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FLEXIBLE E-TEXTILE SENSORS FOR REAL-TIME HEALTH MONITORING AT MICROWAVE FREQUENCIES

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Abstract- This paper reports on testing of the performance of SmartLife® e-textile material. In particular, the response of the integrated conductive pathways at microwave frequencies in the region of 9 kHz to 6 GHz is investigated for both biomedical sensing and signal transmission purposes. The experimental results confirm the viability of exciting the e-textile material at ISM microwave frequencies at mW powers for the purposes of wearable non-invasive sensing. Custom made flexible microwave sensors suitable for integration into smart e-textile fabric were tested in their ability to perform real-time body parameters monitoring, in particular the level and composition of perspiration. Gradual change in both the resonant frequency peak and amplitude was recorded in the 2-3 GHz frequency range with increased volume of fluid (50-350 µl) when in contact with a 5×8 mm^2 sensor.

This fabric with built-in textile sensors could serve as a platform for "high-tech designer outfits" for an advanced healthcare approach where real-time data on patient condition is transmitted wirelessly for immediate processing and corrective action if necessary. The novel sensor reported here was recently patented under milestone UK patent application number GB 2500000.

Index terms: Flexible substrate, build-in textile sensor, personal health indicators, real-time monitoring, advanced healthcare approach.

I. INTRODUCTION

Flexible sensors and sensing systems that are bendable, stretchable, and comfortable for wearing as part of a human outfit and yet able to continuously perform measurements and transmit the information wirelessly are becoming a reality, thanks to the latest advancements in material science, manufacturing, engineering, biology and computing. At a time, the notion of sensitive skin represented a new paradigm in sensing and control [1]. The principles, methodology, and prototypes of sensitive skin-like devices, and the related system intelligence and software that are necessary to make those devices work were presented decades ago and the research towards developing these devices is on-going and fascinating. These devices open doors to a whole class of novel enabling technologies, with far-reaching applications ranging from the healthcare industry and biology to the robotics and defence. Also, assessment of sensing fire fighters uniforms for physiological parameter measurement in harsh environments is of interest [2].

It is believed that a human state in human-machine interaction process, especially human-robotics interaction, highly affects the system performance, and should be monitored via physiological parameters since they reflect the psychological state. Generally, heart rate, skin conductance, skin temperature, operating force, blood alcohol concentration, perspiration rate, and electromyography have a close relation with human state, and can be measured from the human skin. For this purpose, so-called NANO-Skin is being developed to non-intrusively measure physiological cues from human-machine contact surfaces for human state recognition [3].

Flexible sensors and electronics are being envisioned as low-cost, single- or multiple use diagnostic devices that may be implemented for diverse applications in environmental monitoring, personnel radiation protection [4], security and military defence, and preventative medical care [5]. This innovation is driven via industrial advancements in high-throughput printing of such electronics, leading to ever-decreasing cost-per-unit area on flexible substrate.

An important advantage of organic materials for flexible sensor applications is the ability to tune the molecular structure through organic synthesis via control of a wide range of processing and deposition parameters including solubility, functionality, stability, melting point, or sublimation temperature [5]. Consequently, these advantages give rise to cheap, high-throughput methods for device manufacturing, for example by various thin-film deposition techniques, including thermal evaporation in high vacuum and solution spin-coating [6]. For industrial applications, methods such as screen-printing, ink-jet printing or roll-to-roll processing are more feasible for mass sensor production.

Textiles offer a durable platform for embedded sensor and communication systems. For example, textile sensors can be used for detecting the frequency of breathing while the users are sitting still, walking or jogging [7]. A prototype smart healthcare textile system, incorporating multi-lead ECG, pulmonary and heart rate variability monitor, blood pressure and core temperature sensors was reportedly designed and tested [8]. This system provided real-time telemedicine capability especially for cardio-vascular healthcare, diagnosis and early detection of cardiac event.

Healthcare related smart clothes, which are in contact with almost all the surface of the skin, offer huge potential for the location of sensors for non-invasive measurements. Head band, collar, tee-shirt, socks, shoes, belts for chest, arm, wrist, legs – all provide localisation with a specific purpose taking into account their proximity to an organ or some other interesting bio-signal source, while also ensuring adequate ergonomic possibilities [9].

Interestingly, modern electronics in “wearable systems” or “smart textiles” are mainly realised on traditional interconnection substrates, like rigid printed circuit boards or mechanically flexible substrates. In order to achieve higher degree of integration and user comfort, a technology for flexible and stretchable electronic circuits was reportedly developed in [10]. This electronic system was completely embedded in an elastomer material (such as polydimethylsiloxane [PDMS] or silicone), resulting in soft and stretchable electronic modules in the form of meander-shaped copper tracks, so that stretchable systems with complex functionality can be achieved.

The knitted piezoresistive fabric sensors were used for biomechanical monitoring to detect both the respiration signal as a function of thorax movement and the elbow bends [11]. However, they suffered from long response time and non-linearity of the signal.

Notably, a wearable Doppler radar unit with radio data link for use in portable patient monitoring and emergency response was developed by employing microstrip elements for the integrated patch antenna, microwave oscillator, and tuning elements [12]. A commercial 2.48 GHz radio link (TagSense ZT-Link) was used to successfully relay the data wirelessly to a nearby radio base station. The data transport protocol was based on the IEEE 802.15.4 physical layer protocol compatible with low-power operations and ad-hoc wireless sensor networks. However, this system lacks flexibility and impairs the patient's comfort.

While most of the reported efforts focus on the sensing alone, there is a need for a flexible sensor system capable to both sense and wirelessly transmit information; so this paper reports on novel flexible sensors developed for embedding them into e-textile cloth that operate at microwave frequencies and are suitable for both the sensing and the communication.

II. E-TEXTILE FABRIC

SmartLife® is a UK based technology company providing intelligent body monitoring garment technology for use in a number of situations including healthcare and clinical research, sports, hazardous environments and the military. The SmartLife® team developed a novel textile based sensor platform with IP purchased from the University of Manchester. These form a wide variety of on-body, dry sensor, wearable and traditional garments for the monitoring of real time vital health signs, such as ECG, heart rate, EMG, respiration, tidal flow and other sensory inputs – all to comparable clinical quality standards [13].

The ease and use of the technology represents a paradigm shift from traditional high cost patient monitoring in hospitals to affordable, unobtrusive, remote personalised monitoring. Smart garment sensor technology allows healthcare professionals to monitor patients wirelessly, using real-time biometrics or analysed from collected data, which can be stored on the garment.

The purpose of this paper is to report on performance testing of the e-textile material sample. In particular, the response of the integrated conductive pathways at microwave frequencies in the region of 9 kHz to 6 GHz was investigated for both biomedical sensing and signal transmission purposes. The fabric exterior structure is pictured in Fig. 1. It measures ~ 330 x 490 mm^2 and has built-in conductive pathways, strain gauge and push stud connectors. The interior (body facing) side of the fabric contains conductive pressure sensor points, as shown in Fig. 2.

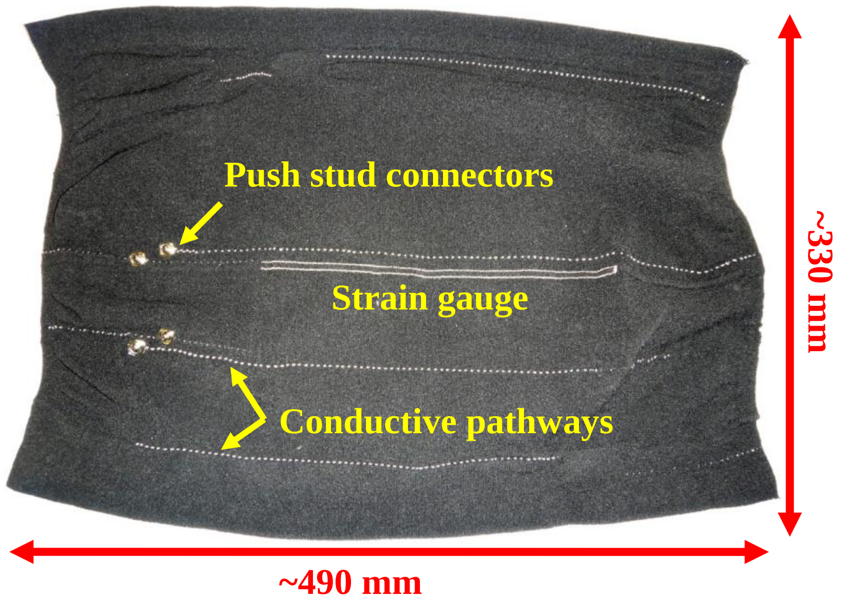

Fig. 1 The SmartLife® material exterior, showing the conductive pathways.

The supplied material panel consisted of a knitted black fabric which is reasonably flexible – dimensions 50% greater than those displayed in Fig. 1 can be achieved relatively easily and the material appears to resume its previous shape once any tensile load is released.

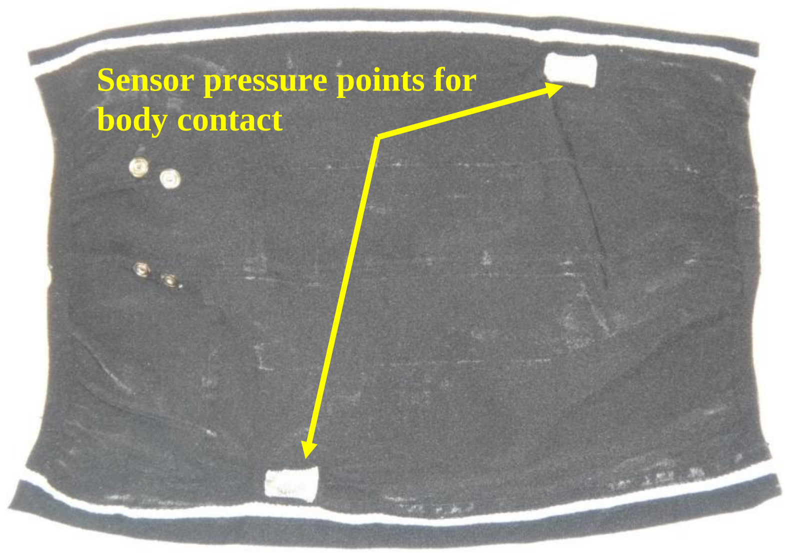

Fig. 2 The SmartLife® material interior with conductive pressure sensor points.

III. MICROWAVE SENSING

Microwave sensing approach has been successfully used for various industrial applications including monitoring the solutions concentrations [14], fluid level measurements [15], material moisture content [16, 17], water quality [18], for continuous process monitoring of biogas plants [19], for the determination of moisture content in soil [20], for non-destructive evaluation of an activated carbon [21] and in the healthcare industry, for example for real-time monitoring of glucose in diabetic patients [22, 23] and for non-invasive monitoring of bodily fluids [24].

Microwave sensing has a range of advantages for biomedical applications. It is a non-ionising technique utilising low power output at around 1 mW (0 dBm) but has good penetration depth and equipment can be portable. The multi parameter nature of broadband microwave analysis can provide unique signal spectrum signatures which are a reflected signal (S_{11}) and/or a transmitted signal (S_{21}) based on parameters such as conductivity and permittivity. Conductivity is a measurement of a material's ability to conduct an electric current. Permittivity is a measurement of how an electric field is affected by a dielectric medium, which is determined by the ability of a material to polarise in response to the field, and reduce the total electric field inside the material. Therefore, permittivity relates to a material's ability to transmit an electric field and is a complex value which varies with changing frequency, and accounts for both the energy stored by a material (ε') as well as any losses of energy (ε'') which might occur. As a material alters in concentration or type, it is likely that its permittivity will change leading to a change in response if the material is the target of microwave radiation. By measuring this response over a range of frequencies, one can characterise materials or biological substances and fluids in order to infer their properties.

The microwave planar printed patterns for various sensing applications are increasingly used due to their versatility, flat profile and low weight. Their design can be tailored to suit particular applications, coupled with reliability and cost-efficiency. They are easily manufactured using common methods for printed circuit board production, and their impedance can be matched to the input line by altering the micro-strip line feed configuration.

The performance of a microstrip resonator depends on its electromagnetic field distribution, resonant frequency and quality factor (Q). Since the emergence of microstrip technology as a dominant architecture, varying types of microstrip resonators have been developed to suit the needs of different microwave circuits [16].

IV. EXPERIMENTAL PROCEDURE

The e-textile fabric material shown in Fig. 1 and 2 provides a panel which can be integrated into wearable garments in order to enable collection of data related to patient movement, in addition to the patient condition via ECG and EMG monitoring, perspiration analysis (pH and composition), temperature and pressure/strain assessment. The panel, as provided, incorporated no active sensors or electronics. Therefore, methods of how this material might be utilised as a microwave sensor and/or on-body antenna was considered.

The material incorporates a number of conductive pathways, which are essentially conductive threads incorporated into the weave. These are approximately 15 µm in diameter and feel not too dissimilar to what one might expect from a typical clothing thread. They provide electrical connectivity between electronics utilised to elicit sensor data from elements that can be integrated into the cloth panel. Such electronics can be easily connected via the press stud system built into the fabric as highlighted in Fig. 1 and 2. In the case of the supplied material, the incorporated sensing elements consist of a strain gauge (for movement monitoring) and pressure pockets for condition monitoring. These are particularly suitable for continuous real-time heart rate monitoring, as increasingly commonly used nowadays for recording the performance of athletes during physical exercise and competitions.

The potential of the SmartLife® material for sensing and communication at microwave frequencies was assessed with the use of a Vector Network Analyser (VNA), which also doubles as a Spectrum Analyser for communications analysis. The particular unit used was a Rohde and Schwarz ZVL6 with an operating range of 9 kHz – 6 GHz. Fig. 3 pictures the ZVL6 unit connected to the cloth via modified SMA bulkhead connectors using RG-316 SMA cables.

A Marconi Instruments signal generator, capable of output at frequencies up to 1 GHz and power levels of 10 dBm, in conjunction with a multipurpose whip antenna was utilised to test the wireless transmit/receive capabilities of the material.

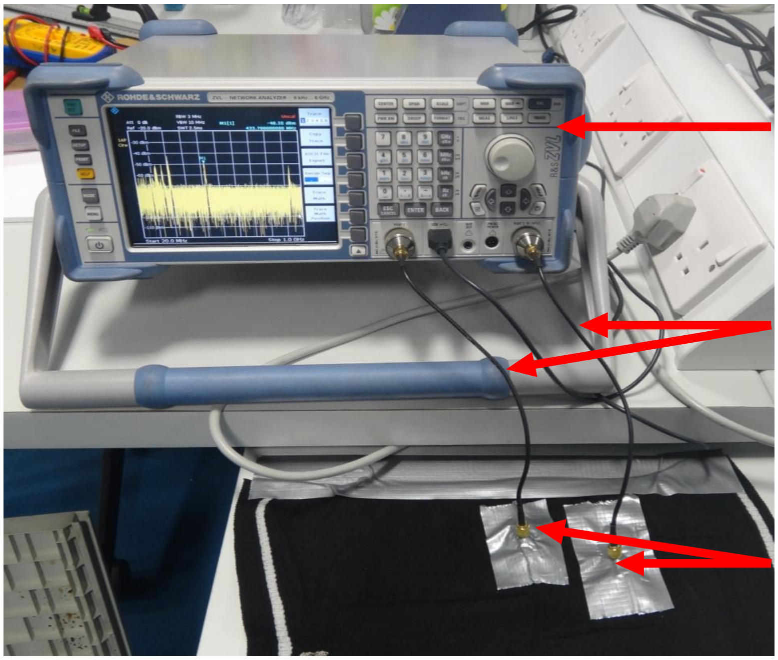

Fig. 3 Experimental setup using the Rohde and Schwarz ZVL6 VNA/Spectrum Analyser.

V. RESULTS AND DISCUSSION

To map the layout of the conductive pathways present in the e-textile fabric material, impedance measurements of the conductive pathways were performed using a digital multimeter and are summarised in Fig. 4. This is important when considering the source (VNA) and the load (fabric) match parameters. Of note is the increased impedance in the region of the strain gauge sensing element as a result of the use of finer thread. In addition to the measurements shown in Fig. 4, there is also approximately 8 Ω impedance when measuring from a push stud to the nearest connected exposed thread. Since the only closed loop pathway incorporated into the material was the strain gauge, the connection was made across it, as it operates similarly to a loop antenna.

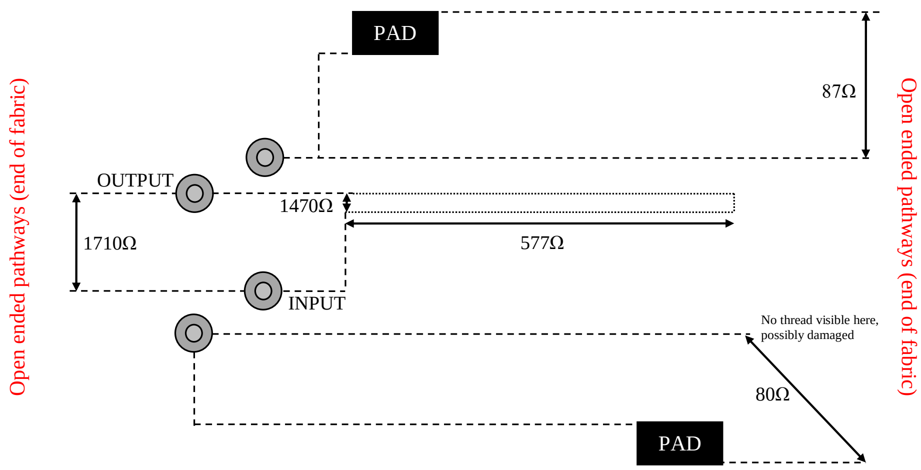

Fig. 4 Overview and impedance measurements of conductive pathways incorporated into the fabric. Note that this diagram is not to scale and is drawn from the perspective of the fabric exterior view. For reference the push studs used for connectivity to the ZVL6 are indicated by INPUT and OUTPUT labels.

The response of the e-textile material to the electromagnetic field was considered in relation to its relaxed, stretched and curled (e.g. as if wrapped around a limb) state. The change in the fabric state was correlated with its response to microwave excitation in both S_{11} and S_{21} transmission modes as an indicator of the extent that stretching may change the response of the material. To simulate curling or wrapping of the material, the material was wrapped around a 1 L measuring cylinder as depicted in Fig. 5.

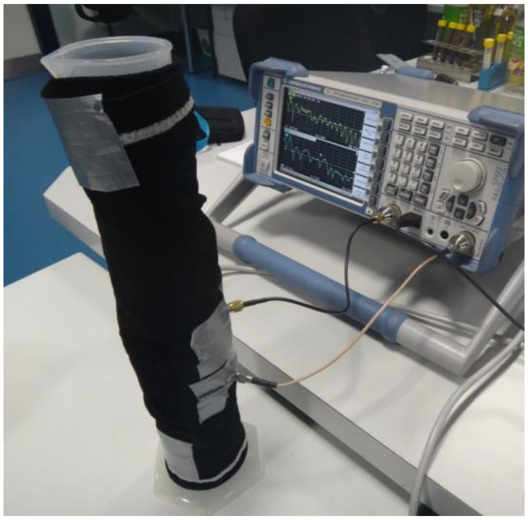

Fig. 5 Testing the response of the material to external stimulus through the use of a water container, and comparative results when both empty (i.e. air filled) and full (i.e. water filled).

As can be seen from the S_{21} data presented in Fig. 6, the material response shows a recognisable trend regardless of condition, although there are notable variations also brought about by the conditions imposed. This is likely to be exacerbated by the size of the element excited (i.e. the strain gauge pathway) in addition to some minor movement of the connection probes. The geometry of a radiating element plays an important role in how it behaves, therefore the extreme flexibility of the sensing element results in the noise signal and higher thread density is more suitable for this application. The impedance mismatch between the source and the load also may contribute to the signal noise.

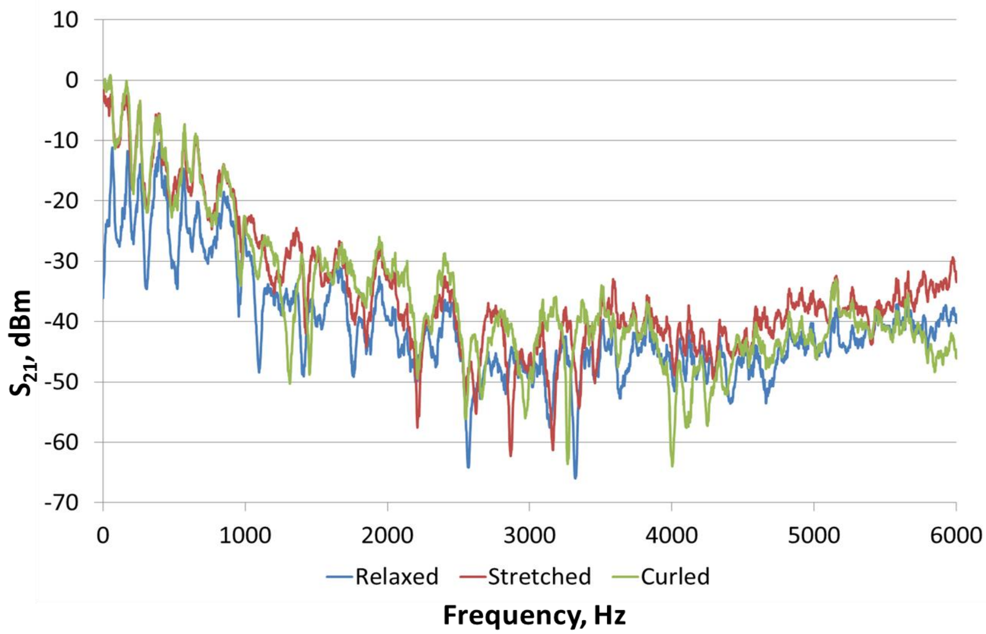

Fig. 6 S_{21} response to various material conditions; the measured response follows a similar trend in each case although notable variations are present depending on the material condition.

Of particular interest is the potential for use of the SmartLife® material as a microwave sensor which could be embedded within a fabric material. The response of the e-textile sample in a curled state to external stimuli was tested using the VNA when the cylinder was empty and filled with water to gauge how the material would react to the change in dielectric material. It is generally accepted that water has a dielectric constant of approximately 81 at room temperature [25], thus often elicits a reaction from microwave sensors which are sensitive to dielectric change. Fig. 7 shows that there is a significant variation apparent when water is present in the measuring cylinder.

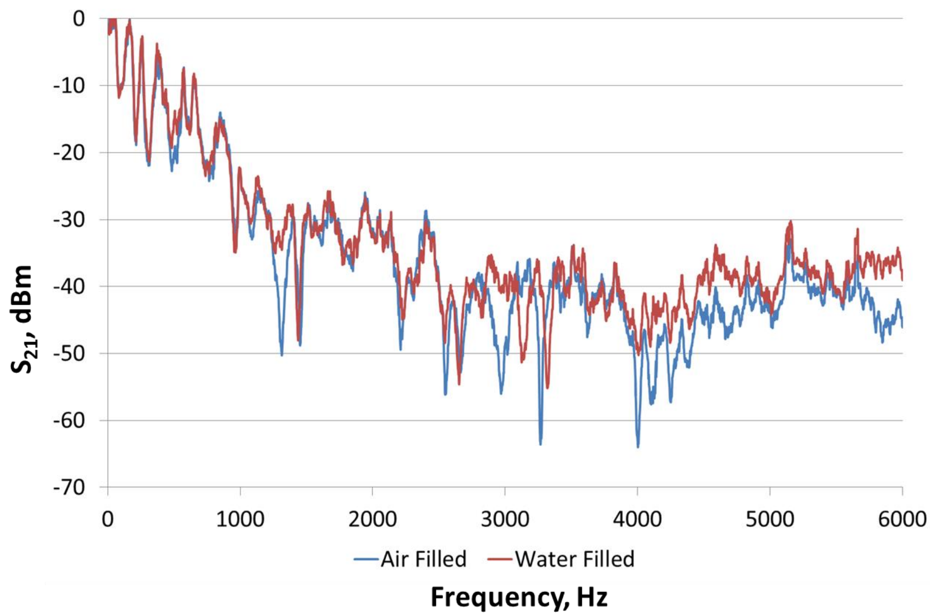

Fig. 7 S_{21} data showing variation between the material response when the measuring cylinder was air filled and water filled.

The e-textile fabric was tested in both transmission and receive mode. To test wireless reception, the material was connected to the ZVL6 VNA and the multipurpose whip antenna to the Marconi signal generator. It is assumed that transmission is reciprocal (i.e. a receiver may transmit if it receives) and so roles were not reversed. The frequencies of 433 MHz and 868 MHz were tested since they are both within the ISM (Industrial, Scientific and Medical) band for UK operation. In addition, consideration was given to what might happen should the material be worn, and so the panel was attached (over the top of existing clothing) to a volunteer, as shown in Fig, 8, to test the impact on communication ability. The maximum line-of-sight range of communications tested was 3.5 m.

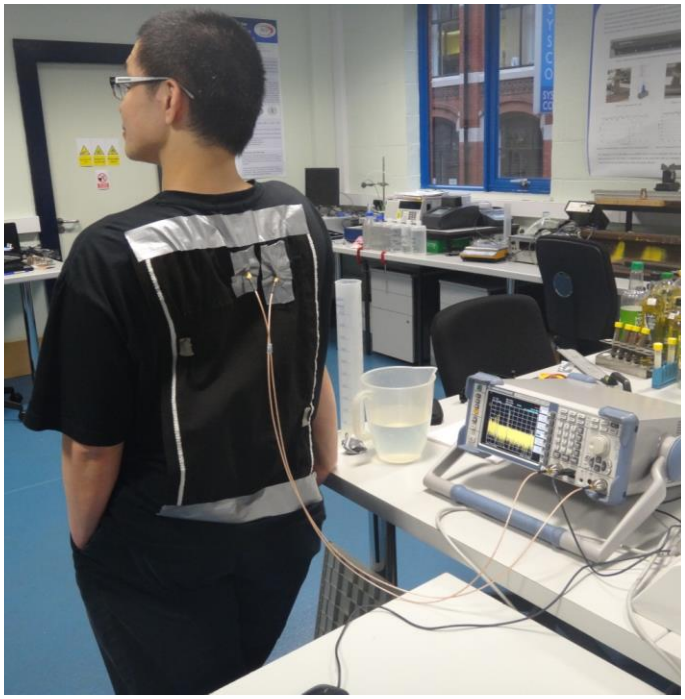

Fig. 8 E-textile attached to a volunteer to ascertain the effect of bodily contact on wireless communication functionality.

Figure 9 shows the received signal spectrum captured from the material when testing at 433 MHz and 868 MHz. Notably, 433 MHz shows a usable signal (approximately 30 dB above background level) at 3.5 m transmission distance when worn. At the higher frequency of 868 MHz the peak is also visible, but is only 5 dBm above the background noise. This could be simply a result of the material geometry rather than some other fundamental limitation.

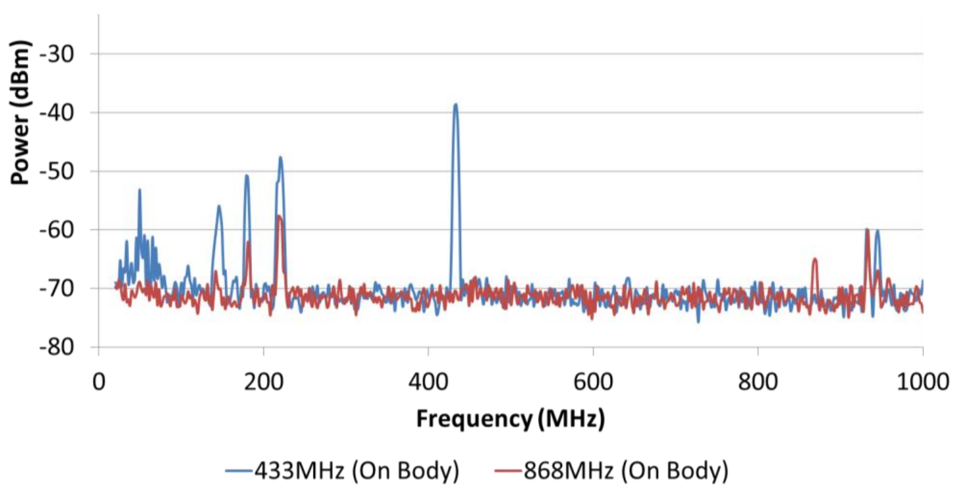

Fig. 9 *Signal spectrum at 433 MHz and 868 MHz when the SmartLife® fabric is worn.*

Having confirmed the suitability of the e-textile for microwave sensing, the research is underway on the development of a number of flexible sensors that can fit into clothing with minimal obstruction of the patient's comfort. Experimental trials of the planar type sensor printed on DuPont™ Pyralux® AP Polyimide Flexible Laminate substrate verified its capability to determine the amount of fluid, in this case deionised water was used, placed on top of the sensor. Fig. 10 presents the S_{11} response of the sensor to increasing volume of water (in µl). As one may see, there is a distinct change in both the resonant peak amplitude and frequency shift recorded in the 2-3 GHz frequency range. The measurements were repeated numerous times and the graphs represent average values.

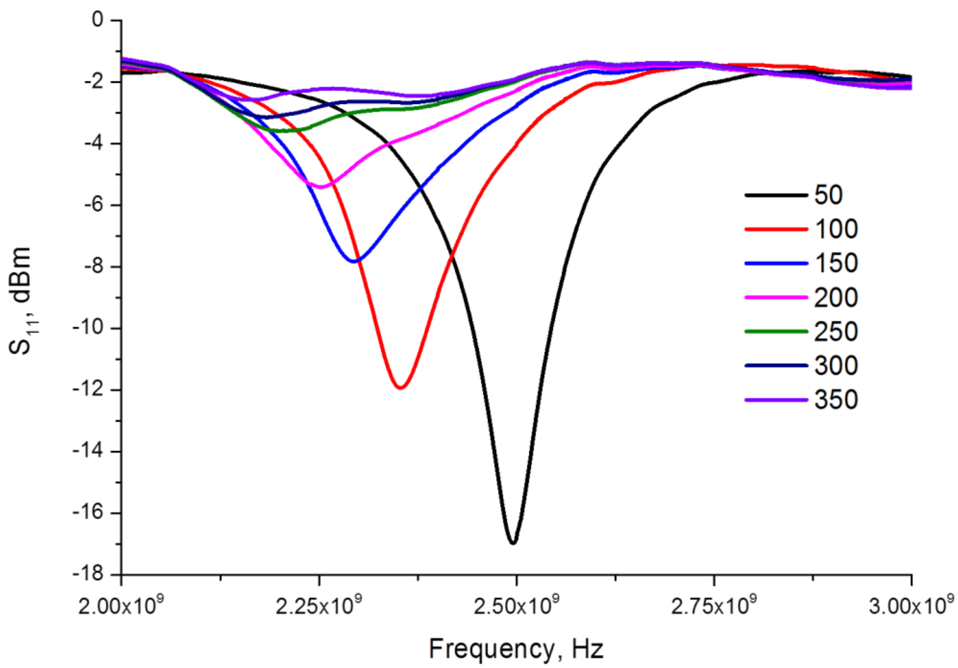

Fig. 10 Dependence of S_{11} signal on the volume of fluid, given in µl, brought it contact with the flexible microwave sensor.

Notably, the sensing area measured 5×8 mm^2 and the thickness of the Ag pattern was 35 µm. It is believed that these features would not cause any discomfort to the person. Contrary, a creative design could even make this sensor an attractive latest fashion trend, were smart e-cloth not only looks like, but has a function of personal health monitor, that could indicate in timely manner if there is a health issue, so that corresponding action could be taken. An example of a set of flexible microwave sensors that can be used for a "high-tech designer outfit" is shown in Fig. 11.

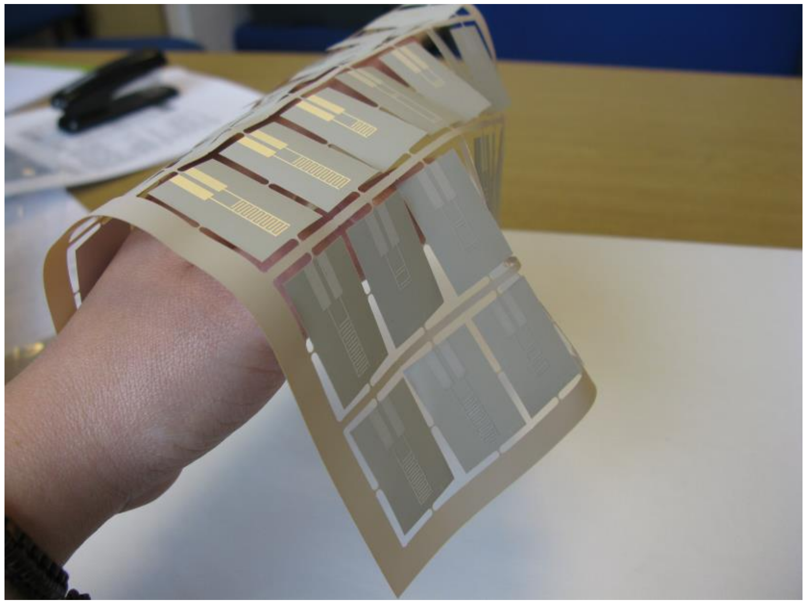

Fig. 11 A set of flexible microwave sensors for "high-tech designer outfit".

This sensor could serve, for example, as a platform for real-time indicator of body sweat amount or other bodily fluids, the chemical composition of which could be further analysed. Perspiration rate and alcohol/drug concentration in it are directly representative of the blood condition, thus monitoring the perspiration composition in real time would eliminate the need for invasive medical procedure and could be an option, for example, for monitoring drug and alcohol addicts on probation. Screening perspiration is also applicable for use in monitoring driving while intoxicated and surveying populations for illicit drug use [26].

There is no doubt that future smart clothing will incorporate the latest research achievements, where sensors that check the health indicators of the owner in real time will be built into the outfit to provide timely advice. Particularly, microwave sensors operating at mW powers are an attractive option for their dual role of both sensing and communication, thus integrating easily into the "internet of things" idea that is especially popular at the moment [27-30].

VI. CONCLUSIONS

This paper presents the results of investigating the performance of e-textile material, in particular, of the integrated conductive pathways at microwave frequencies in the region of 9 kHz to 6 GHz for both biomedical sensing and signal transmission purposes. The presence of external stimuli directly via the conductive pathways in the material was identified, as demonstrated by the experiment with a water-filled vessel. Moreover, the developed flexible sensors, measuring a few mm^2 and having a thickness of <1mm, were able to detect the volume of fluid placed in contact with the sensor in 2-3 GHz range with 50 µl resolution.

Wireless transmission using the conductive pathways was possible (even when worn), and there is evidence that three widely used ISM bands (433 MHz, 868 MHz and 2.4 GHz) could be supported. Thus, the potential of the e-textile material to achieve both sensing and wireless transmission is immense. Wireless devices are become increasingly common, but antennae are often cumbersome or designed only for inefficient short range communication. Materials with antennae inbuilt could be utilised by emergency services, hospitals (for patients) and other such applications. In terms of sensing, this early work shows that it is possible to detect dielectric change, thus meaning that it may be possible to incorporate complex dielectric sensing capability into garments which could be used to identify patient's health indicators via analysis of bodily temperature, ECG and EMG, sweat rate and its composition to infer bodily fluid parameters such as blood glucose or alcohol level, or to monitor the performance of drugs for chronic patients. Coupling both sensing and communication ability, this gives the potential for truly intelligent garments which can unobtrusively perform a multitude of important tasks.

The ability of the material to act as an antenna, i.e. to facilitate wireless transmission between garments, could significantly contribute to currently active research areas such as the "Internet of Things" and "Personal Area Networks".

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