Spatiotemporal multiphysics metamaterials with continuously adjustable functions

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Abstract. Emerging multiphysics metamaterials offer an exciting opportunity to regulate complex physical processes[1-6]. However, their functionality and tunability are limited by two severe constraints. Firstly, multiphysics functionality is fixed once structures and materials are prepared, meaning that only one functionality is available for each physical field. Secondly, continuous tunability is challenging to achieve in multiphysics fields because parameters are hard to change on demand. To overcome these limitations, we propose the concept of spatiotemporal multiphysics metamaterials, which takes into account the temporal dimension. The spatiotemporal feature enables multiple functions for each physical field and their continuous switching. We develop rotatable checkerboard structures with different rotation times, material composition, and geometric shapes that allow for flexible thermal and electric function switching between cloaking, sensing, and concentrating. Real-time thermal and electric functions have been theoretically predicted and confirmed by simulations.

Theoretical prediction.

The spatiotemporal checkerboard structure, made up of two or four materials, as shown in Fig. 1 (a) and (b), can achieve three or five function combinations, respectively.

We utilize the time-dependent effective medium theory [7, 8] to predict real-time thermal and electric functions. The effective thermal and electric conductivities of the checkerboard determine the thermal and electric currents in the central region, as shown in Fig. 1 (c) and (d).

(1) When $\kappa_r/\kappa_\theta<1$ ($\sigma_r/\sigma_\theta<1$), the heat (electric) flow bypasses the central area to achieve thermal (electric) cloaking.

(2) When $\kappa_r/\kappa_\theta=1$ ($\sigma_r/\sigma_\theta=1$), the heat (electric) flow keeps unchanged in the central area to achieve thermal (electric) sensing.

(3) When $\kappa_r/\kappa_\theta>1$ ($\sigma_r/\sigma_\theta>1$), the heat (electric) flow is concentrated in the central area to achieve the effect of thermal (electric) concentrating.

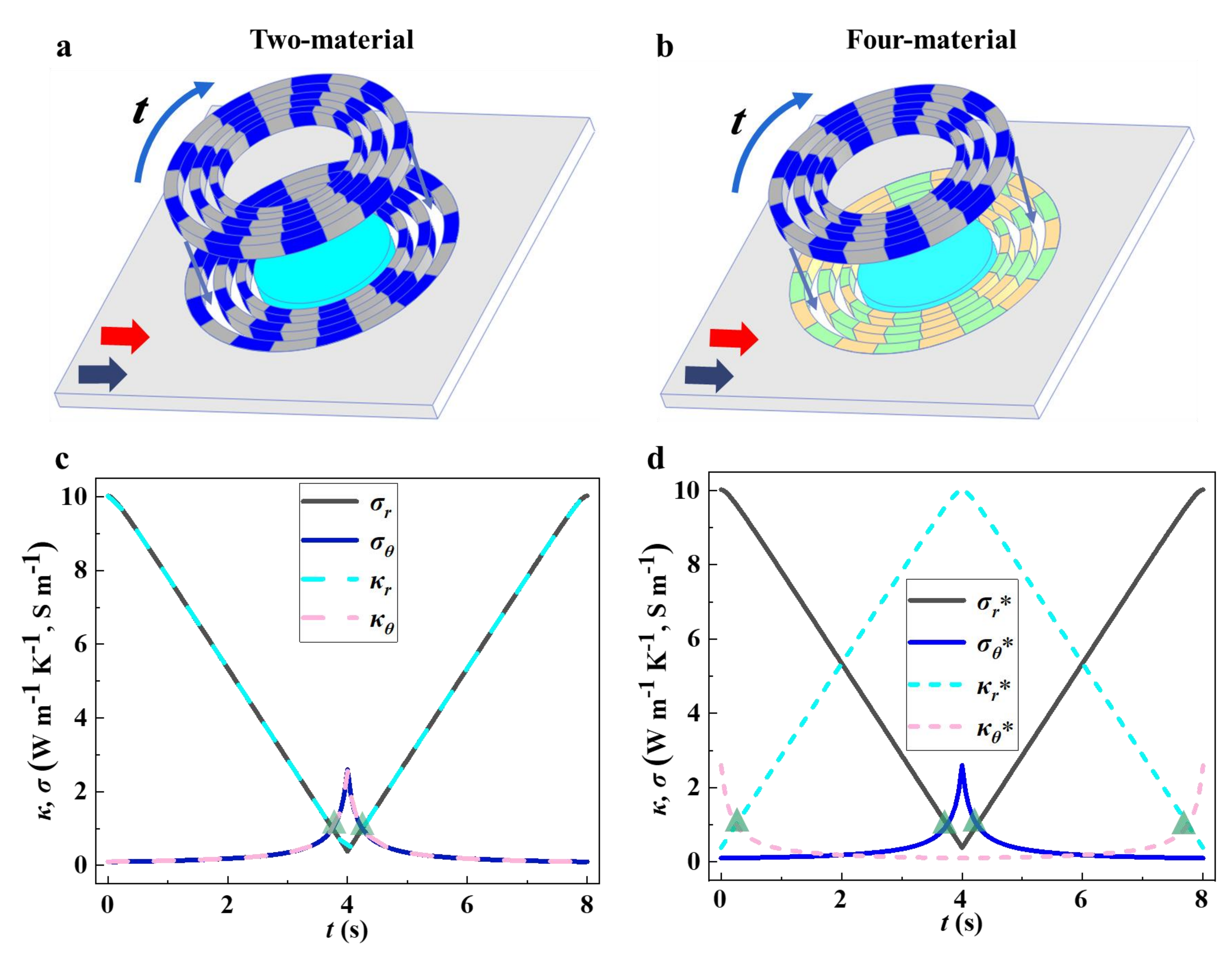

Fig. 1 Diagram of the checkerboard structure and theoretical results over a period.

Conclusion.

- Spatiotemporal multiphysics metamaterials are proposed for heat/electricity control.
- Rotatable checkerboard structures are designed for continuous function switching.
- The time-related effective medium theory is given for real-time function prediction.

Reference.

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Simulation verification.

A. Spatiotemporal multiphysics metamaterials composed of two materials can realize three different function combinations, as shown in Fig. 2. Three moments corresponding to the chessboard structure of three function combinations in simulations: t = 0 s, t = 3.75 s, and t = 4 s. In the theoretical diagram Fig. 1c, these three moments correspond to concentrating, sensing, and cloaking, respectively.

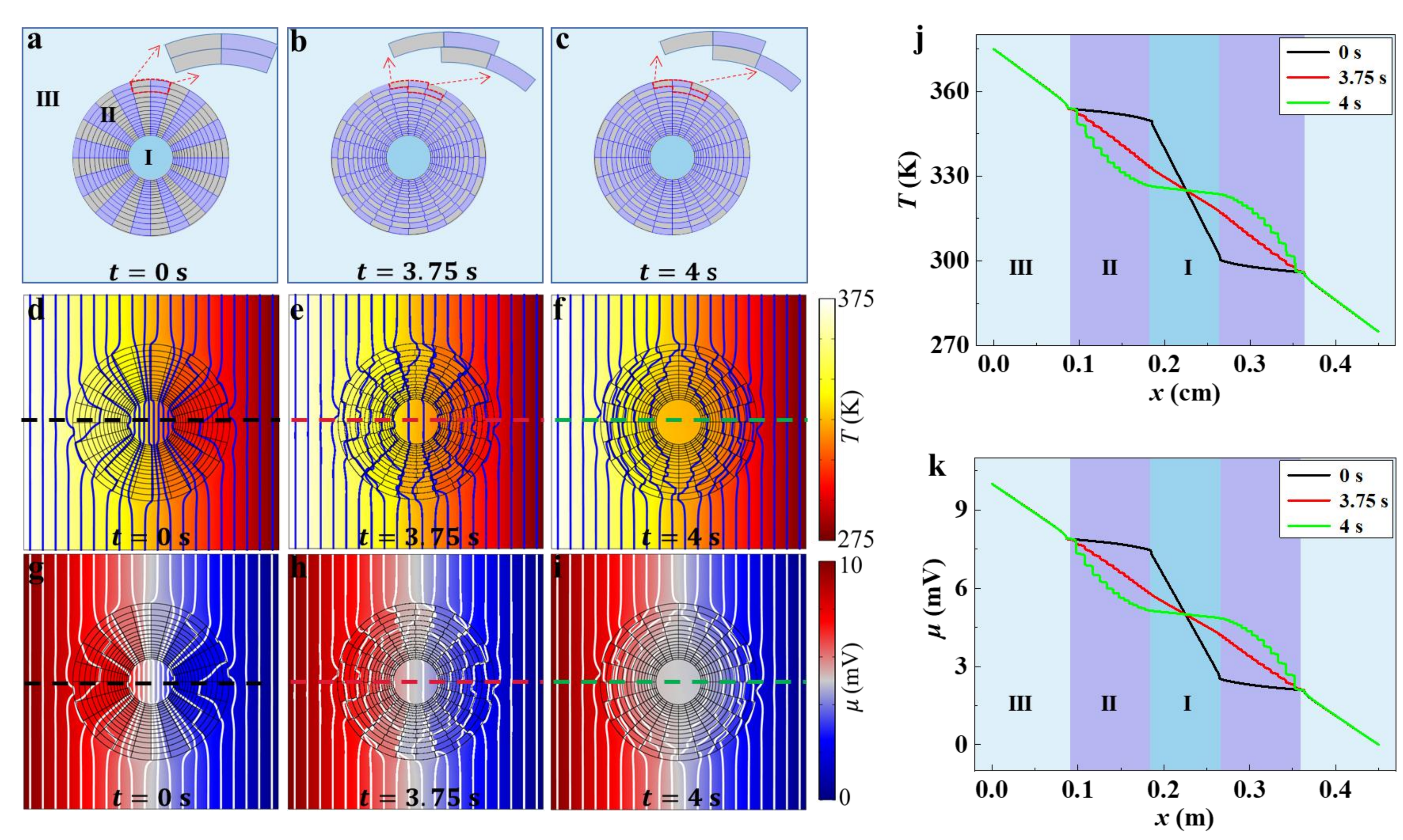

Fig.2 Schematic diagrams and simulation results of a two-material-based checkerboard structure. (a)–(c) Structures. (d)–(f) Simulation results of the thermal field. (g)–(i) Simulation results of the electric field. (j) and (k) Data of the horizontal centerline from the simulation results in (d)–(f) and (g)–(i).

B. Spatiotemporal multiphysics metamaterials composed of four materials can realize five different function combinations, as shown in Fig. 3. Thermal and electric fields can serve different functions. The simulation results at five key moments in Fig. 1(d) are shown here: 0 s, 0.25 s, 2 s, 3.75 s, and 4 s.

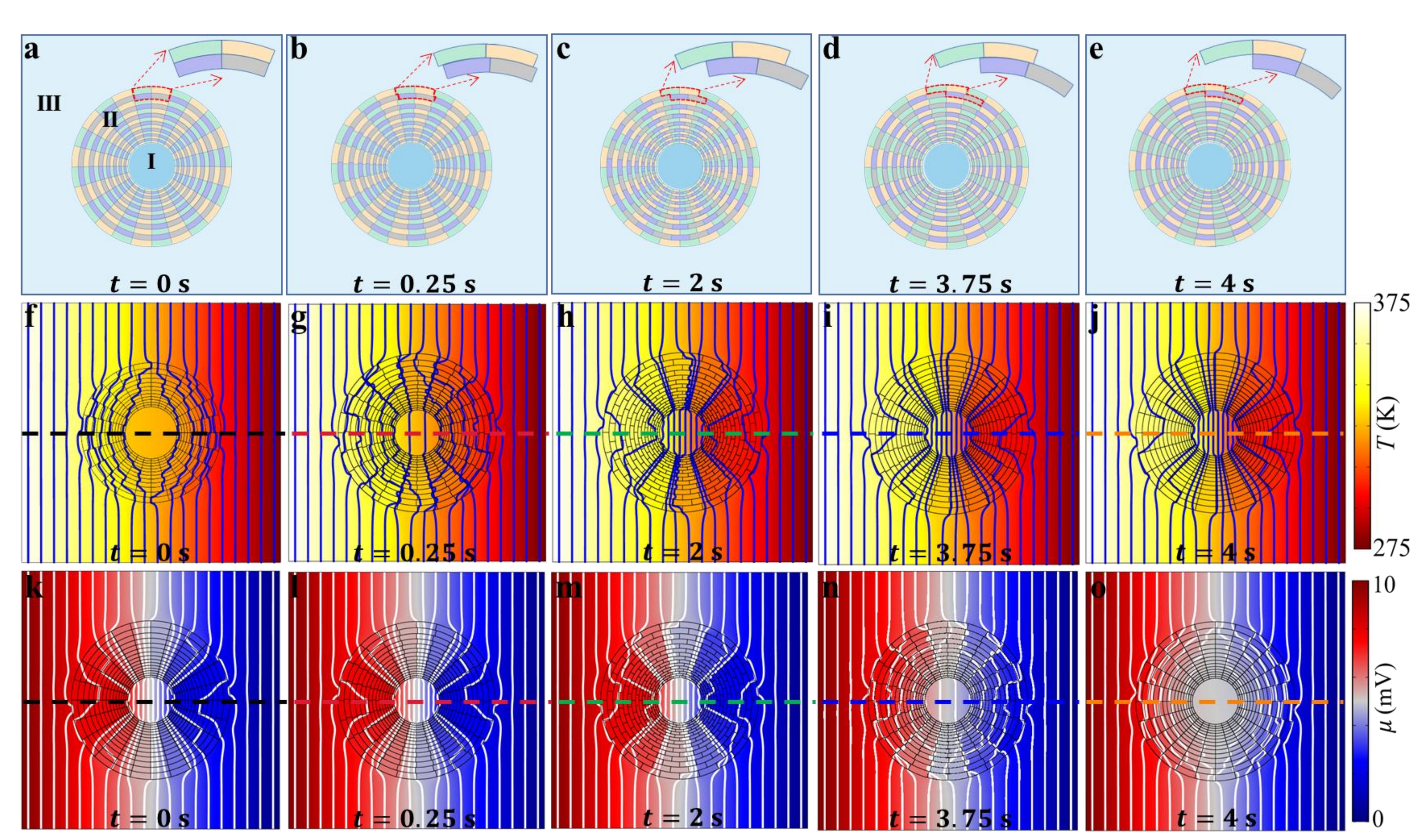

Fig.3 Schematic diagrams and simulation results of a four-material-based checkerboard structure. (a)–(e) Structures. (f)–(j) Simulation results of the thermal field. (k)–(o) Simulation results of the electric field.