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Verification of a large-band metamaterial absorber and its application in the measurement of thermal properties of clothing fabrics

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Abstract

The development and application of smart fabrics is a research hotspots in clothing fabrics. Accurately measuring the thermal conductivity of clothing fabric samples is an important basis for developing corresponding products. Here, thermal properties (thermal resistance and diffusivity) of clothing fabrics were measured through using a metamaterial sensor. The measured thermal resistance and diffusivity of the clothing fabrics could be affected by ambient temperature. The measured thermal resistance was also enhanced by increasing the fabric sample thickness. Similar resonance behaviors could be found in the fitted results based on the heat conduction theory. Finally, under the condition of the same thickness and temperature, the thermal properties of four clothing fabric samples were simulated and measured.

1. Introduction

In recent years, artificially electromagnetic metamaterials had received extensive attention. A wide variety of metamaterials were proposed and verified by researchers [1–4]. Numerous surprising resonance properties of metamaterials were revealed by researchers, such as negative refraction (NR), cloak, lensing [5–8]. Metamaterials were applied due to their resonance behaviors, such as absorption, sensing, reflection, transmission [9–13]. Moreover, metamaterials were widely applied in sensors, such as gas sensors, liquid sensors, temperature sensors, etc [14–17]. Depending on the application purpose and material properties, metamaterials were sensitive to numerous external informations, such as light, voltage/current, laser pulses, thermal energy radiation, etc [18–21]. Therefore, it was feasible to realize metamaterial sensing in ambient temperature. However, the application of metamaterial sensors to the measurement of thermal properties of clothing fabrics samples had not been paid much attention by researchers. At the same time, development of smart fabrics was a research hotspots. At present, the measurement of thermal properties of clothing fabrics were mainly focused on the infrared emissivity and photothermal absorptivity, and many measurement methods were reported [22–25]. In addition, fibers used in clothing fabrics were also extensively studied by researchers [26–28]. However, thermal conduction characteristics of smart fabrics were not extensively studied, for example, the thermal resistance or diffusivity of clothing fabrics, and so on. Based on the sensitive to the temperature or thermal properties, it was feasible to measure thermal conduction characteristics of clothing fabric samples by using the metamaterials sensors.

In this paper, the thermally responsive current, diffusivity, and resistance of the clothing fabric samples were revealed, simulated, and measured by a metamaterial sensor. In experiments, the thermal response current on the standard substrate was revealed during the heat penetrating the clothing fabric samples and reaching the standard substrate. Based on this property, the thermal properties of clothing fabric samples under different temperature conditions were measured. Measured results revealed that the thermal diffusivity and resistance of the fabric samples were changed by ambient temperature. Heat conduction theory was applied to explain the
thermal properties of clothing fabric samples. The effect of the thickness and type of fabric samples on the thermal properties was also measured. The fitting results of heat conduction were basically consistent with measured results. These results exhibited that it is feasible to apply metamaterials to the measurement of thermal properties of fabrics.

2. Structure and metamaterial

The structure of this metamaterial could be found in figures 1(a)–(b). The proposed unit cell consisted of a silicon disk array, SU-8 and metal layers. The geometric parameters were the following: Lattice constant: \( P = 10 \mu m \), material thickness: \( h_1 = 0.1 \mu m \), \( h_2 = 1.4 \mu m \), \( h_3 = 0.4 \mu m \), and diameter: \( D = 8 \mu m \). In simulations, the metal layer can be revealed by the follows:

\[
\varepsilon(\omega) = 1 - \frac{\omega_P^2}{\omega(\omega + i\omega_c)}
\]  

(1)

In the equation (1), the scattering frequency can be achieved by \( \omega_c = 4.08 \times 10^{13} \) Hz, the plasma frequency can be achieved by \( \omega_p = 1.37 \times 10^{16} \) Hz [29]. The SU-8 layer can be revealed by the reported work [30]. The detailed simulation Settings are as follows: the scanning step of simulation frequency is 0.01thz, the heat source is located 2 cm above the unit cell, and the receiver is located 1 cm below the unit cell. Floquet ports are set on and bollow the unit cell. An ideal magnetic guide plate is applied to both boundaries in the Y-axis direction, similarly, an ideal electrical guide plate is applied to both boundaries in the X-axis direction [31]. The sample preparation method of this metamaterial is as follows: (a) a SU-8 layer was achieved by a MSC-400Bz-6N spinner and covered on a glass piece. The glass-SU-8 layers were dried and cured through the hot plate C-MAG HP10. (b) The metal layer was covered on the SU-8 layer through the ZZL-U400C. (c) This glass-SU8-metal layers were soaked in acetone solution. The SU-8 layer was removed and the separate metal layer was obtained. (d) A new SU-8 layer was coved on this metal layer. The metal-SU-8 layers were dried and cured through the hot plate C-MAG HP10. (e) A Si layer was deposited on this SU-8 layer. (f) An CABL-9000C was used to defined the Si disk array. (g) The ultrasonic device VGT-QTD was used to clean the metamaterial samples and the JSM-7610F was used to achieved the SEM of metamaterial, as shown in figure 2(a). During the measurement of thermal conductivity, the fabric to be tested was placed on a standard substrate. The surface of the fabric was completely covered by metamaterial samples and electrode plates, seen in figure 2(b). The upper surface of the electrode plate was covered with a heat insulating coating. The fabric was completely covered and wrapped. The purpose was to eliminate the interference of ambient heat radiation on the thermal conductivity of the fabric. Therefore, during the experimental measurement, the conduction heat received by the standard substrate would mainly come from the energy left by the thermal radiation penetrating the metamaterial and the sample.

Before measuring the thermal properties of clothing fabric samples, the electromagnetic wave transmission or absorption properties of the metamaterial need to be verified. It should be indicated that the thermal properties of the fabric samples need to be measured over a large spectral range. Therefore, to avoid interfering with the measurement signal of clothing fabric samples, the applied sensors should not exhibit obvious resonance modes in the target frequency band. This is because the thermal properties of clothing fabric samples tends to be stable or change slowly over a large frequency spectrum. If an obvious resonance absorption mode is
excited by the sensing device in the target spectrum, the thermal properties of clothing fabric samples near the
resonance frequency would be masked. The error of the measurement signal would be increased and was not
conducive to the measurement application. The transmittance, reflectance and absorption of this metamaterial in
the target frequency band 14–48 THz were shown in figure 3. The measurement results shown that the
transmittance of this metamaterial was basically stable in the range of 14–48 THz (average transmittance of 69.4%).
The lost of the energy of the electromagnetic wave in the process of penetrating the metamaterial was stable. At the
same time, the absorption rate of the metamaterial was also stable in this target frequency band (average absorption
rate was 11.3%). In order to verify the resonance properties of the metamaterial in the range of 14–48 THz, the
electric field intensity distributions at different frequency points were simulated, as shown in figure 4. Within the
target frequency band, four different calculation frequency points were selected: 16 THz, 26 THz, 36 THz, 46 THz,
as shown in figures 4(b)–(e). In the target frequency band, absorption resonance mode can’t be excited by the
metamaterial inside the unit cell, and the energy of the electromagnetic wave was uniformly distributed in the
whole unit cell, as shown in figures 4(b)–(e). This electric field distribution characteristic was consistent with the
absorptivity measurements in figure 3. Instead, two frequency points outside the target band were simulated:
10 THz and 52 THz, as shown in figures 4(a), (f). Obvious resonance absorption mode was effectively excited by
the metamaterial unit (the resonance mode was distributed inside the disk array) when the calculated frequency
were deviated from the operating frequency band, as shown in figures 4(a), (f). Therefore, the electric field

![Figure 2](image1.png)

**Figure 2.** (a) SEM of the metamaterials. (b) Schematic diagram of the fabric sample measurement structure.

![Figure 3](image2.png)

**Figure 3.** The measured transmission, reflection, and absorption of the metamaterials.
distribution results in figures 4(b)–(e) verify that the metamaterial was suitable for measuring the thermal conductivity of fabric samples in the range of 14–48 THz. The resonant nature of the metamaterial was not interfere with the thermal conduction signal of the fabric sample in this target frequency band.

In the first set of measurements, the standard dielectric layer biaxially oriented polypropylene (BOPP) was placed between the metamaterial and the standard substrate (normal temperature, normal pressure). The thermal response current was measured and shown in figure 5, seen in the black curve. The measurement results show that as the thermal radiation continues, the excited thermal response current on the standard substrate was reached a basic steady state in a very short time. The thermal radiation was stably penetrated the metamaterial and the BOPP layer, and reached the standard substrate. Under the continuously output thermal radiation, the surface induced current (thermal response current) was revealed on this substrate stable. Such a measurement method could obtain a continuous thermally responsive current. Based on these thermal response currents, the corresponding thermal response resistance and thermal diffusivity were revealed through analysis. The continuous thermal response current was beneficial to reduce errors and suppress noise in the measurement process, and this continuous signal measurement method was different from the instantaneous measurement method. To reveal the important role of the BOPP layer or the fabric samples, the BOPP layer was removed, and the measured thermal response current was shown in the figure 5, seen in the red curve. Measured results shows that when the BOPP layer was removed and the space between the metamaterial and the standard substrate was filled with air, the magnitude of the thermal response current was significantly reduced. This was because air was a poor conductor of heat, and little heat was reached the standard substrate, resulting in a weak amplitude of the excited thermally responsive current, found the red curve in figure 5. In the third measurements, the BOPP layer was replaced by the clothing fabric samples polyester, and the measured thermal response current was shown in figure 5, seen in the green curve. It should be pointed out that more time was consumed to achieve the maximum thermal response current in the third set of measurements. Moreover, the maximum amplitude was lower than that of the BOPP layer. This is because the thermal properties of this fabric sample polyester was lower than that of the BOPP layer and had a higher thermal resistance.
3. Measured and simulated results

To facilitate the understanding of the thermal properties (including thermal diffusivity, thermal resistance, thermal response current) of the clothing fabric samples, fitting calculation method based on the experimental measurement results in figure 6 was applied. In the calculation process, two fitting methods (Frequency domain fitting (FDF), time domain fitting (TDF)) were verified separately, as shown in figure 6. Time domain fitting and frequency domain fitting were two methods or angles used to analyze signals. There was no essential difference between the two fitting methods, and the Fourier transform relation could be used to transform the signal freely between the two methods. Among them, the time domain fitting method mainly used the way of time axis to reveal the changing relationship of dynamic signals, while the frequency domain fitting method mainly used the method of frequency axis to show the shape of dynamic signals. In general, using the time domain fitting method could get more intuitive and visual results, and using the frequency domain method could simplify the signal analysis process, the analysis of the problem was more profound and convenient. These two fitting methods revealed their own advantages and disadvantages. Therefore, it was usually necessary to compare the two fitting results to determine which fitting method was more consistent with the experimental results. Obviously, the thermal response current obtained by the FDF method were more consistent with the measured results than the

Figure 5. Thermal response current measurement results. Among them, the black curve indicates that the standard medium layer BOPP layer was used in the measurement process, the red curve indicates that the standard medium layer BOPP layer was not used during the measurement process, and the green curve indicates that the fabric sample polyester was used in the measurement process.

Figure 6. Calculation results using different fitting methods. Among them, the measured result is the black curve. The red curve is the simulated result based on the FDF method. The green curve is the simulated result based on the TDF method.
TDF method. In this paper, the FDF method was used to achieve the simulated thermal response current. The basic calculation principle of this method was to determine the thermal diffusivity and thermal resistance by measuring the thermal response current of the fabric sample. Therefore, the method was an indirect measurement method: first, the fabric sample was placed on a substrate with good thermal and electrical conductivity (the substrate uses a metal layer), the surface of the fabric sample was then covered with a metamaterial sensor whose transmission and absorption properties (as shown in Figure 3) were determined. The base material of metamaterial sensor was metal layer, which had good thermal conductivity and electrical conductivity. It should be noted that metamaterials were treated as homogeneous materials in theoretical calculations (according to the equivalent medium theory), whereas both the fabric sample and the substrate were homogeneous and could also be considered as one-dimensional materials, according to heat conduction theory [32]. When heat energy was transferred from the hot plate to the metamaterial sensor, part of the heat energy was absorbed by the metamaterial sensor, and the rest of the energy passed through the fabric sample to the substrate surface. The temperature distribution on the substrate surface was not uniform because of the definite conductivity and insulation of the tested fabric sample. The non-uniformity of temperature results in non-uniformity of surface deformation of substrate. When an external DC electric field was applied to the substrate (shown in Figure 2), this inhomogeneous deformation induces a resonant response of the substrate surface to thermal disturbances, resulting in a thermally responsive current, according to the equations (9–12). According to heat conduction theory [32], the relationship between thermal response current and resistance could be expressed as the schematic diagram in Figure 7:

\[
\frac{\partial \theta_{\text{metamaterial}}}{\partial x^2} = \frac{1}{a_{\text{metamaterial}}} \cdot \frac{\partial \theta_{\text{metamaterial}}}{\partial t} \tag{2}
\]

\[
\frac{\partial \theta_{\text{substrate}}}{\partial x^2} = \frac{1}{a_{\text{substrate}}} \cdot \frac{\partial \theta_{\text{substrate}}}{\partial t} \tag{3}
\]

\[
\frac{\partial \theta_{\text{sample}}}{\partial x^2} = \frac{1}{a_{\text{sample}}} \cdot \frac{\partial \theta_{\text{TIM}}}{\partial t}, \quad l_1 \leq x \leq l_1 + l_2 \tag{4}
\]

The material temperature distribution property was expressed as \(\theta\). Thermal diffusivity was expressed as \(a\). The convective heat transfer coefficient on boundary was expressed as \(\sigma\). In the process of thermal energy passing
through the metamaterial sensor, the fabric sample, and the substrate in turn, the thermal conductivity of the three materials could be determined according to formulas (2–4):

\[ \sigma_{1,\text{sample}}(x) = -k_{\text{metamaterial}} \frac{\partial \theta_{\text{metamaterial}}}{\partial x}, \quad x = l_1 \]  
\[ k_{\text{sample}} \frac{\partial \theta_{\text{sample}}}{\partial x} = k_{\text{metamaterial}} \frac{\partial \theta_{\text{metamaterial}}}{\partial x}, \quad x = l_1 \]  
\[ \sigma_{2,\text{sample}}(x) = -k_{\text{substrate}} \frac{\partial \theta_{\text{substrate}}}{\partial x}, \quad x = l_1 + l_2 \]  
\[ k_{\text{substrate}} \frac{\partial \theta_{\text{substrate}}}{\partial x} = k_{\text{sample}} \frac{\partial \theta_{\text{sample}}}{\partial x}, \quad x = l_1 + l_2 \]  

(5)  
(6)  
(7)  
(8)

The thermal conductivity was expressed as \( k \). The heat conduction boundary condition between the metamaterial sensor and the fabric sample in the process of heat energy penetrating the metamaterial sensor, the fabric sample, and the substrate in turn, the heat conduction boundary condition between the fabric sample and the substrate could be obtained by formula (5–8):

\[ P_{\text{sample}}(x) = P_{\text{device}} - P_{\text{ambient}} \]  
\[ g(x) = (a_c - a_x)E(x) + P_{\text{sample}}(x) \]  
\[ I(t) = \frac{A}{d} \int_0^d g(x) \frac{\partial \Delta T(x, t)}{\partial t} dx \]  

(9)  
(10)  
(11)

The used parameters were as follows: The thermal radiation energy density of the fabric sample, equipment, and environment were expressed as \( P_{\text{sample}}, P_{\text{device}}, P_{\text{ambient}} \), respectively. The thermal resistance of the sample was expressed as \( R_{\text{sample}} \). The thickness of the metamaterial was expressed as \( l_1 \). The thickness of the sample was expressed as \( l_2 \). The thickness of the standard substrate was expressed as \( l_3 \). Therefore, based on the equations (10)–(11), the measured thermal response current could be achieved by applied an electric field on the direct current field. When the thermal pulse reached the interface between the sample and the substrate, the thermal response current was excited and measured. Under the conditions of the applied electric field and equation (9), the equations (10)–(11) could be simplified to equation (12), as follows:

\[ I(t) = \frac{AE(x)K_{eff}}{d} \int_0^d (a_c - a_x) \frac{\partial \Delta T(x, t)}{\partial t} dx \]  

(12)

The thermal resistance of the measurement process was consisted of three parts: the thermal resistance of the metamaterial sensor, the thermal resistance of the fabric sample, and the thermal resistance of the substrate:

\[ R_{\text{Overall}} = R_{\text{Metamaterial}} + R_{\text{Sample}} + R_{\text{Substrate}} \]  
\[ R_{\text{Metamaterial}} = \frac{l_1}{k_{\text{metamaterial}}} \]  
\[ R_{\text{Sample}} = \frac{l_2}{k_{\text{sample}}} \]  
\[ R_{\text{Substrate}} = \frac{l_3}{k_{\text{substrate}}} \]  

(13)  
(14)  
(15)  
(16)

The thermal resistance of the metamaterial sensor, fabric sample, and the substrate were: \( R_{\text{Metamaterial}}, R_{\text{Sample}}, \) and \( R_{\text{Substrate}} \). The thermal resistance of the metamaterial could be determined prior to measuring the fabric sample experiment. Therefore, the overall thermal resistance of the process could be obtained by measuring the thermal response current, so as to further obtain the thermal resistance of the fabric sample.

Measured thermal response current of the clothing fabric samples was exhibited in figure 8 under different temperature conditions. During measurements, the hot plate was set to 25 °C, 30 °C, 35 °C, and 40 °C, respectively, corresponding to the ambient temperature of the clothing fabric samples in applications. The measurement results show that as the external ambient temperature was gradually increased, the thermal response current was quickly reached its maximum value. The thermal response current was gradually enhanced, as shown in figure 8. Moreover, the thermal resistance (unit is \( \text{m}^2\cdot\text{K}/\text{W} \)) or the diffusivity (unit is \( \text{m}^2/\text{s} \)) of the fabric polyester was measured and shown in figure 9. With the increase of ambient temperature, the thermal diffusivity was gradually enhanced, as shown in figure 9(a). The FDF thermal diffusivity was showed similar resonance behaviors. Simultaneously, the measured thermal resistance was also gradually enhanced, seen in the figure 9(b). Obviously, the increasing trend of thermal resistance was lower than the thermal diffusivity (this was also confirmed by the fitting results). Therefore, as the ambient temperature increased, more and more energy was reached and concentrated on the standard substrate. According to equations (10–12), the thermal response current was intensified by the gradually accumulated energy, which could be found in figure 9.
The measured thermal response current (the clothing fabric sample was polyester) with different thicknesses under the same ambient temperature conditions (25 °C) was shown in figure 10. Clearly, the thickness of the fabric sample was shown a direct effect on the resonant behaviors (amplitude and time to peak) of the thermal response current. With the increase of thickness, the thermal response current was decreased gradually, seen in the figure 10. Moreover, thermal response current should take more time to peak. The thermal resistance was enhanced due to the increased of the thickness. Therefore, the energy reaching the standard substrate surface was weakened, and the thermal response current was reduced according to equations (10)–(12), as shown in figure 10. At the same time, thermal diffusivity and thermal resistance for these fabric samples were exhibited in figure 11. Thees results revealed that the amplitude of thermal resistance was directly affected by the thickness of the clothing fabric samples, but the effect on thermal diffusivity could be neglected.
Under the same ambient temperature and the same thickness conditions, the thermal response currents of four clothing fabric samples were measured, as shown in figure 12. The four fabric samples were: polyester, nylon, linen, cotton. Under the exact same measurement conditions, the influence of the fabric sample type on the measurement results was significant. For example, for fabric sample nylon, the thermal response current should take about 5 S to reach maximum. Moreover, the maximum of the thermal current was lower than the thermal currents of polyester, seen in the red curve in figure 12. On the contrary, for sample linen, the amplitude of the thermal current was enhanced, and the time to peak was reduced to about 2S. For fabric sample cotton, the measured thermal response current showed a similar resonance behavior as fabric sample polyester. The corresponding thermal diffusivity and thermal resistance were shown in figure 13. The measured diffusivity diffusivity of four clothing fabric samples were: 6.83 (Polyester), 5.76 (Nylon), 7.72 (Linen), and 6.61 (Cotton), as shown in figure 13(a). Meanwhile, the measured diffusivity resistance of four clothing fabric samples were: 8.16 (Polyester), 8.41 (Nylon), 7.72 (Linen), and 7.94 (Cotton), as shown in figure 13(b). Clearly, the fabric sample type

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**Figure 10.** Measured thermal current (fabric sample was polyester) under 25 °C.

**Figure 11.** (a) Measured and fitted of thermal diffusivity. (b) Measured and fitted of resistance (the fabric sample polyester).
exhibited distinct resonance properties. These resonance behaviors determine the amount of energy reaching the standard substrate surface and the corresponding thermally responsive current. Therefore, the measurement of thermal properties of clothing fabrics using the metamaterial sensor was validated. It should be noted that using the current approaches (e.g., Textest FX 3300 Air Permeability Tester, James Heal Nu-Martindale Abrasion and Pilling Tester, James Heal TruBurst Bursting Strength Tester and other equipment) evaluating the performance of garment fabric sample was valued by researchers [33]. Measured results show that fiber types and their characteristics were important factors in determining clothing fabrics [33]. Therefore, many properties of clothing fabrics could be obtained by E Oner’s measurement method (including: air permeability, abrasion resistance, bursting strength, and bursting distension, thermal properties) and its influencing factors. It should be pointed out that so far, no researchers have applied metamaterial sensors to the measurement of clothing fabrics. In this paper, metamaterial sensors were applied to measure the thermal properties (such as thermal

![Figure 12. Measured thermal current of fabrics (polyester, nylon, linen, cotton).](image1)

![Figure 13. (a) Measurement and simulation of thermal diffusivity. (b) Measurement and simulation of thermal resistance (polyester, nylon, linen, cotton).](image2)
diffusivity, thermal resistance) of different clothing fabric samples. Air permeability, abrasion resistance, bursting strength, and bursting distortion of the clothing fabric samples could not be obtained in this measurement method, because it does not involve the measurement of mechanical properties. Measurement results showed that the thermal diffusion of the linen was significantly higher than that of the polyester and polyamide fabrics [33]. In this paper, the measurement results of thermal properties of different kinds of clothing fabrics (polyester, nylon, linen, Cotton) show that linen has the largest thermal diffusivity (minimum thermal resistance), while nylon had the smallest thermal diffusivity (maximum thermal resistance). The measured results of clothing fabrics shown that the thermal properties are directly affected by the ambient temperature and the thickness of the sample, which were different from the reported results [33].

4. Conclusion

Measurement of the thermal properties of fabrics was an important basis for the development and application of clothing fabrics. At present, the infrared emissivity and photothermal absorption rate of smart fabrics were widely concerned by researchers. However, the thermal resistance and diffusivity were also important factors affecting the performance of clothing fabrics. At the same time, artificially prepared metamaterials were widely used in the field of thermal sensing. In this paper, a metamaterial sensor was applied for revealing the thermal resistance and diffusivity of clothing fabric samples. In experiments, the ambient temperature was gradually increased. The measured thermal resistance and diffusivity of the fabric samples were also enhanced. When the thickness of the clothing fabrics was increased, the thermal resistance was also enhanced. Finally, the type of clothing fabrics revealed an effect on the thermal resistance and thermal diffusivity.

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Data availability statement

No new data were created or analysed in this study.

Conflict of interest and Data availability statement

There are no conflicts of interest in the submission of this manuscript, and No data was used during the study.

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