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Numerical Analysis of the Microwave Treatment of Palm Trees Infested With the Red Palm Weevil Pest by Using a Circular Array of Vivaldi Antennas

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ABSTRACT The Red Palm Weevil (RPW) is one of the most dangerous pests of palms in the world. Among several techniques that have been applied to combat the RPW pest such as phytosanitation, chemical insecticides, pheromone traps and biological control, the use of microwave energy for heat disinfestation seems to be a promoting solution. Its main advantages are rapid heat transfer, volumetric and selective heating, speed of switching on and off and no pollution to the environment. This article presents the design of microwave antenna system for microwave disinfection of date palms application. The microwave system consists of a 3-D circular array of 16 Vivaldi elements. We present an electromagnetic-thermal model, including palm and adult/Larva RPW models, to test their thermal reactions for microwave heating. The 3-D numerical model shows the capability of the microwave system to heat the outer layer of the palm, and reach the RPW lethal temperature. Also, the research discusses the effect of varying the input power and treatment duration to control the RPW. This work provides a powerful tool to simulate the thermal distribution of the palm and RPW insects for different input cases; which help fight against the RPW.

INDEX TERMS Red palm weevil, microwave heating, Vivaldi antenna, circular array.

I. INTRODUCTION

The red palm weevil (RPW), Rhynchophorus ferrugineus Olivier (Coleoptera, Curculionidae) has become the devastating pests of palms in the world, and has caused considerable economic damage to date palm trees. Since its first appearance in the Middle East in the 1980s, this pest has spread slowly during the mid-1990s and quickly thereafter that in many countries especially in the Mediterranean area, Asia, Africa, Europe [1], Caribbean [2] and America [3]. In the Gulf region of the Middle-East, where the date palm is the most cultivated tree, the annual loss due to eradication of severely infested palms has been estimated to range from 5.18 to $25.92 million at 1 and 5% infestation, respectively [4]. By 2023, in Italy, Spain and France, the cost of RPW control and loss of benefits will reach around $225 million [5]. The larva is the most damaging life stage, due to its cause front disfigurement which leads to the death of the palm [6]. The larvae of the red palm weevils penetrate the palm tree trunks and create cavities and tunnels, which weaken the trunk's mechanical-structure and reduce the transfer of nutriments and water between the root system and the crown. However, detecting the weevil Larva at an early stage is a significant challenge [7]. Different mechanical, chemical, biological, and physical techniques have been developed and used against the red palm weevil pest. Physical techniques have been applied to disinfect palms from the red palm weevil pest based especially on the use of x-ray and gamma radiations [8], and electromagnetic energy at microwave frequencies for the eradication of the weevil [9]. The x-ray and gamma radiation of the red palm weevil showed that the males of this insect reported 90% sterility at a dose of 1.5 Krad, and that the weevil was highly radio-sensitive at various stages of the weevil development.

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In the electromagnetic spectrum, microwaves are situated in the 300 MHz-300 GHz frequency range. Their thermal effect is largely employed for the heating and processing of food and in the production of industrial materials. The US Federal Communications Commission (FCC), has allocated the industrial, scientific and medical (ISM) bands (915 MHz $\pm$ 25 MHz, 2450 MHz $\pm$ 50 MHz, 5800 MHz $\pm$ 75 MHz and 24125 MHz $\pm$ 125 MHz) for microwave industrial applications ([10]–[13]). When a dielectric material is subjected to rapid time-varying electromagnetic field at microwave frequencies, the water molecules constituting it can move, oscillate and/or rotate under the effect of the applied electric field, which may produce friction between molecules and heat of the material. The dielectric heating was approved by the Commission on Phytosanitary Measures of the International Plant Protection Convention (IPPC-FAO) as one of the phytosanitary treatments of wood [14]. Moreover, the use of microwave radiation for red palm weevil eradication has more advantages compared to other methods such as speed, efficiency and absence of any toxic or pollution residues. This is added to the fact that the weevils are unlikely to develop resistance to radiation as they often do to chemical insecticides, for instance.

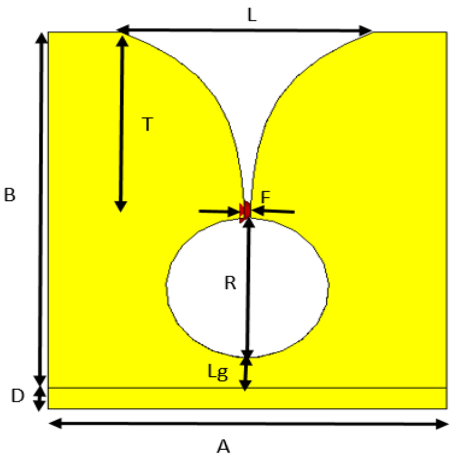
With reference to RPW pest control, the microwave heating had been proposed by several authors. By using an open-ended coaxial probe technique, dielectric measurements were carried on the frequency range 0.5-20 GHz for the health palm, damaged palm and the insect at both larva and adult stages. In addition, the lethal temperatures were estimated by exposing the insects to microwaves generated by a microwave oven (2.45 GHz, 1kW power) [15]. The authors in [16] used the Ecopalm Ring machine; which is a circular ring-shaped device to enable the ring to surround the palm trunk and to make the treatment in depth. The treatment covers a trunk portion of 1.05 metres and the machine generates high electromagnetic power to eradicate the infestation. The resonant cavity technique (waveguide irradiation chamber) was applied by Ali and Al-Jabr [17] in order to prove the possibility of using microwave heating for irradiation of RPW inside healthy and infected palm tree trunks. The designed aluminum rectangular cavity resonates at 2.45 GHz. It is important to know the temperature at which the targeted insects will be killed and at what depth of penetration they are. Woodworms were killed with 100 % mortality rate by using microwave irradiation at 2450 MHz by heating the larvae to 52-53°C for less than 3 minutes [18]. Based on the type of RPW, the treatment duration varies from 20 minutes for adults to 30 minutes for large larvae at 50°C [19]. The penetration depth is an important parameter to define the needed input power and treatment duration. Among a lot of research, the penetration depth of the RPW is defined from 2 to 5.5 cm ([9], [20], [22]). The penetration depth relies on the assumed palm infestation level. The recent publication of Massa *et al.* [9] shows the possibility to reach the lethal temperature at 10 cm of penetration depth by a suitable heating/cooling cycle. It is worth noting that if either the pest or the high temperature reaches the palm core, the palm irremediably dies due to the damage of inner tissues, so the microwave heating has to stay at the outer palm section. A first numerical study on the potentiality of using radiators as a slotted waveguide and dipole antennas for microwave irradiation of RPW insects was done by Ali *et al*. [21]. From this study, we can deduce that preliminary simulation with an electromagnetic software is important for the analysis of the electromagnetic behavior of the system: choice of the microwave radiator, choice of the exciting frequency which is related to the skin depth inside the trunk, determination of the optimum microwave absorption rate (SAR) needed for killing the insect without damage to the palm. As well, R. Massa *et al.* demonstrate the ability of microwave heating to kill insects without damaging the palm [9]. Disinfestations by heating insects by microwaves require high power microwave (HPM) systems where the antenna plays a key role in focusing electromagnetic power. The needed antenna should be efficient, with high gain and composed of materials that can support high powers. For this reason, an antenna array is usually considered for the application of an HPM because it facilitates the distribution of the high input power to a number of radiating elements, which makes it less difficult to realize high power-handling capacity. The antenna design for HPM application has become an interesting issue, many techniques have been developed to satisfy this special requirement ([22]–[25]). The main proposed structures are reflector antennas [22], array of horn antennas [23], Helical array antenna [24], array of microstrip patch antennas [25], Vlasov antennas [26], and COBRA antennas [27]. The tapered-slot antennas [28] such as Vivaldi antennas are well-known by their ultra-wide bandwidth. The Vivaldi antennas could be fabricated using aluminum material [29] to reduce the fabrication cost [30], reduce the dielectric losses, and support high power applications [31]. Tapered slot antennas can be seen in several forms, such as elliptical profiles [32] or exponential profiles [33]. Much research has been done to study the advantages of connecting Vivaldi antenna elements. In [34] wide-band performance can be obtained using Vivaldi elements which are electrically connected. In [35], eight tapered slot elements are arranged on a circular substrate for 4G communication applications in order to realize a horizontally polarized (HP) omnidirectional array antenna. Sixteen Vivaldi antenna elements are connected with each other to achieve an omnidirectional UWB HP antenna [36]. 3-D Circular connected Vivaldi elements are proposed in [37], where the authors used an array of 10 elements with an elliptical taper profile for near-field radar imaging applications. In this work, we are propose a 3-D connected antenna array with 16 elements in a circular configuration for the disinfection, by the application of microwaves, of date palms. The goal behind this configuration is to focus the radiated electromagnetic power on specific spots of the infested palm, then killing the insects by raising their temperature more than 20°C during few minutes, without damaging the plant. The paper is organized as follows: the design of a 3-D single Vivaldi element, the 3-D circular antennas array and the performance of the array in the presence of a palm tree model are presented in Section II. Section III presents a thermal model of a palm tree and Larva/adult insects to analyze their thermal response to microwave heating. Conclusions are drawn in Section IV.

II. DESIGN OF THE MICROWAVE ARRAY SYSTEM

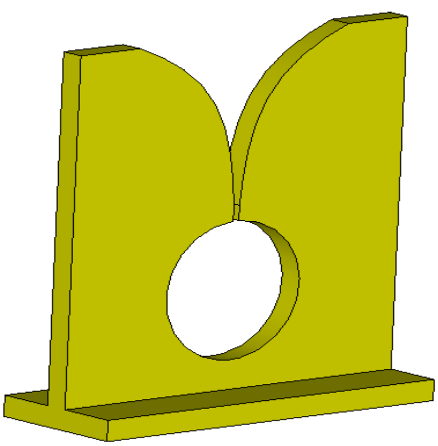
The goal of the following circular array design is to obtain a UWB range starting from 1.5 GHz up to more than 7 GHz, and focus the radiated electromagnetic power inside the available space of the array. The microwave system may serve for the RPW control and insect imaging. For palm tree imaging, UWB systems are highly recommended. Therefore, the proposed work uses UWB antennas to be used for RPW imaging in future developments. In this article, we will focus on the RPW control, which requires a heating system with a good antenna matching at 2.45 GHz.

A. DESIGN OF A 3-D SINGLE VIVALDI ANTENNA

A 3-D traditional single Vivaldi antenna is proposed using CST microwave studio [38], as shown in Fig. 1. The time domain solver is used to provide the antenna performance for the antenna array. The type of taper profile is exponential. A ground plan of 0.5 cm (D parameter in Fig. 1.a is added beneath the antenna to hold it properly and add isolation between the coaxial cable and the antenna body. The antenna thickness is 0.5 cm. The parameter F indicates the distance between the two taper profiles at the position of assigning the discrete port. Practically, the discrete port model is the end of an embedded coax cable inside the 3-D antenna to avoid using balun circuits [39]. The antenna material is set to aluminum. The proposed single antenna design dimensions is summarized in Table 1.



(a)



(b)

FIGURE 1. Single 3-D Vivaldi (a) element dimensions (b) 3-D perspective view.

TABLE 1. Single element dimensions (cm).

A	B	R	L	F	D	T	Lg
8	8.4	3.2	5.1	0.14	0.5	4.5	0.7

B. DESIGN OF A 3-D CIRCULAR ARRAY OF 16 VIVALDI ELEMENTS

Sixteen 3-D Vivaldi elements are arranged in connected circular shape (Fig. 2) to provide 360^o radiation for the palm tree without mechanical support. Fig. 3 presents the antenna array performance in terms of reflection coefficients. It shows a bandwidth from 1.5 GHz to more than 7 GHz below −10 dB criterion, except of a narrow region between 1.95 GHz to 2.5 GHz.

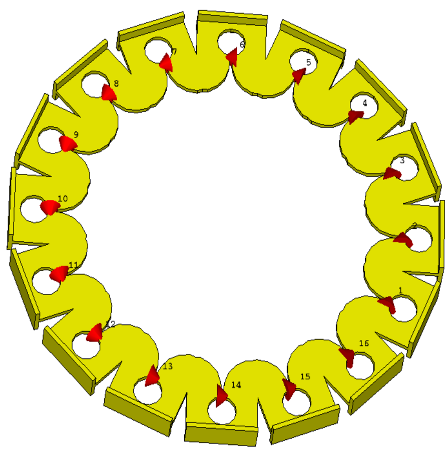


FIGURE 2. Circular array of 16 elements layout.

C. DESIGN OF A 3-D CIRCULAR ARRAY OF 16 VIVALDI ELEMENTS IN THE PRESENCE OF PALM TRUNK

Fig. 4 shows the proposed model of the palm tree. It consists of a cylinder of 26.6 cm in diameter and 10 cm in height. The real part of permittivity of the palm is set to 31.5 and the dielectric loss factor is set to 11.5 at 2.45 GHz [26]. The space available inside the circular array is 32 cm by 32 cm. The distance between the antennas and the palm is a trade-off between keeping a good impedance matching at

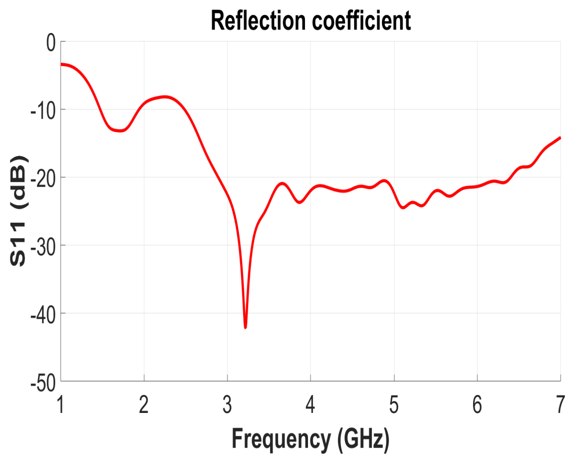


FIGURE 3. Reflection coefficient of the antenna array.

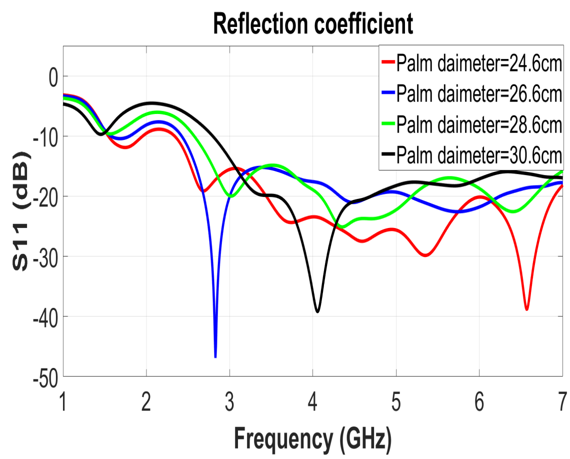


FIGURE 5. Palm tree diameter influence on the array matching.

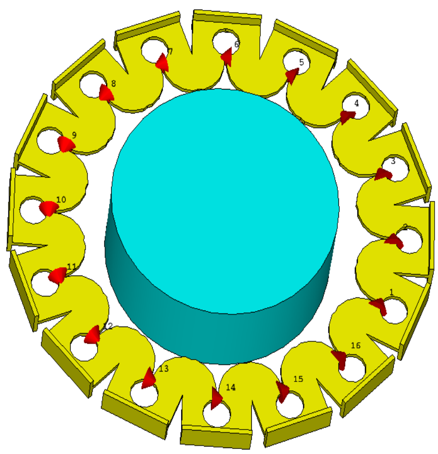


FIGURE 4. Palm tree configuration inside the antenna array.

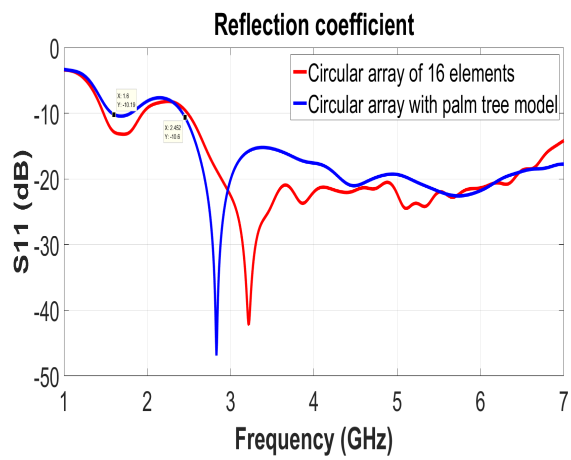


FIGURE 6. Reflection coefficient of the antenna array without and with palm model.

antenna side and approaching from the palm surface to deliver higher radiation inside the palm.

Fig. 5 shows the behavior of the circular antenna array while approaching the palm tree model from the antennas. The effect of increasing the palm tree diameter appears mainly at lower frequencies through strong back-radiations on antennas themselves; which impact on the antenna performance. In other words, a minimum distance between the antennas and the trunk has to be respected to insure a sufficient matching for the array reflection coefficient. The palm diameter of 26.6 cm meets 2.5 cm as the minimum distance to respect. Fig. 6 presents the antenna array performance in the presence of the palm tree and shows a bandwidth between 2.4 GHz up to more than 7 GHz below −10 dB criterion. For the frequency of interest of 2.45 GHz, the S11 has −10.6 dB.

III. THERMAL ANALYSIS

Based on the previous literature review, 53°C is chosen as the lethal temperature goal [24]. The following steps will study the temperature variant over the entire structure based on thermal losses in the conductors and dielectric materials. These thermal losses are computed from the frequency electromagnetic simulation results at 2.45 GHz.

A. THE ELECTROMAGNETIC-THERMAL MODEL

Simulating the heating process of palms is extremely complex, since it involves heat transfer coefficients. The thermal model parameters depend on temperature and water content; which are nonlinear functions. The thermal parameters of palm can vary within relatively wide ranges based on the moisture content. Table 2 summarizes the parameters used in the CST thermal transient solver for the palm [26] and the aluminum material [38]. The following study will take tow RPW types of Larva and adult insects, three nominal input powers of 1 kW, 3.6 kW and 5.6 kW, and three penetration depth pf 2 cm, 5 cm and 10 cm. Based on the input power and the lethal temperature of 53°C, the treatment duration will be calculated to reach the RPW lethal temperature. The real permittivity and conductivity at 2.45 GHz for the Larva is 35.3 and 1.04 S/m, and for adult insect is 9.3 and 0.38 S/m, respectively [13]. Each insect is represented by one cylinder

TABLE 2. Electromagnetic and thermal parameters [26].

	Palm	Aluminum	Unit
Real part of permittivity	31.5	-	-
Dielectric loss factor	11.5	-	-
Electrical conductivity	-	3.72×10^7	S/m
Thermal conductivity	1.5	237	$W/m/K$
Convection coefficient	25	60	$W/m^2/K$
Density	844	2700	Kg/m^3
Heat capacity	3.1	0.9	$KJ/K/Kg$
Temperature	25	25	$Degree$

with 3 cm in height and 0.5 cm in diameter; which consider as a small adult or Larva. According to the technical data sheet [40], the high power level chosen cannot exceed the nominal electrical power of the cables available.

An open boundary condition (Fig. 7), where the ambient temperature is maintained far from the device under study, is considered. Such a boundary condition is ideal when there is a free surrounding.

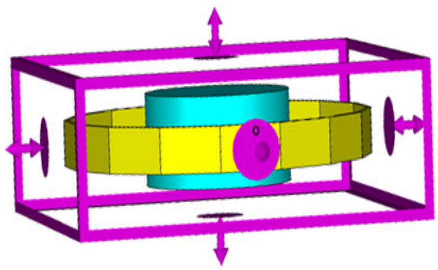


FIGURE 7. Open boundary condition of the entire structure.

1) INPUT POWER OF 1 kW

1.1 Adult versus Larva responses to microwave heating at 2 cm penetration depth: the insect on the left (adult) is located at 2 cm penetration depth, and the insect on the right (Larva) is its symmetry over X axis, as shown in Fig. 8. Both insects have the same parallel orientation to the palm cylinder Z axis.

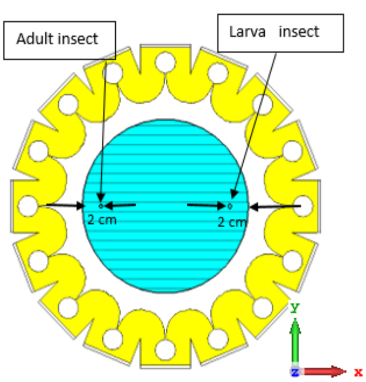


FIGURE 8. Adult and Larva insects configurations.

The goal is to apply the same conditions for Larva and adult, and test their reaction to microwave heating.

The temperature distribution over the palm and insect models (Fig. 9) tells that the small Larva is much more sensitive to microwave heating than the adult one. Also, the palm is more sensitive to microwave heating than RPW insects, where the palm penetration depth of 53°C is larger than RPW insects. Another important remark is the core of palm remains at 25°C; this guarantees that microwaves do not affect the health of the plant. The temperature distribution shows a homogeneous temperature distribution over the whole palm trunk; which is necessary to ensure heating the RPW. The treatment duration records for 7 minutes.

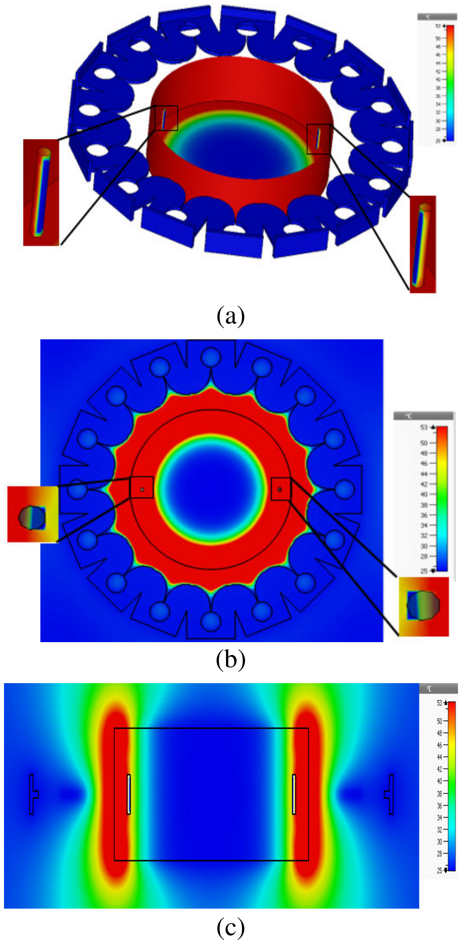


FIGURE 9. (a) Temperature distribution (b) 2-D projection on XY plan (c) 2-D projection on XZ plan for two identical RPW insects at 2cm penetration depth.

2.1 RPW orientation influence at 2 cm penetration depth: in this case is the insect on the right is rotated by 30° to test the insect orientation influence, and both insects are defined as adult type. Longer treatment duration of 9 minutes is used in this case to reach the lethal temperature of most insect body. The temperature distribution (Fig. 10) shows that the effect of microwave heating appears at both insect orientations, which makes RPW sensitive to microwave heating.

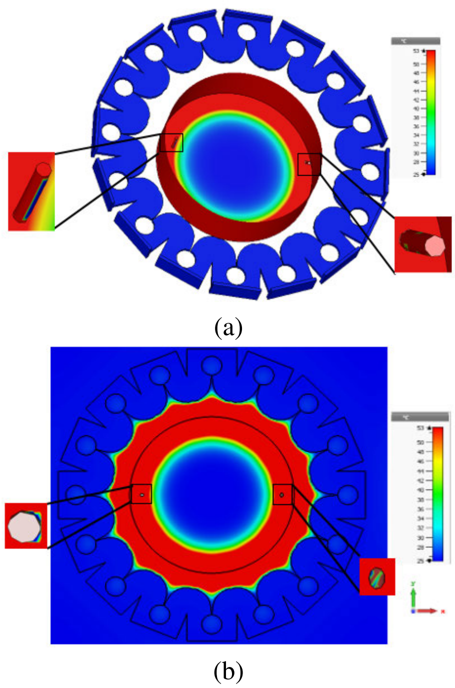


FIGURE 10. (a) Temperature distribution (b) 2-D projection on XY plan for two RPW insects (the right one is rotated by 30°) at 2cm penetration depth.

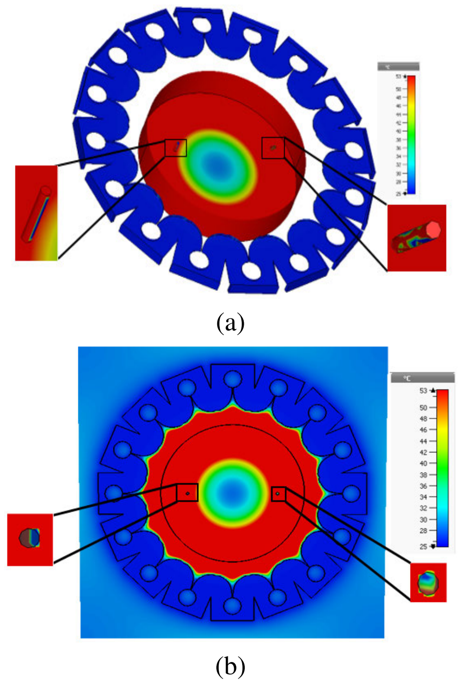


FIGURE 11. (a) Temperature distribution (b) 2-D projection on XY plan at 5 cm of insect penetration depth.

3.1 Penetration depth influence at 5 cm: the same conditions of point 2.1 are considered for this trail. Therefor, the same behavior of the temperature distribution is noticed at 5 cm of insect penetration depth, as shown in Fig. 11. Table 3 summaries the treatment duration for all studied cases.

TABLE 3. Treatment duration for different input powers and penetration depths.

Nominal power (kW)	Penetration depth (cm)	Treatment duration (minutes)
1	2	9
1	5	16
3.5	2	3
3.5	5	8
5.6	5	5
5.6	10	15

2) INPUT POWER OF 3.5 AND 5.6 kW

High power is applied by the microwave system, where its values are calculated from the data-sheet of cable maximum power.

A new case added for an input power of 5.6 kW at 10 cm penetration depth to simulate the worst case for this configuration. Larva model is set for this trail with an oblique orientation.

Fig. 12 displays the whole palm trunk with 53°C, including the small Larva model which is not recommended in the real case due to the damage of the plant core. On the other hand, the palm trunk radii could reach 40 cm which defines 10 cm penetration depth as an outer palm layer. Another important remark is the antenna elements' temperature is increased to 30°C due to high power radiation during the long treatment duration. This is one of the microwave system challenges to reach deep penetration depth. The proposed model shows its capability to predict such a situation before moving to the

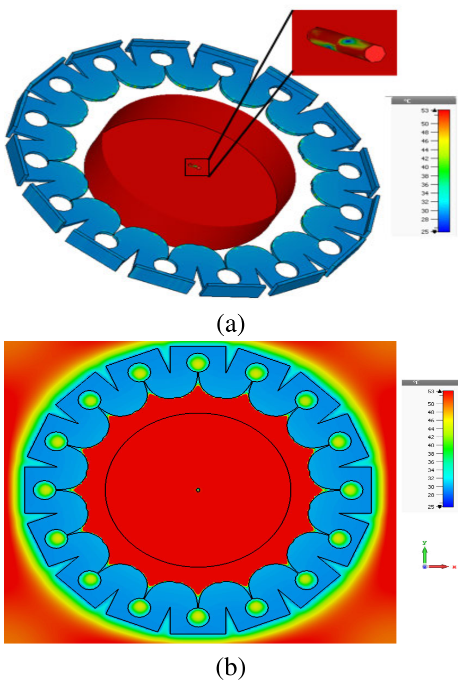


FIGURE 12. (a) Temperature distribution (b) 2-D projection on XY plan at 10 cm of insect penetration depth.

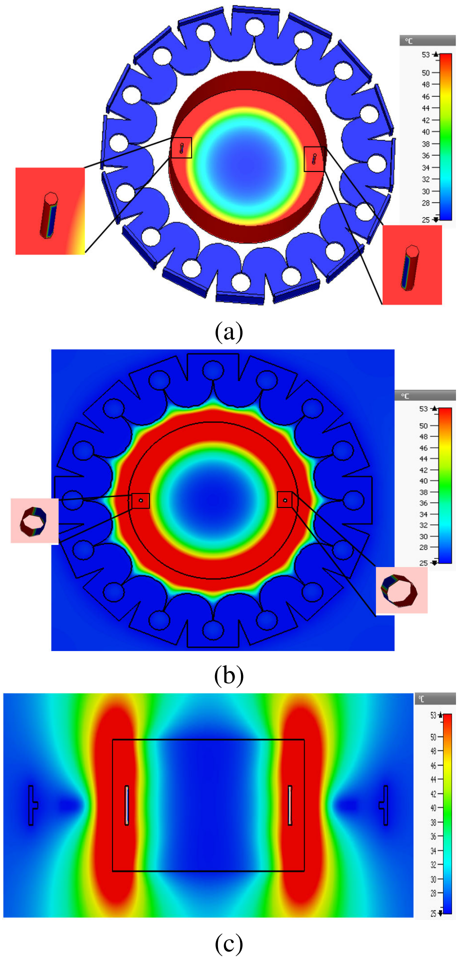


FIGURE 13. **(a) Temperature distribution (b) 2-D projection on XY plan (c) 2-D projection on XZ plan for 1.6 GHz.**

fabrication phase, which is a good tool to know the possible mixture of high power and treatment duration that the system can handle without a cooling-heating cycle.

3) WORKING FREQUENCY INFLUENCE

Due to ISM limitation, the working frequency of 2.45 GHz is used. Another interesting frequency of 1.6 GHz could be used to reach a deeper pentration depth. The same conditions of the first case in Section 1.1 is applied by using 1.6 GHz. Fig. 13 demonstrates a larger temperature distribution area of 53°C than the results obtained in Fig. 9. Also, the referred temperature with 40°C (green color) area is larger than those presented in Fig. 9; which indicates to a larger penetration depth using lower frequencies. The palm core remains with 25°C; which ensures the healthy treatment of microwave frequencies.

IV. CONCLUSION

The design of a circular antennas array for RPW control is presented. The circular array is optimized in the presence of palm trunk to exhibit a UWB between 2.4 up to more than 7 GHz. For the RPW control, special attention is taken at 2.45 GHz to have −10.6 dB for the array reflection coefficient. The minimum distance between the antennas and the palm has to be 2.5 cm to ensure acceptable impedance matching at the interesting frequency of 2.45 GHz. The proposed electromagnetic-thermal model; which uses the input from the calculated thermal losses in the conductor and dielectric materials, is used to simulate the temperature distribution inside the palm model and two RPW insects for disinfestation of palm trunk attacked by RPW. The temperature distribution shows that the small Larva is much more sensitive to microwave heating than adult insect. Putting a thermal sensor inside the palm to measure the RPW lethal temperature maybe not the best solution to control the insect, because the simulation results show that penetration depth of the palm is larger than RPW to reach 53°C; which requests a longer treatment duration. A homogeneous temperature distribution is noticed over the whole palm, with keeping the ambient temperature at the core of the palm. The last remark presents the microwave heating as an eco-compatible solution to control RPW. Higher input power provides less treatment duration; which accelerates the whole treatment process. The treatment duration of an adult insect located at 5 cm penetration depth estimated at 8 minutes for 3.5 kW nominal power. The electromagnetic-thermal model shows its capability to reach 10 cm penetration depth for 15 minutes using 5.6 kW. Using lower frequencies, e.g. 1.6 GHz with the same input power, help reach larger penetration depth inside the palm, but it is not possible to use it due to ISM band limitation. The authors hope that this model could help researchers to understand better the RPW reaction to microwave heating, which supports the fight against RPW spreading.

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REFERENCES

[1] D. Sauvard, M. Branco, F. Lakatos, M. Faccoli, and L. R. Kirkendall, "Weevils and Bark Beetles (Coleoptera, Curculionoidea)," in *Alien Terrestrial Arthropods of Europe*, A. Roques, M. Kenis, D. Lees, C. Lopez-Vaamonde, W. Rabitsch, J. Y. Rasplus, and D. B. Roy, Eds. Sofia, Bulgaria: BioRisk, 2010, ch. 8.2.

[2] "First record of rhynchophorus ferrugineus in Curacao, Netherlands antilles," EPPO (Eur. Medit. Plant Protection Org.), Paris, France, Tech. Rep. 2009/002, 2009.

[3] "First record of rhynchophorus ferrugineus in the USA," EPPO (Eur. Medit. Plant Protection Org.), Paris, France, Tech. Rep. 2009/176, 2010.

[4] A. M. R. El-Sabea, J. R. Faleiro, and M. M. Abo-El-Saad, "The threat of red palm weevil rhynchophorus ferrugineus to date plantations of the gulf region in the middle-east: An economic perspective," *Outlooks Pest Manage.*, vol. 20, no. 3, pp. 131–134, Jun. 2009, doi: 10.1564/20jun11.

[5] Food Chain Crisis. Red Palm Weevil. (2017). *Food and Agricultural Organization of the United Nations*. [Online]. Available: http://www.fao.org/food-chaincrisis/how-we-work/plant-protection/red-palm-weevil/en/

[6] A. M. Idris, T. A. Miller, R. Durvasula, and N. Fedoroff, "Bridging the knowledge gaps for development of basic components of Red palm weevil IPM," in *Sustainable Pest Management in Date Palm: Current Status and Emerging Challenges*, W. Wakil, J. R. Faleiro, and T. A. Miller, Eds. Basel, Switzerland: Springer, 2015, pp. 37–62.

[7] M. Rach, H. Gomis, O. Granado, M. Malumbres, A. Campoy, and J. Martín, ''On the design of a bioacoustic sensor for the early detection of the red palm weevil,'' *Sensors*, vol. 13, no. 2, pp. 1706–1729, Jan. 2013.
[8] C. P. Ramachandran, ''Effects of gamma radiation on various stages of red palm weevil, Rhynchophorus ferrugineus F.,'' *J. Nucl. Agric. Biol.*, vol. 20, no. 3, pp. 218–221, 1991.
[9] R. Massa, E. Caprio, M. De Santis, R. Griffo, M. D. Migliore, G. Panariello, D. Pinchera, and P. Spigno, ''Microwave treatment for pest control: The case of rhynchophorus ferrugineus in phoenix canariensis,'' *Bull. OEPP/EPPO Bull.*, vol. 41, no. 2, pp. 128–135, Aug. 2011.
[10] A. C. Metaxas, *Foundations of Electroheat: A Unified Approach*. Hoboken, NJ, USA: Wiley, 1996.
[11] C. Lorenson, ''The why's and how's of mathematical modelling for microwave heating,'' *Microw. World*, vol. 2, no. 1, pp. 14–22, 1990.
[12] D. C. Dibben and A. C. Metaxas, ''Finite element time domain analysis of multimode applicators using edge elements,'' *J. Microw. Power Electromagn. Energy*, vol. 29, no. 4, pp. 242–251, Jan. 1994.
[13] R. Ehlers and A. C. Metaxas, ''3-D FE discontinuous sheet for microwave heating,'' *IEEE Trans. Microw. Heating Techn.*, vol. 51, no. 3, pp. 718–726, Mar. 2003.
[14] ''Regulation of wood packaging material in international trade,'' Food Agricult. Org. United Nations, Int. Plant Protection Conv., Rome, Italy, Tech. Rep. ISPM-15, 2013.
[15] R. Massa, G. Panariello, M. Migliore, D. Pinchera, F. Schettino, R. Griffo, M. Martano, K. Power, P. Maiolino, and E. Caprio, ''Microwave heating: A promising and eco-compatible solution to fight the spread of red palm weevil,'' *Arab J. Plant Protection*, vol. 37, no. 2, pp. 143–148, Jun. 2019, doi: 10.22268/AJPP-037.2.143148.
[16] C. Y. Khatib, A. Isotton, C. Pasqualotto, and L. Bernabei, ''Ecopalm ring machine: The microwaves technology for the total disinfestations of the palm trees affected by the red palm weevil,'' in *Proc. IV Int. Date Palm Conf.*, vol. 882, 2010, pp. 1027–1032.
[17] I. A. Ali and A. M. Al-Jabr, ''A waveguide irradiation chamber for destruction of red palm weevils (Rhynchophorus Ferrugineus) inside a block sample of a palm tree trunk,'' *J. Microw. Power Electromagn. Energy*, vol. 38, no. 2, pp. 137–146, Jan. 2003.
[18] D. Andreueeetti, M. Bini, A. Ignesti, A. Gambetta, and R. Olani, ''Microwave destruction of woodworms,'' *J. Microw. Power Electromagn. Energy*, vol. 29, no. 3, pp. 153–160, Jan. 1994.
[19] R. Massa, M. D. Migliore, G. Panariello, D. Pinchera, F. Schettino, E. Caprio, and R. Griffo, ''Wide band permittivity measurements of palm (Phoenix canariensis) and rhynchophorus ferrugineus (coleoptera curculionidae) for RF pest control,'' *J. Microw. Power Electromagn. Energy*, vol. 48, no. 3, pp. 158–169, 2014.
[20] R. Massa, G. Panariello, D. Pinchera, F. Schettino, E. Caprio, R. Griffo, and M. D. Migliore, ''Experimental and numerical evaluations on palm microwave heating for red palm weevil pest control,'' *Sci. Rep.*, vol. 7, no. 1, pp. 1–8, May 2017.
[21] I. A. Ali, A. Al-Jabr, and A. R. Memari, ''FDTD simulation and experimental investigation of controlled microwave irradiation of red palm weevils,'' in *Proc. IEEE Middle East Conf. Antennas Propag. (MECAP)*, Cairo, Egypt, Oct. 2010, pp. 1–8.
[22] Y. Rahmat-Samii, D.-W. Duan, D. V. Giri, and L. F. Libelo, ''Canonical examples of reflector antennas for high-power microwave applications,'' *IEEE Trans. Electromagn. Compat.*, vol. 34, no. 3, pp. 197–205, Aug. 1992.
[23] J. Lee and J. M. Woo, ''Design of array synthesis horn antenna for high power microwave,'' in *Proc. PIERS*, Moscow, Russia, Aug. 2012, pp. 1196–1198.
[24] X. Q. Li, Q. X. Liu, J. Q. Zhang, L. Zhao, and Z. Q. Zhang, ''The high-power radial line helical circular array antenna: Theory and development,'' in *Proc. Int. Conf. Microw. Millim. Wave Technol.*, May 2010, pp. 671–674.
[25] J.-C. Diot, T. Tarati, B. Cadilhon, B. Cassany, P. Modin, and E. Merle, ''Wideband patch antenna for HPM applications,'' *IEEE Trans. Plasma Sci.*, vol. 39, no. 6, pp. 1446–1454, Jun. 2011.
[26] S. N. Vlasov and I. M. Orlova, ''Quasioptical transformer which transforms the waves in a waveguide having a circular cross section into highly directional wave beam,'' *Radiofizika*, vol. 17, no. 1, pp. 148–154, 1974.
[27] C. C. Courtney and C. E. Baum, ''The coaxial beam-rotating antenna (COBRA): Theory of operation and measured performance,'' *IEEE Trans. Antennas Propag.*, vol. 48, no. 2, pp. 299–309, 2000.
[28] P. J. Gibson, ''The Vivaldi aerial,'' in *Proc. 9th Eur. Microw. Conf.*, Brighton, U.K., Sep. 1979, pp. 101–105.
[29] K. Alkhalifeh, R. Sarkis, and C. Craeye, ''Wheel-of-time array devoted to near-field imaging applications,'' in *Proc. Int. Conf. Electromagn. Adv. Appl. (ICEAA)*, Turin, Italy, Sep. 2013, pp. 9–13.
[30] R. Maaskant, M. Popova, and R. van den Brink, ''Towards the design of a low-cost wideband demonstrator tile for the SKA,'' presented at the 1st Euro. Conf. Ant. Propag., Nice, France, 2006.
[31] J. E. Lawrance, C. G. Christodoulou, and M. R. Taha, ''A high-power microwave zoom antenna with metal-plate lenses,'' *IEEE Trans. Antennas Propag.*, vol. 63, no. 8, pp. 3380–3389, Aug. 2015.
[32] R. Sarkis and C. Craeye, ''Circular array of wideband 3D Vivaldi antennas,'' in *Proc. URSI Int. Symp. Electromagn. Theory*, Aug. 2010, pp. 792–794.
[33] M. Amiri, F. Tofigh, A. Ghafoorzadeh-Yazdi, and M. Abolhasan, ''Exponential antipodal Vivaldi antenna with exponential dielectric lens,'' *IEEE Antennas Wireless Propag. Lett.*, vol. 16, pp. 1792–1795, 2017.
[34] D. H. Schaubert, S. Kasturi, A. O. Boryssenko, and W. M. Elsallal, ''Vivaldi antenna arrays for wide bandwidth and electronic scanning,'' in *Proc. 2nd Eur. Conf. Antennas Propag. (EuCAP)*, Edinburgh, U.K, Nov. 2007, pp. 1–6.
[35] T. S. P. See, X. Qing, Z. N. Chen, and Z. N. Chen, ''A wideband horizontally polarized omnidirectional antenna,'' in *Proc. IEEE 4th Asia–Pacific Conf. Antennas Propag. (APCAP)*, Kuta, Indonesia, Jun. 2015, pp. 294–295.
[36] H. Liu, Y. Liu, W. Zhang, and S. Gao, ''An ultra-wideband horizontally polarized omnidirectional circular connected Vivaldi antenna array,'' *IEEE Trans. Antennas Propag.*, vol. 65, no. 8, pp. 4351–4356, Aug. 2017.
[37] K. Alkhalifeh, R. Sarkis, and C. Craeye, ''Design of a novel 3D circular Vivaldi antennas array for ultra-wideband near-field radar imaging,'' in *Proc. 6th Eur. Conf. Antennas Propag. (EUCAP)*, Prague, Czech Republic, Mar. 2012, pp. 898–901.
[38] *CST, Computer Simulation Technology GmbH*. [Online]. Available: https://www.cst.com
[39] H. Holter, ''A new type of antenna element for wide-band wide-angle dual polarized phased array antennas,'' in *Proc. IEEE Int. Symp. Phased Array Syst. Technol.*, Oct. 2003, pp. 393–398.
[40] *RG402 Coax Cable with Copper Outer Conductor*. Accessed: Aug. 19, 2020. [Online]. Available: https://www.pasternack.com/images/ProductPDF/RG402-U.pdf

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