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Design and Fabrication of a Microwave Weed Killer Device for Weed Control Applications

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ABSTRACT

In this paper, the design and the results of a microwave radiation system for agriculture applications is discussed. The system is fabricated and successfully tested on weed seeds. The device, which uses a commercial 1 kW magentron, proved to be effective for preventing the germination control of popular weeds of Iran. Seven weed species were tested separately by using this system and then the irradiated soil was cultivated in a greenhouse. The results show that by increasing soil temperature up to 70 °C, the germination rate of weed seeds is less than 20 percent (in some cases zero percent). It should be mentioned that the safety of the system is also studied according to ICNIRP standard.

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NOMENCLATURE

P_T	Total power (W)	ε_0	Vacuum permittivity (Fardays m^{-1})
G	Antenna Gain	ε''	Complex dielectric permittivity (Faradays m^{-1})
W_{av}	Average Power Density (w m^{-2})	E	Electric field (V m^{-1})
APD	Absorbed Power Density	ω	Angular frequency of the microwaves (Rad s^{-1})
r_{min}	Distance from the antenna (m)	n	Magnitude ratio for the coupling between heat and moisture diffusion
π	3.14	k	Thermal conductivity of the material (W m^{-1} K^{-1})
τ	Transmission coefficient for the transfer of microwave energy into the material	h	Convective heat transfer coefficient at the surface of the material (W m^{-1}K^{-1})
γ	Combined heat and moisture diffusion coefficient	μ_0	Vacuum permeability (Henries m^{-1})
t	Microwave heating time for experiment (s)	E_0	Peak strength of the electric field in the aperture of the horn antenna (Vm^{-1})
β	Wave attenuation factor (m^{-1})		

1. INTRODUCTION

Nowadays, electromagnetic energy is employed, not only in telecommunication industry, but also in other industries such as the agriculture industry, where some unsolvable problems exist. The proven effect of electromagnetic waves in agriculture is the heating phenomena, which depend on the imaginary part of the dielectric constant of materials [1]. This has been started from 1946 in food, chemical, and medicine engineering industries. Based on this effect, the continuous rotation of polarized molecules causes the conversion of electromagnetic energy to heat [2]. Other examples of such applications are wood drying [3-4], microwave treatment of animal fodder [5], disinfection of walnuts [6], wheat and stored product pest control [7] thermal disinfection of soils [8], anti-freezing [9], and weed control in farms [1].

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In recent years, weed control has become a serious problem in the agricultural industry, since it causes the highest damage to products [1]. For example, in Iran, three weeds, *Sinapis arvensis*, *Phalaris spp* and *Avena fatua*, cause wheat production reductions of almost 163 kg per hectare[10]; equivalent to 23% damage in wheat fields [11]. The seed banks in the top few centimeters of soil plays an important role in weed germination every year, since vitality and longevity of the seed bank have a major role in the establishment of weeds [12]. Five consecutive years is necessary to effectively control weeds by chemical methods provided there is no herbicide-resistant cases among the seeds [13]. However, nine new biotypes of herbicide-resistant weeds are reported each year [14]. Environmental problems, herbicide-resistant weeds, development of invasive species, as well as demand for healthy products, are among the issues that have led to the reconsideration of non-chemical weed management [15].

Interest on the effect of high-frequency electromagnetic waves on biological materials began in the late 19th century [13] where studies showed that the main effect of electromagnetic waves on a seed is a thermal effect. The ability of each seed to absorb microwave energy depends on its volume and mass as well as its moisture content. In 1991 Barker et al [16] reported that one can prevent weed germination by raising their temperature up to 75 to 85 degrees. Brodie [1] lowered this range to 65º to 80º C. The main focus of this work is on reducing required power density and required weed temprature. The exposure time and exposure profile on the weeds will be concentrated in future works. In general, the weed seeds of the top 20-30 mm of soil have a higher chance of germination [17]. Therefore in order to save power, reduce electromagnetic wave leakage, and also to reduce negative effects of microwaves on the microbial biomass of the treated soil, this work fouces on 20 mm top layer of the soil.

In this work, the design and fabrication of a simple and low cost 2.4 GHz ISM band microwave device, considering the effect of soil parameters, is reported. The system was then tested on various indegnious Iranian weed seeds in order to verify its performance. The system is composed of a microwave magnetron source, the power circuit and at the end a simple pyramidal horn antenna. In section II of the paper, the theory of the system is explained. Section III explains the design of the system followed by the measurement results in section IV. Safety concerns of the system is investigated in section V and finally the paper is concluded in section VI.

2. MICROWAVE HEATING THEORY

Microwave heating is governed by Maxwell's equations and the heat transfer equation. These equations are coupled where the thermal source in the heat transfer equation is provded by dissipation of microwave power in the material. The dissipated electromagentic power follows from the well-known Equation (1).

$$P_{diss} = \frac{\omega \varepsilon_0 \varepsilon''}{2} |\vec{E}|^2 \quad (1)$$

Based on these eqauations, Brodie calculated the temperature distribution in the soil when it is located in front of a horn antenna [1].

$$T = \frac{n\omega\varepsilon_0\varepsilon''\tau^2\left(e^{4\gamma\beta^2 t}-1\right)}{4k\beta^2}\left[e^{-2\beta z} + \left(\frac{h}{k} + 2\beta\right) z e^{\frac{-z^2}{4\gamma t}}\right] cos\left(\frac{\pi}{a}x\right) \quad (2)$$

where, β is the wave attenuation factor (m^{-1}) which is obtained from:

$$\beta = \frac{2\pi f}{\sqrt{\varepsilon_0\mu_0}}\sqrt{\frac{\varepsilon'}{2}\left(\sqrt{1+\left(\frac{\varepsilon''}{\varepsilon'}\right)^2}-1\right)}\ (m^{-1}) \quad (3)$$

The above equations led to the canclusion that the hottest place in the heating pattern was along the center line of the antenna and the temprature is gradually degraded moving away from this center line.

3. SYSTEM DESIGN

In order to expose soil to a high power electromagnetic field, our mobile, 1-kW, prototype Microwave Weed Killer (MWK) was designed, simulated and fabricated (see Figure 1). There has been other similar prototpyes, which are briefly reported by Brodie [12] and by Vidmar [18], even using higher powers. The main application of such a relative lower power system is greenhourse agriculture applications.

The main components of the device, and their specifications, are given in Table 1. As mentioned, a commercial 2.45 GHz WITOL magnetron, normally used in microwave ovens, was used in order to make the device cheaper and easy to produce. A pyramidal horn,

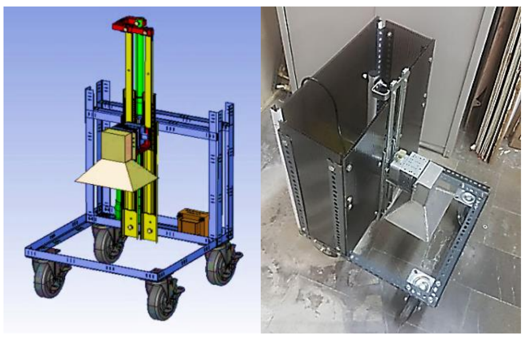

Figure 1. MWK system simulation (left) and fabrication (right)

fed by an S-band waveguide, was designed to match the power transfer from the magnetron's probe to the antenna (see Figure 2).

TABLE 1. Major componentds of MWK prototype

Name	Description
Frequency	2.45 GHz
Antenna	Pyramidal horn
Magnetron	WITOL 2M319J
Circuit	Include (HF Diode, Fuse, Transformer)
Jack	-
Wheels	4

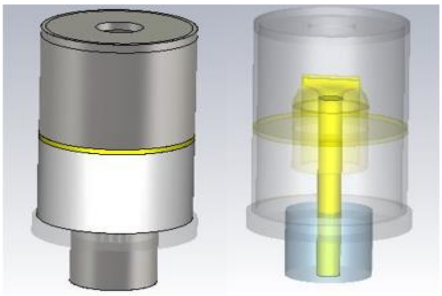

Figure 2. The structure of Magnetron's output probe, simulated in CST Microwave Studio

3. 1. Antenna Design The selected antenna should be a directional high power handling antenna without any lossy material. Among various metalic antenna candidates for this system, horn antenna is a suitable candidate for the MWK system due to its high efficiency, low reflection, relatively high bandwidth and ease of use [19].

However, there is a serious question on how the design of the antenna should be carried out as the antenna normally works downwards in front of soil which not only increases back radiation but also suffers mismatch. Since the parameter of the soil which is in front of the antenna is a statistically changing parameter from dry soil to wet soil, from farm to farm and greenhouse to greenhouse, covers a wide range of dielectric constant values, there is a complicated problem regarding which dielectric constant should be selected for the optimum design. In this work, antenna has been designed considering an open air environment. The optimization of the antenna design will be considered in future works. There are other electromagnetic issues such as the propagation of electromagnetic waves in lossy media [20] and its definition of radiation pattern.

In Table 2, the specifications of the designed horn antenna are listed. The measured antenna's bandwidth is 714 MHz and its aperture efficiency is around 63%, which is very good compared to normal designs.

Every magnetron has its own monopole like feeding probe which is inserted in the antenna's feeding waveguide. However, since it was not possible to measure antenna's reflectivity when it is attached to magnetron, the antenna has been tested using another scenario. As the magnetron probe, shown in Figure 2, is fixed in terms of height and diameter, one can only change its position of insertion so as to match the magnetron to the antenna. This has been done in simulation. In order to verify this design, the antenna's reflection coefficient and radiation pattern has been tested by using another N-type wire probe. The simulated and measured return loss of the antenna using this N-type probe is comapred in Figure 3 showing good agreement. This evidence makes us convinced that the antenna's simulated results, with the magnetron probe, is valid.

The antenna pattern was measured in the anechoic chamber of K. N. Toosi university of technology's antenna lab. As expected, the horn antennna has its main lobe along the center of its aperture. The measurment and simulation result are shown in Figure 4, having good agreement.

3. 2. Heat Transfer To study electromagnetic fields and the transfer of heat to the upper surface of the soil, a full wave simulation was carried out by placing dry and wet soil in front of the antenna in CST Microwave Studio. The dielectric constants of dry soil

TABLE 1. Characteristis of the antenna in simulation

Parameter	Value
Center frequency (GHz)	2.45
Aperture dimension (cm)	22.29×16.64
Directivity	19.8
Bandwidth (MHz)	714
Aperture efficiency	0.63
Length (cm)	20

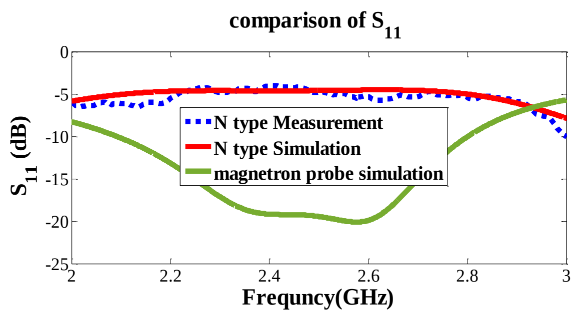

Figure 3. Return loss of antenna fed by magnetron's probe

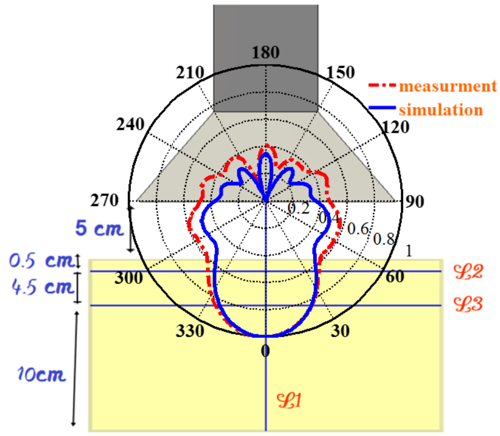

Figure 4. Antenna's far field pattern (simulation and measurement) and L_1, L_2 and L_3 simulation lines

and wet soil (18.8% water) are 2.53-j0.008 and 16.6-j3.6 respectively and for water it is 78-j11.66. The extracted results from the above simulations, 1kW input power on three straight lines, namely L1 along the axis of the antenna, and L2 and L3 parallel to soil surface with 0.5cm and 4.5cm depths respectively are shown in Figures 5, 6 and 7. These lines are illustrated in Figure 4.

Figure 5(a) illustrates that the field level is reduced in the presence of soil and is further decreased when the soil's humidity is higher. However, one can not conclude in which case the absorbed power in soil is higher unless the imaginary part of the dielectric constant is taken into account. This can be calculated from Equation (4) which is the extended *Joule's* law for a normal medium without μ'' (imaginary part of permeability).

$$P_l = \frac{\omega}{2}\int_{v_s} \varepsilon'' |\mathbf{E}|^2 dv = \int_{v_s} APD\, dv \;\; (Watt) \tag{4}$$

where, we call the integrand as Absorbed Power Density (APD). The higher the APD the sooner the soil becomes warm enough. This is shown in Figure 5(b) where APD is plotted on L_1 from 50 mm away from the horn antenna downwards. The APD result of water replacing soil has also been added to Figure 5(b) showing that the wetter soil performs better than dry soil. However, as we are more concerned about the top 20 mm (50 mm to 70 mm) of the soil, increasing the water content from a certain value only reduces APD.

As can be seen in Figures 6 and 7, the lateral distibution of the E-field on L_2 and L_3 are plotted in the soil. In the absense of soil, the distribution is sharper. Though, the higher the wetness of the soil, the more uniform the field distribution is. For wet soil, the 3 dB width of E-field on both L_2 and L_3 are approximately the same size of the horn's aperture, namely 20 cm, resulting in the smooth temprature rise when the device sweeps the soil.

By using COMSOL Multiphysics, the temperature changes vs. time is studied in dry soil. The result shows that the maximum temperature is in the direction of the center of the antenna and the temperature change with time is linear (see Figures 8 and 9). As seen in Figures 8 and 9, the soil temperature exceeds 70 ° C after 60 seconds of radiation.

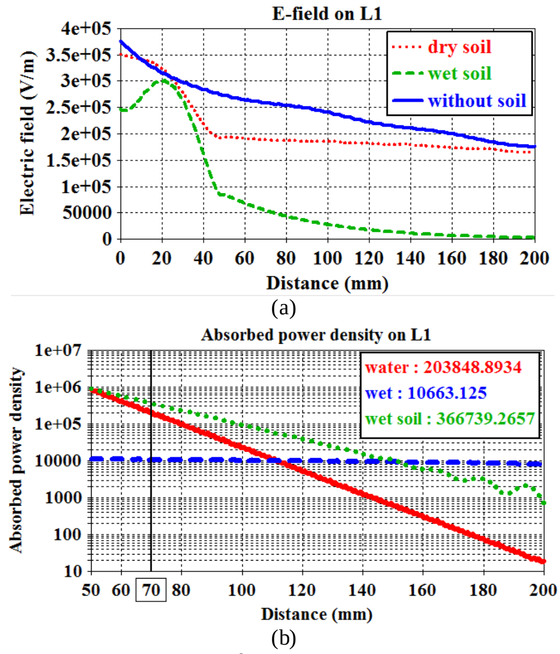

Figure 5. (a) Electric field on L_1 (b) Absorbed Power Density (APD) on L_1 (L_1 is shown in Figure 4)

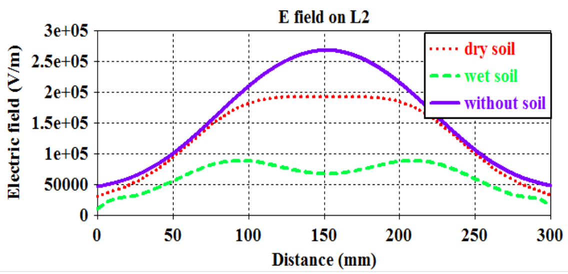

Figure 6. Electric field on L_2 (L_2 is shown in Figure 4)

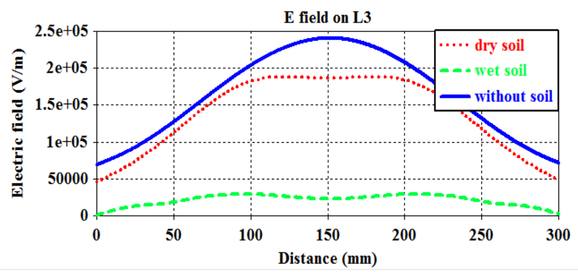

Figure 7. Electric field on L_3 (L_3 is shown in Figure 4)

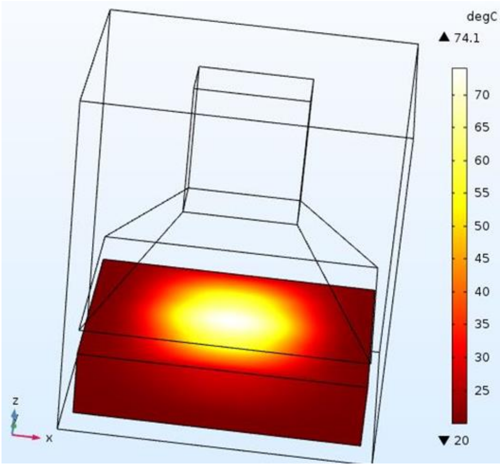

Figure 8. Distribution of temperature (in Celsius) in soil after 60 s radiation (input power 1kW)

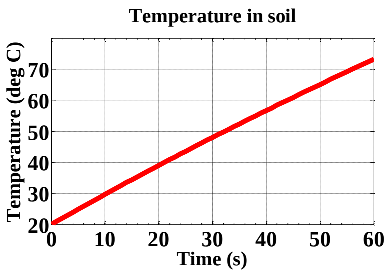

Figure 9. Temprature soil versus time (input power 1kW)

4. EXPERIMENT AND RESULT

Weed seed samples have been provided by the weed research institute of Iran. Among them, some herbicide-resistant weed types also exist. The scientific names of these seeds are *Amaranthus sp, Avena* fatua*(s), Avena fatua(r), Lolium spp(s), Phalaris spp(s), Phalaris spp(r), Chenopodium album(s),* in which *r* stands for herbicide resistant seed and *s* stands for non-herbicide resistant.

In this experiment, four treatments are considered for each seed. In order to reduce the statistical error and to ensure that the test response is valid, four iterations were considered for each treatment. Each treatment includes some soil that contains 20 weed seeds within it. Antenna aperture distance to the soil surface was 5 cm and the treatment was carried out in the same conditions under electromagnetic radiation. Then, samples were sent to the greenhouse of Iran weed research center and cultivated in a pot. In the greenhouse, four pots for each of the treatments were assigned as a control sample with which the results of affected samples under treatment were compared. After 20 days (see Figure 10), the number of germinations for each treatment was counted and data were analyzed by using SAS 9.2 software package based on completely randomized block design. The results of this analysis are demonstrated in Figure 11 showing that all types of weed lost their germination after getting to a temperature of 60 degrees (Celsius). It also shows that the hericide resistant type are even less resistant to microwave power than their non-herbicide resistant types. However, the number of samples are statistically not enough for the conclusion.

5. SAFTY TEST

There are several challenges and the hazards of using high power microwave sources in an outdoor agriculture field, some of which are related to issues coming from the outdoor radiation of electromagnetic waves. First and foremost is the safety of human users of the device. The leaked power from such a device should meet safety limits defined by related standards and recommendations such as ICNIRP [21] and IEEE [22] limiting the Specific Absorption Rate (SAR) of these devices. The second important problem is other related challenges such as biological and environmental issues, which are under research and are not covered here. The safety test of MWK device in the ISM band from 2.4 GHz to 2.5 GHz has been perform during 4 experiments according to the ICNIRP standard using the aaronia spectrum analyzer and printed dipole antenna [23]. The result of this test are shown in Table 3.

The minimum distance from the device is calculated using well-known Equation (4) which is also found in ICNIRP standard.

$$r_{\min} = [\frac{P_T.G}{4\pi W_{\lim}}]^{0.5} = [\frac{1000\times 0.48}{4\times\pi\times 10}]^{0.5} = 1.95m \qquad (4)$$

Figure 10. Seeds cultivated in a pot channel

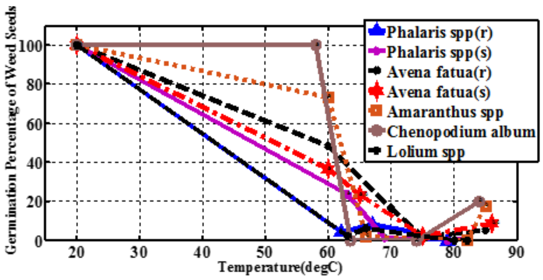

Figure 11. Result of data analyzed using SAS9.2

TABLE 3. Safety test result

No.	Distance from ground	Distance to spectrum analyzer	polarization	Electric Field level (dB)
1	7 cm	10 m	Vertical	-13.8
2	7 cm	10 m	Horizontal	-13.37
3	4 cm	10 m	Vertical	-13.4
4	4 cm	10 m	Horizontal	-13.34

In this equation, the power of the magnetron is considered to be 1000 W and maximum side lobe level of the antenna is assumed to be around 0.73 by using CST Microwave Studio simulations (see Figure 12). Based on this calculation, the device's operator and other people should not be closer than 1.2 m from its antenna, while they are not eletromagentically protected. This distance is affordable and can be improved by the help of some shielding mechanicsms.

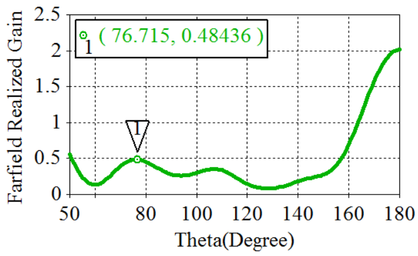

Figure 7. Antenna side lobe level in CST Microwave Studio

6. CONCLUSION

In recent years, the resistance of weeds to herbicides along with other challenges of using them has become a serious challenge. In the paper, the development of a low-cost but efficient microwave device and its analysis on the soil temprature has been reported. The successful measurement of microwave treatment on some weeds of Iran has also been reported. The experimenal results show that increasing the weed's temprature up to between 60° to 70° completely eliminates the gernimation of all sorts or weeds.

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Design and Fabrication of a Microwave Weed Killer Device for Weed Control Applications

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چکیده

در این متن، طراحی و نتایج سامانه تابشی مایکروویوی برای کاربردهای کشاورزی مورد بحث قرار گرفته است. سامانه با موفقیت ساخته و آزمایش شده است. این سامانه که از یک مگنترون ۱ کیلووات استفاده می‌کند. ۷ نوع علف هرز رایج در ایران توسط دستگاه مورد آزمایش قرار گرفته و سپس در گلخانه کشت شده است. نتایج نشان داد که با افزایش دمای خاک تا ۷۰ درجه سلسیوس، جوانه زنی آنها به کمتر از ۲۰ درصد می‌رسد (در برخی موارد نزدیک به صفر). قابل ذکر است که ایمنی این دستگاه با استفاده از استاندارد ایکنیرپ مورد بررسی قرار گرفته است.

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