Microwave impedance matching strategies of an applicator supplied by a bi-directional magnetron waveguide launcher

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ABSTRACT

It is shown that a bi-directional waveguide launcher can be used advantageously for reducing the reflection coefficient mismatch of an input impedance of an applicator. In a simple bi-directional waveguide launcher, the magnetron is placed in the waveguide and generates a nominal field distribution with significant output impedance in both directions of the waveguide. If a standing wave is tolerated in the torus, which connects the launcher and the applicator, the power transfer from the magnetron to the applicator can be optimal, without using special matching devices. It is also possible to match the bi-directional launcher with two inductance stubs near the antenna of the magnetron and use them for supplying a two-input applicator without reflection.

KEYWORDS

Mismatch impedance, input impedance of an applicator, bi-directional magnetron launcher.

RESUMEN

Se muestra que una guía de onda con salida bidireccional puede ser utilizada ventajosamente para reducir la falta de sintonía en el coeficiente de reflexión de la impedancia de entrada de un aplicador. El magnetrón genera una distribución de campo nominal con una impedancia de salida significativa en ambas direcciones de la guía de onda. La potencia transferida del magnetrón hacia el aplicador puede ser óptima, sin utilizar dispositivos especiales de sintonía, si el arreglo que lo conecta a la entrega de la onda tolera a la onda estacionaria. Es posible también tener sintonía con dos tornillos de inducción cerca de la antena del magnetrón y utilizarlos como suministro para dos entradas sin reflexión.

PALABRAS CLAVE

Sintonía de impedancia, impedancia de entrada en un aplicador, magnetrón de salida bidireccional.

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INTRODUCTION

It is well known that a significant amount of power is reflected at the surface of any dielectric material when it is irradiated by a microwave source. For a plane wave, at normal incidence and for a material, for which the permittivity is ε, the power introduced in the material is only $4\sqrt{\varepsilon} / (\sqrt{\varepsilon}+1)^2$. This problem was specially considered in hypothermic techniques.[1] Although many solutions have been proposed including coupling circuits and adapting circuits for impedance and other reflection wave compensations, the problem is still considerable.

In cooking, the penetration of microwave power in foods is also a serious problem because foods have also high permittivity values.

Many years ago, Fritz[2] and Kongmark published and patented a microwave circuit, now known as the RIMM circuit having a high efficiency in heating food. The circuit is a ring in which both the magnetron and the material to be heated are placed as figure 1 shows. The magnetron and the applicator are connected with two identical half torus waveguides. During twenty years the high efficiency of the RIMM circuit has been explained from the possibility of irradiating the material from both sides. It is the main reason but the RIMM circuit also performs a good transfer of power from the magnetron to the material by reducing the mismatch in power, which occurs at the surface of the material, as we will see in this paper.

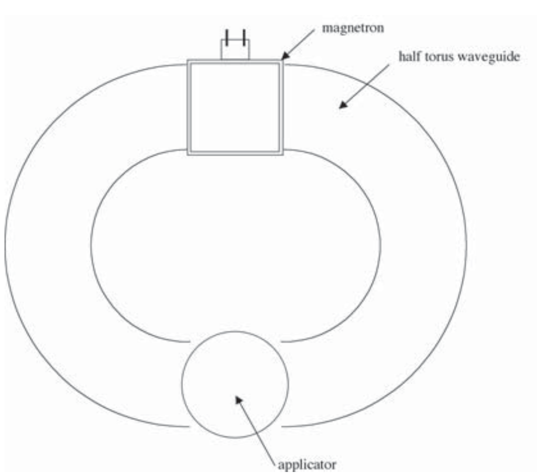

Fig. 1. RIMM circuit incluiding the magnetron, the applicator connected with two half tours wave guides.

THEORETICAL ANALYSIS OF THE RIMM CIRCUIT

In the RIMM circuit the lengths of the two identical half torus of the ring must be defined with care so that the electromagnetic field, emitted by the magnetron in both branches, corresponds to the center point in the Rieke chart of the magnetron. This nominal situation is checked by substituting a probe (available from the manufacturer of the magnetron) for the tube and by verifying with a Vector Network Analyzer that the coaxial branch of the probe presents no reflection at the frequency of the magnetron emission. The check circuit is a symmetric three port microwave circuit, which consists of the probe and of a section of the guide in which the probe is placed. The arrangement is a bi-directional magnetron waveguide launcher (see figure 2).

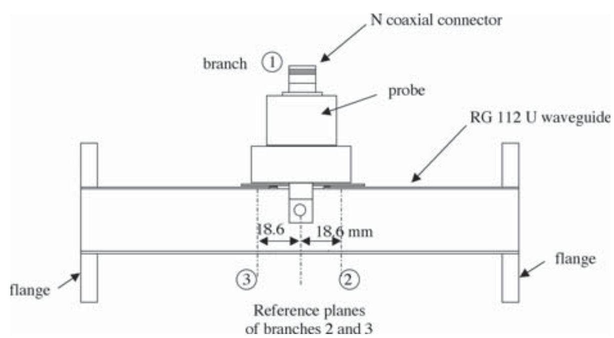

Fig. 2. Bi-directional magnetron waveguide launcher with a probe placed instead of the magnetron.

The parameters of its scattering matrix can be evaluated by referencing the input and output waves in P_1, P_2 and P_3 planes defined as follows. The measured plane P_1 is the coaxial N-connector of the probe; the planes P_2 and P_3 are symmetric and located on either side of the symmetrical plane of the circuit at a distance (usually 18.6 mm), at which the magnetron manufacturer specifies to place a short circuit to get a classical TE_{10} wave guide launcher. The function of the shorting wall is discussed in the book.[3]

Due to the symmetry, the matrix [S] should be written

$$[S]=\begin{bmatrix}\alpha & t & t\\ t & \beta & r\\ t & r & \beta\end{bmatrix}$$

Let us suppose that the circuit with the probe, which simulates the field distribution, which the magnetron must see, is a lossless circuit. The three branches of a lossless (and reciprocal) three port can never be simultaneously matched,[4] because a 3*3 symmetrical matrix having its three diagonal terms all null cannot be unitary (whereas the 2*2 and 4*4 matrices having their diagonal terms null can be unitary).

Determination of the scattering parameter of the simple bi-directional launcher matrix

Instead of calculating α, β, *r* and *t* from the unitarity conditions of the S-matrix, let us consider the lossless two port obtained when the short circuit is placed (again) in the plane P3. Its 2*2 matrix is also unitary.

$$t^2=\alpha(\beta+1) \quad (1)$$

$$r^2=\beta\left(\beta+1\right) \quad (2)$$

and $$t\left(\beta+1-r\right)=\left(\beta+1\right)e^{-j\Psi} \quad (3)$$

In this equation Ψ is the phase angle of the transfer coefficient between 1 and 2 branches. The phase Ψ is defined by the exact location of the reference planes in the coaxial and the waveguide branches. If the probe is directly calibrated for measuring the waveguide impedance in the plane of its antenna with a V.N.A connected to the coaxial branch, and Ψ is the electrical distance between P_3 plane and the antenna. Ψ equals about 38°.

Taking into account now on the fact that [S] is unitary:

$$|\alpha|^2=1-2|t|^2 \quad (4)$$

$$\alpha t^*+t\beta^*+tr^*=0 \quad (5)$$

and $$|\beta|^2+|t|^2+|r|^2=1 \quad (6)$$

these equations can be solved. There are two solutions, but only one has a physical meaning.

$$\beta=0.577\angle+150^{o}$$

$$r=0.577\angle-90^{o}$$

Then

$$t=0.577\angle-\Psi-30^{o}$$

$$\alpha=0.577\angle-2\Psi-90^{o}$$

$$[S]=\begin{bmatrix}0.577\angle-2\Psi-90^{o} & 0.577\angle-\Psi-30^{o} & 0.577\angle-\Psi-30^{o}\\ 0.577\angle-\Psi-30^{o} & 0.577\angle-150^{o} & 0.577\angle-90^{o}\\ 0.577\angle-\Psi-30^{o} & 0.577\angle-90^{o} & 0.577\angle-150^{o}\end{bmatrix}$$

From the scattering matrix, we can calculate the reflection coefficient ρ of two identical loads that we will place in branches 2 and 3 so that branch 1 presents no reflection. It is obtained by solving the system of three equations:

$$0=\alpha E_1'+y\rho E_2''+t\rho E_3''$$

$$E_2''=tE_1'+\beta\,\rho E_2''+r\rho E_3''$$

$$E_3''=tE_1'+r\rho E_2''+\beta\,\rho E_3''$$

In which, E'i and E"i (i = 1, 2 and 3) are respectively the input and the output waves in the branches i. The elimination of E'i and E"i leads to

$$\alpha\left(\beta\rho+r\rho-1\right)=2\rho t^2 \quad (7)$$

or $$\rho=1/\left(r-\beta-2\right)=0.577\angle-150^{o}$$

Modulus of ρ is not zero because the three port divides the input energy in two parts and because the internal mismatch of the three port combines with the impedance of the applicator that the magnetron sees. When the magnetron requires its nominal characteristics, the reflection coefficient of each side of the applicator should have a specified value (not zero).

Determination of the matched bi-directional launcher matrix

By placing two inductance stubs in the section of the antenna of the magnetron as figure 3 shows, the reflection coefficient α can be zero and the impedance of the branches 2 and 3 for which branch 1 presents no reflection can be shifted to $\rho=0$. The bi-directional magnetron launcher is "matched" and its S matrix is then (with other measured planes):

$$[S]=\begin{bmatrix}0 & 0.707 & 0.707\\ 0.707 & 0.5 & -0.5\\ 0.707 & -0.5 & 0.5\end{bmatrix}$$

The matching device should be a stub, type inductance, for taking the place of the shorting circuit, which is introduced in the TE_{10} launcher.

Any other type of matching devices (screw, other stub, or $\lambda_g/4$ length of reduced width of the waveguide section…) is also suitable, providing it is properly tuned.

EXPERIMENTAL RESULTS

Measurements of the scattering parameters of the two bi-directional launcher versions have been performed, at 2 450 MHz, with a HP 8714B Vector Network Analyzer, which is calibrated with a N-coaxial standard kit and with a (OC, SC, AL) waveguide kit for respectively coaxial and waveguide measurements. The probe is an E 4430 Toshiba, which is designed for simulating the 2M172 Toshiba magnetron. We used a RG 112 U standard waveguide.

a. Direct measurement of the scattering parameters of the simple bi-directional launcher.

For the simple bi-directional launcher we got

$$\beta = 0.534\angle +130$$

$$r = 0.580\angle -87^{\circ}$$

$$t = 0.570\angle 25^{\circ}$$

$$\alpha = 0.600\angle 14^{\circ}$$

The magnitudes of the measured parameters are near the predicted ones. Phases may be in error because the exact location of the measured planes is difficult to define, because the VNA cannot be calibrated with mixed coaxial and waveguide standard and, finally, because the circuit is slightly lossy.

The losses appear also when the classical launcher is analyzed, by placing a short circuit in branch 3 and by measuring the coaxial complex reflection coefficient when successively an adapted load, a short circuit and an open circuit are connected to the branch 2: $\rho_{al} = 0.075\angle 143°$, $\rho_{sc} = 0.891\angle -67°$, $\rho_{oc} = 0.887\angle 130°$. Because the two last values have not a unitary magnitude, the probe is lossy. That is probably due to the losses in the ceramic, which is used in the manufacturing of the antennas of both the probe and of the magnetron.

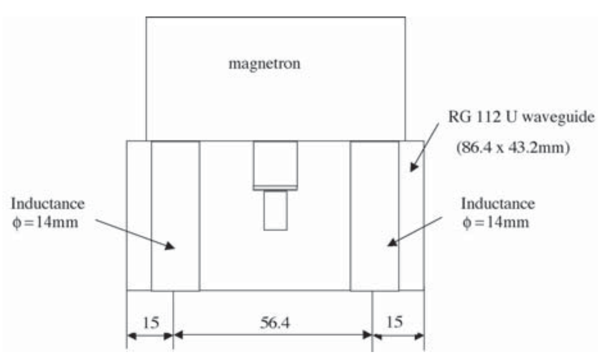

Fig. 3. Matching inductance of a bi-directional waveguide launcher, with inductance stubs.

b. Scattering matrix of the matched bi-directional launcher.

After placing two inductance stubs, as explained in the previous section, we measured the S parameters of the matched bi-directional launcher and obtained the following data: $|\alpha|=0.027$, $|\beta|= 0.498$, $|r| = 0.508$, $|t| = 0.701$.The phase values and the location of the measured planes are ignored, as is usual in the specification of any similar 3db power divider.

All the scattering parameters are near the values, which we predicted above.

IMPEDANCE MATCHING STRATEGIES

There are at least two strategies to optimally transfer the emitted microwave power from the magnetron to the product, which is inside the applicator:

a. The first strategy consists of using a simple bi-directional launcher and inserting two screws, symmetrically placed, in the two half torus and of adjusting both their positions and their penetrations so that the complex reflection coefficient of the applicator (measured in P2 or P3 plane) equals the value given by equation (7).

There is then a stationary wave in the torus, with high and low electric field locations. The standing wave ratio is about three. The electric square field maximum is ten times the electric square field minimum. As long as the total power is low, this standing wave can be acceptable without risk of arcing.

Many applicators in food treatment or in domestic oven have input impedance, with a reflection coefficient, which is near 0.3 in magnitude. In practice when the RIMM circuit is used for supplying these applicators, only the lengths of the two half torus must be adjusted so that the (complex) condition (7) is fully satisfied and so that the power emitted by the magnetron is transferred optimally to the applicator.

It should also be noted, that the optimal reflection coefficient, which is questioned above should take into account both the proper input reflection wave of the applicator and the transmitted waves of the applicator from one side to the other side, if the applicator is partially transparent to the waves.

That strategy was probably applied in many patents describing the design of dual input port oven.[5,6,7]

b. The second strategy is to match the launcher with two inductance stubs in the antenna plane (figure 3) as has been discussed previously. Then the reflection of the applicator is tuned to a no-reflection load by inserting two identical stubs in front of the applicator.

In this strategy there are no standing waves in the torus waveguides but only progressive waves and the lengths of the half torus can be changed without modifying the impedance matching.

The described bi-directional launcher and the presented discussion on impedance matching apply advantageously also to many modern domestic microwave ovens, in which the cavity is supplied by two waveguide inputs from one magnetron. Because the impedance matching inductance stubs not heat at high power electromagnetic field, the design is working with high stability. It can also avoid the use of a mechanical stirrer in many cases and nevertheless, arrives at a good homogeneity of the field distribution. The described matched bi-directional launcher can also be used with magnetron, which has an operating point not in the center of the Rieke chart. The launcher should then be re-matched by inserting two other stubs near the antenna, not exactly in the symmetrical plane, for restoring the required working point in the Rieke chart (in magnitude and in phase).

CONCLUSION

The RIMM circuit's high efficiency in food heating is justified by two reasons, i.e. first, the microwave energy is supplied to the heated material from two opposite sides and, secondly, the RIMM circuit reduces the mismatch of the reflection at the surface.

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