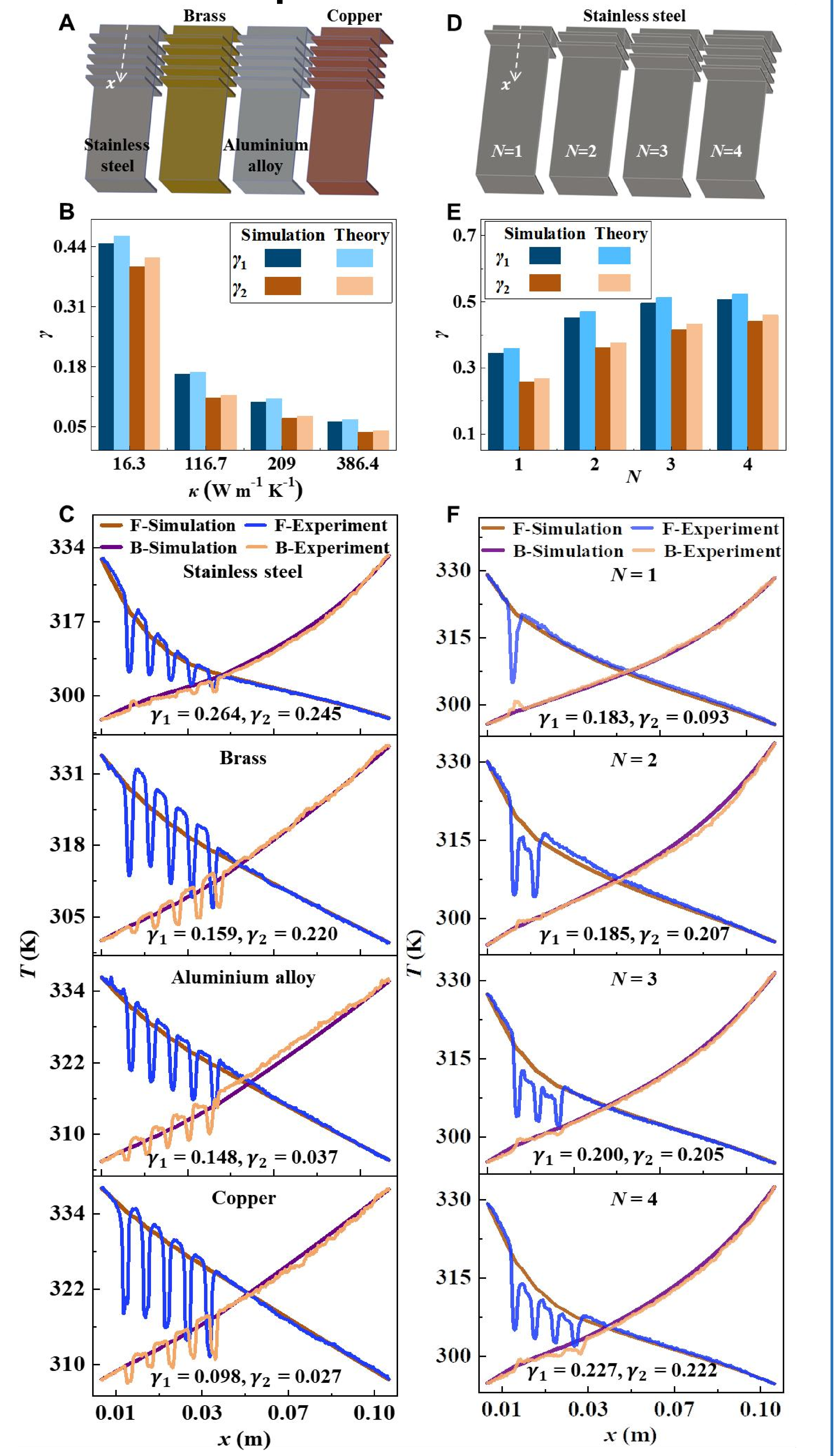

Fig. 3. (A) Structural diagrams of four material configurations: stainless steel (κ = 16.3 W m^{-1} K^{-1}), brass (κ = 116.7 W m^{-1} K^{-1}), aluminum alloy (κ = 209 W m^{-1} K^{-1}), copper (κ = 386.4 W m^{-1} K^{-1}). (B) The variation of rectification ratio with thermal conductivity (γ_1-inflow, γ_2-outflow). (C) A comparative analysis of the temperature distribution along the base plate centerline between experimental results and simulation data. (D)-(F) correspond to structural configurations: N = 1, 2, 3, 4.

Conclusion.

◆ We demonstrate heat loss-induced non-reciprocal metamaterials on asymmetric structures made of natural bulk materials.

◆ Simulations and experimental data show a reconfigurable rectification ratio consistent with our theoretical predictions.

◆ This zero-energy non-reciprocal design provides tunable output over a wide temperature range.

Reference.

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