Thermal Inverter: Negative-Thermal-Coupling Mechanism for Ambient-Temperature Counteraction

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Introduction

Efficient thermal management under fluctuating ambient conditions is crucial, yet most thermal metamaterials exhibit only positive feedback, causing object temperatures to follow environmental variations and limiting adaptive control[1]. Here, we propose a thermal inverter based on a negative-thermal-coupling mechanism, which realizes counteraction of ambient-temperature fluctuations by inducing an inverse correlation between its central temperature and the environment. Both simulations and experiments confirm this counteractive inverse thermal response. Furthermore, we realize an inverse-temperature cloak that maintains an undisturbed background while exhibiting negative thermal coupling at its core. By harnessing negative thermal coupling and inverse-temperature regulation, our work establishes a paradigm for advanced thermal-management technologies[2-4].

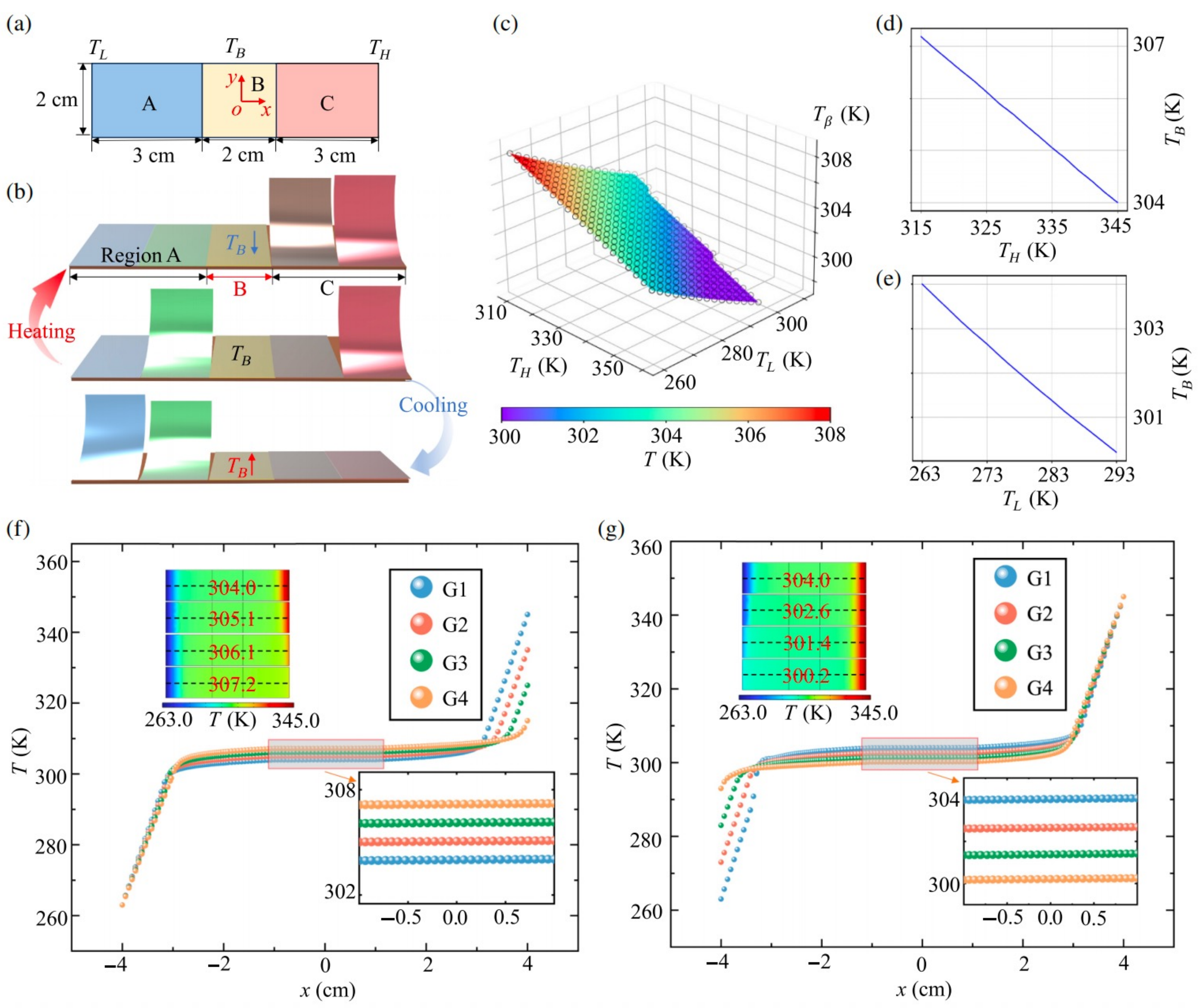

Fig. 1 The concept, design, and thermal response of the thermal inverter.

Theory

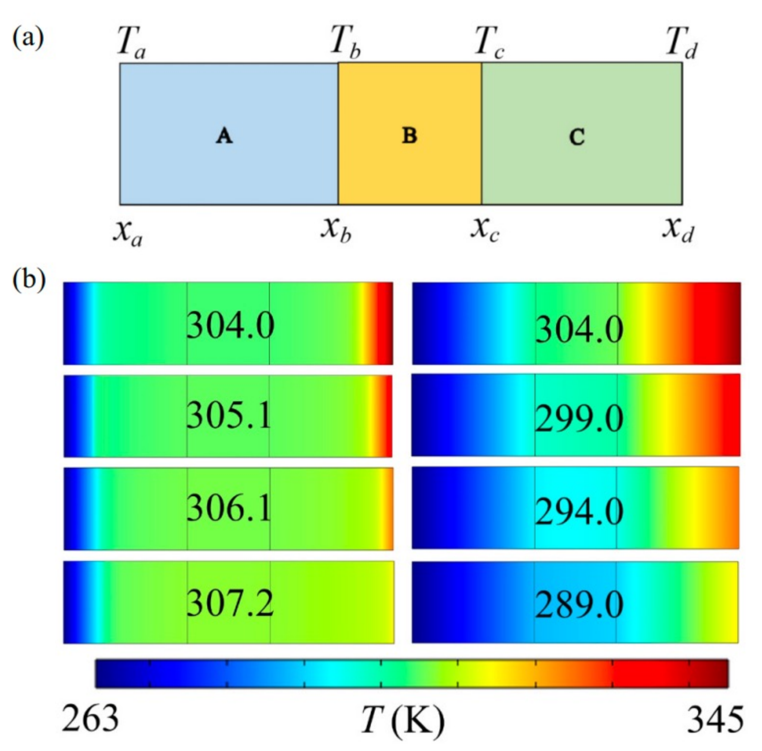

Fig. 2 The thermal-inverter design and temperature simulation results.

$$\kappa_A = \gamma + \frac{\eta e^{T-T_\beta}}{1+e^{T-T_\beta}}, \quad \int_{x_a}^{x_b} q\,dx = -\int_{T_a}^{T_b} \kappa_A\,dT,$$

$$\kappa_C = \gamma + \frac{\eta}{1+e^{T-T_\beta}}, \quad \int_{x_c}^{x_d} q\,dx = -\int_{T_c}^{T_d} \kappa_C\,dT,$$

$$q\,dx = -\kappa\,dT, \quad x_d - x_c = x_b - x_a,$$

$$\int_{T_a}^{T_b} \kappa_A\,dT = \int_{T_c}^{T_d} \kappa_C\,dT.$$

γ is a small value, $T_a \ll T_\beta \ll T_d$,

$$\eta \ln \frac{1+e^{T_b-T_\beta}}{1+e^{T_c-T_\beta}} = \eta(T_d - T_c) - \eta(T_d - T_\beta).$$

$$T_b \approx T_c$$

$$T_\beta \approx T_c \approx T_b$$

$$T_B \approx T_\beta \equiv T_\beta(T_H, T_L).$$

$$T_\beta = 304 + 40(263/T_L - T_H/345)$$

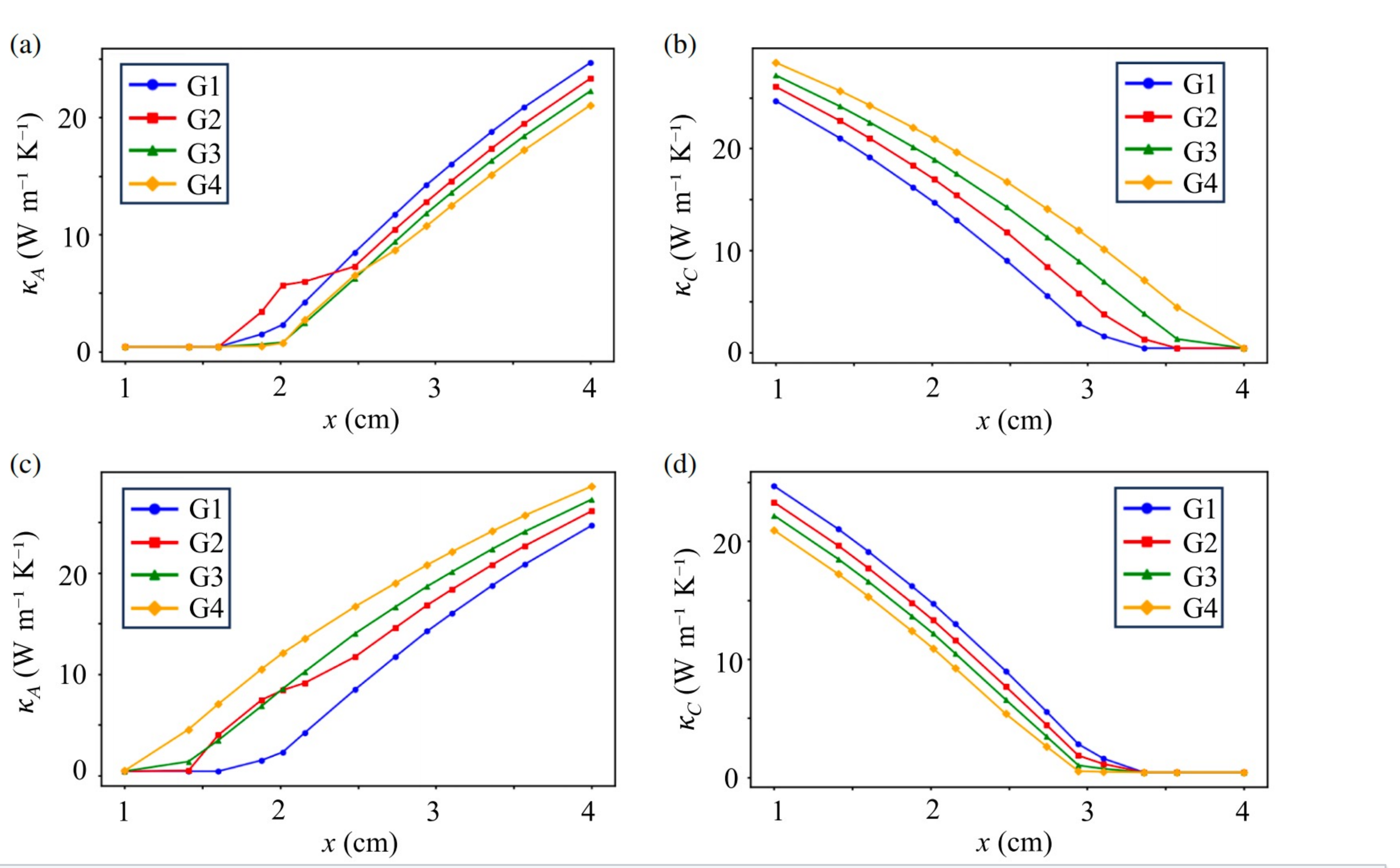

Fig. 3 The spatial distributions of the thermal conductivity in regions A and C for four groups of samples under different boundary temperatures.

Experimental Results

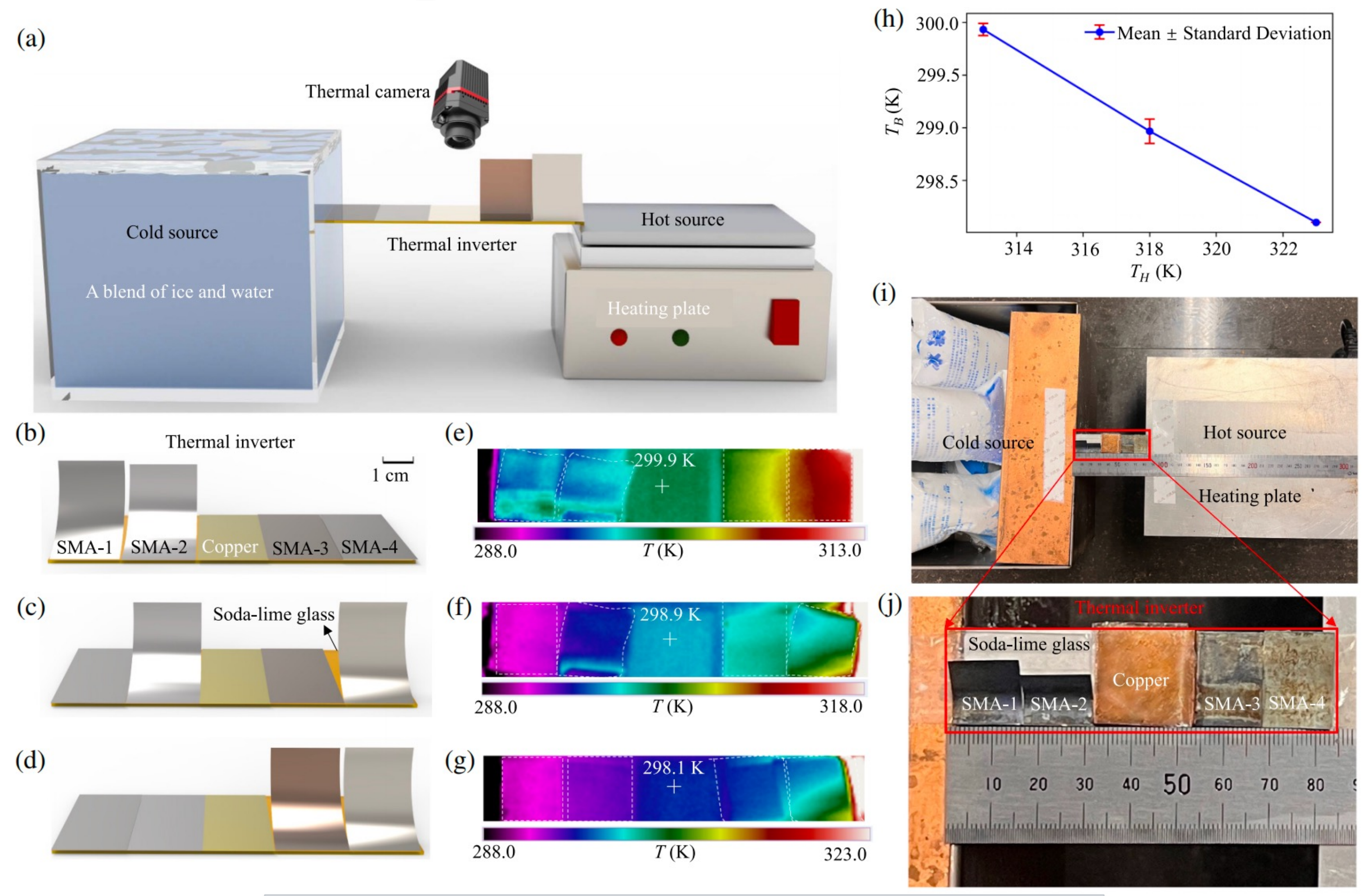

Fig. 4 Experimental results for the thermal inverter.

Application: Inverse-Temperature Cloak

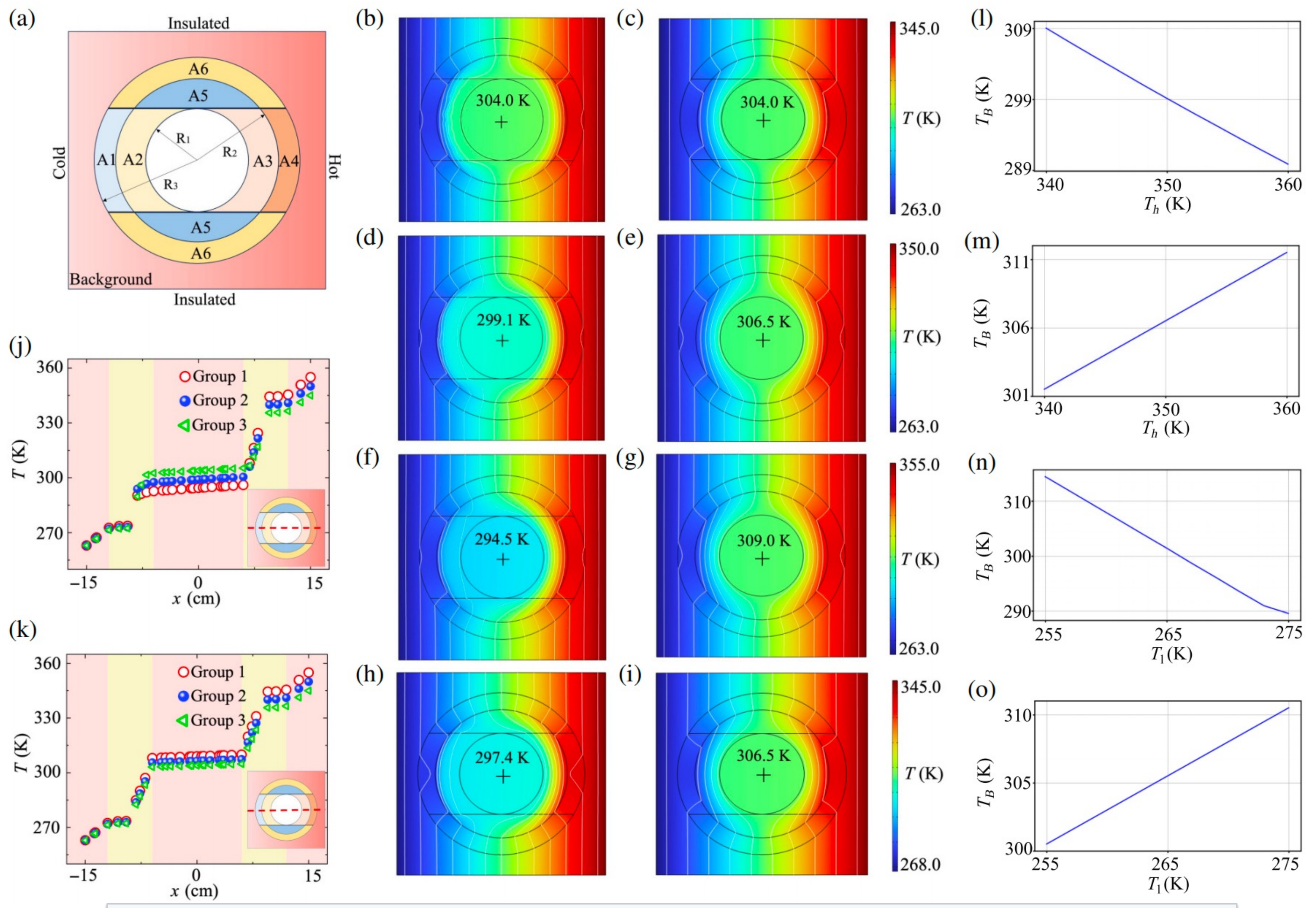

Fig. 5 A comparison of the inverse- and conventional-temperature cloaks.

$$\begin{cases} \kappa_{A5} \to 0, \\ \kappa_{A6} = \kappa_0 \dfrac{R_3^2 + R_2^2}{R_3^2 - R_2^2}, \end{cases}$$

$$\begin{cases} \kappa_{A1} = \kappa_0 + \dfrac{\kappa_{A6} - \kappa_0}{1 + e^{(T-T_\beta)}}, \\ \kappa_{A2} = \kappa_0 - \dfrac{\kappa_0 - \kappa_{A5}}{1 + e^{(T-T_\beta)}}, \\ \kappa_{A3} = \kappa_0 - \dfrac{(\kappa_0 - \kappa_{A5}) e^{(T-T_\beta)}}{1 + e^{(T-T_\beta)}}, \\ \kappa_{A4} = \kappa_0 + \dfrac{(\kappa_{A6} - \kappa_0) e^{(T-T_\beta)}}{1 + e^{(T-T_\beta)}}. \end{cases}$$

$$T_\beta = 304 + 400(345/T_h - T_l/263)$$

Compared with a conventional cloak[5], the inverse cloak keeps the background undisturbed while the core temperature responds oppositely to boundary changes.

Conclusion

- Established a configurable theoretical framework for temperature management.
- Demonstrated a thermal inverter with counteractive response to ambient fluctuations.
- Extended to an inverse-temperature cloak with background preservation.

References

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