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A Remote Microwave Thermal Sterilization Approach for the Coronavirus and Other Pathogens by Wireless Power Transmission

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Abstract

This work describes a proof-of-concept innovative surface sterilization approach using remote microwave heating. The method requires a thin water layer to be applied on the target (i.e., an infected surface). An antenna array then radiates power on the target, raising its physical temperature; this leads to thermal sterilization of the infected surface. In the proposed microwave system, the power is transmitted by a 4×1 microstrip Yagi array operating at 2.4 GHz, however, other antenna arrays and beam-steering systems are also applicable. By varying the distance and the incident angle between the array and the infected surface, theoretical and simulated results demonstrate that the sterilization process requires only a few minutes. This timely sanitization has many benefits in that an operator need not touch any infected surfaces and that the process can be totally automated. A simple experimental system constituted by a single-element antenna is tested and compared with theoretical results. The proposed remote sterilization approach also follows wireless power transmission techniques, abides by safe transmitter power levels, and could be applicable in battles against pathogens and, among others, the new coronavirus which causes COVID-19.

1 Introduction

Many pathogen viruses have appeared in the last few years, such as SARS-CoV in 2002 and H1N1 in 2009 [1]. In 2019, a new coronavirus (SARS-CoV-2) emerged, causing the COVID-19 disease and leading to a pandemic [2]. A number of researches have shown that coronaviruses can survive on dry surfaces, in water, or in human specimens for a few minutes or even hours, depending on the environment conditions [1,2]. For example, SARS-CoV-2 has a viability of 8 h on copper and about 48 h on stainless steel [2]. Therefore, the development of thermal sterilization methods for contaminated surfaces can limit the spreading of viruses, and it is highly desirable in hospitals, emergency vehicles, and within public buildings.

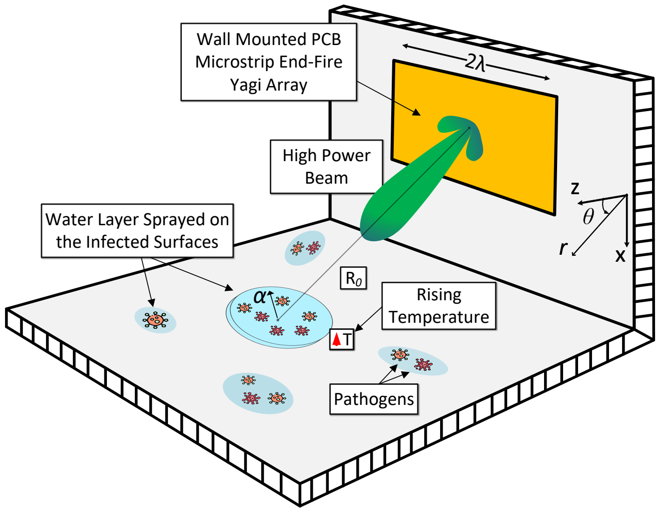

Figure 1. Illustration of the proposed microwave system for thermal sterilization. The transmitting antenna, considered here as a four-element array, could be mounted on a hospital room wall and radiates onto the infected surfaces which are sprayed with a thin water layer.

Nowadays, a number of thermal sterilization techniques exist, with many applications in medical instruments and tools. However, they are not based on remote microwave radiation [3]. Recent works [4], [5] have proved that decontamination and sterilization can be achieved through ultraviolet (UV) radiation or confined acoustic vibrations (CAV). In [4], the authors pointed out that UV radiation has a maximum virucidal effect in wavelengths between 240 – 280 nm and it usually applies in healthcare-associated infections. The decontamination lasts about 15-20 min and it can corroborate the main disinfection process. In [5], a robust method was proposed for the deactivation of airborne virus through stress fractures of their physical composition. A horn antenna was used to conduct the experimental results, operating between 6 to 12 GHz and with a maximum input power of 3.92 W. The experiment was successful as the viruses disseminated within the beam of the horn antenna were destroyed.

This work introduces a novel approach for remote thermal sterilization of infected surfaces using microwaves propagating in free-space. This contact-less thermal sterilization method could be applied in healthcare facilities, such as indoor hospital spaces or ambulances. The study is based on conventional thermodynamic concepts, radar principles, and wireless power transfer (WTP) techniques, typically used in applications such as wireless battery charging [6] and target tracking [7]. The proposed methodology, in this paper, starts by modeling the infected surface as a circular metallic plate (i.e., the target). A microstrip Yagi antenna array, operating at 2.4 GHz, then transfers power to the circular plate operating in near field (NF). Its compact design allows the user to go on operating within the surrounding environment, or, depending on the application, to manually beam steer the antenna array considering a hand-held system. Both concepts require end-fire radiation and other electronic beam steering approaches can compliment the technique. Regardless, Fig. 1 depicts the proposed setup installed onto a hospital room wall. The infected surfaces need to be sprayed by a thin water layer in order to be thermally sterilized.

2 Microstrip Yagi

A 2.4 GHz microstrip Yagi antenna was utilized in this work as a part of the proof-of-concept system setup. The design and analysis of the work in [8] was used for the fabrication of the antenna presented in Fig. 2. A dielectric laminate, ROGERS RT6010LM with ε_r = 10.2 and tanδ = 0.0023, was selected to realize the antenna substrate and to ensure a small and compact structure. The main lobe of the radiation pattern for the single-element Yagi antenna, as reported in Fig. 2, is between 20° and 60° in elevation due to the presence of four parasitic squared elements to achieve directive end-fire radiation. This design allows the mictrostrip Yagi antenna to be mounted on a wall, and thus points its main beam directly towards the ground or other surfaces (see Fig. 1). An antenna array could be alternatively used as transmitter (see Fig. 1), increasing the microwave incident power onto the target and would speed up the thermal sterilization time.

3 Thermal Sterilization Approach

This section describes the use of a 4×1 microstrip Yagi array to thermally sterilize an infected surface, modeled by a metallic circular plate with a known radius (i.e., α) and sprayed with a thin water layer at room temperature. An electromagnetic (EM) signal is transmitted by the array, thus increasing the temperature of the thin water layer and, as a consequence, that of the infected surface Fig. 1. The system architecture (antenna array and target) was implemented using the Computer Simulation Technology (CST). The simulation setup includes the radiating microstrip Yagi array, placed at various distances (R_0) and elevation angles (θ) from the circular plate. The incident on the circular plate power is recorded for each configuration of interest.

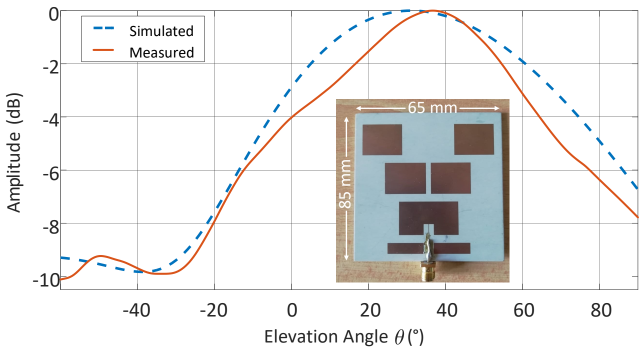

Figure 2. Simulated and measured beam pattern for the single-element planar Yagi designed using microstrip technology. The inset shows the fabricated PCB antenna based on a ROGERS substrate.

The temporal interval required to complete the proposed thermal sterilization method can be determined considering conventional theory. This process has the potential to sterilize the surface, as the new coronavirus is destroyed at 60°C [9].

3.1 Incident Power on the Infected Surface

The array was designed to operate in the NF region, which is bounded by a sphere of about 1.25 m. The incident power on a target, applicable in the NF, can be given by Eq. (2.5) in [10] multiplied by the monostatic Radar Cross Section (RCS), $\sigma(\theta,\phi)$, of the circular target with radius α, given by Eq. (35) in [11].

The array transmits power P_t, with a gain $G_t(\theta,\phi=0°,r)$ that depends on the elevation incidence angle θ, the azimuthal incidence angle ϕ and on distance from the target r = R_0 . Two different simulations using the CST solver were performed in the NF region, one with single-element antenna and the other with the array, in order to evaluate the aforementioned theoretical incident power. For the simulations, the circular plate radius (α) was selected as 3.5 cm and the thin water layer thickness (t) was set to 0.25 mm. It was placed at a distance R_0 = 25 cm, with elevation angle θ taking values from 0° to 75° and azimuthal angle $\phi=0°$. The input power, P_t, of the single-element-antenna and the array were set to 2 W and 0.5 W, respectively. The simulation and theoretical results of the incident power versus the elevation angle are presented in Fig. 3.

3.2 Required Time for Thermal Sterilization

The dimensions of the infected surface, the thermal sterilization duration and the required thermal energy are physical parameters that affect the process; this is described in the following. The energy required to increase the temperature can be determined through equation $E=c_p\Delta Tm$ [12], where c_p is the specific heat capacity, ΔT is the difference in temperature and m is the mass of the substance. According to [12], a surface with given mass and heat capacity has a specific heat capacity c_p. The term c_p [12] can be defined

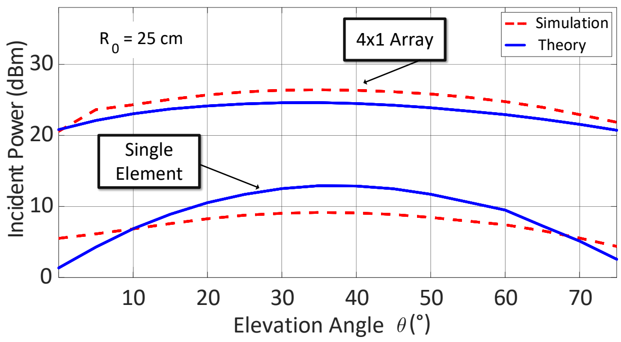

Figure 3. Incident power onto the target in terms of the elevation angle at a distance of 25 cm. The top curves refer to the 4×1 microstrip Yagi array while the bottom are for the planar Yagi single-element antenna (see Fig. 2).

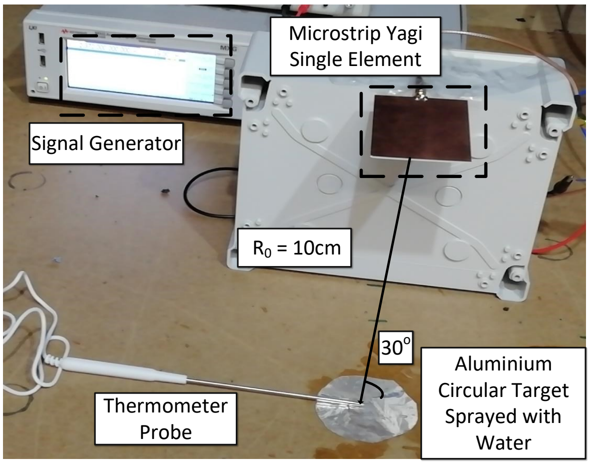

Figure 4. Experimental setup. The target was placed at a 10 cm distance and with an incident angle of 30° with respect to the single-element Yagi antenna.

as the ratio between the mass and heat capacity. The mass m can be expressed as $m = V\rho$ [13], where V is the volume and ρ is the density of the substance.

Assuming that a source is transmitting power at a fixed power level, the expression $t_{\text{total}} = E/P$ gives the required time for receiving a specific amount of energy. Combining the above equations, the total amount of time needed for increasing the temperature of the substance in the NF is as follows

$$t_{\text{total}} = \frac{4\pi r^2}{P_t}\frac{c_p(\mathrm{T}-\mathrm{T}_0)V\rho}{\sigma(\theta,\phi)G_t(\theta,\phi,r)}. \quad (1)$$

To evaluate the performance of the overall system, Eq. (1) is theoretically calculated for three distances R_0 = 10 cm, 20 cm and 25 cm for a fixed incident angle $\theta = 30°$ (Fig. 5). The transmitted power was set to P_t = 2 W, whereas the specific heat capacity of water is c_p = 4179.6 $\mathrm{J\,kg^{-1}\,K^{-1}}$,

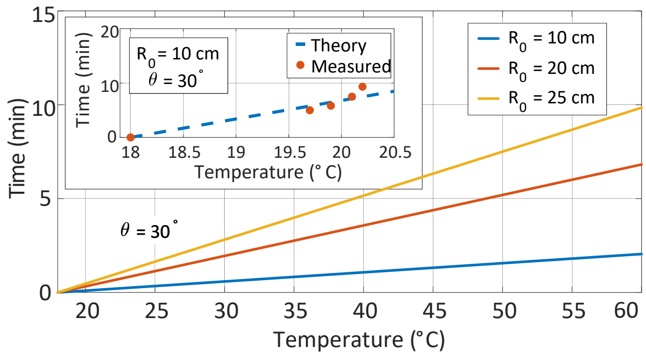

Figure 5. Time versus temperature calculations based on (1) for three different distances whilst considering a 2 W transmitter power. Encapsulated figure: lab measurements as compared to theory for a fixed 10 cm distance, 30° incident angle (see Fig. 4), and a 21.5 dBm transmitter power.

the original temperature T_0 was assumed to be 18°C, the water density is $\rho = 10^3$ $\mathrm{Kg/m^3}$, its volume is defined as $V = \pi\alpha^2 t$ $\mathrm{m^3}$ [13]. Based on the results, none of the three different distances that were investigated demands more than 10 min to reach 60°C (see Fig. 5). In order to validate the simulation results, a proof-of-concept experimental setup was built and tested within an anechoic chamber, including only the fabricated Yagi antenna at 2.4 GHz and a circular aluminium target sprayed by a thin water layer. A signal generator KEYSIGHT MXG N5183B was used with output power equal to −10 dBm, conneted in series with a 30 dB power amplifier MINI-CIRCUITS ZFL-2500+. Therefore, the input power of the antenna was P_t = 21.5 dBm (≈ 0.141 W), including the cable losses. The distance between the antenna and the target was set at 10 cm and the incident angle at 30°, as it is depicted in Fig. 4. The original temperature of the target was measured 18.8°C by a digital thermometer equipped with a probe, recorded at regular time intervals. The temperature inside the chamber remained stable at 19.9°C for the entire duration of the measurements. The experimental results are presented in the inset of Fig. 5. Good agreement can be observed between the measurements and the theoretical temperature values based on (1).

4 Conclusion

A thermal sterilization method applicable against harmful pathogens, such as the coronavirus which causes COVID-19, is presented in this work. The technique uses a 4×1 microstrip Yagi array which transmits power to an infected target until it reaches the required temperature achieving sterilization. As a starting point in the system design and its feasibility, a compact planar Yagi antenna based on microstrip technology was successfully employed for proof-of-concept. Results suggest that the system is feasible offering short sterilization times and for targets in the NF whilst considering safe levels of transmitted power. The four-element array will also be tested in future measurement campaigns in order to maximize the efficiency of the system and to reduce the sterilization time.

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