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# Transformation-Based Flexible Thermal Hose with Homogeneous Conductors in Bilayer Configurations

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**Abstract**—Thermal hose is capable of transferring the thermal energy of a finite source to arbitrary long distance. This is achieved by using stretching transformation and can be ideally constructed by using a material with a highly anisotropic thermal conductivity. For practical realization, such a thermal hose can be made of homogeneous conductors in bilayer configurations, employing only copper and expanded polystyrene. It is shown that the thermal energy can be well confined and almost perfectly transferred in an arbitrarily bending hose, demonstrating excellent flexibility. More interestingly is that when a point heat source is placed at the opening of a split-ring-shaped hose, the temperature of the inner region becomes uniform and reaches nearly as high as the heat source. These novel properties of the proposed flexible thermal hose have been numerically validated in time-dependent case, showing excellent transfer and configuration of thermal energy.

## 1. INTRODUCTION

Researchers have been pursuing effective methodologies to control thermal flux for multifarious applications. The manipulation of heat flow is essential in technology development in many areas such as thermoelectricity [1], solar cells [2], and low thermal conductivity materials [3]. Transformation optics (TO) [4] provides us a powerful tool to design specific parameters for many kinds of novel functional devices such as invisible cloaks [5–8], hyperlens [9], field rotator [10], and so on. In addition to manipulation of electromagnetic waves [5–10], the theoretical tool of coordinate transformation has been extended to acoustic waves [11, 12], matter waves [13, 14], elastic waves [15], dc magnetic fields [16, 17], dc electric fields [18], and heat flux [19–22].

In terms of manipulating heat conduction, significant progress has been made in the past three years [23–32]. In 2012, Guenneau et al. extended TO theory to the thermodynamics field to control thermal conduction [23]. Through tailoring inhomogeneity and anisotropy of conductivities (as well as specific heat and material density), the transient thermal cloaks were experimentally realized in the following year [24, 25]. Meanwhile, steady-state thermal cloaking can be designed with only anisotropic conductivities and its construction can be further simplified by utilizing the multilayered composite approach as demonstrated both theoretically [26] and experimentally [27, 28]. Recently, bilayer thermal cloaks have been experimentally demonstrated in two dimensions [29] and three dimensions [30], respectively. In addition, an active thermal cloak was demonstrated by using active thermoelectric components controlled by input electric voltages [31]. It is noted that long-distance transfer of static magnetic field has been demonstrated recently by using a superconducting-ferromagnet hybrid, working at a much lower temperature (77 K) [33, 34].

Inspired and motivated by the pioneering work [33, 34], we theoretically design a thermal super-transferring (or super-insulating) hose through stretching (or compressing) transformation, which may be fabricated by multilayer composition approach exploiting two naturally occurring materials

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throughout. On one hand, the proposed thermal hose is capable of transferring thermal energy to arbitrary long distance with nearly no attenuation. On the other hand, the hose is extremely flexible, which can be arbitrarily bent with excellent tunnelling performance. More interestingly is that the super-transferring hose shows powerful configuration capability of thermal energy. Practical realization of such super-transferring hose has been suggested by using copper and expanded polystyrene, which is numerically validated in time-dependent case.

## 2. THEORETICAL ANALYSIS

We first design a thermal super-transferring slab that is capable of transferring thermal energy to arbitrarily long distances. This is achieved by using stretching transformation, corresponding to $l_1$ in Fig. 1, where the orange region (denoted with AC′) in virtual space $(\rho', \varphi', z')$ is stretched into the yellow region (denoted with AB) in real space $(\rho, \varphi, z)$. The thickness of the orange region and yellow region are $mH$ and $H$, respectively, where $0 < m < 1$. The stretching transformation is along $z$-axis (the other two components are kept invariant) and can be expressed as $z = z'/m$. Accordingly, the thermal conductivity of the super-transferring slab is expressed as $\overleftrightarrow{\kappa} = \mathrm{diag}(m,\ m,\ 1/m)$. Obviously, we obtain $\kappa_\parallel \to \infty$ and $\kappa_\perp \to 0$ when $m \to 0$, which means infinity and zero conductivities along and perpendicular to the "stretching" direction, respectively. It is known that thermal resistance is inversely proportional to the thermal conductivity. Therefore, the thermal resistance of super-transferring slab is obtained $R_\parallel \to 0$ and $R_\perp \to \infty$, which leads to a super-transferring performance along the "stretching" direction without dissipation.

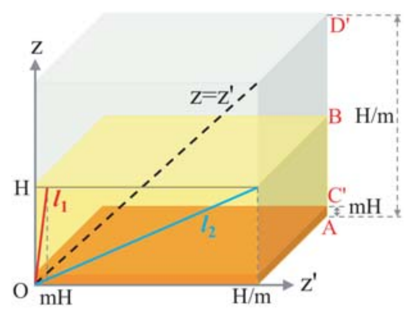


**Figure 1.** (Color Online) Schematic illustration of coordinate transformation in the design of thermal super-transferring and super-insulating slabs, where the former is generated by stretching AC′ into AB, and the latter is generated by compressing AD′ into AB, respectively.

Then we design a thermal super-insulating slab by using compressing transformation, corresponding to $l_2$ in Fig. 1, where the light blue region (denoted with AD′) is compressed into the yellow region (denoted with AB). The compressing transformation is expressed as $z = mz'$, which leads to a thermal conductivity as $\overleftrightarrow{\kappa} = \mathrm{diag}(1/m,\ 1/m,\ m)$. Obviously, we obtain $\kappa_\parallel \to 0$ and $\kappa_\perp \to \infty$ when $m \to 0$, which means zero and infinity conductivities along and perpendicular to the "compressing" direction, respectively. This means that the thermal energy is prevented from transferring along the "compressing" direction.

## 3. SIMULATIONS AND DISCUSSION

In all simulation setups, we used a point thermal source that is set as fixed temperature at 100°C, and the background is set as room temperature (27°C). All of the boundaries are set as convection boundary conditions with convection coefficient of 5 $\mathrm{Wm^{-2}\,K^{-1}}$ throughout [23]. Fig. 2(a) shows the temperature profile of a super-transferring slab with $\kappa_\parallel = 100$ and $\kappa_\perp = 0.01$, and Fig. 2(b) shows the temperature profile of a super-insulating slab with $\kappa_\parallel = 0.01$ and $\kappa_\perp = 100$. The light green rectangle denotes the super-insulating slab in Fig. 2(b), which prevents the thermal energy from entering due to the infinitesimal thermal conductivity in the vertical direction. As expected, both results have good agreement with the theoretical prediction. To quantitatively examine the performance with the change of anisotropy, we may set the thermal conductivity of super-transferring slab as $\kappa_\parallel = 2^n$ and $\kappa_\perp = 2^{-n}$, where $0 < n < \infty$. Similarly, the super-insulating slab is described with $\kappa_\parallel = 2^{-n}$ and $\kappa_\perp = 2^n$. We define a normalized temperature difference (NTD) function as

$$NTD\,(n) = \frac{T_{bottom}\,(0) - T_{top}\,(n)}{T_{bottom}\,(0) - T_{top}\,(0)} \qquad \text{(For super-transferring)} \tag{1}$$

$$NTD\,(n) = \frac{T_{top}\,(n) - T_{Background}}{T_{top}\,(0) - T_{Background}} \qquad \text{(For super-insulating)} \tag{2}$$

where $T_{top}$ and $T_{bottom}$ are the temperatures at the two points (located in the upper and lower surfaces of the slab) just above the thermal source, respectively. The inset of Fig. 2(b) shows the NTD curves with the increase of $n$. It shows that the super-transferring curve attenuates more slowly than the super-insulating curve. It is found that a fairly good performance (NTD $< 0.1$) can be achieved when $n \geq 7$ for super-transferring and $n \geq 3$ for super-insulating, respectively.

Due to the proposed functional devices with finite constant conductivities, it could be easily realized through alternating layered isotropic medium and only two types of isotropic materials (medium A and medium B) are needed throughout [35]. The conductivities of medium A and medium B are defined as $\kappa_{\mathrm{A,B}} = \kappa_\parallel \pm \sqrt{\kappa_\parallel^2 - \kappa_\parallel \kappa_\perp}$. To cater for the practical realization, we choose copper and expanded polystyrene with conductivity of 394 W/mK and 0.03 W/mK, respectively. For the host background material, we may choose thermal epoxy with conductivity of 3.4 W/mK. Interestingly, we note that the performance of such a practical thermal hose with bilayer configurations is comparable with an ideal anisotropic super-transferring medium with $n \approx 7$. Fig. 2(c) shows the transient temperature distributions of the proposed thermal hose with bilayer configurations at different times $t = 10$, 30, 120 s, and steady state, where the temperature at the test point (red point) is also marked. It is apparent that the thermal conduction is well constrained in the hose, which prevents the thermal energy from leaking outside through the lateral surface. As time elapse, thermal energy is transferred from one end to the other end with almost no attenuation, demonstrating excellent super-transferring property.

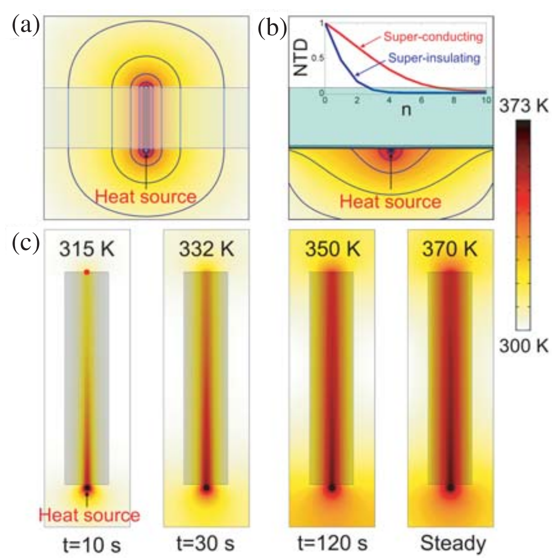


**Figure 2.** (Color Online) Temperature distributions of a (a) super-transferring slab and (b) a super-insulating slab. The inset shows the curves of the normalized temperature difference with the change of anisotropy. (c) Transient temperature distributions of a super-transferring hose made of copper and expanded polystyrene in bilayer configurations at different times $t = 10$, 30, 120 s, and steady state. The temperature at the test point (red point) is also marked. Isothermal lines are also represented with blue color in the panel.

From Fig. 2(c) we can see that a partial of thermal energy diffuses towards the opposite direction respect to the hose, which results in a loss of thermal energy and also degrades the performance of the thermal hose. To prevent the thermal energy from leaking through backward diffusion, a semi-circular super-insulating shell is cascaded to the thermal hose, as shown in Fig. 3(a). The super-insulating shell, which is also constructed through alternating copper and expanded polystyrene, prevents the heat from transferring along radial direction. From Fig. 3(a) we find that almost all of the heat is transferred from one end to the other end without attenuation, demonstrating excellent performance. We next demonstrate the flexibility of the proposed thermal hose. Fig. 3(b) shows the temperature distribution of a thermal hose bent at right. It is clear that thermal energy can be transferred without attenuation in an arbitrarily bending hose. More interestingly is that, when a point heat source is placed at the opening of a split-ring-shaped (SRS) hose, the inner region of SRS hose shows a uniform temperature nearly as high as the heat source, as shown in Fig. 3(c). This is completely different from the uniform heating region generated by using several *sensu*-shaped metamaterial units [32]. For comparison, a reference structure with bare copper is demonstrated in Fig. 3(d). Obviously, the heat is rapidly dissipated with bare copper, thus leading to a much lower temperature compared to the SRS hose.

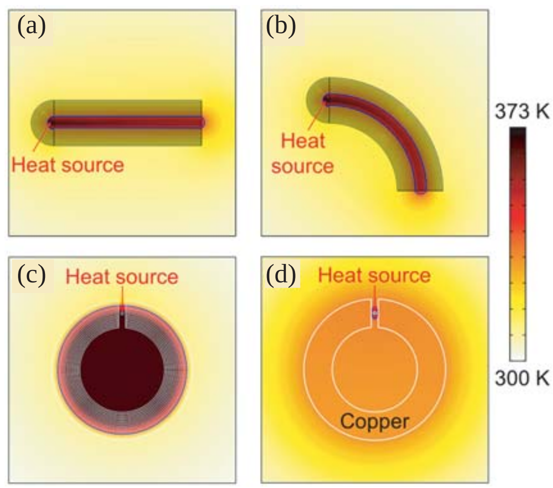


**Figure 3.** (Color Online) Temperature distributions of flexible thermal hoses made of copper and expanded polystyrene in bilayer configurations. (a) A straight thermal hose cascaded with a semi-circular super-insulating shell. (b) A curved thermal hose cascaded with a semi-circular super-insulating shell. (c) A SRS hose. (d) The reference structure composed of bare copper. Isothermal lines are also represented with blue color in the panel.

To understand how the ultrahigh uniform temperature of the inner region is formed in Fig. 3(c), we examine the transient performance of the SRS hose at different times $t = 10$, 30, 120 s, as shown in Figs. 4(a)–4(c). We can see that the thermal conduction is well constrained in the SRS hose in the earlier time, and then a uniform hot ring is formed. The temperature of the hot ring becomes higher and higher as time elapse, which has been validated through comparing the temperature distributions in Figs. 4(a)–4(c). For comparison, temperature distribution of the reference structure at $t = 120$ s is also demonstrated in Fig. 4(d), which shows a much lower temperature compared to the SRS hose in Fig. 4(c). To quantitatively examine the temperature change of the inner region over time, thermal profile of the SRS hose along the observation line "op" at different times is indicated in Fig. 4(e). Obviously, the temperature inside the SRS hose rises much faster than the outside, especially in the first 2 min. As an ideal hose ($\kappa_{\|} \to \infty$ and $\kappa_{\perp} \to 0$) cannot be obtained, the thermal energy leaks through the lateral surface, which leads to the temperature of the inner region continuously rising and finally a uniform heating region is formed with a temperature nearly as high as the heat source. For reference, thermal profile of the copper ring along the observation line "op" at different times is also demonstrated in Fig. 4(f). It is clear that the temperature does not exceed 332 K even in the steady state, which is much lower compared to the SRS hose.

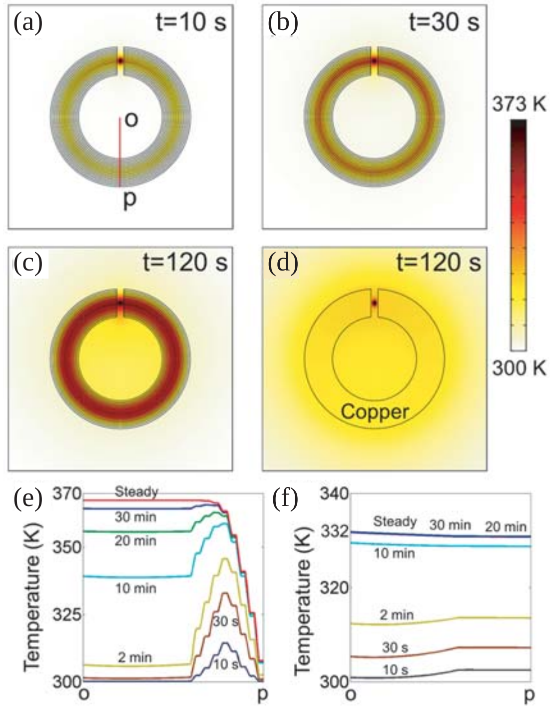


**Figure 4.** (Color Online) Transient temperature distributions of the SRS hose in Fig. 3(c) at different times (a) $t = 10$, (b) $t = 30$, (c) $t = 120\,\mathrm{s}$. (d) Temperature distribution of the reference structure at $t = 120\,\mathrm{s}$. (e) Thermal profile of the SRS hose in (a) along the observation line "op" at different times. (f) Thermal profile of the reference structure in (d) along observation line "op" at different times.

## 4. CONCLUSION

In summary, we propose a thermal super-transferring hose that can be realized using two regular bulk materials (copper and expanded polystyrene), demonstrating unique properties in terms of transferring and redistribution of thermal energy. These novel properties have remarkable robustness on the geometrical size of the proposed thermal hose without having to change the material compositions. Our scheme may find straightforward applications in technological devices such as thermoelectric devices, solar cells, thermal sensors, as well as in thermal therapy applications.

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