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Gel Phantoms for Body Microwave Propagation in the 2-26.5 GHz Frequency Band

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***Abstract*—Tissue phantoms are widely used for assessing the interaction between the electromagnetic waves and the human body. These are especially key in body area networks, where the body itself acts as the propagation medium, since transmission is highly influenced by its diverse dielectric properties. Gels are suitable materials because of their high water content, which is required to mimic the dielectric properties of most tissues. In this work, PHEA gels are suggested for achieving those properties due to their synthetic nature, which gives them the possibility to be swollen reversibly in more types of mixtures, in addition to water. These gels can be tailored to control the amount of liquid they embed so that they can imitate different body tissues in a wide bandwidth (2-26.5 GHz), which includes most of the current mobile communication and medical bands. This versatility offers the chance to create heterogeneous models of particular regions of the body, and thus improve the test realism. Besides, they own better mechanical and stability properties than the widely used agar or gelatin.**

***Index Terms*—Wideband, body area network, dielectric properties, coaxial probe, heterogeneous model.**

I. INTRODUCTION

MOBILE technologies are growing to novel areas thanks to recent research and technological advances. The next step is the inclusion of wireless transmission in the so-called body area networks [1]. Test and evaluation of antenna systems mounted on a person (wearable antennas and electronics) can be a really challenging procedure. Due to ethics, safety and repeatability issues it is not appropriate and always possible to use a real person inside an anechoic chamber for wearable antennas performance evaluation. This requires the design, the realization and the use of an equivalent phantom which represents the human body shape and electrical properties [2], [3]. The use of phantoms for wearable antenna measurements can provide a stable and controllable propagation environment that cannot be easily performed with alive human subjects [4]. Such measurements exclude the dynamic nature of real human bodies and give an ideal and stable wearable antenna performance.

A great deal of phantom formulations is published in reported works, jointly with its own frequency band, accuracy or materials used [5], [6]. Regarding liquid phantoms, recent works of the authors have proven that acetonitrile mixtures are convenient for achieving many of the tissues referenced in literature within a large bandwidth [7], [8]. Their high tailoring capability allows adjusting the dielectric properties in the range of high water-content tissues. In some cases, such as exposure assessment or on-body scenarios [9], working with solid or semisolid materials is more suitable (e.g., where the devices under test do not require to be immersed inside the phantom). Their main advantage is the capability to be constituted with the shape of the tissue of interest without any container [10]. This fact could allow the development of heterogeneous models composed of multiple tissues, in a way that a realistic body phantom could be achieved for testing purposes. These materials are usually made of polymers, either for manufacturing solids (e.g., 3D printing [11]) or for preparing gels [12]. The latter are desirable because of their potential to lodge a large proportion of water, keeping stiffness. These gels are normally created by adding around a 0.5-5% of a natural polymer [13], such as agar or gelatin, within the liquid mixture, so that the gels are mostly water in their composition. However, the drawbacks include a poor durability and the inability to coagulate the mixture as gel in the presence of solvents other than water, like the abovementioned promising acetonitrile. Being able to absorb this liquid is highly desirable to achieve slight slopes in the dielectric trend with frequency, i.e., values do not decrease sharply, which is more similar to the actual behavior of tissues.

Because of that, a potential solution can be a synthetic polymer like polyacrylamide (PAM) or poly(2-hydroxyethyl acrylate) (PHEA). The first one has already been suggested for creating electromagnetic phantoms [14], but not for covering wide bandwidths. It also has been demonstrated to be a good gel for absorbing water but not as good with acetonitrile [15]. On the contrary, PHEA is a material that has been widely used as biomaterial [16], owns the ability to absorb water in addition to other solvents, holds good mechanical properties, can be

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chemically tailored [17] and, unlike natural polymers, PHEA is very stable in most conditions. Besides, this gel can be swollen and dried reversibly, which gives it the ability to be stored long times and use it again without a significant degradation.

The difference between a solid and semisolid material does not lie in its handling but in its composition materials. Semisolid materials allow a higher water concentration, which is in tune with the actual configuration of most of the tissues. However, solid phantoms are common in literature, either as an enclosure for liquids, or homogeneous materials. For instance, in [18], authors propose a solid wideband (up to 10 GHz) phantom that is made of carbon black, graphite and urethane. One can see that the dielectric trend is far from that of the real tissue, mainly in the conductivity. Semisolid phantoms normally achieve better approximations, like in [19] (above 50 GHz), [20] (55-65 GHz), or [21] (15-40 GHz), all of them made of agar and mimicking the skin. The same formulations have been seen not to be as good at lower frequencies regarding the bandwidth attained [22]. It is clear that for high frequencies, the skin rises as the only interesting tissue to imitate due to the limited penetration depth [23]. At lower frequencies (<30 GHz), heterogeneous wideband phantoms are currently pursued [24]. The challenge lies in the bandwidth they usually cover, quite narrow in many reported cases [25]–[27]. The phantoms that try to cover wider bandwidths are mostly based on oil aqueous mixtures [28], but still the number of tissues is short [29], or focused in certain parts like breasts [30], [31], hands [32] or head [33]. Besides, sometimes the accuracy provided in these kinds of phantoms is small [34]–[36].

For all the aforementioned drawbacks, this work aims at studying new kind of materials that are able to imitate the dielectric behavior of the tissues in a large bandwidth. The dielectric measurements have been carried out within the 0.5-26.5 GHz frequency band, using the open-ended coaxial method [37], which is the most suitable one for measuring large bandwidths [38]. In these measurements, the applied pressure with the coaxial probe was taken into account to ensure repeatability and proper contact. Considering that the mechanical properties are key in semisolid phantoms, meaning that they must hold shape without breaking, they have been included within the scope of this paper. This work presents measurements of these polymers, which can be cross-linked to form gels. They can be swollen with water and acetonitrile in any rate so that it is possible to adjust their final structural properties depending on the target. The results presented here are intended to be useful for testing heterogeneous scenarios like the capsule endoscope [39], where the nature of the medium must be represented accurately. The widely referenced Gabriel values [40] have been taken as the reference dielectric properties for the biological tissues.

The remainder of this paper is as follows: in section II, the materials preparation and the characterization methods are explained, as well as the reasons for choosing these materials; next, section III includes the guidelines in order to conform phantoms and the results of their dielectric measurements with comparison to the physical behavior of the real tissues; finally, section IV summarizes the results of the work.

II. GEL PREPARATION AND METHODOLOGY

A. *Gel Preparation*

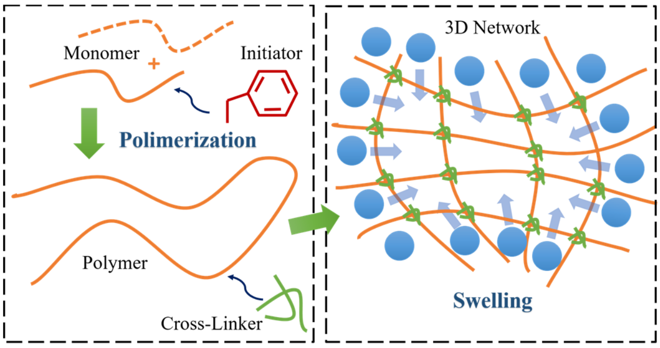

Fig. 1. Scheme of the fabrication steps from the initial compounds until the final gel. Left: Polymerization reaction. Right: Gel swelling with the liquid mixture.

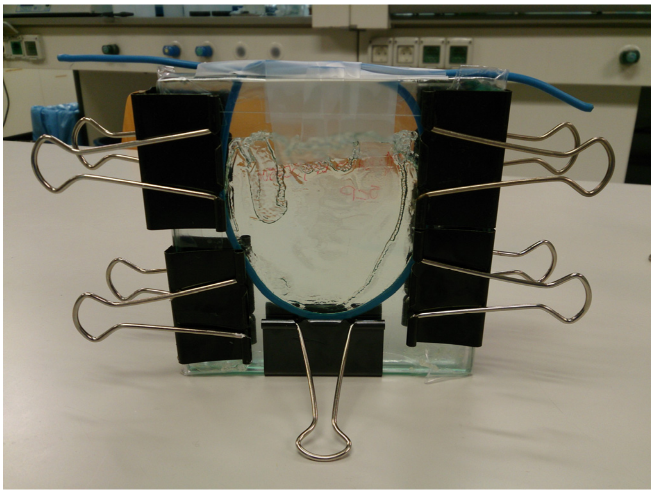

Fig. 2. Glass molds that allowed the passage of UV light to induce the polymerization of the reacting mixture.

The materials chosen for mimicking the dielectric properties of the human tissues were synthetic gels consisting of poly(2-hydroxyethyl acrylate) (PHEA) swollen with aqueous mixtures. These own the stiffness to keep the shape, like a solid, and the ability to hold a great amount of liquid inside, since tissues have a significant amount of water. The synthetic condition provides them of better stability in time, in terms of degradation, as well as the possibility to tailor the chemical structure to the requirements. Besides, they can be swollen and dried reversibly. The polymer was obtained by starting from its monomer, 2-hydroxyethyl acrylate (Sigma-Aldrich), in presence of a cross-linker (0.05-2%) (Fig. 1, step 2), ethylene glycol dimethylacrylate (EGDMA) (Sigma-Aldrich). The radical polymerization reaction does not take place spontaneously, but needs an initiator molecule (Fig. 1, step 1). In this case, a UV initiator was chosen, benzoin (Scharlab). The concentration of all these chemicals can be adjusted according to the desired properties of the structure. In this case, the concentration of initiator was always a 1 wt%, whereas the cross-linker was changed to adjust the swelling degree of the network. The polymers were synthesized following this procedure (Fig. 1):

a) Preparation of the solutions: The initial compounds were weighted and stirred together inside a glass vial until complete dissolution.
b) Polymerization: The previous solutions were poured into glass transparent molds (Fig. 2) with the required dimensions and introduced in an ultraviolet oven for 24 hours. In this case, the molds consisted in two parallel plates with a separation of 3 mm.
c) Post-polymerization: After the initial polymerization, the molds were switched to a heat oven at 90 ºC for 24 hours more, in order to ensure complete reaction.
d) Washing: Once the reaction was finished, the samples were removed from the molds with a scraper and introduced in a glass flask filled with a solution of water and ethanol. This final step warranted the elimination of any remaining monomer molecules, which are harmful. Below the flask there was a heating blanket to heat the solution to the point of boiling. The setup also included a reflux coil, which granted continuous boiling without elimination of the solvent. The gels were washed in two steps of 6 hours each, after which the solvent was renewed to maximize the extraction.
e) Drying and swelling: Once the gels were washed, and still swollen, they were punched out in 8 cm circles and then thoroughly dried out using a vacuum pump. Afterwards, samples were introduced in different solutions, either water or acetonitrile mixtures, and swollen for 24 hours to ensure swelling equilibrium.

As illustrated, gels are prepared in two steps. Firstly, the polymer network was synthesized (Fig. 1, left) and, secondly, the liquid mixture with a particular composition of interest was prepared to swell the xerogel (that is, the dry gel) (Fig. 1, right). One of the advantages of these gels is that they can be dried after using them and swollen again with the mixture.

B. *Characterization Methodology*

The dielectric properties were determined with the open-ended coaxial method (Fig. 3). It consisted of a slim-form open-ended coaxial probe (Keysight 85070E) and a vector network analyser (Keysight N9918A FieldFox Handheld Microwave Analyzer). The output power was -3 dBm, while the IF bandwidth was set at 3 kHz. The system was calibrated before measuring with open circuit, short circuit, methanol and water, which have been proven to be convenient references for wideband permittivity measurements in the range of human tissue values [37]. The sweeping frequency range was configured within its maximum capability, which was from 500 MHz up to 26.5 GHz. The samples size was approximately 5 mm in depth and 1 cm in diameter, which has been reported to be a suitable sensing volume for dielectric measurements with this probe [41]. It was found out that with a thickness greater than 2 mm the measurements did not vary more than the uncertainty of the measurement itself.

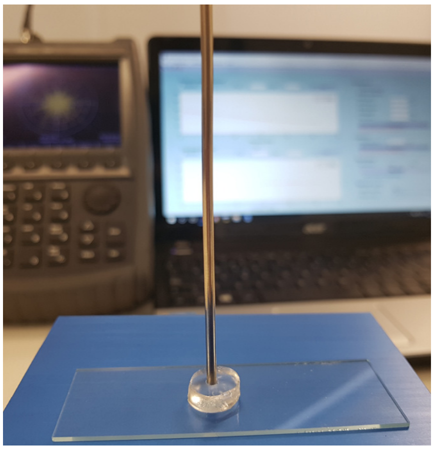
Fig. 3. Measuring a sample with the open-ended coaxial probe (ahead) and the vector network analyzer (behind).

Fig. 4. Single point load cell (left) connected to the strain meter (right), which shows the strength applied to the red surface in newton.

Since the measured materials are semisolids, the pressure applied to their surface deforms them and changes the observed permittivity. A too weak pressure would keep air between the probe and the gel, and an excessive one would pull out the liquid content. Because of that, and also to ensure repeatability in measurements, the samples were measured under 1.5 N of strength, gauged with a single point load cell (Omega, LCAE-3KG) connected to a strain gauge meter (Omega, DP25B-S-230) (Fig. 4), following the guidelines described in [42]. This pressure provides consistent results without breaking the gels. Thus, this strength sensor was placed between the coaxial probe and an elevator, which was adjusted up to reaching the aforementioned force, with the sample being located in between.

C. *Material Selection*

There are several polymers reported in literature able to cross-link and with functional groups affine to water molecules, i.e., able to swell to form gels without being dissolved by it. Depending on their nature, they absorb more or less liquid, and this is a crucial issue. The more quantity it absorbs the more similar to the permittivity of the liquid it will be. Taking into account that the most pursued tissues have high water content, which provides them high dielectric constants, an elevated content in liquid will be required. The way of measuring this ability to absorb liquid is described with the swelling degree (1) , in which m_f is the final mass once the hydrogel is at swelling equilibrium, and m_0 is the mass of the xerogel before swelling, i.e., in its dry state.

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$$SI(\%) = \frac{m_f - m_0}{m_0} \times 100 \qquad (1)$$

This parameter is related to the chemical affinity of the polymer and the liquid mixture, as well as to the concentration of cross-linker added in the polymerization procedure, among other factors. In principle, the less the amount of cross-linker is introduced in the initial step, the larger it will absorb because the polymer network is looser. In the initial steps, two polymers that are well-known for absorbing large amounts of water were considered as candidates to create gels. These polymers were the aforementioned poly(hydroxyethyl acrylate) (PHEA) and also polyacrylamide (PAM) equally cross-linked. The resulting liquid mixtures should contain acetonitrile due to its reported capability to imitate the trend of the permittivity of tissues in the microwave band. Hence, in an exploratory experiment, the swelling degree was assessed by immersing these gels in water and in a 50% acetonitrile mixture. Five samples were analyzed to check this property, whose results are showed in Fig. 5. Despite the PAM gel owns an enormous ability to absorb water, much higher than the PHEA, this latter has better affinity with the acetonitrile mixtures, which are precisely the ones pursued. This fact promoted the choice of PHEA as a suitable candidate for phantom gels, and PAM was discarded for the application.

The cross-linking degree also has influence over this swelling degree. In fact, this is the reason why the standard deviation in the PAM swollen in water is so large, because it includes the results for a range of cross-linking degree from 0.05 to 2 wt%. One can get an idea of how cross-linking affects in the following graph. In Fig. 6, the same experiment was carried out, this time with PHEA gels but with different cross-linking degrees. The descending trend can be observed when the cross-linker percentage is increased, as expected. This influence is not as pronounced as the chemical nature of the gel (the values attained by PAM cannot be obtained with PHEA even at the lowest cross-linking densities), though, and this effect can be exploited to tailor the properties of the gel.

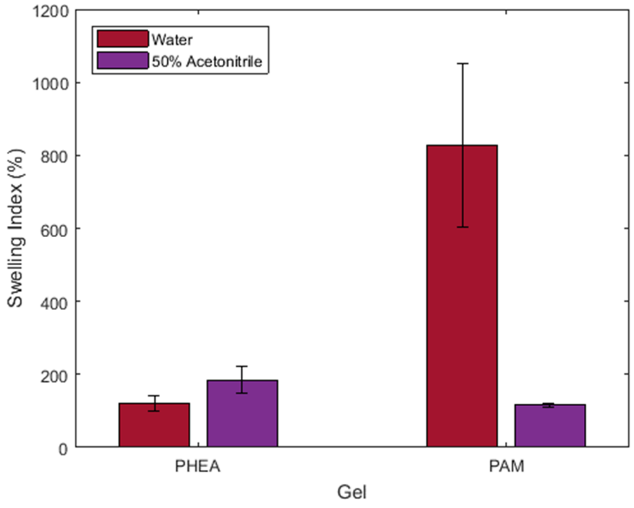

Fig. 5. Average swelling index and standard deviation of the PHEA and PAM gels when swollen in water and in a 50% acetonitrile mixture.

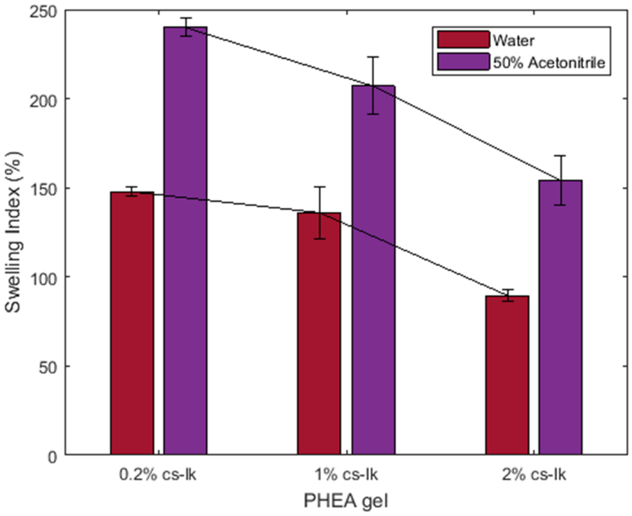

Fig. 6. Average swelling index and standard deviation of PHEA gels, with different cross-linking degrees (percentages), when swollen in water and in a 50% acetonitrile mixture.

Taking into account that the final purpose of the materials is developing a phantom, which should imitate the tissue shape while standing on its own, the mechanical properties are key to guarantee they do not break with ease. In this case, the method used to analyze this feature is subjecting the swollen samples to compression forces until the break point. Since the variability of the measurements is important in these kinds of tests, results are represented in a box-and-whisker diagram (Fig. 8). As the gels were prepared with different amount of cross-linkers each, they have different physical properties in some ways, like the swelling degree. However, tests showed that there was no great difference in terms of the ultimate strength with the swelling degree (Fig. 7). This means that one can control the amount of liquid that the polymer network absorbs without hardly altering the strength that the final gel supports. Even though the range of values is very large, the average ultimate strength is pretty high in all cases.

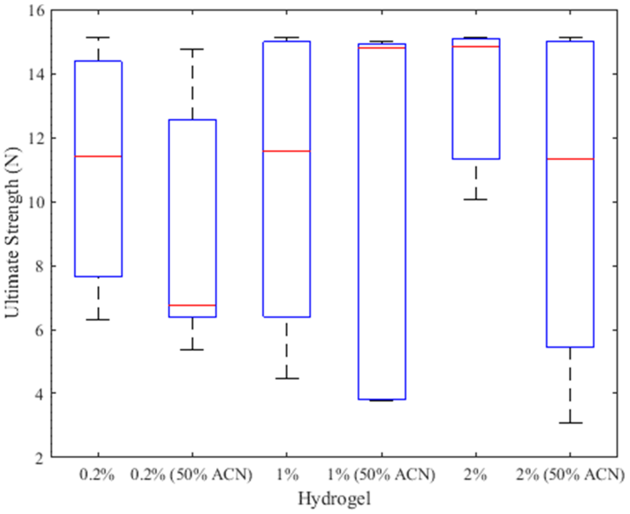

Fig. 7. Box-and-whisker diagram of the ultimate strength for PHEA gels, swollen in water and 50% acetonitrile (ACN) mixtures, with different cross-linking degrees (percentages).

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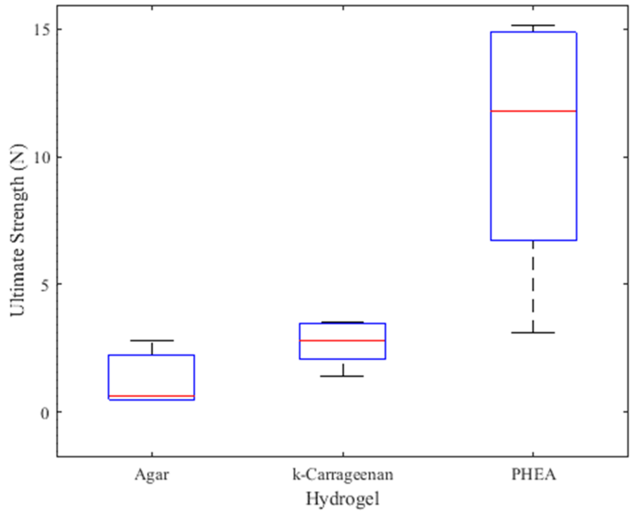


Fig. 8. Box-and-whisker diagram of the ultimate strength for gels made of agar, k-carrageenan and PHEA in water.

Hence, results are grouped among materials but not divided regarding this parameter. If we compare these values to those of other natural polymers which are commonly used for fabricating phantoms, the present results own more promising properties in terms of resistance. This comparison is presented in Fig. 8, where results of agar and k-carrageenan, which were prepared and analyzed as well, are put in contrast with the PHEA ones.

III. SEMISOLID PHANTOM ELABORATION

A. Guidelines for Phantom Design

In the previous section, it has been shown how the cross-linking degree modifies the swelling degree, which is directly related to the dielectric properties. This can be one way to tailor the range of values in which the dielectric properties fall. As showed before, increasing the percentage of cross-linker reduces the amount of liquid that the network is able to absorb. This fact can be seen in Fig. 9, where the dielectric properties of PHEA gels, which have been synthesized with different cross-linking concentrations, are compared. The bars depict the standard error of the measured values.

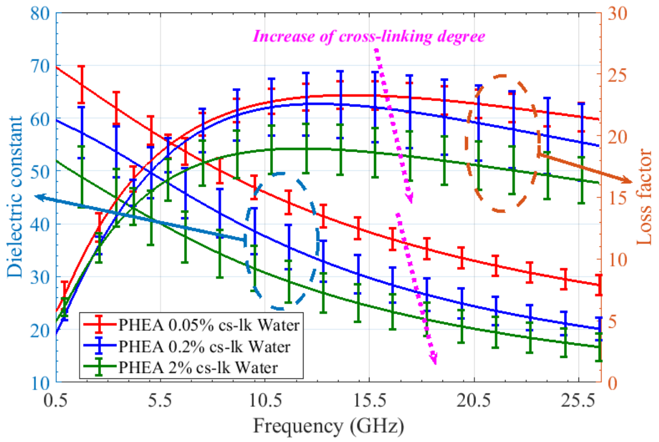
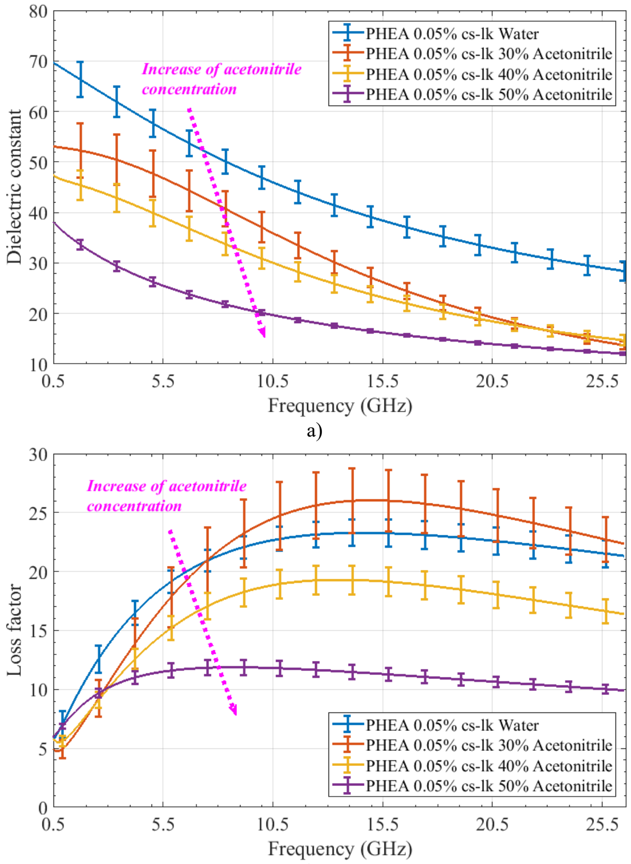


Fig. 9. Relative permittivity of the PHEA gel, swollen in water, with different percentages of cross-linker.



a)

b)

Fig. 10. Relative permittivity of the PHEA gel, with a fixed cross-linking degree of 0.05%, swollen in different acetonitrile mixtures. a) dielectric constant b) loss factor.

As expected, the least swollen gels, i.e., the most cross-linked ones, show the lowest values. The other way to achieve this effect is by introducing acetonitrile in the composition of mixture, whose permittivity is lower than water. Introducing acetonitrile in the gel increases the amount of liquid that the polymer absorbs, whose effect is that the effective permittivity of the gel is closer to that of the liquid. At low acetonitrile concentrations, the values are higher than water due to the increase in the swelling degree, that is later counteracted with the low permittivity of acetonitrile. This effect can be observed in b) Fig. 10, where the gel with a 30% concentration of acetonitrile has higher loss factor values than water, but these values drop considerably when this concentration is increased.

Combining these two parameters can be useful for achieving the different target values and then imitate the different tissues on demand. There is a substantial difference between both methods. When including acetonitrile, the slope of the dielectric constant changes due to its higher relaxation frequency [9], which changes the trend of the values. In contrast, an increase of the cross-linking degree basically reduces the amount of liquid in the gel, and so the ratio with respect to the polymer. This leads to a reduction in both the dielectric constant and the loss factor. Since these materials are based on hydrogels, they are thought to contain an important amount of water. Thus, these are more likely to imitate soft tissues.

B. *Gel Phantoms as Tissue Models*

The previous guidelines were followed to match the dielectric properties of the gels to those of the tissues within the measured frequency range. Soft tissues were considered the target to search, since these are involved in the main propagation scenarios and in the outermost layers, which are the ones considered for exposure issues. This means that the target values are considerably high, and thus the liquid content of the gels. If phantoms are exposed directly to the air, they will slowly lose liquid through diffusion into the air, like any gel, so it is recommended to cover them when they are not used or swell them up again. These gels can be swollen and dried many times without degradation, and their synthetic nature gives them a very high durability, which reaches several months. Down below, some phantoms are proposed for several tissues, shown in different plots where the solid lines are the Gabriel values [40]. The dashed lines are the candidate gels, with a shaded area that represents its standard deviation.

One can notice that under 2 GHz the difference between phantoms and tissues in the loss factor is significant. This is related to the ionic conductivity, which is determinant up to this frequency and it is not present in the gels. Thus, it was considered that these gels are valid from this frequency. Gel phantoms could be improved within this particular region by adding a salt to the swelling mixture. Regarding the highest part of the frequency, one can see that the trend of the curves is very similar, which suggests that the phantoms may match the dielectric properties of tissues at further frequencies.

A cross-linking degree of 1% is found out to be suitable for imitating tissues with a mid-range content of water. For instance, the cerebellum tissue can be mimicked by using PHEA cross-linked a 1%, swollen in a 40% acetonitrile mixture, as can be seen in Fig. 11. The same kind of gel can be swollen in a different mixture, this time increasing the acetonitrile concentration up to 60%. This change is made in order to reduce the values of the dielectric constant to those of another important tissue, the skin, which is especially key in exposure assessment at high frequencies. One can see in Fig. 12 that the slope is better rendered in this case, even though the values are a bit lower.

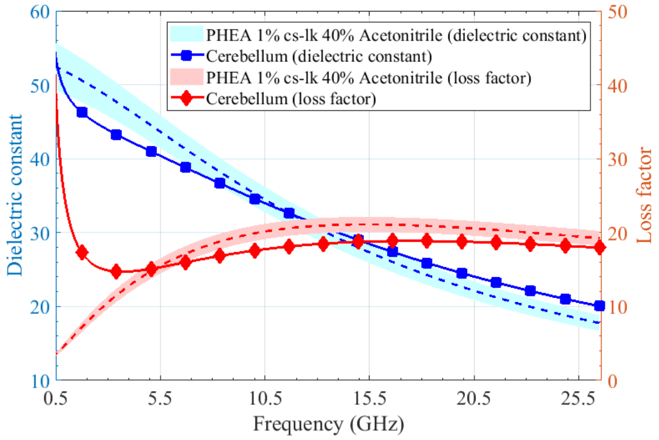


Fig. 11. Relative permittivity of PHEA gels, with a 1% cross-linking degree, swollen in a 40% acetonitrile mixture, compared to the cerebellum values.

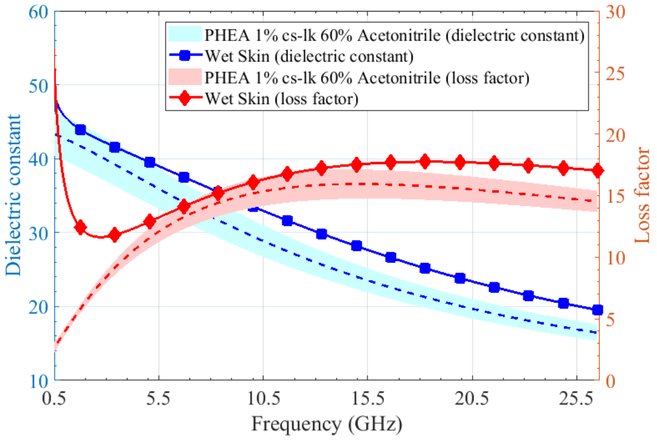


Fig. 12. Relative permittivity of PHEA gels, with a 1% cross-linking degree, swollen in a 60% acetonitrile mixture, compared to the wet skin values.

Other tissues, like the liver, own a steeper slope in the real part of the permittivity. When this trend takes place, the inclusion of acetonitrile is meaningless, since it causes just the opposite effect. Water should be used instead, taking into account that the swelling degree will be smaller (see Fig. 5) and so the dielectric values. It can be deduced that the steepest slope that can be achieved with this method is that of water. Whenever the slope of the dielectric constant of the phantom is the correct one, the best way to displace the values of the curve is by modifying the cross-linking degree, since it does not alter their trend with frequency. In Fig. 13, the liver tissue is compared to the PHEA hydrogel, i.e., swollen in water, with a 1% cross-linking degree.

Another way to fit a steeper slope for high permittivity values is to decrease the concentration of cross-linker in the polymer, so that the network absorbs more liquid, and then reduce the values and slope by adding acetonitrile in the swelling mixture. This is the case of the tendon, which can be approximated with a PHEA gel with a 0.2% cross-linking degree, by swelling it with a 60% acetonitrile mixture (Fig. 14). This tissue could be a matter of interest for some researchers to study the heat impact over a tissue as delicate as tendon in an ankle wearable.

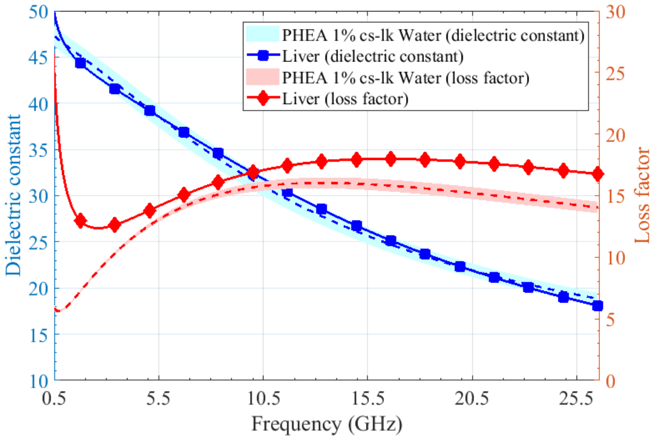


Fig. 13. Relative permittivity of PHEA gels, with a 1% cross-linking degree, swollen in water, compared to the liver values.

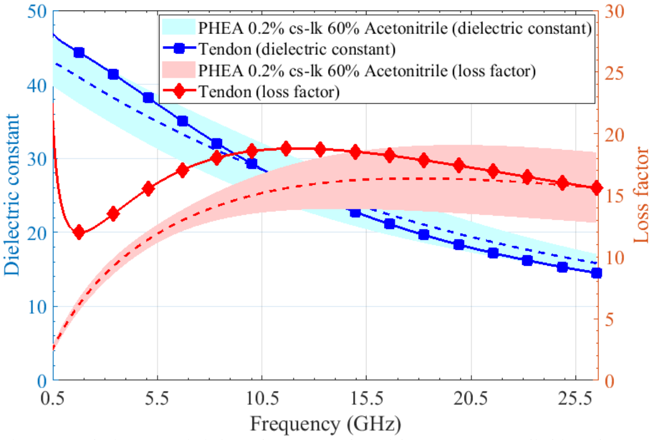


Fig. 14. Relative permittivity of PHEA gels, with a 0.2% cross-linking degree, swollen in a 60% acetonitrile mixture, compared to the tendon values.

Reducing even more the cross-linking degree is possible, and even necessary for tissues with higher water contents. Henceforth, the depicted gels are those with a 0.05% cross-linking degree, which was the lowest achieved. The tissue with the highest values that was pursued is the colon, and the best match is the one shown in Fig. 15, with just water as swelling liquid. A fact that might seem a drawback is that this type of gels contains less liquid than the natural ones, which can reach nearly the 99% in mass. This is certainly one of the factors that make them weak. However, the levels of liquid content that are achieved with these gels is sufficient to imitate the soft tissues.

Another tissue with a similar range of values to those of the colon is the muscle tissue. The difference lies in the loss factor, which is around ten units lower than in the previous case. Keeping the dielectric constant and changing the loss factor is really challenging, since both parameters are related. Because of this, in the following phantom, the slope is compromised to better fit the loss factor and maintain the average values of the dielectric constant. The best way to decrease the loss factor, while keeping the cross-linking degree, is to add acetonitrile. The results of this adjust is shown in Fig. 16, where the PHEA gel is swollen with a watery mixture with just a 10% of acetonitrile and compared to the muscle values.

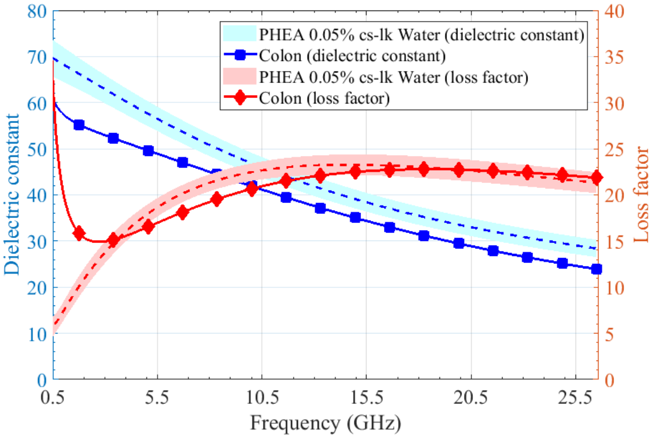


Fig. 15. Relative permittivity of PHEA gels, with a 0.05% cross-linking degree, swollen in water, compared to the colon values.

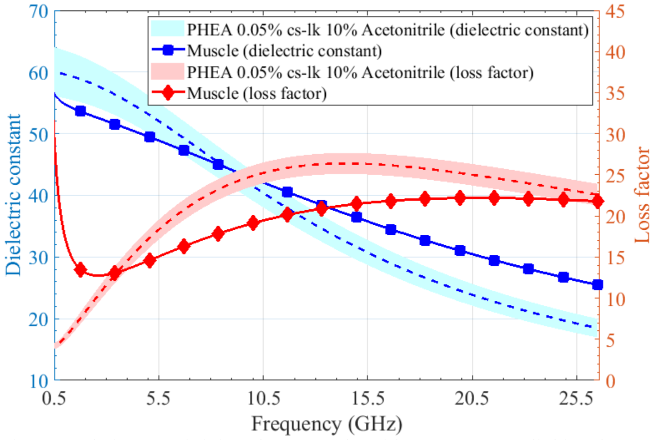


Fig. 16. Relative permittivity of PHEA gels, with a 0.05% cross-linking degree, swollen in a 10% acetonitrile mixture, compared to the muscle values.

Cartilage is a crucial tissue because of the ear, which is mainly exposed to the radiation of mobile phones. It is imitated by increasing the concentration of the same gel until a 40% of acetonitrile. Thanks to this addition, the gel achieves a good approximation to the values of the tissue, as well as its trend. These results can be observed in Fig. 17.

Finally, the nerve tissue is depicted in Fig. 18, alongside the dielectric values of the gel that better followed its values, which is the PHEA, cross-linked at 0.05%, next swollen in a 50% acetonitrile aqueous mixture. This is the main component of the nervous system, so this phantom may be determinant in the assessment of the influence to the exposure simultaneous narrowband or wideband technologies over this body region.

As one can see, the phantoms have been shown across the full bandwidth regardless the possible applications that may arise, as frequency bands used for the different communication scenarios evolve over time. For instance, current intracorporal communications do not usually exceed the 800 MHz band, but this is something that can change with the ultrawideband technology. As a summary, Table I picks up the composition of the gel phantoms that have been progressively shown along this section jointly with the RMSE values, from 2 up to 26.5 GHz, for the real (dielectric constant) and the imaginary part (loss factor) of the relative permittivity.

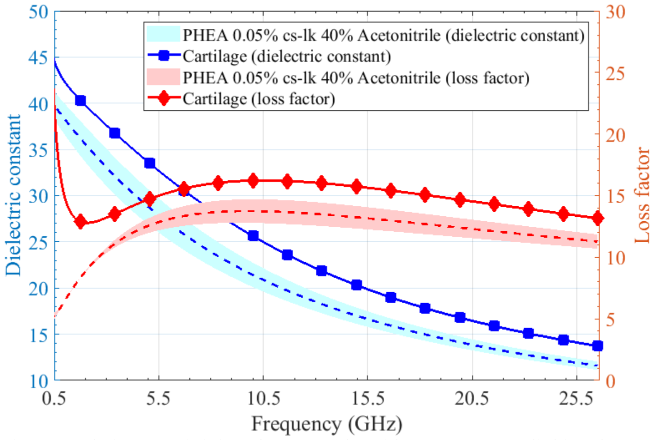


Fig. 17. Relative permittivity of PHEA gels, with a 0.05% cross-linking degree, swollen in a 40% acetonitrile mixture, compared to the cartilage values.

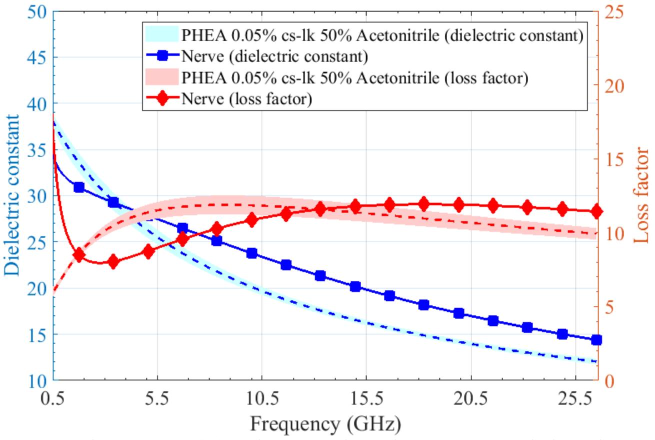


Fig. 18. Relative permittivity of PHEA gels, with a 0.05% cross-linking degree, swollen in a 50% acetonitrile mixture, compared to the nerve values.

TABLE I
COMPOSITION FOR TISSUE PHANTOMS WITH THEIR DEVIATION (2-26.5 GHZ)

Tissue Phantom	Composition	RMSE (ε_r' | ε_r'')
Cerebellum	PHEA with a 1% of cross-linker swollen in a 40% acetonitrile aqueous mixture	2.23 | 2.32
Wet Skin	PHEA with a 1% of cross-linker swollen in a 60% acetonitrile aqueous mixture	3.63 | 1.97
Liver	PHEA with a 1% of cross-linker swollen in water	0.55 | 2.12
Tendon	PHEA with a 0.2% of cross-linker swollen in a 60% acetonitrile aqueous mixture	1.63 | 2.84
Colon	PHEA with a 0.05% of cross-linker swollen in water	5.59 | 1.26
Muscle	PHEA with a 0.05% of cross-linker swollen in a 10% acetonitrile aqueous mixture	5.00 | 3.97
Cartilage	PHEA with a 0.05% of cross-linker swollen in a 40% acetonitrile aqueous mixture	3.62 | 2.35
Nerve	PHEA with a 0.05% of cross-linker swollen in a 50% acetonitrile aqueous mixture	3.01 | 1.46

Thus, one can make a comparison with those phantoms reported in literature, within a similar frequency range, where deviations are provided. For instance, wet skin suggested in [29] owns a RMSE of 2.62 (real part) and 2.44 (imaginary part), which is better in the real part than the one presented here. However, they achieved these errors considering a narrower bandwidth (up to 20 GHz) and weaker mechanical properties due to the gelatin composition. In [43], authors present also a skin phantom, just until 10 GHz, with a 10% relative error for the real part in the best case and a 21% in the imaginary part, both larger than that here presented. In the case of liver, in [44] a solid rather than semisolid phantom is presented, with a significantly smaller accuracy, 8.55 of RMSE for the real part in the best case, and 5.49 for the imaginary one. Muscle phantom is reported in [29] as well, with a better approximation than the one achieved here, i.e., 4.6 and 2.49 of RMSE, for the real and imaginary part, respectively. But once again there is the drawback of its gelatin loose structure.

IV. CONCLUSION

In this work, new candidate gels have been proposed to imitate the trend of the dielectric properties of the body tissues within the microwave frequency range. Their novelty lies in the fact that they can be tailored to control the liquid content and absorb different mixtures in addition to water. This fact allows the inclusion of acetonitrile, which has been proven to be suitable for wideband phantoms. The gels were measured with the open-ended coaxial method in a wide frequency range following a careful methodology in which the pressure of the probe was controlled. Several tissues have been mimicked in a wide frequency band (2-26.5 GHz) by means of the gel tailoring possibilities. The difference of these gels with respect to others that have been proposed previously is their synthetic nature. These work better with high-water content tissues, since they are based on hydrogels, but they could be cross-linked in high percentages to have a very little water content, and thus approximate tissues such as bones or fat.

Moreover, they are mechanically much more resistant than natural polymers, can be swollen reversibly, and are more stable in general. A good option to avoid dehydration may be to cover them with a plastic film of a few microns thick. Anyway, they can be swollen up again if necessary. The selected polymer was PHEA due to its affinity with the acetonitrile mixtures, which are suitable for imitating the body tissues. The use of PHEA-based gels will allow researchers and industry workers to develop complex heterogeneous models and to imitate the body scenario in an accurate way. The final applications include propagation studies and exposure assessment, and their main advantage is the possibility of imitating soft tissues within a wide frequency band (up to 26.5 GHz), allowing the test of different technologies at once.

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