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PASSIVE UHF RFID STRAIN SENSOR TAG FOR DETECTING LIMB MOVEMENT

S. Merilampi[1], T. Björninen[2], L. Sydänheimo[2], L. Ukkonen[2]
1. Satakunta University of Applied Sciences, Technology and Maritime Management, Tekniikantie 2, 28600 Pori, Finland
2. Tampere University of Technology, Department of Electronics, Rauma Research Unit, Kalliokatu 2, 26100 Rauma, Finland
Emails: sari.merilampi@samk.fi, toni.bjorninen@tut.fi, lauri.sydanheimo@tut.fi, leena.ukkonen@tut.fi

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Abstract- A strain sensor tag with screen printed antenna for seamless integration with clothing is examined to provide a wireless method for monitoring of human body movements. The strain response of the tag is investigated in air and on human body. While the results indicate strong antenna-body interaction, the strain response of the tag is found to be a monotonic function of the strain.

Index terms*:* Radio frequency identification (RFID), wearable sensor, passive sensor, tag-based sensing, polymer thick films, printed electronics

I. INTRODUCTION

Different passive Radio Frequency Identification (RFID) systems have been adopted in automatic identification of various objects. One novel use of RFID is tag based sensing in which an RFID tag is used for sensing instead of identification. The use of passive RFID tags is especially interesting, because passive tags need no on-tag energy source for operation. Additionally, they can be embedded into object that is monitored since they are maintenance free, wireless and thin. There are two types of passive RFID sensor tags: an RFID tag with the traditional sensor attached as a part of the tag and a tag in which the sensing ability is integrated into the tag structure. In the former type the RFID tag is typically used in power supply and data transfer, and in the latter the tag performs the sensor function itself [1]. Especially the self-sensing tags are interesting, because they are relatively inexpensive and easy to manufacture. The cost of an individual self-sensing tag depends on the manufacturing volumes and materials, but the cost is no more than the price of a traditional passive tag. The challenge considering the self-sensing tags is the designing of the “sensor component” in the tag geometry.

In [1] the idea of using passive Ultra-High-Frequency (UHF) RFID tag in strain sensing was investigated. The strain sensitivity of the printed tags was based on the changes in the printed film and the dimensional changes of the tag during straining [1, 2]. However, no attempt was done to evaluate the performance of such strain-sensing tag on human body. In this paper the same sensing mechanism is used but the main focus is on the behavior of dipole-type strain-sensing tags on human body. The motivation of such investigation is the significant number of applications related to human body monitoring that this kind of strain sensor would offer.

RFID based strain sensing is a promising method considering human body movement monitoring. Since passive UHF RFID tags does not require any batteries or wires they are easily integrated into clothing. The human body movement (relatively large strains) could be monitored by attaching the strain sensitive tag in such places on the human body that experience strain (elbows, knees etc.). Such sensor could be used in many ways. It could count the movements during an exercise, for example. It could also be used to monitor a certain body limb or joint and for example its recovery and trajectory after surgery. The sensors could also be used to monitor that not too large of movement is done with a healing body limb. Also small strains could be monitored by increasing the sensitivity of the sensor and thus monitoring of breathing would be possible. [3, 4]

II. THEORETICAL BACKGROUND

In passive UHF RFID systems the reader sends electromagnetic waves to the tag and the tag responds by modulating the backscattered wave. The tag consists of an antenna and a microchip and it modulates the carrier wave by changing the impedance of the chip between two states (typically one matched and the other mismatched to the antenna). The response from the tag is affected by the surrounding materials and especially metals and aqueous liquids have a strong effect on the tag antenna properties [5-7]. Human body contains approximately one third of water and many tissue types share similar dielectric properties with water (high dielectric constant in the microwave regime and relatively high conductivity) [8, 9]. Therefore, human body is considered as a challenging platform for antennas: the antenna impedance is strongly affected and additional loss is introduced. Special tag antenna designs and promising results about on-body tags have already been reported [10-13]. Although the effect of the environment on the tag functioning is challenging considering identification of different kind of products, it also forms the basis for self-sensing tags. It is actually the same parameters that can be used in sensing that also make identification of different objects difficult.

Wireless reading is one reason that makes passive UHF RFID tag-based sensing interesting. Transmitted threshold power and backscattered signal power of a tag are parameters which can be wirelessly measured. Both the transmitted threshold power and the backscattered signal power of the tag are affected by the surroundings of the tag.

The transmitted threshold power is the minimum sufficient power required from the reader to activate the IC-chip (in matched state). Threshold measurement is performed by increasing the transmitted power until the tag can respond to the query command of the reader. Considering that the power P_t is transmitted, the power delivered to the IC, P_{chip} at distance *d,* can be calculated as:

$$P_{chip} = (1 - |\Gamma_{tag}|^2) P_{tag} = (1 - |\Gamma_{tag}|^2) G_t G_{tag} \left(\frac{\lambda}{4\pi d} \right)^2 P_t \qquad (1)$$

where P_{tag} is the power received by the tag antenna; G_t is reader's transmitting antenna gain; G_{tag} is tag antenna gain, and λ is the wavelength. Parameter Γ_{tag} is the power reflection coefficient. Obviously, P_{chip} in equation (1) is maximized by minimizing Γ_{tag}. In practice, this is achieved by designing the tag antenna impedance to be the complex conjugate of the microchip impedance. When the tag antenna is stretched, the power reflection coefficient is affected because the tag antenna impedance changes. In addition, the radiation efficiency and the directivity of the tag antenna changes due to the changed effective conductivity of the ink [2] and the changes in antenna dimensions. Since G_{tag} is the product of the directivity and radiation efficiency of the tag ($G = \eta_{rad} D$), G_{tag} in (1) changes during stretching. Since the above mentioned parameters affect the amount of power received by the chip, the minimum power required to activate the tag (threshold power) is changed and the deformation (strain) can therefore be observed wirelessly by measurement of the threshold power. [1]

If the polarization of the tag and the reader antenna(s) is not matched, additional power loss is caused by this. Polarization loss factor is excluded from equation (1) (and also from equation (2)) since the polarizations were matched in the measurements performed to the samples. The polarization loss is also presumed not to be a function of strain.

Another parameter which can be used to measure the strain in self-sensing stretchable tags is the backscattered signal power. The backscattered signal power is the time-average power detected from tag response at the receiver. Using the Friis' propagation model, the power of the tag signal at the receiver $P_{received,signal}$ is [14]:

$$P_{received,signal} = P_{transmitted} G_{tag}^2 G_t^2 \left(\frac{\lambda}{4\pi d} \right)^4 \alpha \left| \rho_1 - \rho_2 \right|^2, \qquad (2)$$

where $P_{transmitted}$ is the transmitted power from the reader, G_{tag} is the gain of the tag antenna, G_t is the gain of the reader (transmit/receive) antenna (G_t^2 is the product of transmitting and receiving reader antenna gain in the case of a bi-static reader), λ is wavelength, d is distance from the tag, ρ_1 and ρ_2 are the power wave reflection coefficients [15]of the tag in matched and mismatched chip impedance states and α is a coefficient which depends on the specific modulation details. Equation (2) shows that the received backscattered signal power depends on the power wave reflection coefficients in both chip impedance states as well as on the tag antenna gain. As discussed earlier, gain of the tag is the product of the directivity and radiation efficiency, both of which are dependent on the surrounding materials. In addition, the tag antenna impedance changes according to the materials near the tag and thus affecting parameters ρ_{-} and ρ_{-}. The parameters G_{tag}, ρ_{-} and ρ_{-} are all also functions of strain experienced by a printed tag due to changed impedance of the antenna, changed effective conductivity (radiation efficiency) of the printed film and changed antenna dimension (directivity) during straining. This is exploited in tag-based strain sensing when using the backscattered signal power as the wirelessly readable parameter. [4]

III. EXPERIMENTAL ARRANGEMENTS

A simple dipole geometry was used in articles [1] and due to promising behavior, it was selected as the geometry also in this article. The tag geometry is illustrated in Fig 1. The dimensions of the tag in Fig 1 are in millimeters.

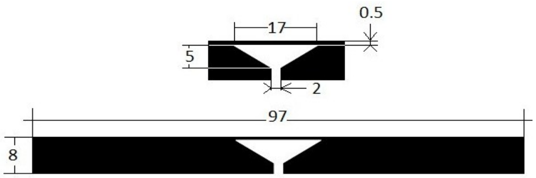

Figure. 1 Simple dipole tag geometry .

Prototype tags were manufactured by screen printing polymer thick film (PTF) silver ink on elastic polyvinylchloride (PVC) substrate. The characteristics of the ink are presented in Table 1.

Table 1. The characteristics of the silver ink.

Description	**Curing (°C, min)**	**Cured film Conductivity (MS/m)**
Polymer thick film silver ink mainly consisting of silver particles which are mixed in polyester resin. Particle sizes from 3 to15µm.	120, 20	1.25

The PVC substrate is meant for heat-pressing into textiles and thus it is easily integrated as a part of clothing allowing wearable sensor tags.

IV. MEASUREMENTS

Voyantic Tagformance RFID measurement system was used in the measurements [16]. The device is a complete measurement solution for evaluating the functionality and performance of EPC Class 1 Gen 2 tags. It is essentially a vector network analyzer with RFID capabilities. All measurements were performed in an anechoic chamber. Monostatic reader with a linearly polarized antenna of gain of 9.5 dBi was used. The measurement distance was 68 cm.

Power on tag (dBm) was used to study the threshold power of the tag. Power on tag is defined as the power that would be acquired at the location of the tag with a power matched 0 dBi antenna. Power on tag is equal to equation (1) when the realized gain of the tag ($(1-\Gamma_{tag})G_{tag}$) is 1 = 0 dBi. It can thus be interpreted as the power which would be absorbed by the RFID chip if it was connected to a perfectly matched 0 dBi tag antenna [14]. The lower the measured power on tag, the higher the realized gain of the tag antenna.

The measured transmitted threshold power can be used to derive the power on tag. Power on tag is the transmitted threshold power normalized by the power loss factor (path loss) from the output port of the generator to the antenna port of a 0 dBi antenna. This means that power on tag is the threshold power multiplied by the power loss factor. It is the minimum power necessary to activate the chip, assuming 0 dBi tag antenna gain and perfect matching. The normalization of the transmitted threshold power makes it possible to compare the tag antennas consistently.

In addition to the power on tag, **the backscattered signal power** (dBm) is the time-average power detected from tag response at the receiver. It was measured by using the threshold power as the reader transmitted power. Both, the power on tag and backscattered power measurements were first performed in air in unloaded conditions. After this, strain was applied on the tag and the measurements were repeated at different strain levels.

The tag was then attached on a thigh of a testee to investigate the effect of human body on the behavior of the tag. The before-mentioned measurements were repeated after attaching the tag on the leg.

V. RESUTS AND DISCUSSION

Before evaluating the tag behavior on human body, the measurements were performed in air to provide a reference. Figs. 2-3 show the results from the measurements.

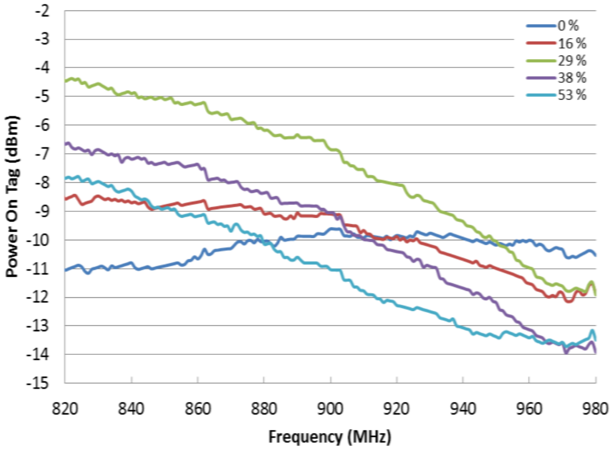

Figure 2. Power on tag of the tag on PVC at different strain levels in air.

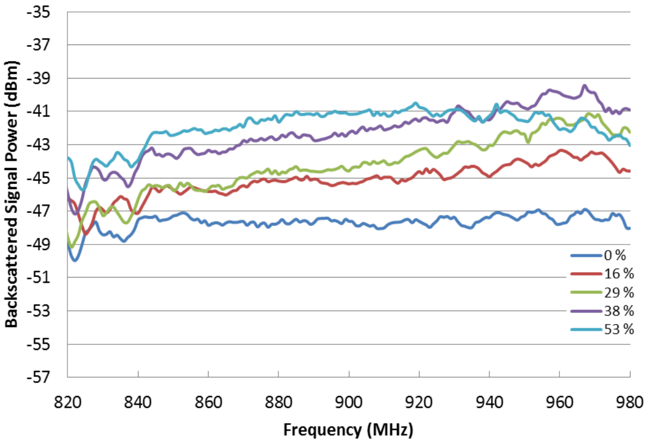

Figure 3. Backscattered signal power of the tag on PVC at different strain levels in air.

It can be seen in Fig. 2 that the power on tag measured from the tag in air shows ambiguous behavior as a function of strain. The backscattered signal power as a function of strain (Fig. 3) illustrates more unambiguous behavior between frequencies 860 - 920 MHz even up to 53 % strain. If we take a look at the results from the same measurements made with the tag when it was attached on a thigh, the behavior seems different. Figs. 4-5 illustrate that the power on tag as a function of strain is less ambiguous that in case where the tag was measured in air. The backscattered signal power of the tag on leg seems to decrease as a function of strain whereas in air it is increasing.

In general, the power on tag is higher and the backscattered power lower in case the tag is attached to a leg. This is due to the losses caused by the human body.

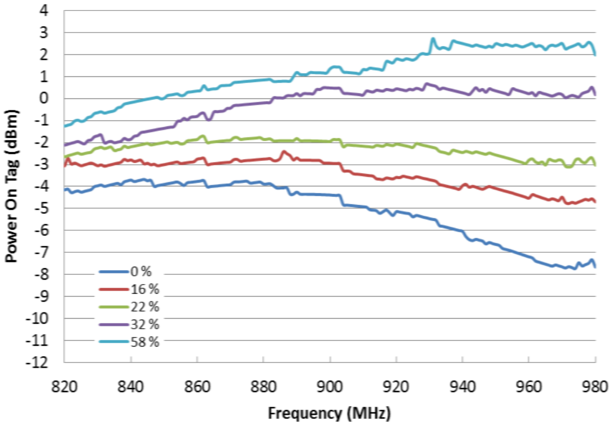

Figure 4. Power on tag of the tag on PVC at different strain levels on leg.

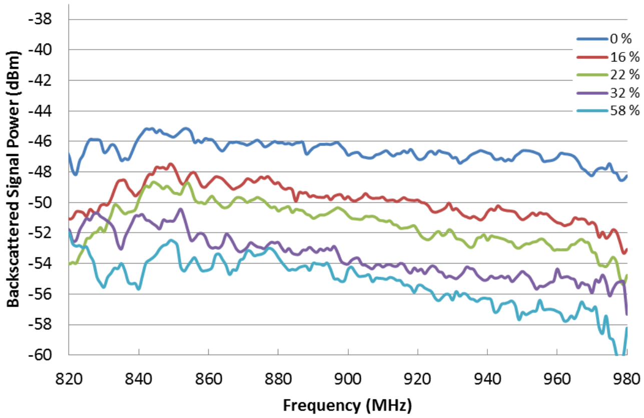

Figure 5. Backscattered signal power of the tag on PVC at different strain levels on leg.

To give a clear vision on the behavior of the difference of the behavior of the tag in air and on a leg, Figs. 6-9 illustrate the power on tag and the backscattered signal power as a function of strain at three frequencies that are 866 MHz, 915 MHz and 955 MHz which relate to the UHF RFID frequencies used in Europe, America and Asia.

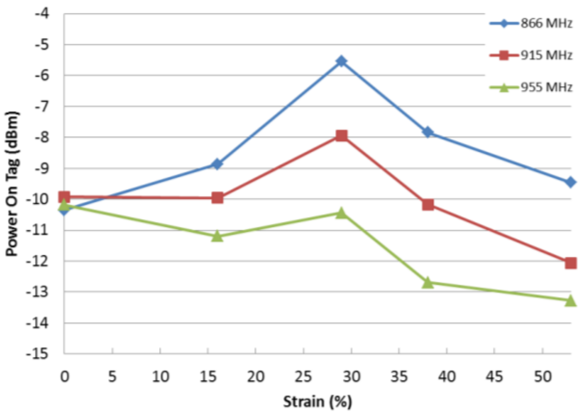

Figure 6. Power on tag of the tag on PVC as a function of strain in air.

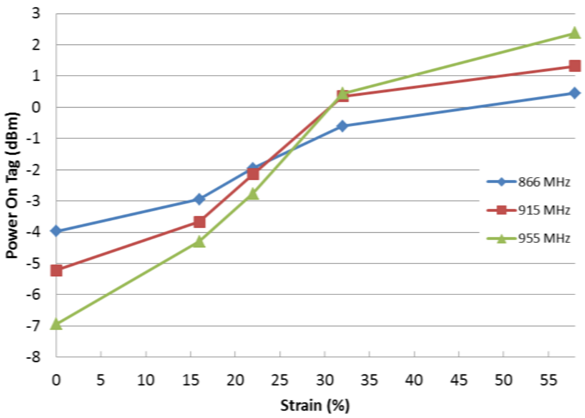

Figure 7. Power on tag of the tag on PVC as a function of strain on leg.

Fig. 6 show that the power on tag in air increases at 866 MHz up to 30% strain after which the curve start to decrease. At 915 MHz the power on tag at rest and at 15 % strain is the same and at 30% strain level, the power on tag has increased. In case of using measurement frequency of 955 MHz the power on tag first decreases slightly, but again at 30 % it has increased from the value measured with 15 % strain applied. After 30 % strain, the power on tag again starts to decrease also in case of 915 MHz and 955 MHz frequencies.

When the tag is attached on a lag the power on tag monotonically increases as a function of strain. Although the power that is required to activate the tag decreases as the tag is stretched, this behavior is promising considering practical applications, if the measurement distance is small enough. The theoretical read ranges are further discussed later in this article.

The ohmic losses in the antenna structure increase when the tag is strained [1, 4]. This decreases the radiation efficiency of the tag thus increasing the power on tag and decreasing the backscattered signal power as a function of strain. The directivity of the antenna on the other hand behaves vice versa. It increases as a function of strain as the tag antenna length approaches to half-wave length. In addition, due to significant change in the tag response the impedance matching is presumed to play an important role as well. The impedance matching of the tag is changed while the tag is stretched due to changed antenna impedance. Similarly, the antenna impedance changes when attaching it on leg. It is actually the impedance matching and thus the power reflection coefficient which is assumed to be the main cause of difference between the behavior of tag in air and tag on leg. The tag antenna is originally designed to be used in air at unloaded conditions. By comparing measurement result at 0 % strain (Figs. 2 and 4) it is seen that the tag is tuned at higher frequencies on leg. If we then look at the results in air, we can find that also the stretching tunes the tag to higher frequencies.

It can be seen from Fig.6 that the lower the measurement frequency is the higher the power on tag and thus the required power to activate the tag. This is partly explained by the antenna directivity which is dependent on the electrical length of the antenna. However, if we look at the results measured with the same tag on leg, we find that after about 25 % strain the tag requires more power to activate the higher the measurement frequency. Figures 6 and 7 imply that in air the impedance matching is improved when the tag is strained but on leg the impedance matching is worsen during straining. Thus the impedance of the tag changes differently in air and on leg as a function of strain. This is also affecting the different behavior of the tag as a function of frequency. However, further investigation of the frequency response of the tag during straining should be performed to support this conclusion.

The backscattered signal power of the tag in air and on leg as a function of strain, measured at 866, 915 and 955 MHz is illustrated in Figs. 8-9.

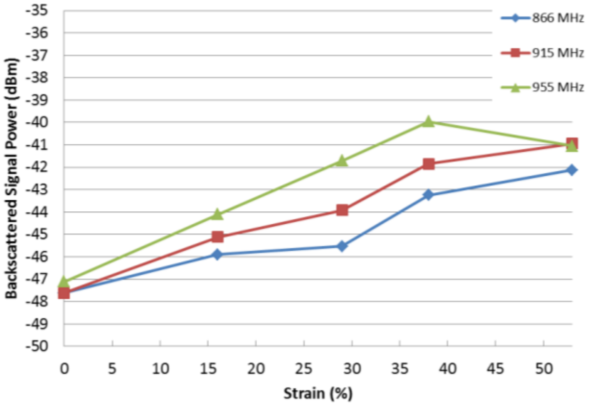

Figure 8. Backscattered signal power of the tag on PVC as a function of frequency in air.

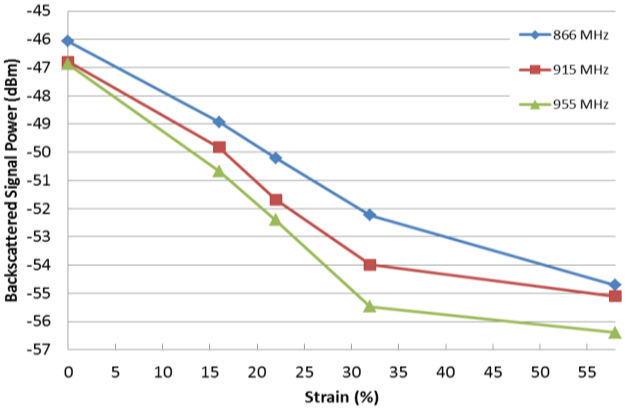

Figure 9. Backscattered signal power of the tag on PVC as a function of frequency on leg.

The backscattered signal power of the tag in air increases, partly due to increased antenna directivity. After further stretching the ohmic losses increase and the radiation efficiency decreases. This increase in ohmic losses finally start to dominate and the backscattered signal power start to decrease as a function of frequency. This is already seen from the results measured at 955 MHz. The change in the backscattered signal during straining in air is also caused by the term $|\rho - \rho|^2$, because of the the power wave reflection coefficients are changed during straining. The coefficient α in equation 2 on the other hand is presumed independent on the strain. The increase of the backscattered signal power in air at relatively large strain levels is encouraging considering the tag-based strain sensing.

The backscattered signal power of the tag on leg also shows unambiguous behavior as a function of strain at 866, 915 and 955 MHz. The behavior is significantly different on leg but still useful considering strain sensing. Although the directivity of the tag on leg also increases due to increasing tag antenna length the losses also increase. The losses are greater if the tag is on leg as discussed already in the case of power on tag measurements. The ohmic losses also increase as a function of strain. The total losses are thus greater on leg and they might overcome the increase of the directivity. Also the power wave reflection coefficient in both chip impedance states (matched and mismatched) is affected by the presence of leg. Thus the term $|\rho - \rho|^2$ may change differently as a function of strain than in case of tag in air.

When the strain-sensor tag is used in real applications, it is important that they can be read from suitable distance. Considering the read ranges of the sensor tag, the increase of the backscattered signal power as a function of strain seems more practical than the decrease of it. However, typically the limiting factor is the forward link (reader to tag) i.e. the threshold power of the tag. Theoretical read ranges of a tag can be calculated for the forward link from equation (1) by replacing P_{chip} with IC wake-up power, and for reverse link from equation (2) by replacing $P_{received,signal}$ with reader sensitivity, and solving r. However, the sensitivity of the reader receiving system is normally orders of magnitude better than the wake-up power of the tag IC. Therefore, the sensitivity of the reader is typically not a constraint and the forward link is more critical [14]. However, it should be noted that while ICs are becoming more sensitive (≈−18 dBm sensitivity has recently been reported [17-19]), the return link limited operation becomes more likely. In the future RFID systems this may be the limiting factor, unless the readers are be further improved as well [20, 21]. The theoretical read range of the tag on leg forward link is 1 m at worst where as for the reverse link (tag to reader) it is approximately 5 m at worst (on 955 MHz at 58 % strain in nonreflecting environment, see Fig. 9). The worst theoretical read ranges in air are: for the forward link approximately 3 m at 25 % strain on 866 MHz and for the reverse link approximately 13 m at 0 % on 866 MHz. Although these read ranges are only theoretical and the real values are dependent on the environment and exact parameters of the equipment, they give some idea of the usability of the sensor in practice. The reading distance is at the worst case 1 m and this appears when the tag is wrapped around a leg and 58 % strain is applied. The strain levels seldom are as high as 58 % suggesting longer reading distances.

Our future work is to investigate stretchable fabric as the substrate material and investigate their strain sensitivity in similar circumstance to this study. Future work is also to test the strain sensor tags in their real using environment, to gather user experience and to investigate, if “textile sensors” are well accepted by the user group. The effect of environmental stress on the stretchability will also be investigated.

VI. CONCLUSIONS

In this study the behavior of passive UHF RFID tag-based strain sensor was investigated in the presence of human body as well as in air. The samples were printed on stretchable substrate with polymer thick film silver ink. The effect of the strain in the wirelessly measureable parameters, threshold power and backscattered power was investigated. We found that the response from the tag was significantly changed when the tag was placed on human body. However, both the threshold power and the backscattered power were measureable from reasonable distance and the response was monotonic as a function of strain. Additionally the tags were manufactured from materials which can be integrated as a part of other structures, especially clothing. Stretchable passive UHF RFID tags of this study can thus be used in wireless strain sensors for monitoring human body movements as well as many other applications.

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