Manipulating thermoelectric fields with bilayer schemes beyond Laplacian metamaterials

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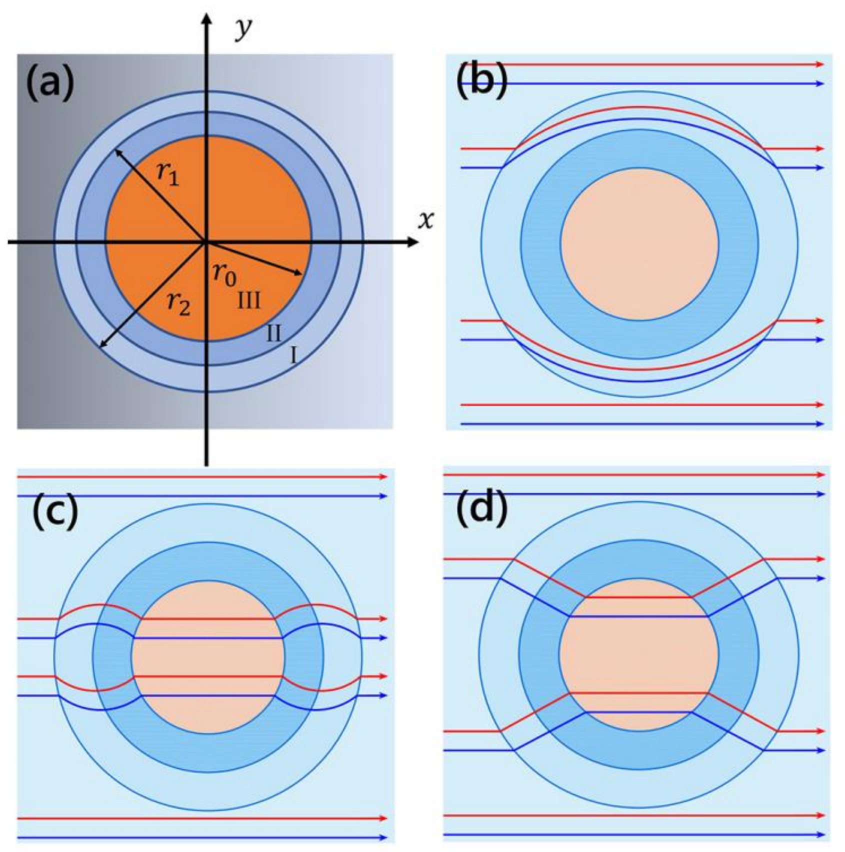
Abstract

We theoretically design a category of bilayer thermoelectric metamaterials with the generalized scattering-cancellation method. By solving the governing equations directly, we formulate the specific parameter requirements for desired functionalities beyond existing single-field or decoupled multi-field Laplacian metamaterials. Compared with the recently reported transformation optics for thermoelectric flows, bilayer schemes do not require inhomogeneity and anisotropy in constitutive materials. Finite-element simulations confirm the analytical results and show robustness under various exterior conditions. Feasible experimental design with naturally occuring materials is also proposed for further proof-of-principle verification. Our theoretical method and device design may be extended to other coupled multiphysical systems such as thermo-optics, thermomagnetics, optomechanics, etc.

Introduction



$$\boldsymbol{j} = -\sigma\boldsymbol{\nabla}\mu - \sigma S\boldsymbol{\nabla}T,$$
$$\boldsymbol{\nabla}\cdot\boldsymbol{j} = 0,$$
$$\boldsymbol{q} = -\kappa\boldsymbol{\nabla}T + TS\boldsymbol{j},$$
$$\boldsymbol{\nabla}\cdot\boldsymbol{q} = -\boldsymbol{\nabla}\mu\cdot\boldsymbol{j},$$

Figure 1. (a) Schematic diagram of bilayer TE metamaterials. The electrical conductivities, thermal conductivities, and Seeback coefficient S are homogeneous isotropic scalars in each regions. (b) Illustration of a TE cloak. (c) Illustration of a TE invisible sensor. (d) Illustration of a TE concentrator. Red and blue lines represent heat and electrical fluxes respectively in (b)-(d).

- Metamaterials have shown superior control ability beyond naturally occurring materials in both wave and diffusion systems.
- Novel functions concentrating in corresponding fields such as cloaking, invisible sensing and, have already been achieved by decoupled thermal and electrical metamaterials.
- However, in many cases thermal and electrical currents are coupled via joule effect and Seebeck effect, making them difficult to manipulate because their governing equations are no longer in Laplacian form.
- Here, a bilayer scheme based on the scattering-cancellation method is proposed for manipulating TE fields with naturally-occurring TE materials by introducing an auxiliary generalized potential.

Theory

We introduce an auxiliary generalized potential

$$U = \mu + TS.$$

And obtain from the original governing equations:

$$\sigma\boldsymbol{\nabla}^2 U = 0$$

and

$$\kappa\boldsymbol{\nabla}^2 T = \sigma\boldsymbol{\nabla}U\cdot\boldsymbol{\nabla}U.$$

- Then we discuss the relationship between the auxiliary generalized potential and temperature/potential. We find that their gradients can be parallel in some cases.
- On top of that, we deduce the condition for parallel gradients by analyzing boundary conditions, which are i. Proportional thermal and electrical conductivities; ii. Invariant Seebeck coefficient in all domains; iii. Parallel boundary gradients of temperature and potential.
- Once the conditions are met, we can manipulate the two fields by tailoring the auxiliary generalized potential. And the parameters of TE cloak, invisible sensor and concentrator can thus be designed

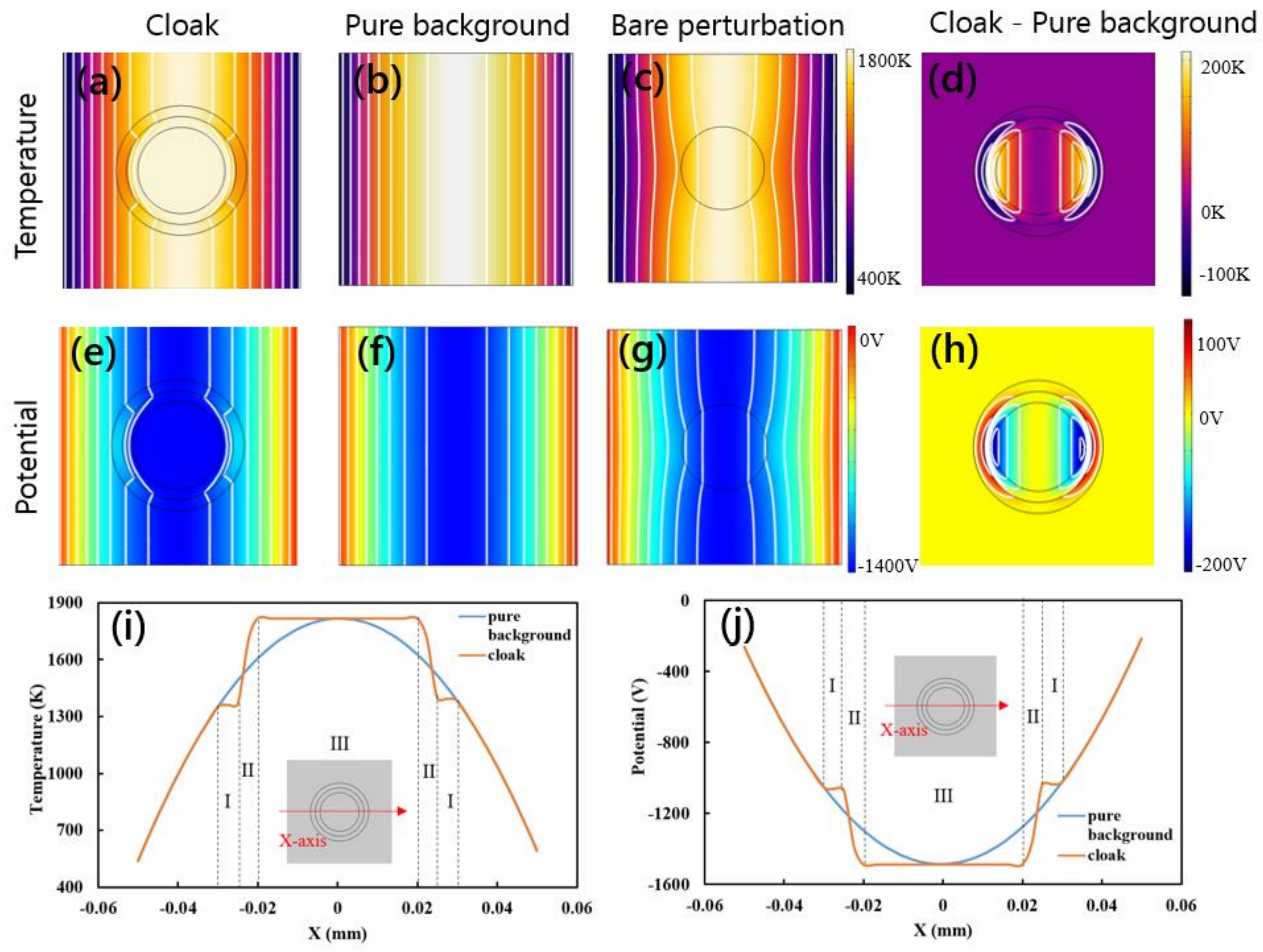


Fig 2. Simulation results of the TE cloak under parallel external thermal and electricalfields. Isothermal or isopotential lines are marked in white..

Simulation Results

- To confirm the proposed theoretical models, we perform finite-element simulations with the commercial software COMSOL Multiphysics.
- Not only do the results verify our theory but also show the robustness of the proposed bilayer design under various conditions.

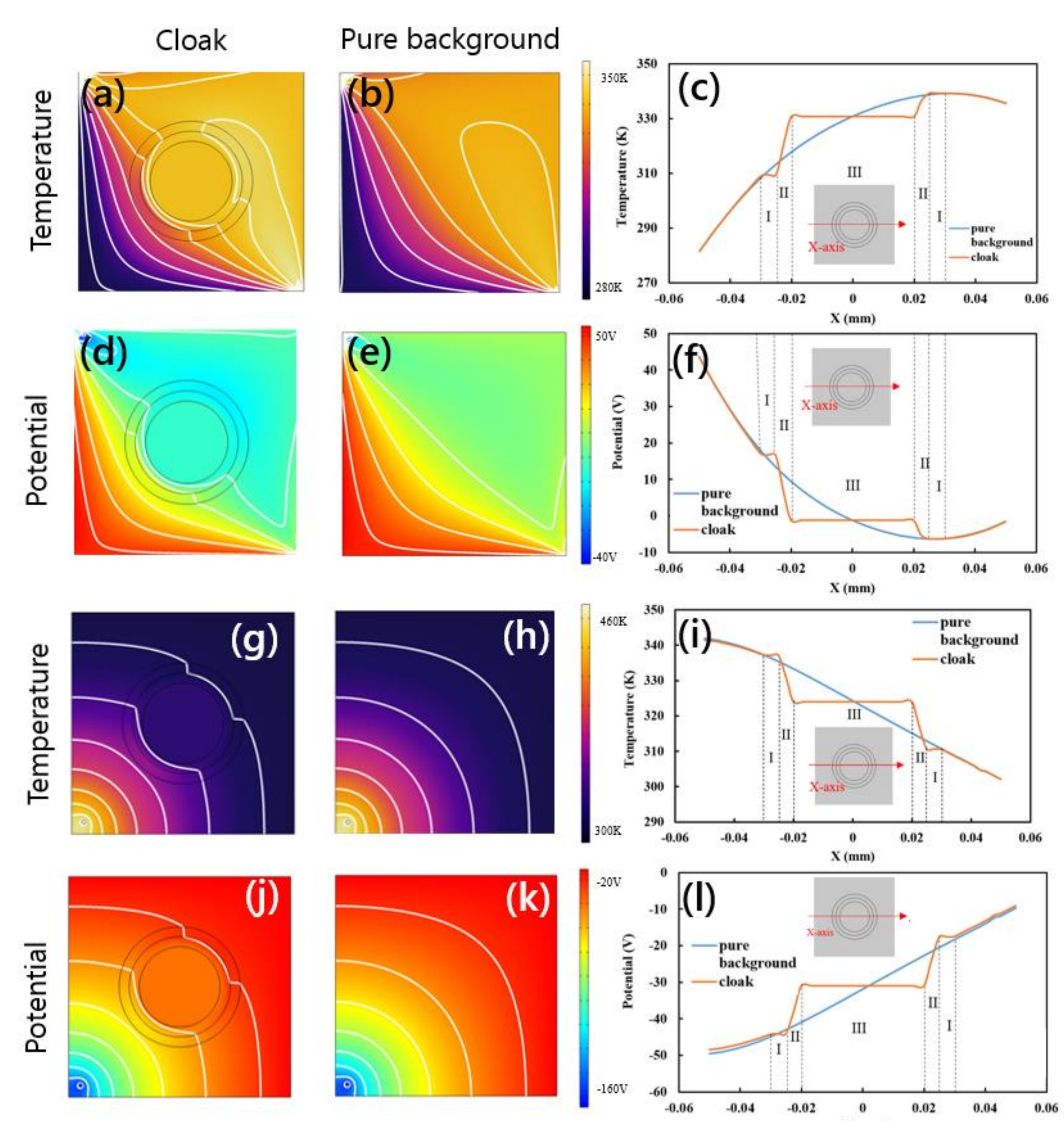


Fig 3. (a)-(f) Simulation results of the TE cloak under the perpendicular boundary temperature and potential fields. Isothermal or isopotential lines are marked in white. (a) Temperature distribution of the matrix plus cloak. (g)-(l) Simulation results of the TE cloak under the y-direction external potential fields and point heat sources at the left-bottom corner.

Conclusions

- We have built a scattering-cancellation method for manipulating coupled TE fields and designed three representative devices with bilayer schemes.
- Our work may provide hints for manipulating coupled multiphysical fields beyond single-physics Laplacian transport, which doubtlessly simplifies the requirements on materials and structures of existing transformation metamaterials.

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