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SIMULATION STUDY OF AN EBG-M APPLICATOR TOWARDS NON-INVASIVE BREAST HYPERTHERMIA CANCER PROCEDURE

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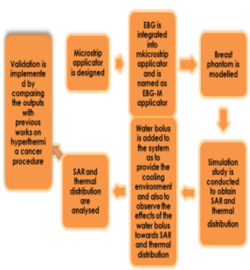
Graphical abstract



Abstract

Interest in the development of hyperthermia for cancer procedure is growth explosively all over the years as it is able to damage and kill the cancer cell non-invasively. An EBG-M antenna is designed with FDTD simulation packages, which is then applied towards treated cancerous area, where for the purpose of this simulation studies, breast is developed as the targeted cancer area to be treated. The radiation absorption is presented as the results obtained to be compared with previous works and also to be analyzed. It has been recognized that the designed antenna or also called as the applicator is able to offer depth radiation absorption and also improved the focusing, which is represented by the specific absorption rate (SAR) distribution towards breast hyperthermia cancer procedure.

Keywords: Hyperthermia, non-invasive, EBG-M applicator, SAR

1.0 INTRODUCTION

Over recent years, there has been an explosive growth of interest in the development of an applicator for non-invasive hyperthermia cancer procedure. Hyperthermia is currently classified as an alternative therapy for cancer. Hyperthermia utilizes slightly high heat, which is around 41^{0}C-45^{0}C [1]–[5], where it is capable to denaturate the cancerous tissue into the necrotic tissue, which then may damage and also kill the treated tissue with minimal side effects. Hyperthermia can be invasive and non-invasive. It is significantly dependent on the heat applicator used for the treatment either it is applied towards the human body internally or externally, respectively. Although the internal applied applicator is invasive, it is significant for deep-seated cancer. On the other hand, the non-invasive applicator is benefited towards in situ, localized, regional and whole body type of cancer. Various invasive and non-invasive applicators have been designed, developed and investigated. Example for invasive applicators, which are either interstitial or intracavitary are as in [6]–[8] and [9], respectively. Then, the external applicators such as presented in [3], [5], [10]–[14].

Both of the applicators offer substantial effectiveness towards hyperthermia for cancer therapy, however, since massive concerns increase for safer, less invasive and at the same time effective therapy, non-invasive type applicator for non-invasive hyperthermia procedure has been more attracted and fascinated to be studied, investigated and improved so that it may provide significant results in deducing and damaging the treated cancer cell. Various applicators for non-invasive effects were introduced in [13], [14]. The strengths and limitations were discussed and microstrip applicator has been chosen to be explored further as it may offer the utmost outcomes. The microstrip is categorized as a low profile applicator, where it can be effortlessly modified in term of its shape, size and also it structure. Furthermore, the advantages are far outweighed its limitations.

Hyperthermia with microstrip applicator may obtain a variety of findings with a variation of radiation depth and focusing impacts towards the treated cancerous area. Through the observation of previous works, the essential deficiency, which indispensables to overcome is to ensure the generation of heat within the region of interest leaving all the vicinity of it unaffected [15]. Complementary to this, electromagnetic band gap is proposed to be embedded with the microstrip applicator, which is then called as an EBG-M applicator. This integration is mainly to improve in minimizing the unwanted hotspots generated surrounding the cancerous area to be treated, where the focusing and depth penetration towards the treated cancer area are enhanced simultaneously.

Electromagnetic band gap (EBG) is a periodic structure used to control the propagation of electromagnetic energy [16] produced by the microstrip applicator, which is expected to deduce the unwanted hotspots surrounding the treated cancer area. By complementing the EBG with microstrip applicator, the enhancement in depth penetration and also minimizing the unwanted hotspots, so that all the vicinity surrounding the treated cancer region is unaffected from massive damage might be achieved. In the telecommunication industry, the microstrip embedded with EBG structure is currently experiencing an enormous advance for the past few years and it is still undergoing monumental investigation and development. However, in medical application, especially towards cancer procedure, the microstrip with the integration of EBG, which is called as EBG-M in this research, is recently introduced as to diversify the methods for hyperthermia cancer procedure through electromagnetic heating technique where at the same time to improve and enhance the hyperthermia performance for cancer procedure.

2.0 DESIGN OF SIMULATION

Before proceeding on the simulation study of non-invasive EBG-M applicator towards breast hyperthermia cancer procedure, there are a few steps required to be implemented. First, the microstrip applicator is designed, where for the purpose of this investigation; a rectangular microstrip applicator is emphasized. Since 2.45GHz frequency is used as operating frequency and FR-4 used as a substrate, the following equations are utilized in order to obtain the width and length of the rectangular microstrip applicator.

$$w = c/2f \times \sqrt{(2/\varepsilon_r+1)} \quad (1)$$

$$\varepsilon_{eff} = [(\varepsilon_r+1)/2] + [(\varepsilon_r-1)/2][1 + 10h/w]^{-0.5} \quad (2)$$

$$L_{eff} = c/ (2f\sqrt{\varepsilon_{eff}}) \quad (3)$$

$$\Delta L = 0.412 \times h \times (\varepsilon_{eff} + 0.3)/(\varepsilon_{eff} - 0.258) \times (w/h + 0.264)/(w/h + 0.8) \quad (4)$$

$$L = L_{eff} - 2\Delta L \quad (5)$$

$$L_g = 6h + L \quad (6)$$

$$W_g = 6h + w \quad (7)$$

After that, the electromagnetic band gap (EBG) structure is integrated with the designed rectangular microstrip applicator. Rectangular EBG with mushroom-like structure is embedded into microstrip applicator. The following equations (8) – (11) present the basic operating mechanism of the mushroom-like EBG structure, which is based on the LC circuit as illustrated in Figure 1.

$$L = \mu_0 h \quad (8)$$

$$C = [W\varepsilon_0 (1 + \varepsilon_r)]/\pi \cosh^{-1} [(2W + g)]/g \quad (9)$$

$$\omega = 1/\sqrt{(LC)} \quad (10)$$

$$BW = 1/\eta \sqrt{(L/C)}, \text{ with } \eta = 120\pi \quad (11)$$

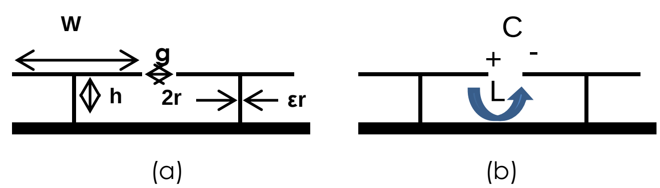


Figure 1 Mushroom-like EBG structure (a) EBG structure (b) LC model

Breast phantom is modelled after the integration of rectangular microstrip and mushroom-like EBG structure, which is so called as the EBG-M applicator. The breast phantom consists of breast fat and breast tumor. The phantom breast tumor is positioned 50mm deep from the outer side of the breast skin. The radius for breast fat is 100mm, while the breast tumor phantom has a radius of 50mm. The properties of breast fat and tumor are provided in Table 1, while, breast phantom model is presented in Figure 2.

Water bolus is developed optionally as to observe the effect of cooling system onto the radiation absorption pattern towards breast hyperthermia procedure. Furthermore, the water bolus is assisted in minimizing the skin burn problem during the execution of hyperthermia procedure. Water bolus utilized water distilled as a coolant fluid with εr, σ and ρ are 76.7, 5e-005 and 1000, respectively.

Table 1 Electrical and Thermal properties for breast fat and breast tumor

	Relative Permittivity, εr	Electrical Conductivity, σ (S/m)	Density, ρ(kg/m3)	Specific Heat Capacity, C (J/kg/K)	Thermal Conductivity, K (W/m/K)
Breast Fat	5.14	0.125	911	2348.33	0.209
Breast Tumor	5.14	0.125	1911	2352.55	0.789

Figure 3 presents the block diagram of the simulation study processes.

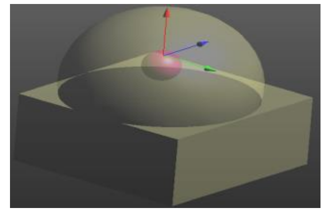


Figure 2 Breast phantom model

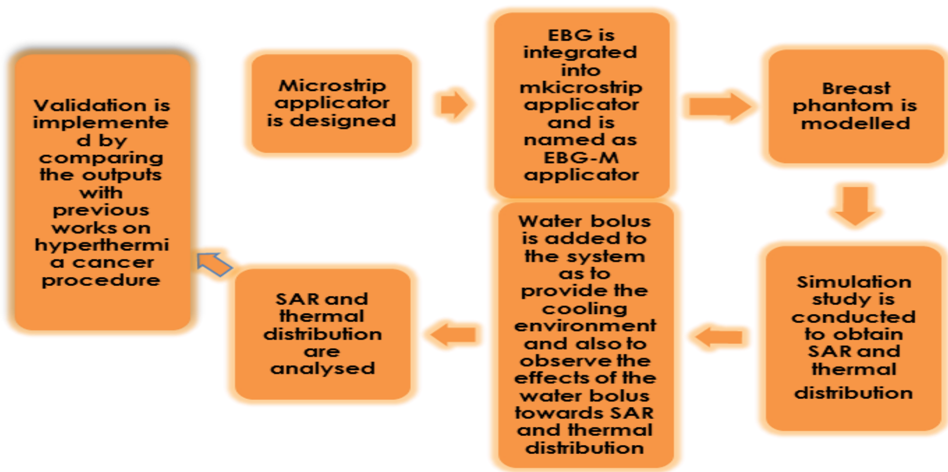


Figure 3 Block diagram of the simulation study processes

3.0 RESULTS AND DISCUSSION

Based on the equations (1) – (7), the parameter specifications of rectangular microstrip applicators are tabulated in Table 2.

Table 2 Rectangular Microstrip Applicator Specifications

	Dimension	Unit
Dielectric Constant (εr)	**4**	
Substrate Thickness (h)	2	mm
Operating frequency (f)	2.45	GHz
Length (L)	30	mm
Width (W)	39	mm
Width of feed	2	mm
Ground Length (Lg)	44	mm
Ground Width (Wg)	51	mm

Dimensional view of rectangular microstrip applicator with microstrip feed line is illustrated in Figure 4. Meanwhile, in Figure 5, the EBG-M applicator is presented. This EBG is fabricated on the FR-4 substrate with a length and width dimension of every single EBG is 2mm X 2mm. Both of the applicators are simulated as to obtain the S_{11}. The scattering parameters, S_{11} for microstrip applicator and EBG-M are provided in Figure 6. The S_{11} basically shows how much power is reflected from the applicator, which ensures low loss is obtained. This is useful in order to optimize heat energy transferred from the applicator towards the treated cancer area. As a consequence, depth penetration can be acquired.

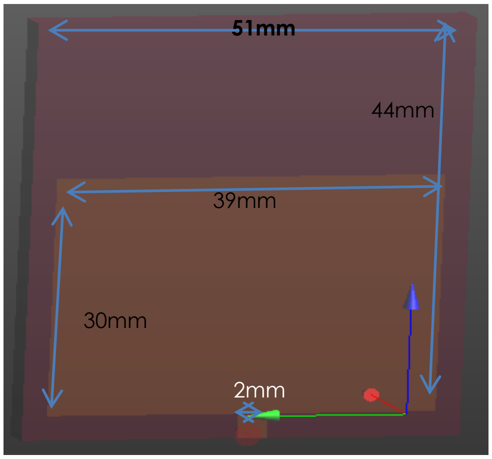
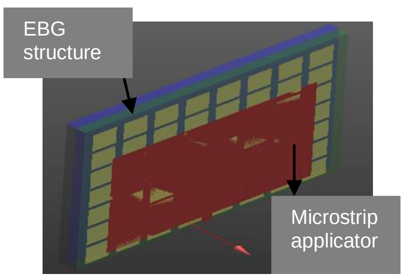
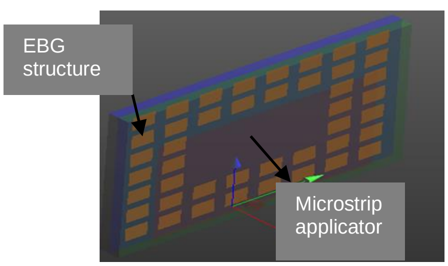


Figure 4 Dimensional view of rectangular microstrip applicator

Notwithstanding, the impacts of S_{11} onto the radiation absorption of hyperthermia cancer procedure is less significant.



(a) EBG-M1 applicator



(b) EBG-M2 applicator

Figure 5 EBG-M applicator

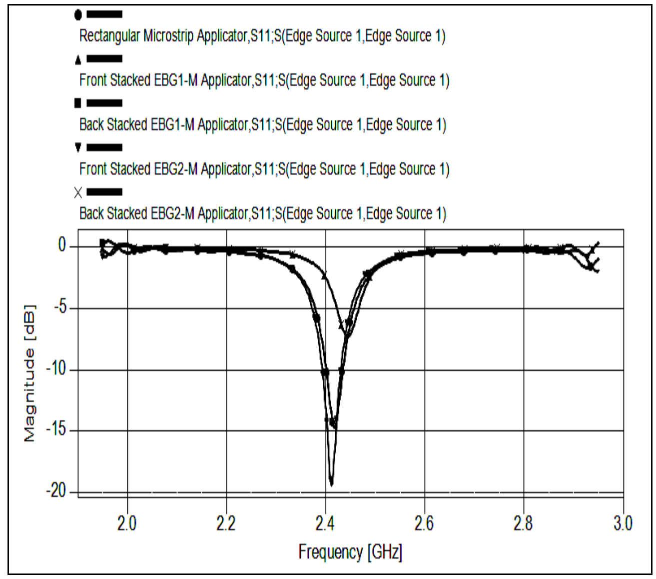


Figure 6 S_{11} for microstrip and EBG-M applicator

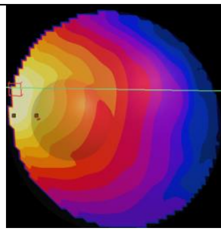
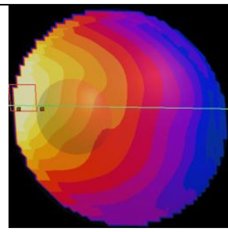
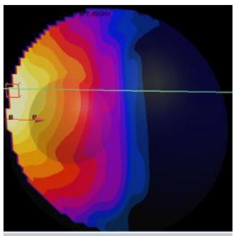
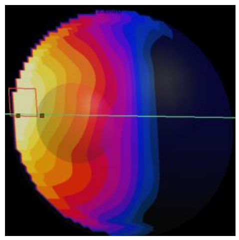
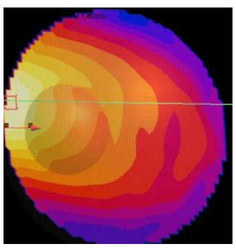
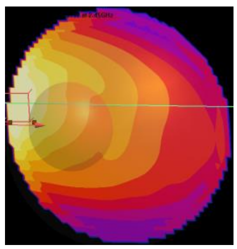
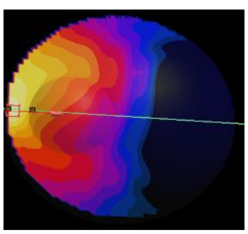
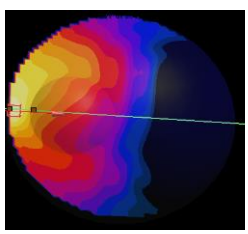
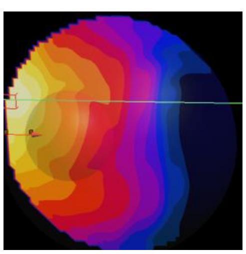
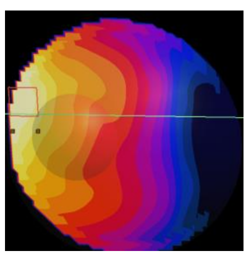
Figure 6 shows the S_{11} of the five (5) applicators. The values of the return lost are calculated using Equation (12). The results are; for the rectangular microstrip applicator through power is RL=97%, front stacked EBG1-M (RL=80%), front stacked EBG2-M (RL=99%), back stacked EBG1-M (RL=80%), and back stacked EBG2-M (RL=80%). In antenna design for transmission application, the reference level for a very good impedance matching and return loss is -10dB [17]. This is where 90% of power is received by the antenna for radiation, while the other 10% is considered as reflection loss.

$$\text{Return Loss (dB)} = 10 \log (P_{incident}/P_{reflected}) \quad (12)$$

Therefore, more radiated power contributed to deeper penetration, while less radiated power, however, is good to be used to increase the focusing capability with minimal adverse impact to healthy tissues surrounding areas of the treated cancer tissue.

Based on Table 3, microstrip and back stacked EBG1- M provided the best penetration depth, up to 80mm when compared to rectangular microstrip applicator, front stacked EBG1-M, front stacked EBG2-M and back stacked EBG2-M which penetrated to roughly up to 50mm only.

Table 3 SAR for different hyperthermia applicator structures and positions

Hyperthermia Applicator	1g	10g
Rectangular Microstrip Applicator		
Front Stacked EBG1-M		
Back Stacked EBG1-M		
Front Stacked EBG2-M		
Back Stacked EBG2-M		

However, they are contributed towards better focusing effects, where the unwanted hotspots are reduced at the surrounding healthy tissue. The operating power used is 1W. As observed from Table 3 also, for SAR with 1g and 10g weight, the distribution patterns are occurrence in the same way and only the SAR values are changed.

Two essential equations, Equation (13) – (14) for hyperthermia procedure is known specific absorption rate (SAR) and Penne bio-heat, which are represented the radiation and thermal distribution, respectively.

$$SAR = (\sigma/2\rho)\ |E|^2\ (W/kg) \text{ or } mW/g \quad (13)$$

Where σ is the conductivity of tissue (S/m), E is an electric field (V/m) and ρ is a density of tissue (kg/m^3).The SAR, which is also called as local SAR, varies directly with σ. Thus, tissue with higher water content, for example is cancer/tumor is more lossy for a given E field magnitude than drier tissue such as bone and fat. Furthermore, the SAR is high when E field is high. This can be observed in Table 4, with 1W operating power for SAR of weight 1g and 10g. The electric field is transferred in body and turn into heat, which is required by hyperthermia procedure. The E field can transfer energy to electric charges through forces it exert on them, but the B field does not transmit energy to charges. Hence, this latter effect is not prominent in EM biological interaction.

Next, for Penne bio-heat equation, it consists of C, which is stand for specific heat tissue (J/kg/K), k, thermal conductivity of tissue (W/m/K), T, temperature of tissue (^{0}C), Tb is a blood temperature (^{0}C) and convective heat transfer coefficient, hb (kg/m3).

$$(\rho C)\delta T/\delta t + \nabla.(-k\nabla T) = hb\ (Tb - T) + \rho.\ SAR \quad (14)$$

As observed from Equation (14), the Penne bio-heat equation is related with SAR in equation (13). Since, the temperature rise in tissue is determine by the rate of electromagnetic power deposition in tissue (Wem) and metabolic heating rate (Wm), as well as the thermal dissipation by conduction (Wc) and blood flow (Wb), the bio-heat equation is also written as in Equation (15).

$$\delta(\Delta T)/\delta t = (1/4186C)\ (Wem + Wm - Wc - Wb) \quad (15)$$

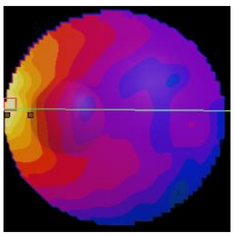
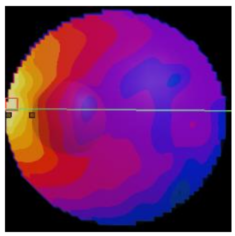
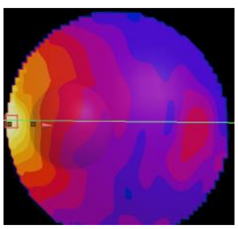
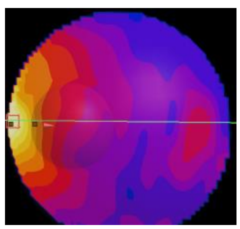
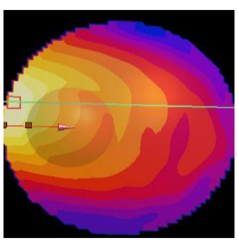
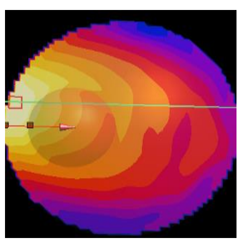
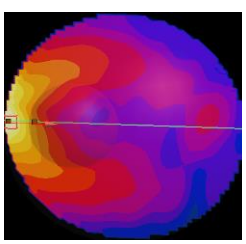
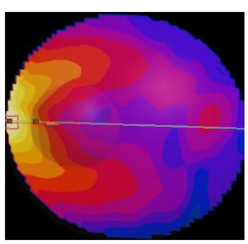
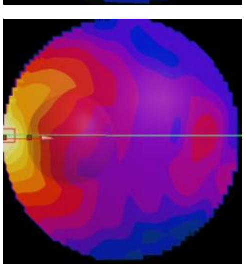
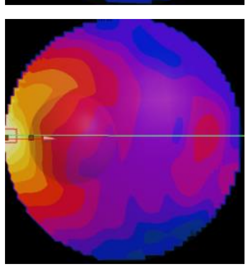
Additionally, in minimizing the skin burn problem, water bolus, which plays as coolant during hyperthermia procedure is added into the system. It effects towards the radiation absorption is also investigated and tabulated in Table 5. The water bolus reshapes the SAR, and yet maintains the depth and focusing towards the treated area.

Table 4 E field and SAR Value for different hyperthermia applicator structures and positions

Hyperthermia Applicator	E field (V/m)	SAR (mW/g)	
		1g	*10g*
Rectangular Microstrip Applicator	266	1.49	0.899
Front Stacked EBG1-M	179	0.89	0.551
Back Stacked EBG1-M	283	6.25	4.54

Hyperthermia Applicator	E field (V/m)	SAR (mW/g)	
		1g	*10g*
Front Stacked EBG2-M	216	16.4	5.62
Back Stacked EBG2-M	179	0.89	0.551

Table 5 SAR for different hyperthermia applicator structures and positions with water bolus integration

Hyperthermia Applicator	1g	10g
Rectangular Microstrip Applicator		
Front Stacked EBG1-M		
Back Stacked EBG1-M		
Front Stacked EBG2-M		
Back Stacked EBG2-M		

Based on the simulation study, the proposed EBG-M applicator is able to offer good penetration depth and focusing towards non-invasive hyperthermia procedure similar to other types of applicators from previous studies.

4.0 CONCLUSION

In conclusion, the different structures and positions of the EBG contribute towards the different level of S_{11}, which subsequently provide the effect onto the penetration depth and focusing into the tumour tissue for hyperthermia cancer procedure. By adding the water bolus into the system, it shows that the water bolus capable to reshape the radiation absorption distribution pattern or SAR, besides benefitting as a coolant during hyperthermia procedure, which assists in avoiding massive skin burn problems.

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