Suppression of Surface Currents at Microwave Frequency Using Graphene-Application to Microwave Cancer Treatment

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Abstract ─ In this work we consider the problem of surface currents suppression using graphene in the context of microwave cancer treatment. Most of the research on graphene has been focused on its applications at terahertz frequencies, and not at microwave frequencies. The use of microwave cancer ablation technique using a coaxial slot antenna is being limited because of the existence of surface currents which lead to the heating of the healthy tissues along its outer surface. In this work we propose to use graphene which is a single-atom sheet of carbon, as a solution to prevent the propagation of surface currents on the outer conductor of the coaxial antenna. We show that by properly designing and tuning the conductivity of the graphene layer, we can not only suppress the surface currents, but also control the amount of energy deposited in the surrounding tissue.

I. INTRODUCTION

Currently surgery, chemotherapy and radiotherapy are the most widely methods for cancer treatment. We note however, that only 25% of the patients are candidates for surgery, and radiotherapy can treat only 1-2 cm of the targeted area [1]. As for chemotherapy, it has numerous physical and non-physical side effects which affect the life of the patients [2].

The microwave ablation technique has attracted increased attention in recent years, owing to its ability to heat much larger lesion size but with a shorter treatment time. Microwave ablation treatment is performed by using a small interstitial antenna, which radiates electromagnetic energy into the tissue through an aperture positioned at its end. The most common applicator is of coaxial type classified as dipole, monopole or slot antenna [3]. Although these antennas have several important advantages, such as increased power deposition near the aperture within a shorter treatment time, they have drawbacks that prevent them to be considered as alternatives to the RF ablation devices [4], which has witnessed extensive use in recent years. This is because with these antennas, electromagnetic power is not only deposited near the aperture (or slot), but also all the way along the interstitial antenna, towards the feed point. This phenomenon can be primarily associated with the surface currents that travel along the outer conductor of the coaxial antenna and cause an overheating of the healthy tissues in the vicinity of the coaxial line. As can be seen from the discussion presented in the subsequent sections, considerable research has been carried out in attempts to reduce the backward-heating problem, and thereby increase the radiation properties of the antenna. For example, in [5] and [6] the authors have proposed to use cap-chokes or sleeves to impede the propagation of the surface currents. Although the results obtained were somewhat promising, it was found that the surface currents were not completely suppressed and the overheating problem was not eliminated entirely.

In this work, we propose a new approach based on the use of graphene, to reduce the surface currents along the antenna and to maximize the SAR in the region where the cancerous tissue is present. The use of graphene at microwaves is novel, since it has primarily been a potential candidate at terahertz and other applications [7].

The paper is organized as follows: Section II reviews the basics of microwave cancer ablation and proposed techniques to reduce the backward heating problem. Section III presents a review of the properties of the graphene, and its recent electromagnetic applications. The use of a graphene materials as a high impedance surfaces is also discussed in Section III. Numerical results showing the performance of a graphene layer as a wrapper for the coaxial slot antenna

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are presented in Section IV.

II. MICROWAVE CANCER ABLATION

Cancer therapy using microwaves energy is based on the interaction between electromagnetic waves and biological tissues. Cell destruction is induced by transferring high microwave energy into the tissue via a thin applicator that we call hereafter "antenna". The heat generated at the targeted cancerous cells increases the tissue temperature locally and leads to a shrinkage of the tumor. Generally, this type of treatment is referred as hyperthermia or thermal therapy. Temperatures ranging between 50-60 °C are needed to have coagulation and necrosis of cells [8]. The physical phenomena behind the hyperthermia is the ability of the high frequency waves to induce oscillation of the polar water molecules contained in the tissue, which in turn causes frictional heating. Hence, microwave heating strongly depends on the water content of the tissue. The more the percentage of water is high the more microwave energy is absorbed into the tissue such as liver, kidney, etc.

Ablation with microwaves have several advantages over the RF ablation methods. For the RF ablation technique, a closed electrical circuit must be created by the use of a ground pad which is the main cause of the skin burn [9]. The electrical conduction of the tissue plays an important role for the tissue heating. As the temperature in the tissue increases during the RF ablation, its impedance increases and the electrical current conduction becomes more difficult. This leads to a restricted area of ablation. Microwaves does not need a high conductivity tissue in order to propagate through it. Thus, the increase in the impedance with the temperature is not a limitation. Therefore, the treatment is faster and larger volume around the antenna can be reached and coagulated [4], [10], [11]. Also, microwaves does not require a ground pad.

A. Microwave antennas as applicators

Microwave energy is transferred to the tissue via an antenna. There has been intensive theoretical, experimental and clinical research to study which type of antenna to use and how to solve problems that occur while performing ablation. The microwave antenna should be minimally invasive, i.e., the organ being ablated must not be damaged by the insertion or contact of the antenna. Also it should be bio-compatible. Generally, in the beginning of its development tumor is localized in a small zone in the tissue. Hence, the aim of the microwave ablation should be highly localizing the microwave energy to this area. Otherwise, an ablation zone larger than that of the tumor can lead to the death of healthy tissues. Moreover, the localized power must be as large as the tumor so that it is completely eradicated. The microwave antenna must be designed so that maximum power is radiated into the tissue. At the operating frequency the return loss, i.e., the reflection coefficient should be as low as possible.

Several antenna types that have followed the design criteria cited above have been proposed in the literature. Monopoles [12], dipoles [13], tri-axials antennas [14], coaxial slot antennas [15], etc., are among the most widely used linear element antennas. Only a few examples of applications using loops [16] and helical [17] antennas exist in the literature. Among the linear element antenna cited above, coaxial slot antenna is one the most widely investigated. It consists of a coaxial line covered by a catheter usually made of Polytetrafluoroethylene (PTFE). The catheter avoid adhesion of the antenna to the ablated tissue. The electromagnetic energy is radiated through a small annular aperture (slot) positioned close to the end of the antenna. The coaxial slot antenna has a relatively low return loss and it concentrates the radiation around the slot. However, in common with other coaxial type antennas, it suffers from unwanted backward heating along the antenna, especially near the region of the feed. This phenomenon can lead to the overheating of the healthy tissues – one of main drawbacks which limits the use of microwaves as an alternative treatment technique in clinics. Some of the works published on this topic are briefly reviewed in the following.

B. Backward heating

Backward heating is attributed to the propagation of surface currents, generated at the slot, between the outer conductor of the coaxial cable and the catheter. Numerous attempts to limit this problem have been made. One of them is to use a cooling system along with the antenna, and either gas or water is used for this purpose [18]. Choked antenna design is a common technique to limit the propagation of surface currents appearing on coaxial antennas [19]. The choke is a metallic ring connected to the outer conductor of the coaxial antenna. Usually a choke length of $\lambda/4$ (λ is the wavelength) is necessary to achieve a good performance with lowest backward heating. In addition to the choke, the use of a cap at the distal end of the antenna has been also proposed [5] to increase the power radiated in the tissue. Sleeve antennas [6] and floating sleeve antennas [20], are some of the designs that are commonly used for the same purpose. In a previous work, the authors have shown that, a double choke element can improve the radiation pattern and further decrease the backward heating, if properly oriented and spaced. Readers interested in learning more about this new design and others on the backward heating reducing techniques are referred to [21]. It appears that the introduction of a choke can substantially increase the radial size of the antenna [22]. This is conflicting with the nature of an interstitial antenna which must be non-invasive. In [22], the authors have proposed to use a miniaturized choke which could lead to a minimally invasive interstitial heating.

In the present work, we propose a novel approach which is based on the use of a very thin graphene layer (1-atom thick) as a high impedance surface. The low profile is important for microwave cancer ablation because, in contrast to the other techniques, the use of 1-atom thick graphene does not increase the radial size of the antenna. As it will be shown later, at microwave frequencies, the graphene layer could be made to behave as a poor conductor. We take advantage of this highly important characteristic to stop the propagation of surface currents and thereby mitigating the backward heating problem.

III. GRAPHENE

Although the graphene has been known for many decades, it is only in 2014 that a group of researchers isolated it from graphite by means of a simple method using mechanical exfoliation [23]. Since, this novel material which has engendered considerable research activities in fundamental sciences as well as in engineering. Electromagnetics is one these area in which the researchers are attempting to improve devices such as antennas, filters, transistor etc., to achieve improved performances with smaller element sizes. The conductivity of graphene is a tunable parameter, which makes it attractive and useful for many applications. For instance, tunable low pass THz filters [24], graphene-based nano-antennas [25], reconfigurable absorbers [26] are few examples.

The conductivity of the graphene can be expressed following the Kubo's formalism which shows a frequency dependency [27]. It is approximated as the sum of a Drude-like intraband contribution and an interband contribution. At microwaves frequencies, the total conductivity is mostly dominated by the intraband contribution; hence, the interband contribution can be neglected at the frequency region of interest. In a local form, the Drude-like intraband contribution can be expressed as follows [28]:

$$\sigma(\omega) = \frac{2e^2}{\pi\hbar}\frac{k_BT}{\hbar} ln\left[2cosh\left[\frac{\mu_c}{2k_BT}\right]\right]\frac{j}{\omega+j\tau^{-1}}, \quad (1)$$

where $\tau=10^{-13}$s is the relaxation time, μ_c is the chemical potential, k_B is the Boltzmann's constant, ħ is the reduced Planck's constant, T is the room temperature in Kelvin, ω is the radian frequency and e is the charge of an electron.

The tunability of the conductivity is due to the presence of the chemical potential μ_c. Indeed, the chemical potential depends on the carrier density which can either be controlled by an electrostatic bias (gate voltage) or a chemical doping. The evolution of the graphene conductivity, from microwaves to terahertz frequencies, calculated by means of the above expression (1) is depicted in Fig. 1.

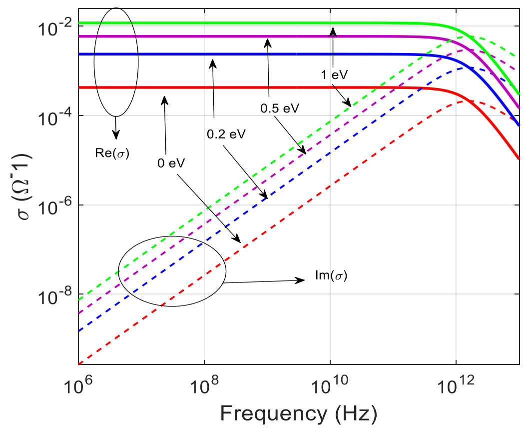

Fig. 1. Real and imaginary parts of the electrical conductivity of the graphene sheet as a function of the frequency for different values of the chemical potential.

The graphene sheet can be modeled either by considering a finite thickness material with corresponding dielectric/electrical properties, or by approximating it as an equivalent infinitesimal thin surface represented by its surface impedance. It is obvious that the first method involves a time consuming task because the geometrical size ratio of the sheet is very high. In this work, we model the graphene by using its surface impedance, given by:

$$Z(\omega) = \frac{1}{\sigma(\omega)}. \quad (2)$$

The corresponding surface impedance of the graphene sheet (at 2.45 GHz) as a function of the chemical potential is plotted in Fig. 2. It is evident that at the frequency of interest (frequency at which we perform the microwave ablation), the graphene has a very high resistance which depends on the chemical potential, which makes it a relatively poor conductor. The impedance can be lowered or increased either by using a chemical doping or by applying a gate voltage.

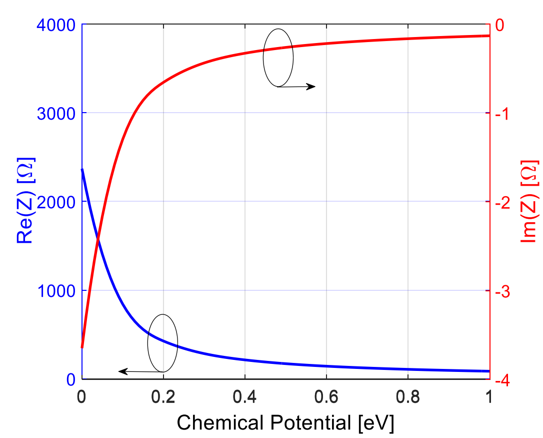

Fig. 2. Resistance and the reactance of the surface impedance of a graphene sheet as functions of the chemical potential.

IV. DESIGN OF THE MICROWAVE CANCER ABLATION ANTENNA AND NUMERICAL RESULTS

The proposed design consists of the coaxial slot antenna which has a sheet of graphene wrapped around. The overall antenna operating in a biological tissue environment is modeled by using the full-wave simulation software HFSS. In this work, we use the liver as a host medium for our antenna. A sketch of the coaxial slot antenna in the biological tissue is shown in Fig. 3.

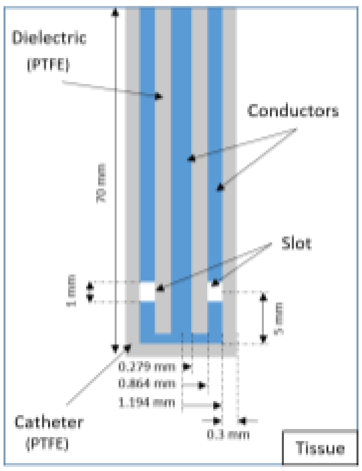

Fig. 3. Schematic 2D view of the microwave coaxial antenna in the biological tissue (not drawn to scale).

Figure 4 shows three different configurations studied in this work. Only the coaxial slot antenna and the graphene are represented. The catheter which enclose the entire antenna is not shown.

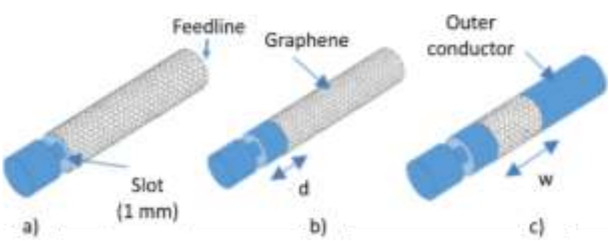

Fig. 4. Microwave coaxial antenna with the graphene sheet: (a) antenna fully covered by the graphene sheet from the slot all the way to the feedline; (b) graphene shifted from the slot and covering all the way to the feedline; (c) graphene strip shifted from the slot.

As mentioned earlier, the catheter and the coaxial antenna dielectric are considered to be PTFE. An annular slot located in the outer conductor is modeled as an air gap. Table 1 shows the values for the dielectric constant and the electrical conductivity of the liver and the antenna along with the catheter values at 2.45 GHz. For all configurations, the antenna is modeled as a perfect electric conductor (PEC). The tip of the coaxial antenna is short-circuited. The slot width is 1 mm and it is positioned at 5 mm from the distal tip. The total insertion depth of the antenna is 70 mm.

First, the configuration where the graphene sheet covers the entire antenna from the slot position to the feedline is considered (Fig. 4 (a), and the effect of the graphene sheet on the antenna performance is investigated.

Table 1: Physical constant for the liver and the antenna

Parameter	Value
Dielectric constant of the liver	43.03
Electrical conductivity of the liver	1.68 S/m
Dielectric constant of the catheter	2.2
Dielectric constant of the coaxial antenna dielectric	2.2

One can see from Fig. 5 that the presence of the graphene shifts considerably the resonance to higher frequencies. The resonance is an important characteristic of an antenna that occurs when the antenna input impedance matches the impedance of the source. For a well matched antenna, most of the energy is transferred to the medium. However, for our antenna wrapped with the graphene sheet, most of the energy is reflected back from the slot to the coaxial cable and only a small portion is transferred to the tissue at 2.45 GHz. The antenna becomes poorly matched at this frequency. Obviously, for the sake of the ablation, this is not desirable. Otherwise, the returned energy would heat up the coaxial cable and damage the equipment especially if high power radiation is used.

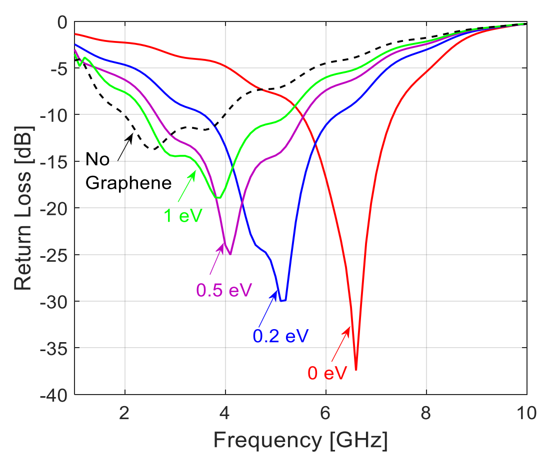

Fig. 5. Return loss obtained with and without graphene sheet for different chemical potential level.

The Specific Absorption Rates (SARs) calculated at a distance of 1.5 mm from the outer conductor of the antenna, for different values of the chemical potential, are presented in Fig. 6. We note that although the SAR level along the longitudinal direction of the antenna is lower away from the slot, the maximum SAR which should be high around the slot, is also reduced. One can thus deduce that surface currents created on the outer conductor enhance the efficiency of the antenna and increase the amount of energy deposited in the cancerous tissue. The simulation result with the surface currents are presented in Figs. 5 and 6 with the label “No Graphene”. Since graphene conductivity (accordingly the surface impedance) can be dynamically tuned, the resonance frequency (with the lowest return loss) and therefore the SAR absorbed in the tissue can be controlled in a simple and efficient manner. The more we augment the chemical potential the more we increase the carrier (electrons and/or holes) density. Thus, the electrical conductivity (resp. the surface impedance) is higher (resp. lower). Figure 6 clearly shows that the SAR along the antenna as well as around the slot is highly dependent on the chemical potential.

Since the surface currents contribute to the efficiency of the antenna, the next step in our work is naturally to use a graphene sheet partially enclosing the antenna. This 2nd configuration is depicted in Fig. 4 (b). Surface currents contributing the most to the radiation into the tissue are those very nearby the slot. As a remainder, we want to reduce the SAR far away from the slot, outside the cancerous tissue region. For this reason, we have deliberately left some distance between the graphene and the slot. By doing this, the current generated at the slot and propagating towards the feedline radiates into the tissue and takes part in the efficiency of the antenna before getting stopped by the graphene.

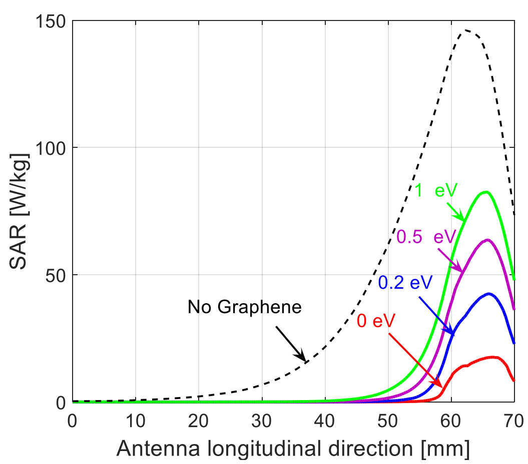

Fig. 6. Specific Absorption Rate (SAR) along the antenna at 1.5 mm from the outer conductor for the 1st configuration where the graphene cover all the way from the slot to the feedline. The feedline is at 0 mm and the slot is located at 65 mm.

The return loss in the case of the 2nd configuration is shown in Fig. 7. The return loss (Fig. 7) and the SAR (Fig. 8) characteristics are plotted for different spacings between the slot and the graphene sheet, as listed in Table 2.

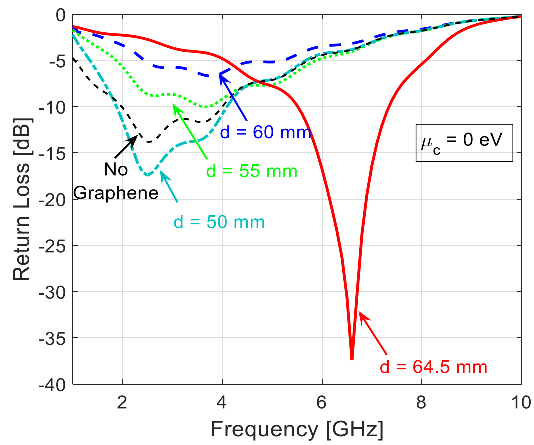

Fig. 7. Return loss obtained with the second configuration for different distances between the graphene and the slot.

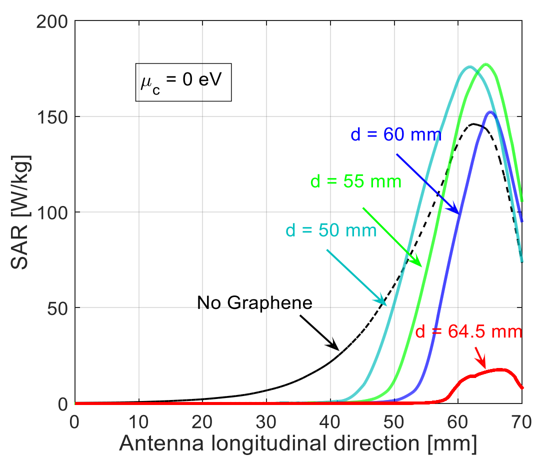

Fig. 8. Specific Absorption Rate (SAR) along the antenna at 1.5 mm from the outer conductor for the 2nd configuration for different distances between graphene and the slot. The feedline is at 0 mm and the slot is located at 65 mm.

Table 2: Spacing between the slot and the graphene sheet

Distance d	Value (mm)
d0	0
d1	4.5
d2	14.5

For this configuration, the chemical potential is taken as 0 eV. It is worthwhile to note that, introducing a spacing between the slot and the graphene causes the minimum return loss frequency to shift back to lower frequencies, eventually attaining the desired 2.45 GHz, the operating frequency for the cancer ablation. The return loss at 2.45 GHz is even better with a gap of d2 = 14.5 mm between the graphene and the slot, than it is for the reference antenna without graphene.

The corresponding SAR distribution along the longitudinal direction of the antenna is presented in Fig. 8. Although the SAR peak is shifted toward the feedline because the graphene is displaced, its level along the longitudinal direction remains largely acceptable compared to the case where there is no graphene. The results also confirm the fact that surface currents are participating in the radiation in the tissue through the slot. In fact, the maximum SAR becomes higher when there is a gap between the slot and the graphene.

Although with the current nano-engineering technologies one can grow a large size of graphene sheet, it should be interesting to consider only a narrow strip of graphene and to study the effect of its width when it is wrapped-up on a small portion of the outer conductor of the coaxial antenna.

This third configuration is shown in Fig. 3 (c). The graphene is placed at a distance d1 from the slot. The effect of its width on the SAR at 30 mm from the feedline and 1.5 mm away from the outer conductor is depicted in Fig. 9, for different values of the chemical potential (i.e, for different surface impedances). It is useful to note that, the SAR is computed at a position between the feedline and the graphene strip.

The effect of the width is clearly seen in Fig. 9. The SAR values decrease as the graphene width is increased. For a very narrow strip, the SAR level is closed to the reference case where there is no graphene. On the other hand, as the graphene becomes wider, the SAR characteristics tend to behave as those for the case of the second configuration when the graphene is extended all the way to the feedline. For instance, for a graphene width of 2 mm, it is possible to have seven times lower SAR level at this position.

Finally, Fig. 10 shows the SAR distribution on a plane parallel to the axis of the microwave coaxial antenna for the two different configurations (2 and 3). For the sake of comparison, the result for the reference antenna where the graphene is not present, is also displayed. The distance d between the slot and the graphene is 4.5 mm and the μ_c = 0 eV. For the 3rd configuration, the width of the graphene strip is 3 mm. The plots show considerable improvement of the antenna performance, and we note that the "tail" present in the case of the reference antenna no longer exists.

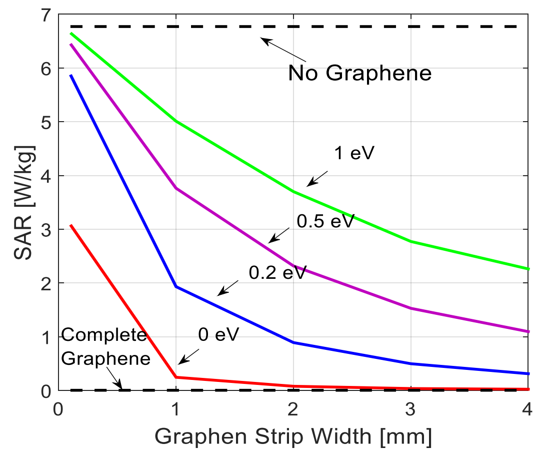

Fig. 9. SAR at 30 mm from the feedline vs. the width w of the graphene strip, for different level of chemical potential.

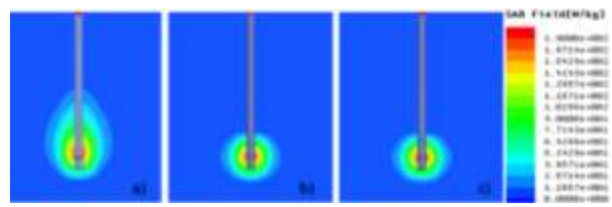

Fig. 10. SAR on a plane parallel to the axis of the antenna: (a) the reference antenna, (b) 2nd configuration (Fig. 4 (b)), 3rd configuration (Fig. 4(c)).

V. CONCLUSION

The backward heating is an important problem which must be addressed in order to increase the performance of a microwave coaxial antenna used as an ablation device. In this contribution we have proposed an alternative to reduce or even eliminate the surface currents that are responsible for that unwanted radiation along the antenna. The graphene is used as a high impedance surface to block the surface currents propagating along the antenna. Results show that, the graphene sheet can significantly reduce the SAR level while improving the efficiency of the antenna. Since graphene is extremely thin (only 1-atom thickness), it satisfies the criterion that the antenna must be minimally invasive.

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