Proceedings of the 18th UK Heat Transfer Conference

9-11 September 2024, Birmingham

UKHTC2024-158

THERMAL METAMATERIALS FOR COOLING FLEXIBLE POLYMER SUBSTRATE ELECTRONICS

Joel Yi Yang Loh[1,2*], Siah Chun Fei[1], Lim Yeow Kheng [1,2],

[1]SHINE Centre for Microelectronics, National University of Singapore, Singapore

[2]Department of Electrical and Computing Engineering, National University of Singapore, Singapore

1. ABSTRACT

Thermal metamaterials can effectively redistribute heat through simple designs, offering a cost-efficient solution for cooling flexible electronics, which often suffer from low thermal conductivity in their polymeric substrates like polyimide. A simple sensu-fan design can reduce a 350°C central heat source by nearly 250°C while maintaining a high temperature of ~90°C throughout the fan structure, with an optimal cooling effect achieved by varying the fan's thickness logarithmically. A linear thickness profile is however ideal for achieving a high temperature of 96°C at the fan blades. These findings suggest that using less material in specific thickness profiles can effectively distribute thermal energy across a polymer substrate. Additionally, a thermal cloaking shield made from the sensu fan can block heat conduction to sensitive areas, making the structure ideal for managing heat distribution without exceeding the limitations of flexible substrates.

2. INTRODUCTION

Flexible electronics refer to electronic devices that are bendable, stretchable, or foldable, allowing for unique and versatile form factors and applications in various industries such as healthcare, wearables, and flexible displays. These devices typically utilize flexible substrates like plastic, polymer, or metal foil, enabling them to conform to different shapes and surfaces. Flexible electronics present challenges for thermal management due to their non-traditional form factors and potential limitations in material selection. The typical materials used as the substrate are polyimide, hydrogel, PDMS, which have thermal conductivity well below 10 W/mK. As the field of flexible electronics continues to evolve, more functionalities will be packed onto single device with more power consumption and thus more heat to be dissipated.

The geometric transformation of a sensu-fan in the context of thermal metamaterials is based on the principles from transformation optics [1]. Essentially, the transformation involves mapping a semi-annular region (where the circular heat source replaces the centre of the circle) in virtual space to a larger region in real space. This is achieved through specific transformation equations: $r = \frac{(b-a)}{\delta}(r'-b)+b$ where the semi-annular region $(b-\delta < r' < b)$ in virtual space is extruded to a region $(a \le r \le b)$. Thus, the thermal conductivity in this region is $\underset{k}{\leftrightarrow} = diag\left(\frac{b-a}{\delta}\left(\frac{r'}{r}\right)^2 \frac{\delta}{b-a}\right)$. When $\delta \to 0$, we obtain $\underset{k}{\leftrightarrow} = diag(\infty, 0)$. So, the thermal conductivity of the region becomes $k_r = k_b 2^n$ and $k_\theta = k_b 2^{-n}$ with large n. Thus, from theory it is possible to realize an anisotropic structure by alternately stacking two materials [2] with high and low thermal conductivity (copper and vacuum) in the azimuthal direction (**Fig. 1**).

*Corresponding Author: eleykl@nus.edu.sg ; jloh24@nus.edu.sg

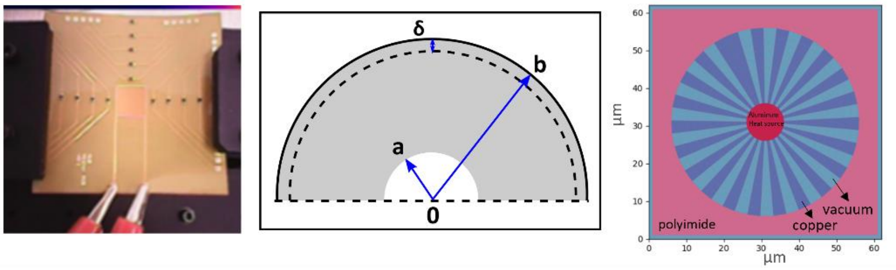

Fig 1. Left, an example of a heat source on a flexible polyimide substrate. Centre, transformation principle of a sensu fan metamaterial. Right, the top view of the simulated aluminium circular heat source and alternating slices of copper and vacuum, on polyimide substrate.

3. METHDOLOGY

A python-based heat solver was coded to enable faster simulation thorough-put, which uses the steady-state heat equation $-\ k\nabla^2 T = s$ with temperature and flux continuity conditions on the interfaces between different materials: $T_1 = T_2$, $k_1 \frac{\delta T_1}{\delta n} = \ k_2 \frac{\delta T_1}{\delta n}$. The package is a Tidy3D API. The thickness of the aluminum heater is 1.4 µm, polyimide substrate 1 µm, maximum thickness of the fan structure 9.6 µm, with the arc length of the fan slices 5°. The thermal conductivity of the aluminum, polyimide and copper is 250, 10 and 400 W / (µm . K) respectively. The width of the cell is set as 62 µm, radius of the fan 25 µm, and width of the heat source is 10 µm.

4. RESULTS

The results show that not only the fan metamaterial effective in distributing heat away from the heat source (lower temperature in the centre and higher temperatures on the surrounding substrate), **Fig. 2**, it can be made more effective with varying the thickness throughout the radial of the fan metamaterial. As can be seen in Figure 2b, a variety of 11 step profiles are tested, and (with exception of quadratic profile), they end at 9.6 µm at the last step. As can be seen the logarithm step profile performs the best amongst non-linear or constant profiles, in having a high temperature on the blades while significantly lowering the central heat source by 220°C (**Fig. 3**). However, the highest temperatures on the fan blades are associated with linear and hyperbolic tangent thickness profiles. Surprisingly, despite having a higher thickness in the last steps (intuitively resulting in a higher effective thermal conductivity), the quadratic profile has amongst the highest central temperature and the lowest blade temperatures. Given that the ideal heat distribution would be a low central temperature and a high blade temperature, it seems that a custom defined combination of the linear and logarithm thickness profile will achieve a more uniform temperature.

In addition, we show the effectiveness of the sensu fan metamaterials as thermal cloaking [3, 4], by manipulating heat flow around the heat source. In **Fig. 4**, we show that while inward facing thermal metamaterials are able to interact with each other to form a uniform temperature from 4 corner heat sources, the thermal metamaterial arcs serve as a thermal cloaking shield that prevents half of the substrate from receiving thermal input from the heat sources. This is another example of the versatility of the fan metamaterial.

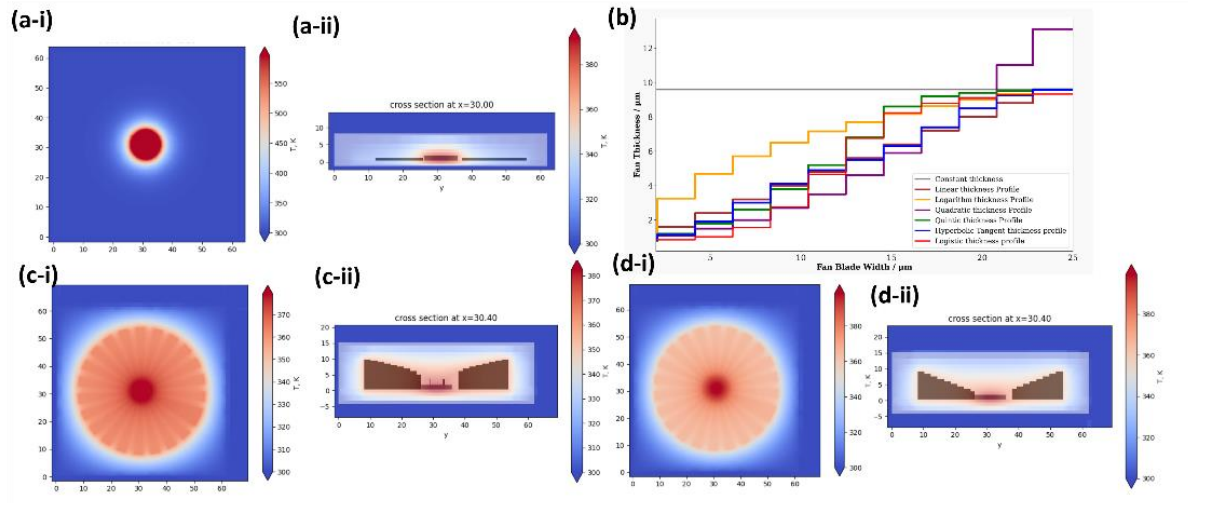

Fig 2. (a, c, d) top view and cross-sectional view of the heat source on polyimide substrate with the associated temperatures through the central heat source for no fan, fan with logarithm profile thickness, and fan with linear profile thicknesses respectively. **(b)** shows the various step profiles for constant thickness, linear, logarithm, quadratic, quintic, hyperbolic and logistic thickness profiles.

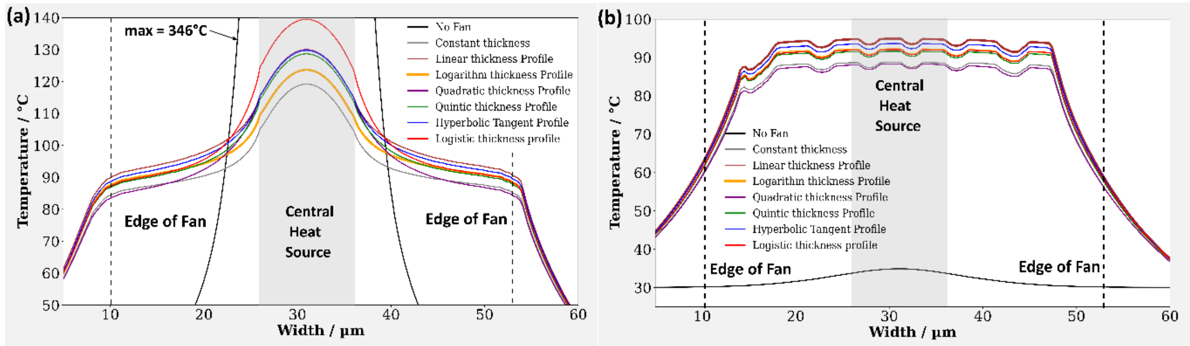

Fig. 3. Temperature distributions across the centre (**a**) (30 µm y axis) and across the fan blades (**b**) (15 µm y axis) in the Fig 2 top view plots. In (a) a constant thickness profile has the lowest central and blade temperatures, and logarithm shows a relatively low central temperature and high blade temperatures relative to the other profiles. However, in (b) both hyperbolic and linear thickness profile fan blades have high temperatures.

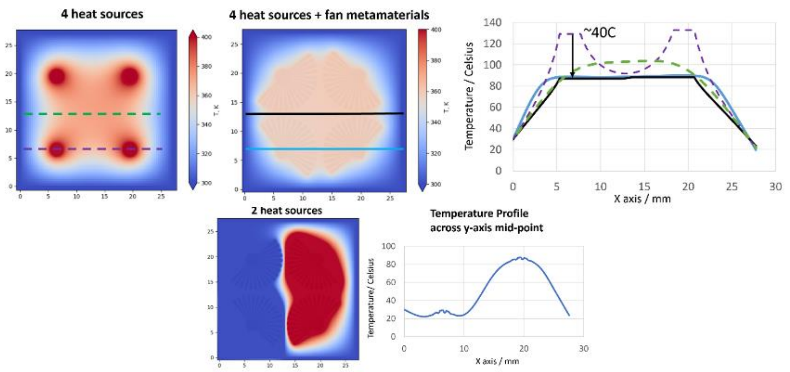

Fig. 4. Temperature distribution of four heat sources shows a high and non-uniform PI temperature, but with appropriately angled half-fan metamaterials of 35°, shows a highly uniform temperature distribution, and a drop of 40°C in the heat sources. In the bottom row, an example of the heat cloaking effect is shown with only 2 heat sources activated. The fans on the left side of the plot prevent thermal flow, and doubles the temperature on the right side of the plot.

5. CONCLUSIONS

We demonstrate that a sensu-fan metamaterial can be optimized to achieve various temperature distributions on a poorly conductive polymer substrate, using less material while adapting to substrate flexing, and also blocking heat with a thermal cloaking effect, though further optimization is needed for uniform distribution.

ACKNOWLEDGMENT The authors sincerely acknowledge the staff of SHINE centre of microelectronics in National University of Singapore for their support

REFERENCES

[1] Pendry, J. B., Schurig, D., & Smith, D. R. Controlling electromagnetic fields. Science, 312 (2006), 1780–1782

[2] Moccia, M., Castaldi, G., Savo, S., Sato, Y., & Galdi, V. Independent manipulation of heat and electrical current via bifunctional metamaterials. Physical Review X, 4 (2014), 021025.

[3] Narayana, S., Savo, S., & Sato, Y. Transient heat flux shielding using thermal metamaterials. Applied Physics Letters, 102 (2013), 201904.

[4] Han, T., Yuan, T., Li, B., & Qiu, C.-W. Experimental demonstration of a bilayer thermal cloak. Physical Review Letters, 112 (2014), 054302.