Supporting Information
A textured surface platform for dual-mode temperature regulation in photonic textiles

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1 Thermal analysis and circuit model

A simple approximate method to combine the radiative and non-radiative heat transfers in a system is to use the framework of electric circuits with Ohm's law, where temperature represents the potential and heat transfer represents the current. The thermal resistance for heat transfers that occur simultaneously between the same two interfaces will be represented as parallel resistances, while for heat transfers that occur between consecutive sets of interfaces as resistances in series.

The total heat transfer through a system in dry conditions can be expressed as:

$$Q = \frac{T_{\text{skin}} - T_{\text{amb}}}{R_{\text{tot}}}, \tag{1}$$

where T_{skin} and T_{amb} are the skin and ambient temperatures, while R_{tot} is the total thermal resistance of the whole system. Using the circuit model we evaluate the minimum and maximum temperatures for maintaining thermal comfort.

Thermal comfort is achieved when total heat transfer is equal to the heat generated by the body; the maximum and minimum ambient setpoint temperatures can be determined by solving the inequalities:

$$Q > Q_{\text{gen}} \text{ and } Q < Q_{\text{gen}}. \tag{2}$$

The first inequality corresponds to the situation where the ambient temperature is low so that the heat transfer through the textile exceeds the heat generated by the body: the person loses heat and feels cold. The second inequality corresponds to the case when the ambient temperature is high so that the heat generated by the body cannot be evacuated by heat transfer through the textile: the person feels hot. By combining equation 1 and inequalities 2, we get the condition that the body is cold, i.e., the textile is not heating enough when

$$T_{\text{amb}} < T_{\text{skin}} - R_{\text{tot}} Q_{\text{gen}}. \tag{3}$$

Whereas the body is hot, i.e., the textile is not cooling enough when:

$$T_{\text{amb}} > T_{\text{skin}} - R_{\text{tot}} Q_{\text{gen}}. \tag{4}$$

Since the textile has different radiative properties when it is planar or wrinkled, the total thermal resistance will be different in the heating and cooling cases. We can thus write the heating setpoint as

$$T_{\text{amb,heat}} = T_{\text{skin}} - R^{\text{h}}_{\text{tot}} Q_{\text{gen}} \tag{5}$$

where $R^{\mathrm{h}}_{\mathrm{tot}}$ is the total thermal resistance of the system in heating mode, when the fabric is planar (low emission). While the cooling setpoint reads as

$$T_{\mathrm{amb,cool}} = T_{\mathrm{skin}} - R^{\mathrm{c}}_{\mathrm{tot}} Q_{\mathrm{gen}} \tag{6}$$

where $R^{\mathrm{c}}_{\mathrm{tot}}$ is the total thermal resistance of the system in cooling mode, when the fabric is textured (high emission).

Following Fourier's law for thermal conduction, the conductive thermal resistances through the air gap and the textile are

$$R_{\mathrm{cond,air}} = \frac{t_{\mathrm{air}}}{k_{\mathrm{air}}} \text{ and } R_{\mathrm{cond,tex}} = \frac{t_{\mathrm{tex}}}{k_{\mathrm{tex}}}, \tag{7}$$

where t_{air} and t_{tex} are air and textile thickness, k_{air} is the thermal conductivity coefficient of air and k_{tex} for the textile, which is retrieved using classical effective medium theory as done in ref.[1] Convective heat transfer from the fabric's outer surface to the ambient follows from Newton's law of cooling. Subsequently, the convective thermal resistance of the ambient air is:

$$R_{\mathrm{conv}} = \frac{1}{h_{\mathrm{air}}}, \tag{8}$$

where h_{air} is the convective coefficient of air.

For the radiative thermal resistances in the air gap and the ambient air, we have

$$Q_{\mathrm{rad,air}} = \frac{1}{4\sigma \bar{T}^3_{\mathrm{skin,in}}}\left(\frac{1}{\varepsilon_{\mathrm{s}}} + \frac{1}{\varepsilon_{\mathrm{i}}} - 1\right) \text{ and } R_{\mathrm{rad,amb}} = \frac{1}{4\sigma \bar{T}^3_{\mathrm{out,amb}}}\left(\frac{1}{\varepsilon_{\mathrm{o}}} + \frac{1}{\varepsilon_{\mathrm{a}}} - 1\right) \tag{9}$$

where σ is the Stefan-Boltzmann constant, $\varepsilon_{\mathrm{s,i,o,a}}$ are the emissivities of the skin, inner and outer textile surfaces, and ambient environment. Here we considered the following simplification for temperatures:[2] $T_1^4 - T_2^4 \approx (T_1^2 - T_2^2)(T_1 + T_2)(T_1 - T_2)$, and we assume

$$\overline{T}^2 = \left(\frac{T_1 + T_2}{2}\right)^2 \approx T_1 T_2, \tag{10}$$

so $T_1^4 - T_2^4 = 4\overline{T}^3 \Delta T$, where $\Delta T = T_1 - T_2$.

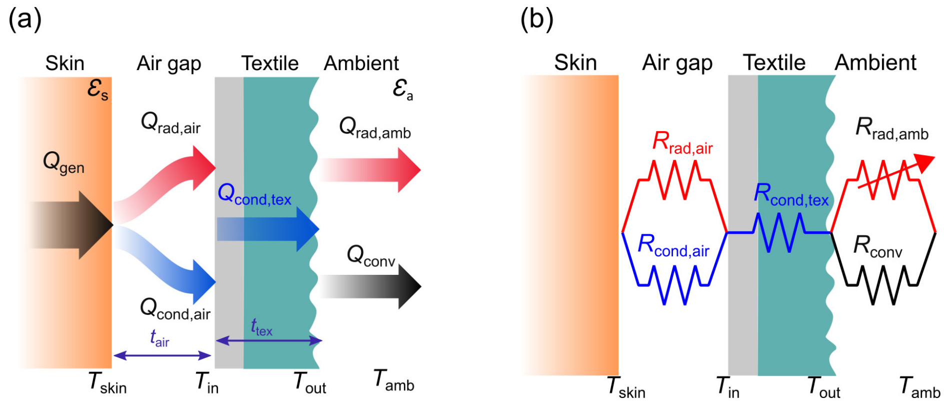

Figure S1. (a) The main heat flow channels when the fabric covers skin, with an air gap in between. (b) Corresponding thermal circuit analogy.

Finally, we use the thermal circuit model shown in Fig. S1b, and implement basic summing rules to calculate the total thermal resistance:

$$R_{\text{tot}} = \left(\frac{1}{R_{\text{air}} + R_{\text{cond,tex}} + R_{\text{amb}}} \right)^{-1} \tag{11}$$

with

$$R_{\text{air}} = \left(\frac{1}{R_{\text{rad,air}}} + \frac{1}{R_{\text{cond,air}}} \right)^{-1} \text{ and } R_{\text{amb}} = \left(\frac{1}{R_{\text{rad,amb}}} + \frac{1}{R_{\text{conv}}} \right)^{-1}. \tag{12}$$

The radiative thermal resistances between the fabric surface and the ambient change when the fabric texture varies (flat and textured), which creates its dual behavior. When the fabric is in heating mode, with the surface being planar, the outer surface emissivity ε_{o} will be low. When the fabric is in cooling mode, with the textured fabric, ε_{o} will be high.

The heating and cooling setpoints $T_{\text{amb,heat}}$ and $T_{\text{amb,cool}}$ can then be calculated using equations 5 and 6 by replacing each of the parameters in R_{tot} (Eq. 11) to obtain its value and taking $Q_{\text{gen}} = 70\ \text{W/m}^2$. The parameters in R_{tot} are the conductive, convective, and radiative properties of the system components, and will change according to the structure geometry and materials.

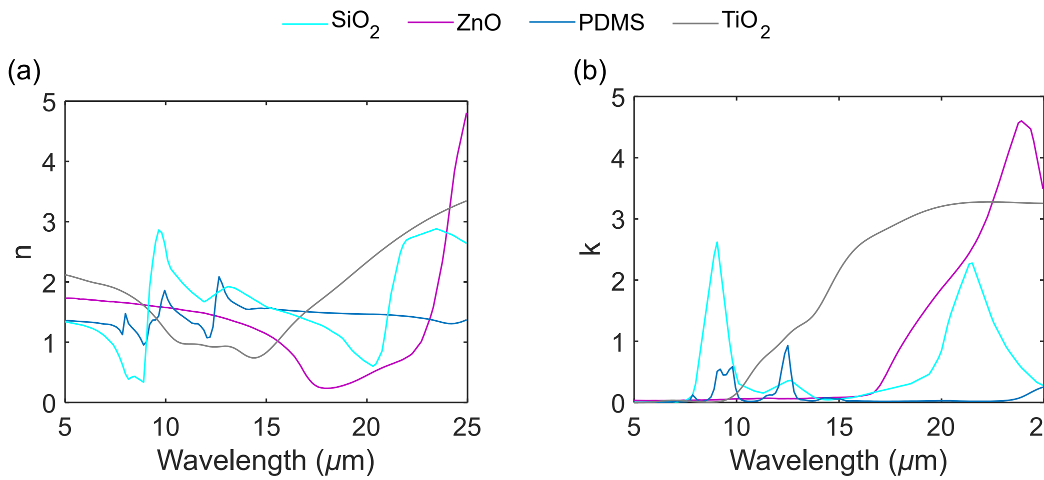

Figure S2. Refractive index (n) and extinction coefficient (k) of SiO_2, ZnO, PDMS, and TiO_2. Data obtained from[3–6] respectively.

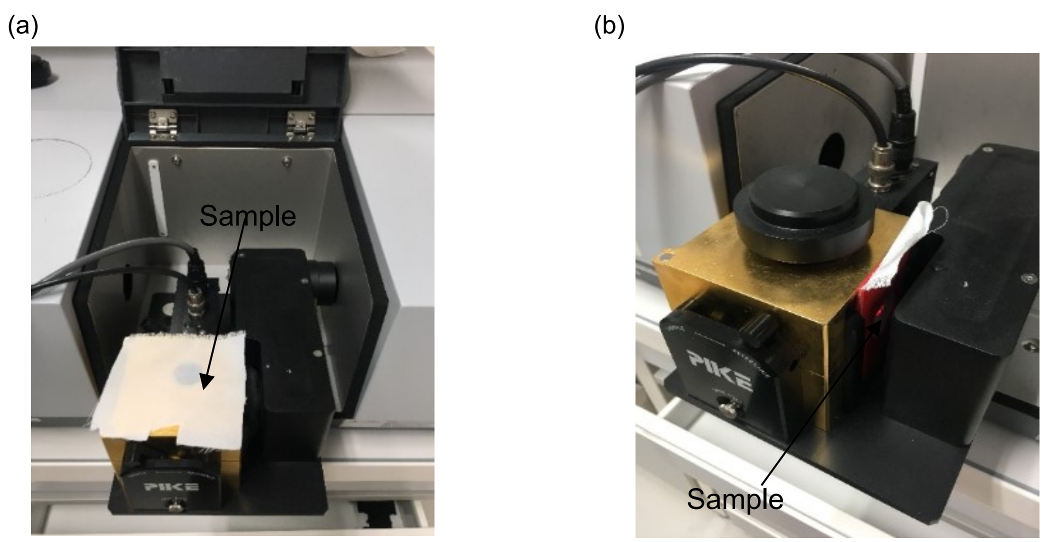

Figure S3. The samples were characterized by Fourier Transformed Infrared (FTIR) spectrometry (Shimadzu IR Prestige 21 spectrometer) to evaluate the reflectance and transmittance. The infrared measurements were carried out with an integrating sphere (Mid-IR IntegratIR—PIKE technologies) which features a 12-degree illumination of the sample in order to measure the total (diffuse and specular) relative (standard gold sample) reflectance. The samples were placed directly onto the sample port (diameter = 2.5 cm) located on the top of the sphere for reflectance measurements (a). For the transmittance measurements, the samples were placed in front of the entrance port and the sample port located on the top of the sphere was covered with the gold reference material (b). The absorptance was calculated by 1 - transmittance - reflectance.

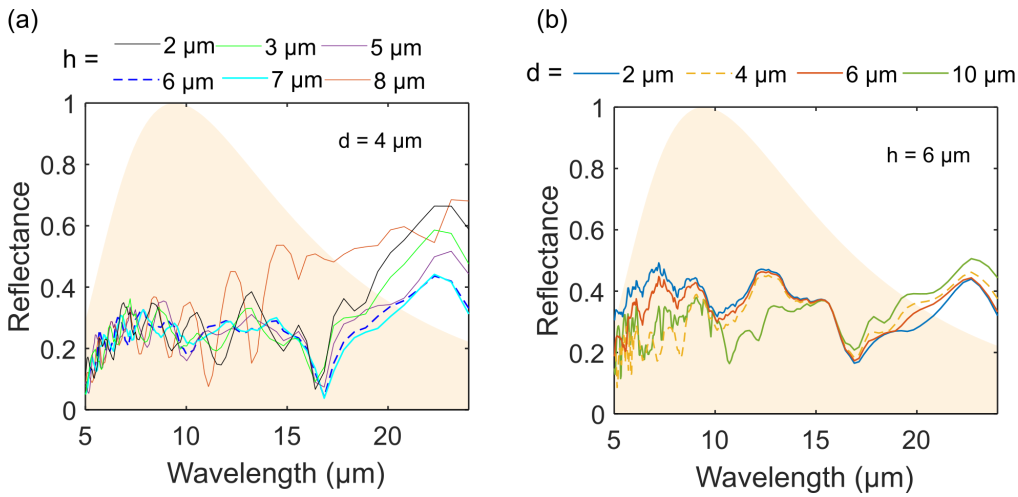

Figure S4. Simulated spectral reflectance of periodic wrinkling structure for (a) different h values for fixed d (4 μm) and (b) different d values with fixed h (6 μm).

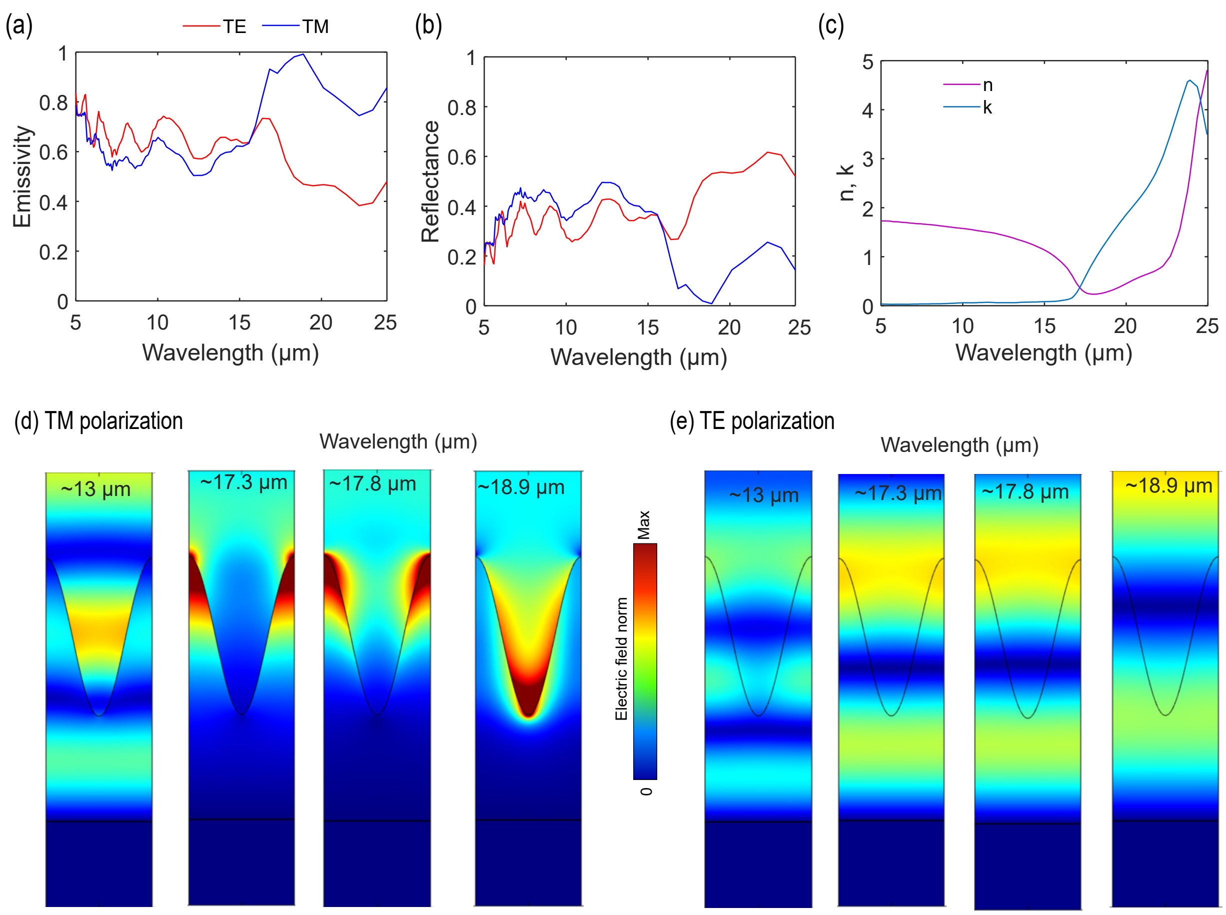

Figure S5. (a) Spectral emissivity of a periodic wrinkled ZnO/Ag for TE and TM polarization. (b) The corresponding spectral reflectance. (c) Refractive (n) and extinction coefficient (k) of ZnO. (d) The electric field norm at various wavelengths for TM polarisation and (e) TE-polarization.

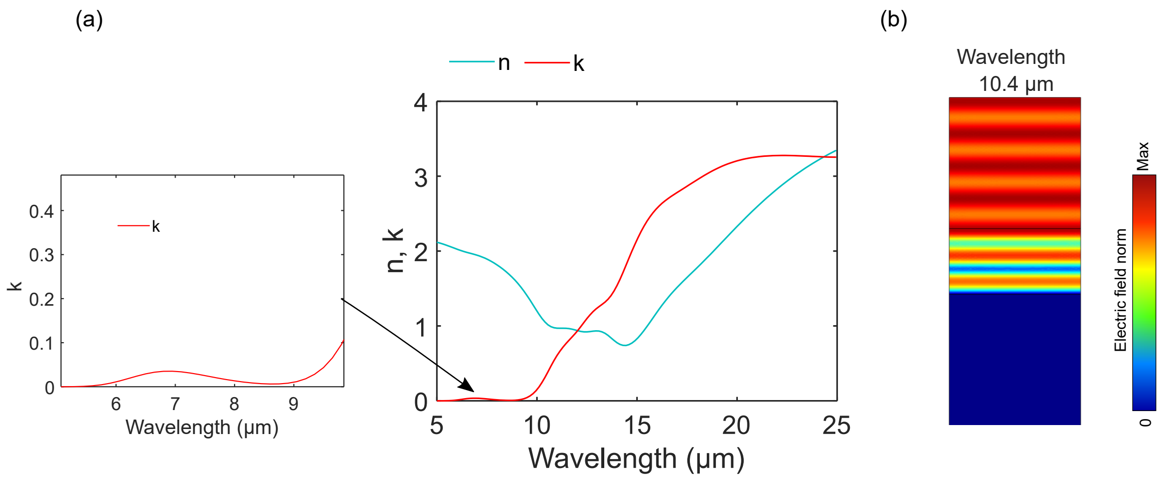

Figure S5. (a) Refractive index (n) and extinction coefficient (k) of TiO_2 (zoom on left side). (b) The electric field norm.

References

(1) Abebe, M. G.; Rosolen, G.; Khousakoun, E.; Odent, J.; Raquez, J.-M.; Desprez, S.; Maes, B. Dynamic Thermal-Regulating Textiles with Metallic Fibers Based on a Switchable Transmittance. *Physical Review Applied* **2020**, *14*, 044030.

(2) Hsu, P.-C.; Liu, C.; Song, A. Y.; Zhang, Z.; Peng, Y.; Xie, J.; Liu, K.; Wu, C.-L.; Catrysse, P. B.; Cai, L., et al. A dual-mode textile for human body radiative heating and cooling. *Science Advances* **2017**, *3*, e1700895.

(3) Kischkat, J.; Peters, S.; Gruska, B.; Semtsiv, M.; Chashnikova, M.; Klinkmüller, M.; Fedosenko, O.; Machulik, S.; Aleksandrova, A.; Monastyrskyi, G., et al. Mid-infrared optical properties of thin films of aluminum oxide, titanium dioxide, silicon dioxide, aluminum nitride, and silicon nitride. *Applied Optics* **2012**, *51*, 6789–6798.

(4) Querry, M. Optical Constants, contractor report. *US Army Chemical Research, Development and Engineering Center (CRDC), Aberdeen Proving Ground, MD* **1985**, *418*.

(5) Zhang, X.; Qiu, J.; Li, X.; Zhao, J.; Liu, L. Complex refractive indices measurements of polymers in visible and near-infrared bands. *Applied Optics* **2020**, *59*, 2337–2344.

(6) Siefke, T.; Kroker, S.; Pfeiffer, K.; Puffky, O.; Dietrich, K.; Franta, D.; Ohlídal, I.; Szeghalmi, A.; Kley, E.-B.; Tünnermann, A. Materials pushing the application limits of wire grid polarizers further into the deep ultraviolet spectral range. *Advanced Optical Materials* **2016**, *4*, 1780–1786.