Microwave Memos
Memo 23

14 November 2013

Particle-in-Cell Modeling of Oven Magnetron: A Review

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Abstract: *The conventional microwave oven with the 2.45 GHz "cooker" magnetron producing output microwave power of 0.7-1.0 kW has become de-facto one of the "must-have" from the long line of different kitchen appliances available for everyday use in every single US home or office. A problem has arisen, however, during the last 10 years with the rise of numerous wireless systems, most notable of which is the IEEE 802.11/WiFi system, operating at the same frequency 2.45 GHz in a close proximity to the working microwave oven. The problem is called the Electro-Magnetic Interference (EMI) and it is making life really complicated for nearby wireless computer networks and numerous home/office wireless devices. One of the possible solutions of the EMI problem is to redesign the "cooker" magnetron to operate at the frequency located at the outer edge of the Wi-Fi spectrum, 2.48 GHz for example. The paper describes how the modern computer particle-in-cell (PIC) simulations of a conventional double-strapped ten-cavity non-relativistic magnetron may help one to design and build the new 2.48 GHz "cooker" magnetron with the reduced EMI problem to home/office 2.45 GHz wireless devices.*

Keywords: Microwave oven, cavity magnetron, particle-in-cell simulations.

INTRODUCTION:

Modern 2.45 GHz "cooker" magnetron is not a noisy device. "*Continuous wave (CW) magnetrons and in particular cooker magnetrons ... had particularly noisy spectra before the introduction of the carburized, thoriated, tungsten cathodes. The poor noise performance was partly attributable to ion emission from the cathode. Work sponsored by the National Aeronautical and Space Administration (NASA) and the Department of Energy (DoE) in the late 1970s revealed that magnetrons with carburized, thoriated, tungsten cathodes had very low noise levels when operated from well-filtered dc power supplies and with the cathode heater current turned off. The interest in this case was to beam electrical power to Earth from solar satellite farms* [1]."

Conventional "microwave" ovens are, however, particularly quite electromagnetically "noisy" cooking machines by reason of driving their 2.45 GHz cooker magnetrons with the rectified *ac* voltage instead of the well-filtered *dc* one. By other words, the noisiness of the conventional microwave ovens is explained not by the noisiness of their 2.45 GHz cooker magnetrons but by *"...the rectified a.c. drive of the cooker magnetron by the typical half-wave doubler supply of almost all microwave ovens. In this case the anode voltage waveform is approximately a square wave at around 4 kV peak applied during one half cycle at the line frequency (50 or 60 Hz.) while the corresponding anode current waveform approximates a half-sinusoid. Thus the anode current is repeatedly swept from zero to some peak around 1 Ampere and then back to zero for oven power between 700 and 1000 Watts* [2]".

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There are typically *"... three values of anode current corresponding to* (i) *high noise,* (ii) *spurious oscillation, and* (iii) *low noise. ... At an anode current of 0.2 A, we see broadband random noise on both sides of the fundamental signal at around* f_0*=2.45 GHz. We call this noise sideband noise since it tends to peak up at frequencies like* $f_0 \pm \Delta f$*. The value of* Δf *increases with anode current perhaps as the square root of anode current. Associated with these noise sidebands is low-frequency noise that is conducted and radiated from the high-voltage cathode leads. This low-frequency noise will exhibit peaks at* Δf*, which tends to vary within the range of 150 to 300 MHz typically. This noise and its harmonics (e.g. 300 to 600 MHz) will cause some discernible interference with either VHF or UHF TV or both in the case of a microwave oven. In this case RFI* [radio-frequency interference] *varies periodically with a period of about a second in synchronism with the mode-stirrer cycle. At an anode current of 0.5 A, we see discrete spurious (sideband) oscillations at* $f_0 \pm \Delta f$*. These peaks can be quite strong, e.g. only 30 dB or less below the fundamental. The associated low-frequency power at the cathode can be quite high. Values as much as 10 Watts have been measured at the cathode. Clearly the magnetron anode voltage is being modulated strongly at a rate in the VHF range with subsequent AM and FM phenomena across the whole spectrum, i.e. sidebands around the fundamental and all harmonics. At the peak anode current of 1.0 A we find no measurable noise above the floor of the spectrum analyzer. Clearly we are in the low-noise region at 1.0 A* [3]".

In addition to the existing RFI problem caused by the low-frequency noise occurred during the conventional microwave oven operation [2], [3], another serious issue has arisen, during the last 15 years of technological progress, with the rise of numerous wireless systems operating at the same frequency 2.45 GHz (such as Bluetooth, IEEE 802.11/WiFi, IEEE 802.15.4/ZigBee and other personal area networks [4]), when they happen to be in the close proximity to the operating at the frequency 2.45 GHz microwave oven. The issue is called electromagnetic interference (EMI) and it makes life really complicated for nearby wireless computer networks and numerous home/office wireless devices [5].

One of the possible solutions of the EMI problem is to slightly redesign an internal slow-wave structure (SWS) of existing cooker magnetrons to make it operate at the fundamental located near the outer edge of the WiFi frequency spectrum, 2.48 GHz for example [7]. In this case, the magnetron operating frequency 2.48 GHz will be still within the allowed by the Radio Regulations 7th ISM frequency band, 2.40-2.50 GHz [4], and well within the absorption (equivalent to dielectric loss) spectrum of the liquid water, which spans within the broad microwave frequency range with a maximum dielectric loss factor 40 at ~8 GHz and characteristic dielectric loss factor 10 at ~1 GHz and ~75 GHz, when the water temperature is ~ 0^{o}C [6]. Another solution would be to build a conventional microwave oven around the 5.80 GHz magnetron [8], but this would probably require total reconsideration and reexamination of the current concept of "microwave cooking", which might be pretty much time- and money-consuming effort.

So, what does it practically mean – to redesign the existing SWS of the cooker 2.45 GHz magnetron to make it operational at different frequency, 2.48 GHz? The answer is – in the beginning of the XXI century it means: (i) to build the virtual model (VM) of the device, (ii) to perform extensive computer simulations of the device operation, and (iii) to come up with such a design variation of an existing device that will allow this device to demonstrate in simulations a new characteristic of its operation – a turn of events within the virtual reality that saves both time and money in the real world. Only after this turn of events, an experimental prototype of the device with the new design variation might be built and the new characteristic, which is in this case the increased from 2.45 GHz to 2.48 GHz fundamental of the cooker magnetron operation, might be experimentally studied using the built prototype of the device. Indeed, there is so much faith in computer simulations today that the Raytheon Company, as an example of one of many research centers dealing with microwave vacuum electronic devices (MVEDs), will not begin to build a single microwave source until the Company's scientists and engineers are entirely happy with the predicted in computer simulations operational characteristics of the device.

PARTICLE-IN-CELL COMPUTER SIMULATION OF 2.45 GHZ MAGNETRON:

Simulations of cavity magnetrons and other MVEDs, both relativistic and non-relativistic, are performed using modern three-dimensional (3D) finite-difference time-domain (FDTD) particle-in-cell (PIC) computer codes allowing scientists and engineers to analyze most important features and regularities affecting MVEDs operation.

The first noticeable attempt to numerically simulate the heavily-strapped non-relativistic ten-cavity 2.45 GHz cooker magnetron with modern 3D PIC code was done by scientists from Seoul National University and Samsung Electronics, Korea in 2003-2004 using MAGIC code [9]-[12]. Results of these simulations were compared with measured output parameters of the real cooker magnetron manufactured by Samsung Electronics. Simulations showed "… *the formation of the five electron spokes in the oscillation region* [that] *confirms the π-mode oscillation of a 10-vane strapped resonator showing its mode separation with the adjacent mode to be 82%. The measured operating frequency of 2.465 GHz and the saturated output power of 1.04 kW are in good agreement with the simulated values of 2.470 GHz and 1.07 kW, respectively. The magnetron with an efficiency of 75% is operated at the beam voltage of 4.3 kV, the anode current of 0.33 A, and the cathode current of 1.08 A when external axial magnetic field of 0.19 T is applied. The measured second and third harmonics of the radiated output are 4.93 and 7.43 GHz and, [when] compared with the simulated one ..., agree well with each other* [12]*."*

Another group of scientists from University of Michigan, Ann Arbor and NumerEx, Albuquerque numerically simulated 2.45 GHz cooker magnetron in 2004-2005 using ICEPIC code [13]-[16]. In the course of this research, not only a standard microwave oven magnetron operation (4 kV, 0.17 T) was studied, but a possibility to reduce the noise level and shorten start-up time of magnetron oscillations using so-called "magnetic priming was investigated. Experimentally [17], [18], magnetic priming "*was implemented by placing a number of small perturbing magnets on the perimeter of the existing annular magnets of the kW magnetron, providing an azimuthally varying axial magnetic field (axially asymmetric). ... For an N-cavity magnetron operating in the pi-mode, magnetic priming consists of the imposition of N/2 magnetic field perturbations in the azimuthal direction. ... In terms of frequency, anode current, and output power the simulated model was reasonable close to the real magnetron"* [15], [16]*". "Peak power operation occurred around 1 A of emitted current which resulted in 340 mA of anode current due to spoke formation in the insulated electron flow. Operation at this level resulted in output power on the order of 750 W ... for the case of uniform magnetic field. Both the steady-state anode current (340 mA) and the output power level (~750 W) are consistent with ... experimental results (300 mA and ~730 W), suggesting that the simulation is providing a good model of the strapped oven magnetron* [14]*."*
It was observed that without magnetic priming, the simulated model produced a power envelope having a strong modulation with a period of about 2.5 ns. ... Also, the simulated model shows a preoscillation stage, nearly 20 ns, when no power produced. When five perturbing magnets were added (at one end of the magnetron axis) to simulate the azimuthally varying axial magnetic field geometry (axially asymmetric, magnetic priming), respecting roughly the experimental magnet size, strength, and position, the signal history changed dramatically. The signal exhibits no pre-oscillation stage, mode growth is very rapid, spokes are immediately formed, and power envelope lacks the strong modulation [15]*".*

Magnetic priming of the cooker 2.45 GHz magnetron operation was also studied by group of scientists from University of Electronic Science and Technology of China and Queen Mary University of London, England in 2005 using MAGIC code [19]. "*The simulation of the magnetron performance was carried out using three distributions of magnetic fields, i.e. the uniform distributed one (axial component only), the step distributed one (axial component varying with the radial distance) and the real distribution (axial and radial components) obtained from computer modeling with the verification in measurements. The simulations show that with the uniform magnetic field, the performance of the magnetron in terms of oscillations start up time, frequency spectrum and stability is inferior compared with those using the non-uniformed magnetic fields. In fact the non-uniform magnetic field can substantially reduce the start up time and improve the frequency spectrum and stability. This observation suggests that non-uniformed magnetic field is a better choice for the magnetron operation, which challenges the conventional approach in magnetron design, in which a uniform magnetic field is always perused"* [19].

In the following years, numerical simulations of the 2.45 GHz cooker magnetron operation using MAGIC code were continued in Korea and China with introducing a number of interesting technical approached allowing magnetron manufacturers to improve operational characteristics of their devices. The most noticeable publications described:

- the use of the five-fold perturbation of the radial electric field along the azimuthal direction by anode shape modification (anode priming) [20]. "*This magnetron was operated at the beam voltage of 4.3 kV, an* *axial magnetic field of 0.19 T, and an anode current of 330 mA, which is the nominal operating current at an output power of 1 kW near the 2.46 GHz operating frequency. ... Fast oscillation startup in a strapped magnetron using electrically primed electrons is demonstrated. The startup time is advanced from 62 to 52 ns, and the steady-state is reached in a shorter time span, from 130 to 85 ns when the radial variation of the protrusion and recession of the central region of the anode is 0.3 mm with an angular width of 0.5 mm*" [20].

- the use of transparent cathode made of three, five, and ten single emitters arranged along a circle in the center of the magnetron SWS (cathode priming) [21]. " … *it has been observed that the fast start-oscillation, fast π-mode spoke formation, parasitic mode suppression is not sensitive to the N/2 cathode zones in N-cavity magnetron*." [21]. It has been also shown that the transparent cathode reduces startup time of magnetron oscillations from 60 ns to almost 10 ns, and decrease the time necessary to reach the saturated output power from 130 ns to almost 40 ns [21].
- the use of various mismatched loads modeled by different length of the output antenna connecting one of ten vanes of the SWS with the output port of the magnetron simulation model [22], [23]. Simulations showed that "*… formation of magnetron bunches are loose or tight depending on the magnitude of the microwave power because of the magnitude and the phase of the reflected wave in the magnetron resonator. Changes in the electron-wave interaction mechanism eventually affect the operating voltage, the output microwave power, the microwave frequency and the return current*" [23].

There should be also noted recent numerical simulations of a classical oven 2.45 GHz magnetron using VORPAL code (part of VSimSuite) [24] and CST PARTICLE STUDIO (part of CST STUDIO SUITE) [7] aimed studying possibilities of, respectively, phase-locking of a number of cooker magnetrons into a coherent network of phase-locked oscillators [24], and testing the electrical, magnetic, thermal, and mechanical characteristics of a low-interference magnetron design [7].

CONCLUSION:

Review of the published results of numerical simulations of a cooker 2.45 GHz magnetron [7]-[24] shows that all these simulation were performed using an idealized flat input voltage pulse with a very short rise-time (1 ns in [9]-[12], 5 ns in [13]-[16], for example) and the total pulse duration from tens nanoseconds to a few hundreds nanoseconds. The use of such short fronts (rise-times) of the input voltage, which is, however, very typical for PIC simulations of MVEDs operation, completely eliminates any possibility to numerically study the RFI problem caused by the low-frequency noise radiated by microwave ovens (by cooker magnetrons), during the gradual rise (on the hundreds milliseconds time scale) of the emitted cathode current from 0 to a peak value of 1 A [2], [3] in a half-cycle of the magnetron power supply at the line frequency of 50/60 Hz.

The short rise-times and sub-microseconds durations of the steady-state input voltage in PIC simulations of the cooker 2.45 GHz still allow one to numerically study the EMI problem caused by interference of the microwave oven's fundamental, 2.45 GHz, with different wireless systems operating at the same frequency 2.45 GHz. There are no doubts that this is very interesting topic for research, which may be used, for example, in an attempt of redesigning the 2.45 GHz SWS of the cooker magnetron into the one oscillating at 2.48 GHz, for example.

However, in order to numerically simulate the low-frequency spectrum of the microwave oven, i.e. study the RFI problem, the hundreds milliseconds durations of the input voltage pulses with a realistic half-sinusoid pulse shape should be used in PIC simulations of the 2.45 GHz cooker magnetron operation. Fortunately, this is not-unrealistic task, as it may be thought even five years ago, given the current capabilities of the modern computer codes, such as ICEPIC and VORPAL. Those codes already allow the advanced MVED designers to perform PIC simulations on, literally, hundreds of thousands of processors by employing parallel processing techniques, such as message passing and load balancing algorithms available at the existing supercomputing architectures.

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