COMPUTATIONAL ANALYSIS OF A TAPERED SLOTTED WAVEGUIDE AS A RADIATING ELEMENT

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ABSTRACT

An irregular (tapered) waveguide with a non-linear longitudinal slot suggested in paper[6] as a radiator providing uniform field distribution of the surface of an elongated dielectric slab the near-field zone is analyzed with the use of the 3D conformal FDTD simulator *QuickWave-3D*. Advanced computational study reveals the structure's limited potential for microwave high power applications because of its low radiation efficiency and uneven radiated electric field. Valuable capabilities of the used software in analysis and design of microwave applicators are also demonstrated.

INTRODUCTION

The recent review of electromagnetic (EM) software[1,2] has shown that there are several simulators on the market, which are suitable for modeling of processes and systems of microwave (MW) heating. *QuickWave-3D* (*QW3D*) (http://www.qwed.com.pl), the 3D full-wave conformal FDTD simulator has been identified as a particularly useful tool due to a number of implemented specific extensions and helpful functions (field envelopes, energy coupling, basic heating module, and others)[2]. The heating intensity in the food loads in a MW oven computed with *QW3D* was presented in[3]. This modeling package was used to characterize single- and multi-mode systems, which are typical in MW chemistry[4]. In paper[5], *QW3D* was utilized to find characteristics of a 915 MHz water load and especially those ones which cannot be measured. This experimentally verified computational analysis has suggested that many existing MW systems and elements developed on the basis of extensive experimentations and simplified calculations could be accurately studied with the use of this computational tool in order to characterize EM processes in these devices more precisely and to get the ideas on possible ways of their modification and optimization.

The present paper pursues such a goal with respect to a special radiating element (RE)[6], which reportedly provides relatively uniform field distribution on the surface of an irradiated dielectric slab in the near-field zone. Rigorous analysis of this structure appears to be extremely difficult, so it has been synthesized by its authors from an admittance integral equation and with the use of the perturbation theory under a number of assumptions. A RE with the claimed capability would be of high value for many MW heating applications

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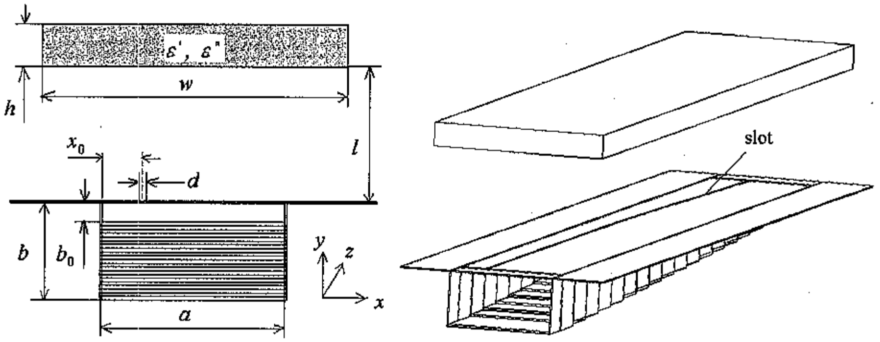

Fig. 1. Vertical profile and 3D view of the applicator with the irradiated dielectric layer

(particularly, in wood processing). However, the method used for its design doesn't allow engineers to figure out important characteristics of the system in detail, and experimental options here are either limited, or expensive. We show that valuable and reliable information about this RE can be generated by accurate *QW3D* simulation and with the use of modest computational resources.

APPLICATOR

The irregular (i.e., tapered) rectangular waveguide with non-linear longitudinal radiating slot cut in its broad wall (Fig. 1) has been proposed in[5] for heating of sheet and band materials. The radiation from the RE is supposed to be uniform when the amplitude of the transverse current induced by the TE_{10} mode is constant with respect to the longitudinal *z*-coordinate. The RE's authors suggest that this amplitude primarily depends on the waveguide narrow wall, the distance from this wall to the slot, and the fundamental mode's attenuation constant. From this assumption, the slot was found to be of curvilinear profile.

Paper[6] also describes an experimental verification of the synthesized RE at 2.45 GHz, but does not provide complete information about the experiment: material parameters of the irradiated plate are not specified, presence of other objects near the RE is not mentioned, etc. Therefore, direct comparison between the experimental data and simulations is not possible. For this reason, our goal has been to create a parameterized computer model wherein all structure dimensions, materials parameters and excitation can easily be changed, and independently validate with this model the principle of the RE operation and compute its characteristics inaccessible for the simplified analysis preformed by the RE's authors.

MODEL

The scenario has been modeled by *QW3D* as an open structure. The slotted waveguide and the wood plate were considered surrounded by the surfaces imitating the near-to-far field transformation and the absorbing boundary conditions. The slot profile $x_0(z)$ has been approximated by two straight-line segments. Following[6], in our computations, the length of the slotted waveguide was 1,000 mm; $a \times b = 90 \times 45$ mm and $a \times b_0 = 90 \times 9$ mm were the input and output waveguide cross-sections respectively; the width of the slot d was constant (2 mm). The rectangular wood plate of 1,000 mm length ($w = 150$ mm, $h = 20$ mm) was placed in parallel to the waveguide (with $l = 100$ mm). Dielectric constant ε' and loss factor ε'' of the wood plate unknown in the experiment[6] were taken equal to 3.8 and 0.87 respectively.

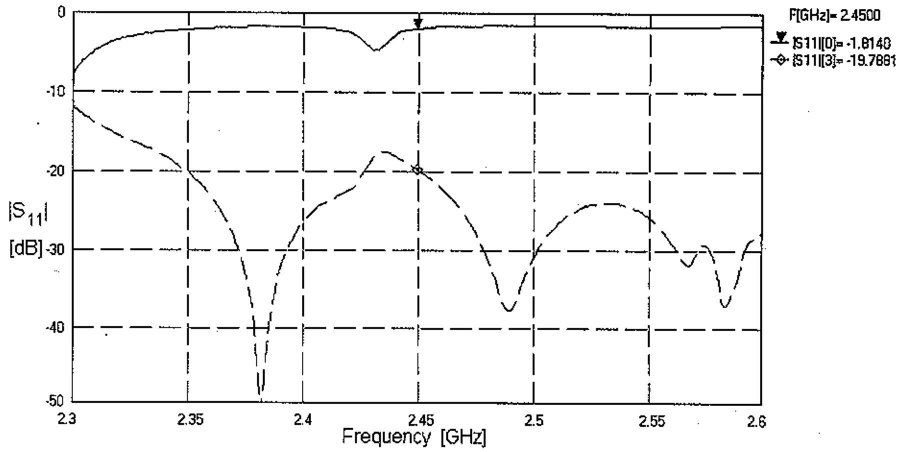

Fig. 2. Return loss with (dotted curve) and without (solid curve) a matched load in the tapered end of the waveguide.

Simulation with a wide-band pulse excitation has been used to compute reflections in the slotted waveguide and to calculate the radiation pattern of the RE. Sinusoidal modal excitation at 2.45 GHz (TE_{10} mode) has been applied then to determine distribution of the field and dissipated power.

The space within the coordinate planes with the absorbing boundary conditions has been discretized with the use of a non-uniform mesh consisting of the cells varying in size from 2×4×10 mm to 10×8×10 mm: the larger cells are in air while the smaller ones are placed within the wood plate and around the narrow slot to guarantee its good approximation. These cell sizes are smaller than typically recommended for a conventional FDTD discretization (10 cells per wavelength in a medium), thus the accuracy of computation is supposed to be satisfactorily high. To make sure that this is the case, the results have been tested on a denser mesh, and no noticeable change have been found.

The chosen non-uniform mesh (total about 1 million cells in the model) has requested about 90 MB of RAM. It took a Pentium III 850 MHz PC near 3 hours to get steady state results. The developed model is quite adequate and flexible, so it can be used for detailed studying of the structure and finding its specific characteristics as well as exploring the ways of improvement of its performance.

RESULTS

Reflection

In the experimental validation[6], the field radiated from the RE was measured in the presence of the matched load in the tapered end of the waveguide. Our simulations show that

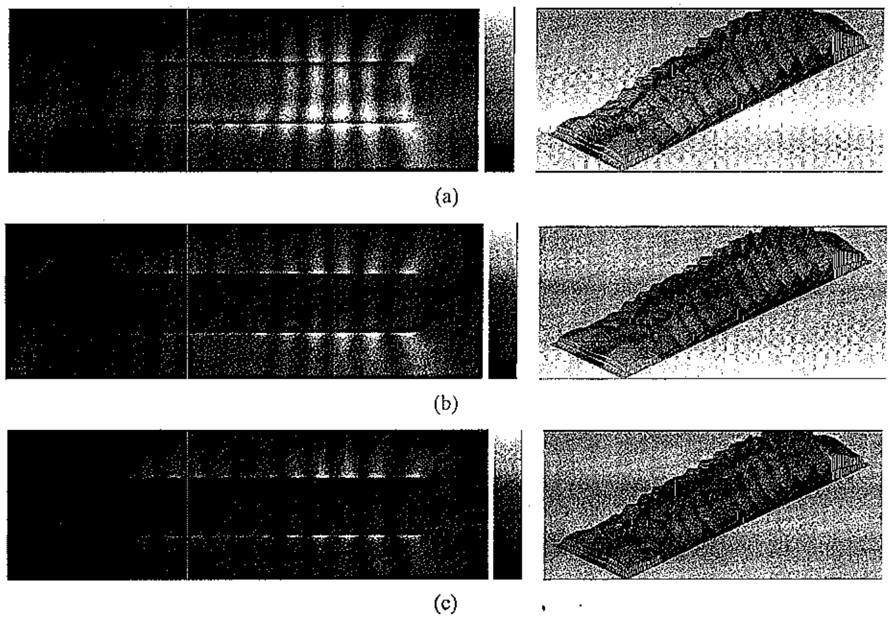

Fig. 3. Thermal (left) and hilltop (right) presentations of the electric field (envelope) in the horizontal planes through the wood plate: top (a), centre (b), and bottom layers (c).

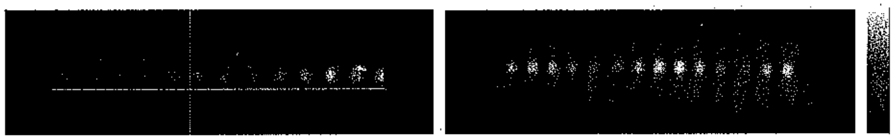

Fig. 4. Electric field in the horizontal planes: instantaneous field inside the waveguide (7 mm from the wall with the slot (left)) and a field envelope outside the waveguide (7 mm from this wall (right)).

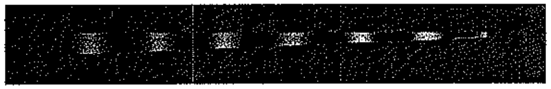

Fig. 5. Instantaneous electric field in the vertical plane through the center of the waveguide

in this case the return loss at 2.45 GHz is -19.8 dB, i.e., only about 1% of power is reflected back to the source (Fig. 2). However, without the waveguide load, the return loss is -1.8 dB, which means that as little as 34% of generated EM energy leaves the waveguide for the outer space. This suggests that the construction under consideration does not appear to be an efficient radiator: the low level of reflections determined in[5] in fact means that a larger part of the magnetron power was absorbed by the terminal dummy load rather than radiated.

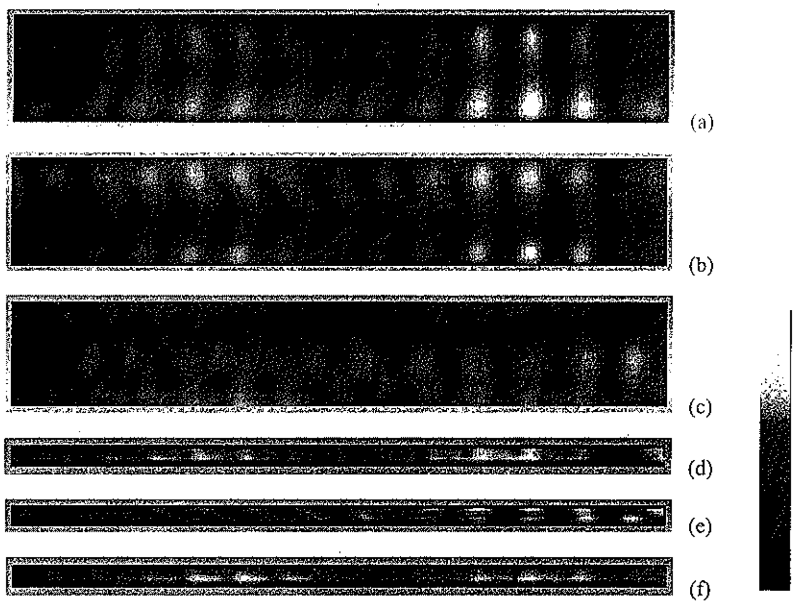

Fig. 6. Patterns of dissipated power in the wood plate: in the horizontal planes through the top (a), central (b), and bottom layers (c); in the vertical planes through the layers on the left (d) and right (f) edges and through the center (e).

Electric Field and Dissipated Power

In contrast to the suggested uniformity[6], the patterns of the electric field in the horizontal planes through the wood plate (Fig. 3) reveal increasing field magnitude towards the plate's edges. Moreover, in the longitudinal direction, the field distribution is characterized by alternating maxima and minima. This standing wave pattern depends on material parameters, so we conclude that the experiment[6] likely dealt with a different (unspecified) wood material. Fig. 4 shows that the pattern of the full field in the waveguide near the top wall is slightly different from the TE_{10} mode, which is explained by contributions by others than the vertical field components emerged due to the longitudinal slot. It is also seen that the trend in the patterns of the radiated field revealed in the planes through the wood plate (alternating maxima and minima along the *z*-axis shown in Fig. 3) is formed in outer space right near the slotted wall.

The pattern in the *yz*-plane (Fig. 5) suggests that the field magnitude inside and outside the waveguide is very different; numerical comparison gives the difference by at least the order of two. This confirms that the considered slotted structure is characterized by low radiation efficiency. It appears that the use of this element in high power applications without the internal matched load is not possible, but employing such a load would diminish the value of the structure as an RE.

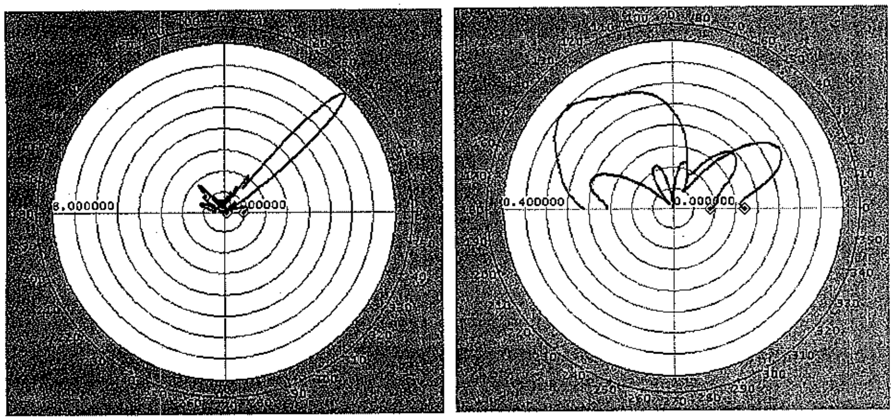

Fig. 7. Two spherical components of the radiation patterns in the longitudinal (left) and transverse (right) vertical planes.

Computations also show that the EM power is dissipated in the wood also non-uniformly forming the "hot" and "cold" spots generally following the alternating maxima and minima of the electric field (Fig. 6).

Radiation Pattern

As shown in Fig. 7, in the *yz*-plane, the radiation pattern of the considered RE is characterized by a strong and narrow main lobe rotated at approximately 45° from the positive direction of the *z*-axis whereas in the *xy*-plane the radiation is more uniform though much weaker: the peak of the transversal distribution is 23 times smaller that the longitudinal one. These angle distributions seem to be well matched with the horizontal field patterns in Fig. 3 showing a higher concentration of the field along the plate's edges and on the part of the plate located above the tapered end of the slotted waveguide. It is also worth mentioning that strong directivity of the radiation pattern can increase the possibility that the device would violate the safety standards.

CONCLUSION

In this paper, we have presented specific characteristics of the tapered slotted waveguide[5] to allow engineers to evaluate its applicability in microwave heating applications as a radiating element. Our computational analysis has shown its low radiation efficiency, high directivity of the main narrow lobe, and alternating maxima/minima in the magnitude of the radiated electric field. The depicted results generated by the *QW3D* model and containing the data on the internal reflections, field distributions and heating patterns in the wood plate provide comprehensive description of the key EM processes in the applicator that can be used for further numerical study of the system towards the improvement of heating uniformity, radiation efficiency, and safety of the device.

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