Microwave Generator For Scientific And Medical Applications

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Abstract. Nowadays power microwave radiation is widely used in medical applications as hyperthermia, diathermy or ablation and for scientific applications such as plasma generation, digestion, or as a catalyst in green chemistry. Nevertheless, designing a suitably adapted microwave generator that meets both the scientific and the more restrictive medical criteria remains a difficult task. We present here a simplified approach in designing such a microwave generator, according to the IEC60601 medical standard. The generator, based on a continuous wave (CW) magnetron, is coupled via a TE10 waveguide to feed either a hyperthermia applicator or a reactor chamber. Microwave interactions with the probe (or the tissue) depend strongly on the magnetron's power supply parameters and the impedance match of the entire microwave circuit. Any unmatched elements (magnetron to waveguide, waveguide to applicator, applicator to patient) give rise to a large voltage standing wave ratio (VSWR) which loads the generator with a surplus energy, converted to heat. Extra heating of the magnetron will deteriorate the amplitude of the generated microwave power field. We show here that, by using a proprietary patented temperature sensor sheet, we were able to detect and improve the impedance matching of the microwave circuit.

Keywords: magnetron, wave-guide, termographic detector, high voltage power supply.
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INTRODUCTION

The continuous wave (CW) magnetron, invented back in 1921 by Albert Hull at General Electric, is the oldest thermoelectric vacuum device which generates microwaves (MW) [1]. The resonant cavity version (invented 14 years later by Hans Hollman at Telefunken) [2] is still present nowadays in domestic microwave ovens or in linear accelerators (LINAC) [3] used for X-ray generators as well.

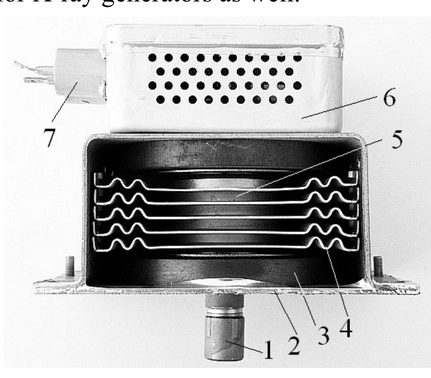

FIGURE 1. The CW magnetron aspect: 1-antenna, 2-mounting plate, 3-magnet, 4-heat sink, 5-anode, 6-filter box, 7-cathode and filament terminals.

The magnetron is widely used in medical devices for generation of controlled thermal effects inside the body tissues [4]. The magnetron operating theory is well known [5]; however, the practical approach in extracting the microwave radiation from the magnetron antenna (1, see Figure 1) and transfer it to the probe, may cause various types of problems, from MW circuit impedance mismatch to spark-over voltage generation into the waveguide. Running the magnetron has two operating aspects: the power supply level, which refers to the anode and the filament voltage parameters for keeping the magnetron in the active oscillating area, and the MW level, which includes the propagation aspects over the entire microwave circuit. The power supply parameters are modifying the MW output spectrum [5-6] (bandwidth, stability of the MW central frequency). The magnetron waveguide parameters are influencing the amplitude of the MW energy which travels to the load (while a part of it may be reflected back to the magnetron).

MATERIAL AND METHODS

The simplified schematic of the microwave generator is presented in Figure 2. It uses a CW magnetron (3) as the heart of the device, mounted on a waveguide (4) with a coaxial adapter to feed an applicator (5).

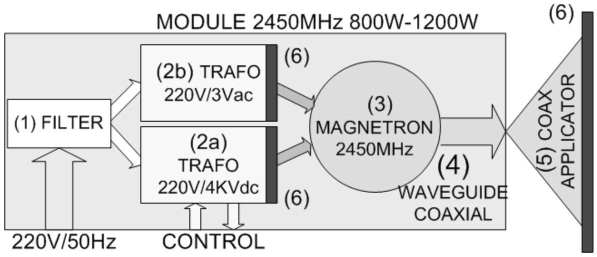

FIGURE 2. Microwave generator structure: 1-low pass filter (LPF), 2a-anode supply, 2b-filament supply, 3-magnetron, 4-waveguide to coaxial, 5-coaxial applicator, 6-isolation barrier.

The Electric Circuits

A continuous wave, 2458 MHz magnetron, model AM701, rated at 850W [7], has been used (Figure 3). The power supply is a zero cross, pulse width modulated (PWM), high voltage anode transformer followed by a voltage doubler. The filament is powered from a separate, highly isolated, transformer (the filament voltage has the same potential as the cathode voltage, ground being the reference point). This particular supplying topology, in which the anode is mechanically (Figure 4) and electrically grounded (Figure 5), does not meet the electrical isolation criteria regarding the pacient, as stipulated by the IEC60601 standard [8]. That is why, an electrical isolation barrier between the microwave waveguide and the pacient is mounted on the applicator aperture (Figure 2), the isolation barrier between the power supply and magnetrons being ensured by the transformers. Two types of isolator materials have been used for the applicator, both transparent to the microwave radiation: FR2 (pertinax) and PFTE (teflon).

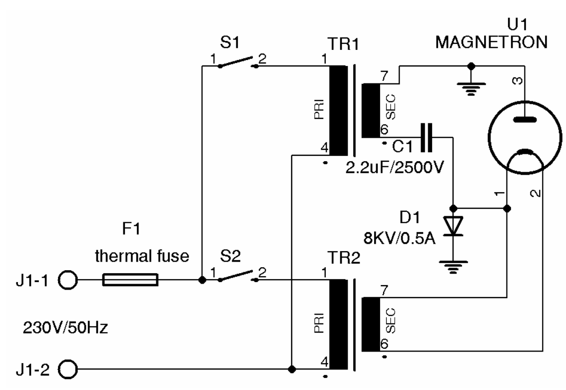

FIGURE 3. Classic magnetron power supply: TR1-anode transformer, TR2-filament transformer, F1-thermal fuse, C1 and D1-voltage doubler, S1 and S2-zero cross electronic switch, U1-CW magnetron.

TABLE 1. Isolator materials parameters

Material	Permittivity @1MHz	Dielectric strength [V/mil]	Loss tangent
FR2 (pertinax)	4.5	min 740	0.024-0.26 at 1MHz
PFTE (teflon)	2.1	min 1000	$15\cdot10^{-4}$ at 3GHz

The zero cross electronic switches (Figure 3) are using solid state relays (SSR), designed and manufactured with power triacs driven by MOC3061 optocouplers [9]. An universal embedded system [10] is driving the SSRs, based on the probe's temperature variation and using a proprietary PWM algorithm. Both transformer- and inverter-based magnetron power supplies can be driven by this embedded system.

The Microwave Circuits

The key for obtaining a properly transversal electric TE10 distribution into the waveguide is to maintain the position of the magnetron antenna at a distance L from the waveguide flange:

$$L = n \cdot \lambda_g / 4 + \lambda_g / 8 \qquad (1)$$

where n = even integer number (2, 4, 6…).

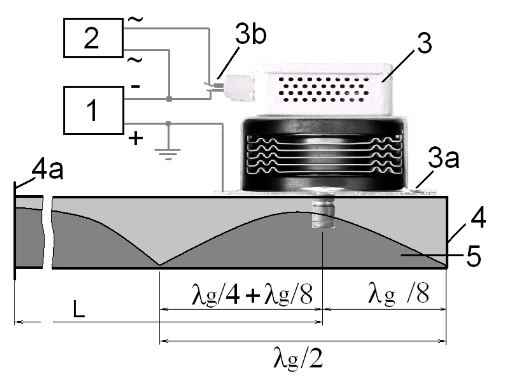

FIGURE 4. Magnetron placement on the waveguide: 1-anode power supply, 2-filament transformer, 3-magnetron, 3a-anode, 3b-filament and cathode, 4-waveguide, 4a-waveguide flange, 5-electric field distribution.

This particularity is explained by the magnetron internal distance between the antenna and resonators, which is approx. $\lambda_g/8$. Since coupling in the electric field maximum has been chosen (Figure 4), the maximum electric field appears at approximately $\lambda_g/8$, as measured from the waveguide end.

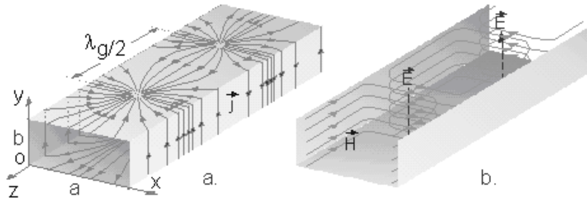

FIGURE 5. TE10 theoretical microwave field distribution. (H-magnetic field, E-electric field, J-current density, λ_g= waveguide wavelength).

The theoretical TE10 field distribution into the waveguide is presented in Figure 5. As shown, the current density (J) through the waveguide walls has maximum distribution in the maximum intensity of the electric field (E). Therefore using a conductive material (copper, or even inoxidable iron) for the waveguide walls is mandatory, since the skin depth (2) is smaller.

$$\delta = \sqrt{\frac{2\rho}{\omega\mu}} \qquad (2)$$

where:
ρ[S/m]= conductor resistivity
ω[rad/s]=angular frequency of the current
μ[H/m]=magnetic permeability of the material

TABLE 1. Skin depth in the waveguide walls at 2.45 GHz

Material	Skin depth [μm]
copper	1.33
iron	3.16

The waveguide length is given by:

$$\lambda_g = \frac{\lambda_0}{\sqrt{1-(\lambda_0/\lambda_c)^2}} \qquad (3)$$

where:
λ_0[mm]≈300/f_0 is the open space radiation wavelength
f_0[GHz] = open space frequency
λ_c[mm]=2π/k critical waveguide radiation wavelength Here k represents the wave number:

$$k = \sqrt{\left(\frac{m\pi}{a}\right)^2 + \left(\frac{n\pi}{b}\right)^2} \qquad (4)$$

where:
m=1 and n=0 are the mode propagation coefficients for TE(mn) = TE(10); a[mm] and b[mm] are the waveguide geometric dimensions on Oy and Ox axes (Figure 5) and a = 2b.

The waveguide impedance is:

$$Z_{TE} = Z_0 / \sqrt{1-\left(\frac{f_c}{f_0}\right)^2} \qquad (5)$$

where: Z_0[Ω]=120π is the free space impedance
f_0[GHz] = open space frequency
and:

$$f_c \approx 300/\lambda_c \qquad (6)$$

is the critical frequency [GHz]. The critical frequency is the frequency limit for which the radiation does not propagate anymore in the waveguide. Table 2 contains the waveguide computed parameters, which have been used for practical design of the waveguide.

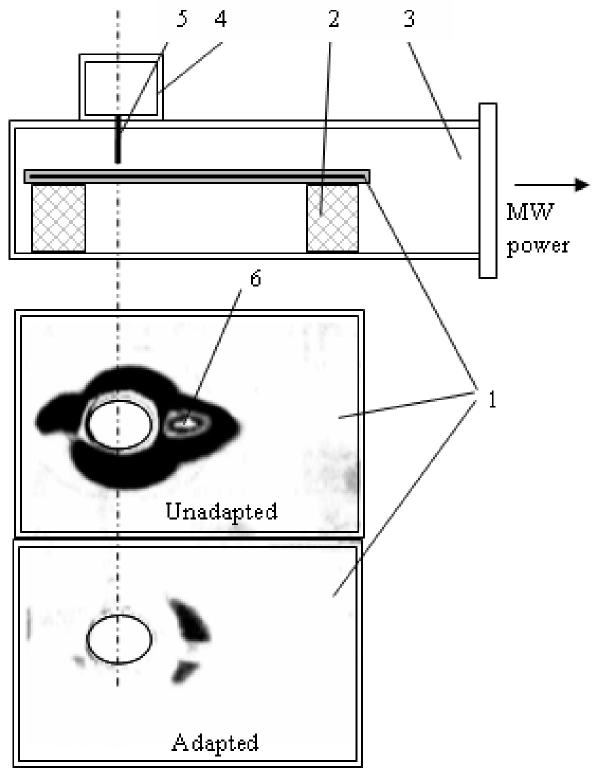

FIGURE 6. Coaxial to waveguide adapting measurements with patented termographic transducer: 1-termographic transducer sheet showing the MW power distribution for adapted and unadapted cases; 2-dielectric support (honeycomb material); 3-microwaves waveguide; 4- CW magnetron; 5-magnetron antenna; 6-trace of the microwave power leakage in the unadapted case.

TABLE 2. Waveguide computed parameters

f_o[GHz]	f_c[GHz]	λ_c[mm]	λ_g[mm]	Z_{TE}[ohm]	l[mm]	a[mm]	b[mm]
2.45	1.78	168	179	550	156	84	42

Testing the MW circuits

Testing the MW circuits adaptation has been accomplished using a patented MW thermographic transducer. The termographic transducer acts as a photographic paper in the microwaves power field. The local density of the microwaves power is visible as a gray scale image on the transducer. To acquire the image of the microwaves power density, the transducer sheet is positioned in the desired section of the MW circuit (Figure 6) and is exposed to the MW radiation for a specific period of time (30s-180s) [11]. In this particular experiment, we have tested the magnetron to waveguide transition, to analyze the impedance match, hence the power rate transfer from the magnetron to the load through the waveguide. It can be observed that in the unadapted case, there is a stationary power field distribution around the magnetron antenna and a local high voltage leakage occurs. Adjusting the magnetron adaptation is still possible by slightly modifying the $\lambda_g/8$ length between the magnetron antenna and the closed end of the waveguide (Figure 4) by using a piston. The leakage can create sparks, mostly when the air humidity in the waveguide is increased. Even if the magnetron is a robust device, uncontrolled sparks near the magnetron antenna can create large voltage standing wave ratio (VSWR) so that huge electric fields appear inside the resonant cavities of the magnetron and may damage the MW generator device irreversibly.

CONCLUSIONS

Even if the theory of MW generation using a CW magnetron is well known, the practical approach for designing, manufacturing and testing a microwave generator using a CW magnetron for being used in the scientific or medical applications is still a challenge (Figure 7). Using the PWM technique for driving the magnetron power supply allows to control the MW radiation energy over a wide range. However, since the smallest MW pulses still have an output power of 800W, the microwave circuit must meet the MW high power design criteria, meaning that a proper adaptation between the magnetron, the waveguide and the load is an important issue. Rather than simulating, real tests on the MW generator and circuits are mandatory in order to achieve an operational equipment. A CW magnetron with its particular power supply scheme as described, will meet the IEC60601 electrical isolation requirements, despite the fact that the MW waveguide is connected to the protective ground.

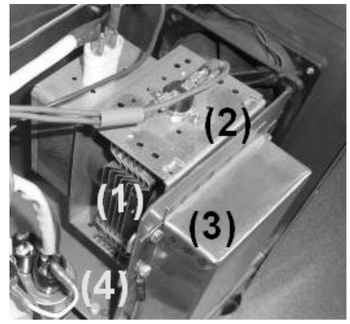

FIGURE 7. MW generator appearance: (1) CW magnetron, (2) temperature switch, (3) waveguide, (4) power supply

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