6.
CONCLUSIONS AND SCOPE FOR FURTHER WORK

This chapter summarizes and concludes the research work presented in different chapters of the thesis. The future scopes and extension of the present work are also described in this chapter.

6.1 Conclusions

It is well known that hyperthermia (heating cancerous cell in the temperature range 41 – 45 ^{o}C) in conjunction with radiation therapy is more effective. Many types of applicators at microwave frequencies including waveguides/horns and planar applicators are described in the literature for hyperthermia. These waveguide/horn and planar applicators have their relative merits and demerits. The performance of a hyperthermia applicator is characterized in terms of specific absorption rate (SAR) and the study of temperature distribution in the cancerous tissue. SAR has been used by researchers to determine the amount of energy deposition and heating pattern in tissues/bio-models. The SAR is defined as the rate at which EM energy is absorbed per unit mass of biological tissue. The temperature distribution inside the realistic tissue/bio-model can be evaluated using bio-heat equation (BHE); which includes SAR parameter also. Following goals are set while performing thermal optimization using a hyperthermia applicator: (i) to achieve a target temperature distribution, (ii) to optimize heating of tumor without raising the temperature of adjacent healthy tissues, (iii) to avoid formation of hot spots, and (iv) to maximize tumor heating volume.

The present work is motivated in part by the need to design and develop efficient, practical, non-invasive, direct-contact horn antennas/conformal antenna as effective hyperthermia applicators at microwave frequencies which have the focusing ability, provide greater penetration depth (PD) in a bio-medium/bio-media and/or remain compact and conformal with the curved portion of the human body.

In the present thesis, the author has done simulation/experimental/theoretical studies of the fields, SAR and temperature distributions in a bio-medium/bio-media, which is in direct contact/close proximity with water-loaded diagonal horns/conformal antenna applicators. These applicators include water-loaded conventional metal diagonal horn, water-loaded improved metal diagonal horn, and water-loaded metal-dielectric wall diagonal horn (MDWDH), each terminated in a bio-medium/bio-media along with a novel conformal and modified microstrip slot antenna integrated with a novel and compact artificial magnetic conductor (AMC) in close proximity with bio-medium/bio-media.

The author has studied water-loaded conventional metal diagonal horn (MDH) through simulation, theoretically and experimentally at 2450 MHz and through simulation and theoretically at 915 MHz for hyperthermia application. The conventional MDH is a type of multimode horn in which the internal field consists of superposition of the orthogonal TE_{01} and TE_{10} modes in the square waveguide. Therefore, the electric field distribution over the aperture of conventional MDH is identical in E- and H-planes, resulting in circularly symmetric field distribution. The conventional MDH is loaded with water to provide good impedance matching between the antenna and phantom bio-medium/bio-media which ensures maximum transmission of power from the antenna to the bio-medium/bio-media. Also, size of the antenna applicator reduces considerably due to water-loading. The simulation study of the water-loaded conventional MDHs designed at 2450 and 915 MHz was carried out using computer simulation technology microwave studio (CST MWS) 2011 software, which is based on finite integration numerical technique. Further, the horn designed at 2450 MHz was fabricated to demonstrate the technical feasibility of the horn. The experimental study of SAR distributions in a phantom bio-medium of known physical properties was carried out at 2450 MHz with the help of Vidyut Yantra make 50 Ω coaxial L-shaped and straight monopole probes and Agilent make spectrum analyser (Model: E4448A). The simulation results for SAR distributions in phantom bio-medium (muscle medium), which is in direct contact with each of the water-loaded horns designed at 2450 and 915 MHz have been obtained and hyperthermia parameters PD and effective field size (EFS) have been extracted from these distributions and compared with the corresponding theoretical and/or experimental results at 2450 and 915 MHz. The theoretical investigation of fields in the planar phantom muscle medium due to each water-loaded conventional MDH makes use of plane wave spectral technique for computation of SAR distribution in the medium. The theoretical field components and SAR distributions were numerically evaluated using MATLAB software. The simulation results for water-loaded conventional MDH terminated in single layer phantom bio-medium have been found to be nearly in agreement with the theoretical and/or experimental results. Further, the author has extended the work and performed simulation study of SAR and/or temperature distributions in realistic tri-layered bio-media (skin, fat and muscle) without and with embedded oval-/irregular-shaped tumor due to the water-loaded conventional MDHs designed at 2450 and 915 MHz. It is inferred from the study that SAR distributions in the bio-media at both frequencies are circularly symmetric. Further, the values of PD and EFS are significantly higher at 915 MHz as compared to those at 2450 MHz. Moreover, presence of tumor does not alter PD and EFS significantly. However, the value of SAR increases in the tumor region due to higher conductivity of tumor as compared to the healthy tissue. The temperature distributions in the realistic bio-models obtained through thermal simulation indicate that the proposed conventional MDH designed at 915 MHz with 13 W input power can be used as effective hyperthermia applicator for irregular-/oval-shaped tumors in superficial abdominal/thoracic region of the body. Additionally, it is observed that the tumor temperature reaches to a higher value as compared to the healthy tissue. Further, it is observed that PD in the tri-layered bio-model due to the proposed conventional MDH designed at 2450 MHz is not sufficient to heat whole tumor depth effectively.

Although water-loaded conventional MDH antenna provides circularly symmetric heating pattern, PD in the biological media is not good enough. Therefore, it is thought to modify the aperture field distribution of the water-loaded conventional MDH without changing its aperture size in order to obtain enhanced PD in addition to symmetric EFS in the biological medium/media. Keeping this aspect in view, the author has modified the conventional MDH and named it the 'improved metal diagonal horn'. Improved MDH is a modified version of conventional MDH in which the aperture field is modified by introducing two pairs of conducting pins at appropriate locations near the horn aperture. Due to presence of conducting pins, the resultant field over the aperture of each of the improved MDH antennas designed at 2450 and 915 MHz and terminated in a bio-medium/bio-media corresponds to a combination of TE_{10}, TE_{30}, TE_{01}, and TE_{03} mode fields. Hence, field distribution over the aperture of each improved MDH is a closer approximation to the uniform distribution that may ensure uniform absorbed-power distribution in the bio-medium/bio-media and prevent steep power gradient in bio-media. Each improved MDH is filled with water to provide good impedance matching between the horn and bio-medium/bio-media, which ensures good transmission into the bio-medium/bio-media. Water-loaded improved MDHs have been investigated through simulation, theoretically and experimentally at 2450 MHz and through simulation and theoretically at 915 MHz for hyperthermia application. Direct-contact water-loaded improved MDHs were designed and optimized using CST MWS 2011 software. Further, the improved MDH designed at 2450 MHz was also fabricated to demonstrate the technical feasibility of the horn for hyperthermia. Simulation study was performed to study the modification of aperture field distributions of water-loaded improved MDHs designed at 2450 and 915 MHz due to introduction of conducting pins slightly inside the horn apertures, and the resulting SAR distributions in phantom muscle due to these horns. To verify the simulation results for aperture field distributions of the water-loaded improved horns designed at 2450 and 915 MHz, theoretical analysis was carried out which includes the effect of higher order TE_{30} and TE_{03} modes also in addition to TE_{10} and TE_{01} modes. The simulation of aperture field distributions of both the horn antennas and SAR distributions in phantom muscle due to these antennas was carried out using CST MWS software. The theoretical investigation of fields in the planar phantom muscle medium due to each water-loaded improved MDH antenna makes use of 'plane wave spectral technique' for computation of SAR distribution in the medium. The theoretical field components, aperture field distributions and SAR distributions were numerically evaluated using MATLAB software. The experimental relative SAR distributions in the phantom muscle medium were obtained with the help of Vidyut Yantra make 50 Ω coaxial L-shaped and straight monopole probes and Agilent make spectrum analyser (Model: E4448A). The simulation results for SAR distribution in the phantom bio-medium at 2450 MHz are compared with the experimental distribution also in addition to theoretical distribution. The simulation results for water-loaded improved MDHs terminated in single layer phantom bio-medium have been found in agreement with the corresponding theoretical and/or experimental results. Additionally, the values of PD in the bio-medium due to the improved MDHs designed at 2450 and 915 MHz are larger than corresponding values obtained using respective conventional MDHs. Hence, it can also be said that proposed improved MDHs are superior to corresponding conventional diagonal horns for effective hyperthermia of superficial tumors at greater depth. Further, the work is extended by performing simulation study of SAR and temperature distributions in a planar realistic tri-layered bio-media without and with embedded irregular-/oval-shaped tumors due to the water-loaded improved MDHs. It is observed that presence of tumor does not alter PD and EFS significantly in each case. Additionally, it is observed that values of PD in the tri-layered bio-model due to the improved MDHs designed at 2450 and 915 MHz are sufficient to cover whole tumor depth for effective hyperthermia of superficial tumors and provides circularly symmetric distributions. Also, values of SAR observed at the skin surface using each of the improved water-loaded diagonal horn applicators are minimum. The temperature distributions in the realistic bio-models obtained through thermal simulation indicate that the proposed improved MDHs with 4 and 10 W input power levels at 2450 and 915 MHz respectively can be used as effective hyperthermia applicators for oval-/irregular shaped tumors in superficial abdominal/thoracic region of the body.

The aperture field distribution of conventional MDH can be made more uniform through another technique in which the major portions of the antenna walls in the central regions are made of plastic (Perspex, $\varepsilon_r' = 2.59$) dielectric sheets while remaining wall portions are made of metal, considering the region of the antenna from throat to aperture. Due to the presence of partial dielectric material on the antenna walls, hybrid modes are generated which make the field distribution across its aperture more uniform and prevent steep power gradient in the bio-medium/bio-media. Considering these aspects, the author proposed a new hybrid horn and named it 'Metal-dielectric wall diagonal horn'. Direct-contact water-loaded metal-dielectric wall diagonal horns (MDWDHs) were designed at 2450 and 915 MHz and optimized using CST MWS 2011 software. Each MDWDH is filled with water to provide good impedance matching between the horn and bio-medium/bio-media. Further, the MDWDH designed at 2450 MHz was also fabricated to demonstrate the technical feasibility of the horn for hyperthermia. Simulation was performed to study the modification of aperture field distributions of water-loaded MDWDHs due to the presence of partial dielectric regions in the walls of these horns. It is observed that the simulated aperture electric field distributions across the apertures of proposed MDWDHs have become more uniform as compared with the corresponding conventional MDHs of same sizes. Simulation and/or experimental study of SAR distributions in phantom muscle due to the horns designed at 2450 and 915 MHz were also carried out. The experimental study of SAR distributions in a phantom bio-medium of known physical properties was carried out at 2450 MHz with the help of Vidyut Yantra make 50 Ω coaxial L-shaped and straight monopole probes and Agilent make spectrum analyser (Model: E4448A). The simulation results for SAR distribution in the phantom bio-medium at 2450 MHz have also been compared with the experimental distribution and these distributions have been found to be nearly in agreement with each other. The values of PD and EFS in the bio-medium due to the proposed MDWDHs have been found to be higher than the corresponding values obtained due to their conventional counterparts. Hence, it can be said that the proposed MDWDHs are superior to their conventional metal counterparts for hyperthermia applications. Further, the work was extended by performing simulation study of SAR and temperature distributions in a planar realistic tri-layered bio-media without and with embedded oval-/irregular-shaped tumors due to the water-loaded MDWDHs. It has been observed that the values of PD in the tri-layered bio-model due to the water-loaded MDWDHs are sufficient to heat whole tumor depth in muscle region effectively. It is observed that shape of tumor does not alter PD and EFS significantly in each case. In addition, these horns also have provided circularly symmetric SAR/temperature distributions in the bio-media. The temperature distributions in the realistic bio-models obtained through thermal simulation indicate that the proposed horns with 4 and 9 W input power levels at 2450 and 915 MHz respectively can be used as effective hyperthermia applicators for treating oval- and irregular-shaped tumors located in the abdominal/thoracic region of the body.

A disadvantage with waveguide/horn applicators is that these applicators are heavy, large in size and have fixed form of aperture. Use of microstrip antenna applicator can solve most of these problems, because it is small in size, flexible and light in weight. Several approaches can be used to improve the efficacy of the conventional microstrip patch antenna for hyperthermia. The use of a slot antenna and microstrip feedline improves the bandwidth, EFS and PD. However, slot antenna has bidirectional radiation which leads to safety concerns. Several techniques have been reported in the literature to solve the aforesaid problem including the use of back shield and conducting ground plane which would make the applicator either of large profile or complex. An AMC could be the better option to suppress back field and redirect the back field constructively toward the patient in hyperthermia treatment for low profile applicators. The characteristics of conventional slot antenna with AMC in free space are described in the literature but its application to hyperthermia was not explored yet. Keeping this aspect in view, author proposed a new conformal slot antenna integrated with a novel and compact AMC for hyperthermia application. A new conformal and modified microstrip slot antenna integrated with a novel and compact AMC reflector was designed at 2450 MHz using CST MWS software. Further, the antenna and AMC reflector was fabricated. The simulated input characteristics along with near field distribution of the proposed antenna with AMC reflector in presence of phantom bio-medium and SAR distributions in phantom muscle medium/multi-layered bio-media due to the applicator are investigated. The proposed antenna integrated with the AMC was designed to effectively radiate into the muscle medium. The AMC structure has been utilized to provide in-phase reflection, which significantly enhances the front-to-back ratio and consequently enhances the PD in the muscle medium/multi-layered bio-media. Further, the input characteristics and SAR parameters for the proposed antenna without AMC, conventional rectangular patch antenna without AMC and the proposed antenna-AMC and the antenna-conventional perfect electric conductor (PEC) combinations in proximity with phantom bio-medium have also been compared through simulation. It is inferred that the proposed antenna without AMC is compact and provides more uniform SAR distribution as compared to the conventional rectangular patch antenna designed at 2450 MHz. Moreover, it has been observed that as compared to the antenna-conventional PEC combination, the proposed antenna-AMC combination is of lower profile and provides greater PD as well as wider EFS. The reflection coefficient-frequency characteristic of the applicator and normalized SAR distribution in phantom muscle medium due to the applicator with AMC were measured and the experimental results have been compared with the respective simulation results. It has been found that experimental results are nearly in agreement with respective simulation results. Furthermore, the effects of variations in the dielectric properties of bio-medium on the input reflection coefficient of the proposed antenna with AMC have also been studied through simulation. Additionally, the effects of change in the radius of curvature of proposed applicator and bio-model on input reflection coefficient, SAR distribution in both homogeneous and tri-layered bio-models have been investigated as well. Thermal simulation was also performed for the realistic tri-layered bio-model without and with oval-/irregular-shaped tumor, which is in close proximity with the antenna-AMC combination. The temperature distributions in the realistic bio-models obtained through thermal simulation indicate that the proposed applicator designed at 2.45 GHz with 2.6 W input power can be used as effective hyperthermia applicator for oval-and irregular-shaped small tumors in superficial abdominal region of the body. Further, work was extended by simulating the proposed applicator with AMC in close proximity with cylindrical thigh and arm models for the treatment of tumor present in limb regions of the body and input power levels were optimized for effective hyperthermia. It is found that desired temperature range (41 – 45 °C) in the cylindrical thigh and arm models for effective hyperthermia are achieved for 3.5 and 2.2 W input power levels respectively at the frequency of 2450 MHz. The unique characteristic features of this new type of applicator include its compactness, high efficiency, relative insensitivity to variations in the dielectric property of bio-medium, providing enhanced heating depth, the safety for the person/operator operating this kind of hyperthermia applicator who would not get exposed to hazardous level of microwave radiation due to highly suppressed back field response/high front-to-back ratio of the applicator, and its compatibility with the curved surface of human body such as abdomen and limbs.

6.2 Limitations and scope for further work

SAR and temperature distributions in bio-medium/bio-media in direct contact/close proximity with the proposed horns/conformal antenna determined through simulation and/or experimental/theoretical studies have been presented in the present thesis. Further simulation study may be focussed on evaluating the performance of the proposed horns and conformal antenna in a realistic human phantom environment.

The fields in single layered bio-medium (muscle) in direct contact with water-loaded conventional/improved metal diagonal horn have been analysed theoretically through plane wave spectral technique in the present thesis. Further work may be carried out to theoretically analyse the fields in tri-layered bio-media (skin, fat and muscle layers) in direct contact with a water-loaded conventional/ improved metal diagonal horns using various approaches.

The proposed horn applicators have been designed at 2.45 GHz and 915 MHz for the treatment of superficial tumors. In the present thesis, experimental investigations on the horn applicators have been reported only at 2.45 GHz. In future, experimental investigations on the proposed horn applicators at 915 MHz may be carried out. Studies may also be performed on metal-dielectric wall diagonal horn applicator for varying thicknesses of metal/dielectric walls.

In the present thesis, a new conformal microstrip slot antenna for the treatment of superficial tumors has been proposed at 2.45 GHz. Possible future work could focus on the design and development of conformal microstrip slot antenna at lower ISM frequency (433 or 915 MHz) for the treatment of tumors at greater depth.

Further investigation may be carried out on phased array antenna with proposed horns/conformal antenna acting as individual array elements at 2450/915 MHz so that beam from the array can be focussed at any desired tumor site located much deeper into the body for effective hyperthermia.

Analysis of heat transfer between tissue and applicator medium/environment may be carried out in the future study.

Finally, an effort may be made to analyse the effect of thickness and temperature of water bolus (not used in the present investigations) on hyperthermia performance owing to the proposed applicators.