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Avail of the glass wool properties using the aperture-coupled technique to design a thermal smart jacket

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ABSTRACT

Regulation of temperature between the body and clothing makes it possible for thebody to stay in the proper temperature range in different conditions. For this purpose,various materials and methods are used in the process of designing clothes. Glasswool is commonly used in jackets and other clothes as a thermal insulator. Designingan antenna based on the properties of glass wool provides an opportunity to producesmart thermoregulatory jackets. We propose an aperture-coupled antenna sensor thatuses glass wool's thermal properties. First, the dielectric properties of glass wool wereassessed between 35 °C to 41 °C, and there was a 0.05 change in relative permittivityper one-degree change in temperature. Second, the sensor was designed in a bilayerstructure with glass wool as the top substrate and FR4 as the bottom substrate in the Xfrequency band. The results showed a 60MHz shift in the antenna's resonancefrequency per one-degree increase.

1 Introduction

A lot of research has been done to integrate fashion with information technology in the past years [1]. The goal is to add detection and wireless communication capabilities to clothing to provide users with functions to help them daily [2]. From where the clothes are placed at the closest possible distance from the body, devices can be integrated into them for heart rate measurement, body heat regulation, touch, diabetes care, weight monitoring, and sports performance so that the clothes have a digital application in addition to their traditional use [3–6]. The importance of wearable technology is that they perform its functions without hindering the ease of movement and discomfort for users [7]. The growing capacity of this technology and its significant growth in the global market have made several large companies, such as Google, Apple, Samsung, and Fitbit, invest in this field [1, 3]. Considering the state-of-art requirements and the bright future of wearable technologies, the need for extensive research in this field and examining the dos and don'ts is completely felt; Because there are still many challenges ahead of us.

When significant advances in wireless communications were made in the 2000s, wearable technologies

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entered new territory. On the other hand, clothes are a suitable option for implementing wearable technologies because they are constantly present on the body. As a sample, in the Jacquard project, Google's technology and advanced projects group in collaboration with clothing manufacturer Levi Strauss & Co, smart jackets were produced that were based on digital performance [3]. Ref. 1 presents a multipurpose smart jacket that supports functions such as Bluetooth hands-free, heart rate monitoring, emergency calls, temperature-reactive heating, fall detection and automatic emergency calls, and ultraviolet monitoring. One of the required features that smart jackets need is the ability to regulate the temperature between the environment and the body. Because in this way, access to air and the wearer's skin are provided to avoid discomfort [1, 3, 8]. Kuzubasoglu et al. used a method based on thermistors to determine the temperature [9]. A thermistor is a semiconductor-resistive temperature sensor made from sintered oxides of various metals. This method can be suitable for wearable technologies. The main drawback of this method is the need for linearization of measurement circuits. Another technique used to wearable regulate temperature is the field effect transistor (FET) method. In this method, the FETs respond to the infrared radiation of the human body and can be adjusted to the temperature. However, they cannot provide acceptable results for the human body due to the simultaneous reaction to pressure and temperature changes [10]. One of the suggested methods for adding temperature regulation to jackets is using passive microwave structures. These structures, with dual functions for detection and communication, can detect temperature changes and act to adjust them [11–13]. Ref. 11 reported the thermoregulatory ability of passive wearable structures, which function based on the relatively linear association between temperature and relative permittivity (ε_r) of textiles. Generally, fabric as a dielectric is a material introduced with a certain relative permittivity and loss tangent ($\tan\delta$). The most important advantages of this method are its light weight, flexibility, easy integration, and cost-effectiveness.

Glass wool, as thermal insulation, is a material that can be used in the clothes of firefighters, astronauts, police officers, and mountaineers [14–16]. In this study, we intend to use the electrical properties of glass wool for the first time using a passive microwave structure to regulate the jacket's temperature [17]. We aim to establish a relationship between the electrical properties of glass wool and body temperature to design a smart thermal jacket. In Sect. 2, we first investigate the effect of body temperature on glass wool. Then, an antenna sensor was designed based on subSect. 2.1. In Sect. 3, the developed sensor was tested at different temperatures. Finally, in Sect. 4, the research results were evaluated.

2 The principle concepts

2.1 The electrical parameters of glass wool

Glass wool has a particular structure that absorbs heat and water vapor [16], which causes higher rates of change in relative permittivity after temperature changes than other textiles. Also, glass wool can be defined electrically by two structural parameters relative permittivity and loss tangent similar to other dielectric [18]. Hence, the broad utilization of glass wool in clothes made it a potential choice for sensor design. However, there are some challenges in using glass wool instead of commonly used fabrics. First, there is no proper surface for attaching the patch element, which means that it cannot be used directly as the antenna substrate. To solve this problem, we used the bilayer structure of jackets with two layers of memory fabric, providing a proper structure for antenna attachment and a layer of glass wool in between. The second problem is the height of the glass wool, which varies among different clothes. In this study, we used a height of 9.5 mm, which did not show plausible results in the simulation of a microstrip patch antenna using CST Studio Suite 2021 and we cannot use it as the direct antenna substrate. The proposed height is considered due to the antenna sensor's provision of the thermometry possibility. The main problems are the antenna's mismatch impedance and difficulty fed when implementing the structure. Also, changes in the height of the substrate in rectangular microstrip patch antennas significantly affect the measurements. To solve this problem, we used the aperture-coupled technique which was used for wearable clothes in previous studies [19–23]; however, this is the first study using this method in an antenna sensor with glass wool.

One of the aims this letter is to evaluate the relationship between temperature and electrical permittivity of glass wool to provide a passive structure for

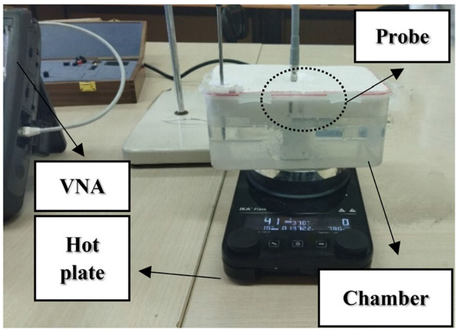

Fig. 1 Glass wool permittivity measurement setup

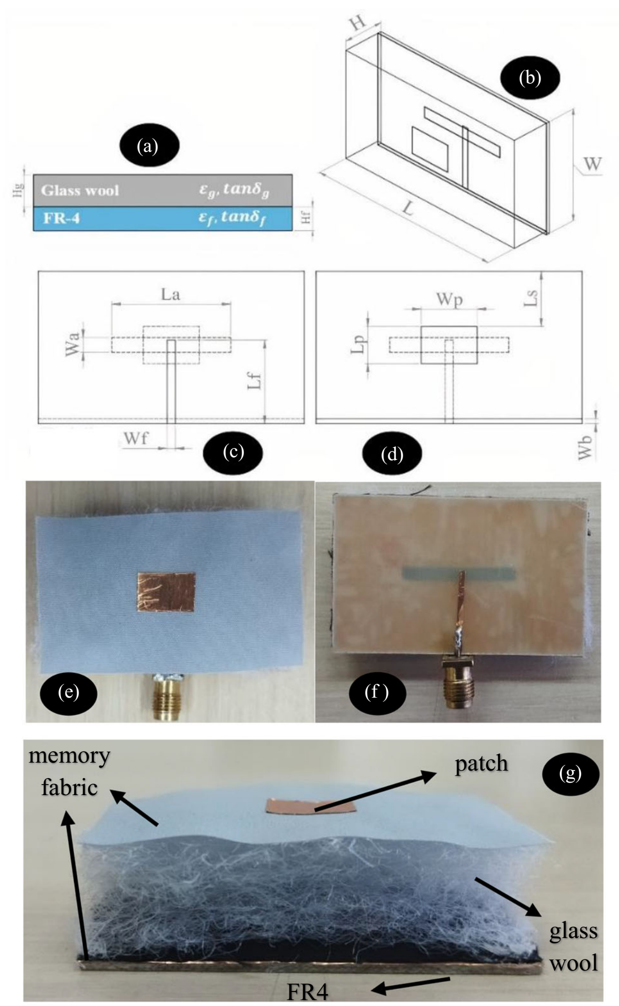

Fig. 2 Simulation aperture-couple antenna: **a** side-view, **b** overview, **c** bottom-view, **d** top-view. Implemented prototype **e** top-view, **f** bottom-view, **g** overview

use as a wearable sensor. Thus, a setup was designed to measure the changes in the electrical permittivity of glass wool between 35 °C to 41 °C (Fig. 1). At 12 GHz, ε_r and tanδ were 1.5448 and 0.1050,

Table 1 Optimized antenna dimensions

Parameter	Value (mm)	Parameter	Value (mm)
Wp	10.5	*Hg*	9.5
Wf	1.5	*Lp*	7.5
Wa	3	*Hf*	0.81
La	22.4	*Ls*	11.25
Lf	17	*Wb*	1
W	31	*L*	50

respectively. The change in relative permittivity was 0.05 per one-degree change in temperature. The open-ended coaxial probe method (Keysight N1501A-101 probe with N9917A network analyzer) was used to assess the relative permittivity of the multilayer textile.

2.2 Antenna sensor design

Based on the Sect. 2 results, the proposed antenna sensor is developed using the aperture-coupled technique. The aperture-coupled rectangular patch antenna is used as a microstrip. This antenna uses two substrates with a ground plane between them. The patch element on the top substrate is coupled through a slot in the ground plane to the feed network on the bottom substrate. Since the patch coupled aperture provides various options for the top and bottom substrate, the thicker substrate with lower relative permittivity for the patch element (glass wool sandwiched between two memory fabric layers), and a thinner substrate with higher relative permittivity (FR4) can be used for the feed network. At 12 GHz, FR4 with ε_r of 4.3 and tanδ of 0.025 was used as the bottom substrate. One of the most critical challenges in wearable antennas is their feed network because when the shape of the antenna and its transmission line change, the parameters of the antennas are mentioned in Refs. 24–27 are messed up. The FR4 provides the stability of the feed network when the rest of the antenna can change in shape.

The optimized dimensions of the antenna illustrate according to Fig. 2(a, b, c, d) in Table 1. Dimensions of the antenna were determined to involve a specific volume of glass wool to act as a thermal sensor. CST Studio Suite 2021 simulated the sensor in the X band frequency. This frequency band was selected based on the previous studies reporting that in lower frequency bands (Such as ISM), the changes in electrical permittivity of textiles were insignificant. Figure 2(e, f, g) shows implemented antenna sensor.

3 Results and discussion

The S_{11} (reflection coefficient) simulated results of the antenna sensor between 35 °C to 41 °C with 2 °C steps are indicated in Fig. 3(a). The substrate properties of multilayer fabric (ε_r and tanδ) were determined based on the data of the measured setup. As seen in Fig. 3(a), in the simulated model, there is a frequency shift of about 340 MHz for a temperature range of 35 °C to 41 °C, which indicates a frequency shift of about 55 to 60 MHz per a degree temperature change. The measure results from the sensor are comparable to the simulation and show the total shifting of 370 MHz in the antenna resonant frequency and 50–70 MHz shift per degree (see Fig. 3(b)). The proposed antenna sensor with previous studies is compared in Table 2. By comparison, our method demonstrates the significant advantage that the sensor has more frequency shift.

When the sensor is used in a jacket, there will be inevitable changes in height. Thus, we examined the effect of changes in fabric elevation on the sensor function by reducing the height of the top substrate with 2 mm steps. The S_{11} results of simulation and measurements (Fig. 4(a, b)) show that the sensor will be operating until the height of 5.5 mm and due to the ability of glass wool to return to its standard height after the compression is removed, the changes in height will not significantly affect the sensor measurements in the long term. Moreover, the S_{11} of the antenna was measured when the body was on or off. Figure 4(c) demonstrates the body's limited and non-significant effect on antenna performance.

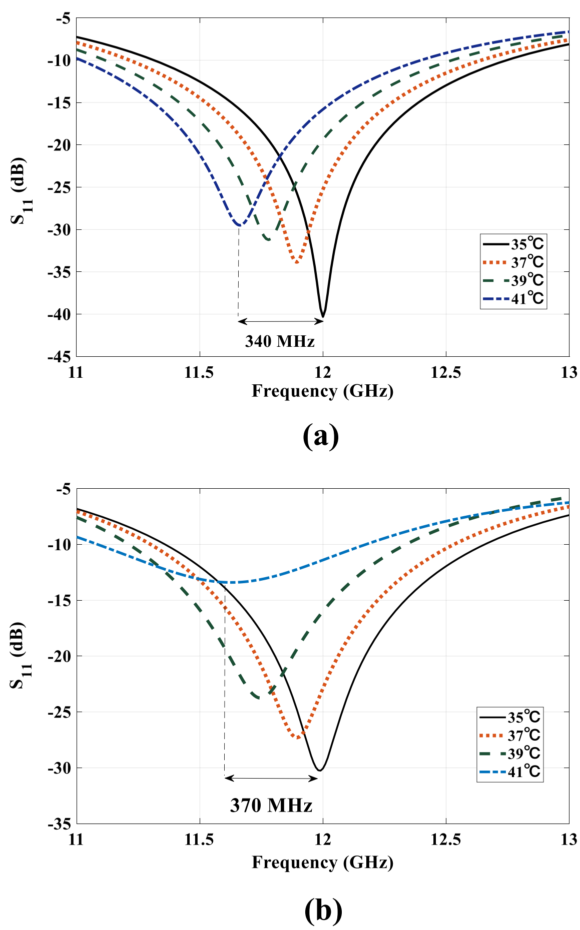

Fig. 3 **a** The simulated S_{11} for each 2 °C change in temperature. **b** The measured S_{11} for each 2 °C change in temperature

4 Conclusion and future work

That is the first report of using the aperture-coupled antenna with a glass wool. The proposed design can be implemented correctly in jackets where glass wool is used for thermoregulation and provides a more accurate method for monitoring the temperature in different conditions. Also, our results indicate that the sensor works in different conditions, even when

Table 2 Summary of reported works on thermometer antenna sensors

Frequency shift with 1 °C temperature step	Measurement parameter	Frequency (GHz)	Antenna type	References
Unchanged	Frequency shift	S band	Rectangular patch	[11]
Unchanged	Frequency shift	X band		
15 MHz	Frequency shift	Ka band		
Unchanged	Frequency shift	ISM band	Rectangular patch	[12]
16 MHz	Frequency shift	38 GHz	Rectangular patch	[13]
60 MHz	Frequency shift	X band	Aperture-couple	Current work

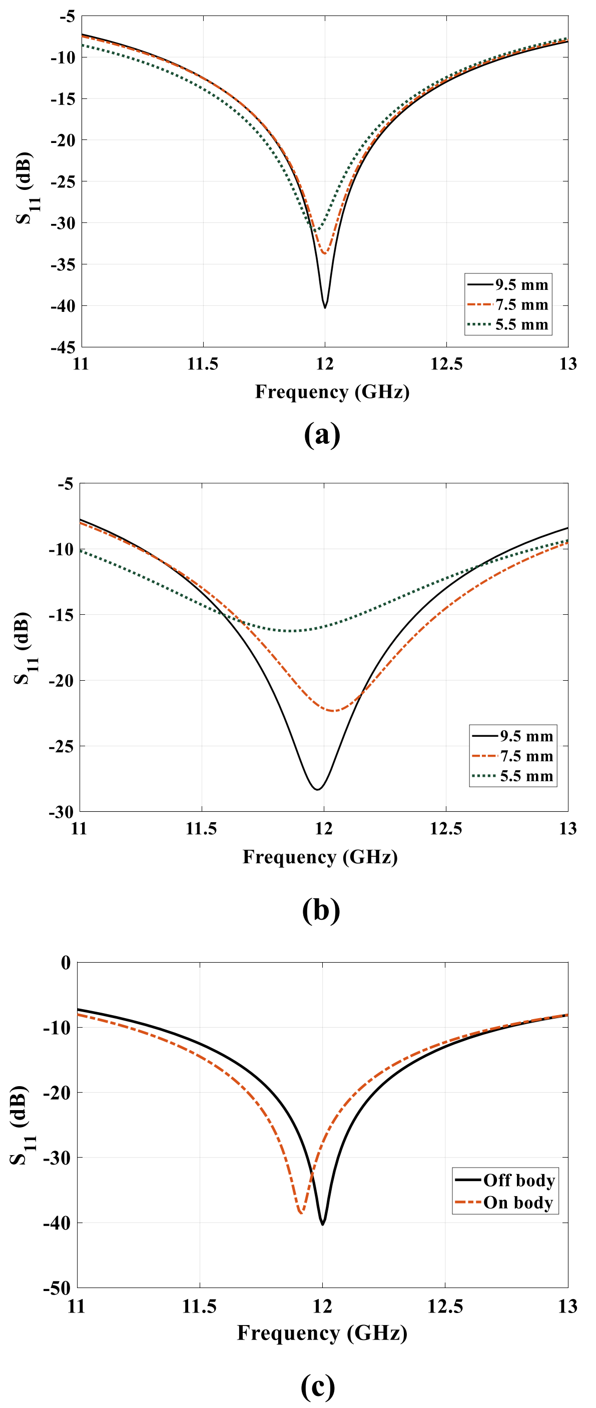

Fig. 4 **a** The simulated S_{11} for each 2 mm change in glass wool height. **b** The measured S_{11} for each 2 mm change in glass wool height. **c** body effect on the antenna

there are changes in the height of the top substrate. In addition, there was a frequency shift of 60 MHz for each per degree change in temperature which to the best of our knowledge is the highest amount of change in this study and previous ones. This sensor can also be used in the ISM frequency band, and its effectiveness should be investigated in future studies.

Authors contribution

Investigation, Conceptualization, Ex-Experiments, Design of measurement setup, Methodology, Software, Writing, Formal analysis, Implementation, Resources and writing original draft was done by Sina Rahmani Charvadeh. Javad Ghalibafan contributed to the study review and editing as a supervisor. All authors read and approved the final manuscript.

Data availability

The datasets generated during and /or analyzed during the current study are available from the corresponding author on reasonable request.

The article has no financial conflict. Research does not involve human and /or animal participants.

Declarations

Conflict of interest The authors have no financial or proprietary interests in any material discussed in this article.

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