Demystifying the Magnetron Antenna Probe

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Abstract

We review basics of the magnetron antenna probes, recapitulate the conventional method of their use, and introduce an improved procedure, based on a vector reflectometer calibration. A probe properly calibrated can be used in an arbitrary installation for accurate, direct, real-time, swept observation of the magnetron Rieke diagram-related load reflection coefficient.

Keywords — Magnetron antenna probe, Rieke diagram, vector reflectometer calibration.

Introduction

Magnetron antenna probes are devices used for evaluation of magnetron loads with standard low-power laboratory equipment. This knowledge is important when designing applications without circulators. Antenna probes are accompanied by characterizing data tables and instructions for their use. The instructions are often obscure and the data unreliable, making the operators uncertain if the probe is being used correctly, and hence if they can trust the results obtained. The procedure is awkward to employ, extremely slow, prone to human errors, and the results are biased by an irremovable systematic error. Availability and proper use of modern vector network analyzers (VNA) allows eliminating of all of the mentioned drawbacks.

This article summarizes the basics of the antenna probes, elucidates the conventional method of their use, and presents an improved procedure, which is essentially a standard vector reflectometer calibration using a simple specific equipment, consisting of a reference magnetron launcher and a set of three waveguide calibration shorts. A probe thus calibrated can be used in an arbitrary installation for accurate, direct, real-time, swept observation of the reflection coefficient related to Rieke diagram. We illustrate this case on a measurement example and compare the two methods. More details can be found in the original publication[1].

Rieke Reflection Coefficient

A magnetron generated frequency f_g and the net delivered power P_L depend on the reflection coefficient $\Gamma_R = |\Gamma_R|\exp(j\varphi_R)$ from the magnetron's load. By convention, Γ_R (henceforth termed *Rieke reflection coefficient*) is defined as the reflection coefficient observed looking toward the load in a rectangular waveguide arrangement called *reference launcher* (Fig. 1). The launcher dimensions are stipulated in magnetron datasheets.

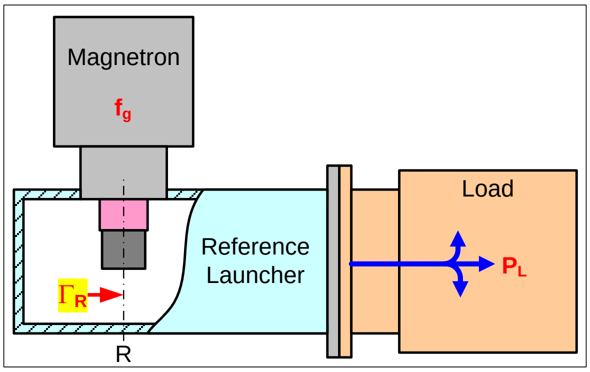

Figure 1. Magnetron in a reference launcher; a definition of the Rieke reflection coefficient Γ_R.

The dependence of f_g and P_L on thus defined Γ_R is visualized in the form of the *Rieke diagram*[2], which is a polar plot in the complex plane of Γ_R (a Smith chart) also displaying a family of contours of constant f_g and of constant P_L (Fig. 2). An applicator design goal is to restrict Γ_R within a range where the magnetron behaves properly (the area covered by the contours).

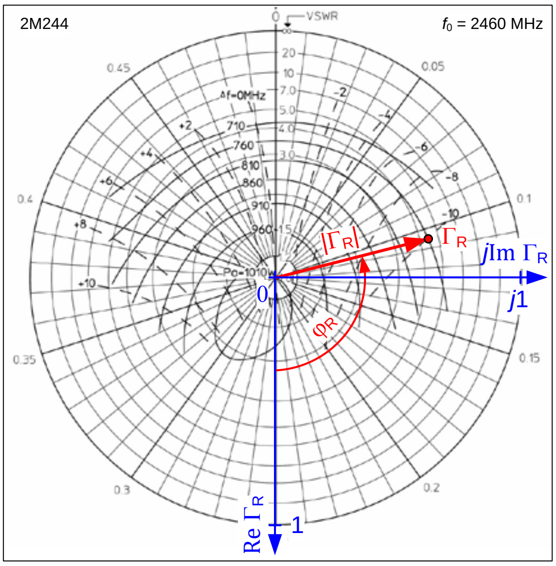

Figure 2. Rieke diagram of 2M244 magnetron.

Except in the reference arrangement, Γ_R may be an abstract quantity (imagine for instance a magnetron radiating into a free space). Still, we need to refer to it in order to predict the magnetron behavior in an *arbitrary* arrangement. This is enabled by magnetron antenna probes.

Magnetron Antenna Probe

Magnetron antenna probe (Fig. 3) mocks the antenna structure of the associated magnetron but routes the signal to an auxiliary coaxial connector serving for the reflection coefficient (Γ_p) measurement. For this purpose, the probe is installed in place of the magnetron.

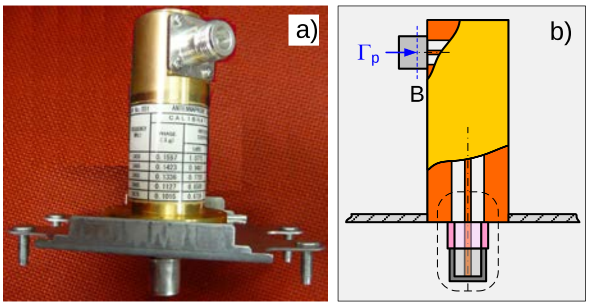

Figure 3. A magnetron antenna probe example (a), and the probe internal structure (b). The portion in the dashed frame is identical with that of the magnetron. B is reference plane for Γ_p definition.

The equality of the antenna structures establishes a relation between the measurable Γ_p and the Rieke reflection coefficient Γ_R for the associated magnetron, as follows[3]

$$\Gamma_R = \frac{\Gamma_p - S_{11}}{S_{22}\Gamma_p - S_{11}S_{22} + S_{21}^2}, \tag{1}$$

where S_{ij} are the complex scattering parameters of the probe and the launcher conjunction (Fig. 4). If S_{ij} are known, Γ_R can be deduced from Γ_p regardless of the object to which the magnetron is installed.

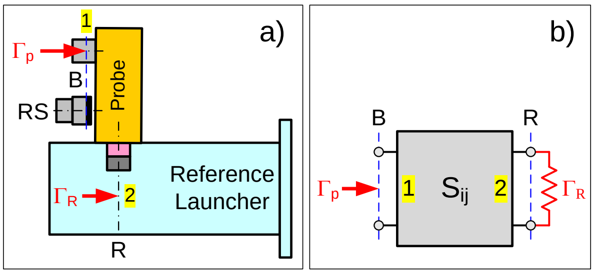

Figure 4. An antenna probe in the reference launcher (a), and the equivalent two-port model (b). RS is a reference short supplied with the probe for plane B definition.

Since the practical application of Eq. (1) is quite cumbersome, antenna probes have been designed to be well matched ($S_{11} \approx 0$, $S_{22} \approx 0$). This reduces (1) to

$$\Gamma_R = \Gamma_p \left|S_{21}\right|^{-2} \exp(-j2\varphi_{21}), \tag{2}$$

where $S_{21} = |S_{21}|\exp(j\varphi_{21})$. Equation (2) now represents mere scaling and rotation of the measured Γ_p in the complex plane.

Conventional Method

Conventional method of applying antenna probes essentially consists in implementing Eq. (2) using the manufacturer-provided data table. To obtain Γ_R, proceed as follows:

1. Using a VNA calibrated at plane B (Fig. 4a), measure the probe input reflection coefficient Γ_p at a desired frequency or in a desired band.
2. For each frequency of interest, interpolate from the data table the parameters characterizing the probe.
3. Transform these parameters to S_{21}–related values, $|S_{21}|^2$ and $2\varphi_{21}$. More details can be found in the literature[1].
4. To obtain the magnitude $|\Gamma_R|$, divide the magnitude $|\Gamma_p|$ by $|S_{21}|^2$.

5. To obtain the phase φ_R, rotate the vector Γ_p clockwise by $2\varphi_{21}$, i.e. subtract $2\varphi_{21}$ from the measured phase of Γ_p.

Evidently, the procedure is still cumbersome and can hardly serve for efficient applicator design. In addition, Γ_R is biased by a systematic error by the neglected S_{11} (typically, $|S_{11}| \approx 0.1$).

VNA Calibration

Modern VNAs, when appropriately calibrated, make possible direct, high-accuracy, swept measurement of Γ_R. The procedure is actually a standard one-port VNA calibration[4] with the probe installed in the reference launcher. A calibration setup is depicted in Fig. 5. The procedure consists in connecting a series of *calibration standards*, i.e. loads with known and distinctly differing reflection coefficients, and recording the corresponding measured reflection coefficients in a frequency range of interest. A preferred choice for the standards is a set of three waveguide shorts with lengths

$$L_i = (i-1)\lambda_{g0}/6 \qquad i = 1,\ 2,\ 3 \tag{3}$$

where λ_{g0} is the launcher guide wavelength at the magnetron nominal frequency f_0.

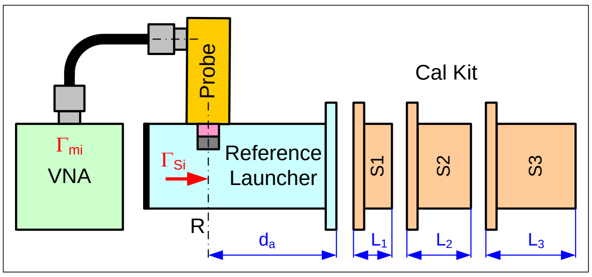

Figure 5. A VNA calibration setup using three different shorts for Rieke reflection coefficient measurement.

At plane R, the unity reflection coefficients of thus defined standards are

$$\Gamma_{Si}(f) = \exp j\left[\pi - 4\pi(L_i + d_a)/\lambda_g(f)\right] \tag{4}$$

The VNA guides the operator through the calibration process and performs all mathematical operations required. After completion, the probe can be removed from the reference launcher, installed into any structure of interest, and the real-time swept measurement of Γ_R can start.

Experiments

Experiments with a 2M244 magnetron antenna probe have been made to demonstrate the proposed approach. Figure 6 shows the calibration setup.

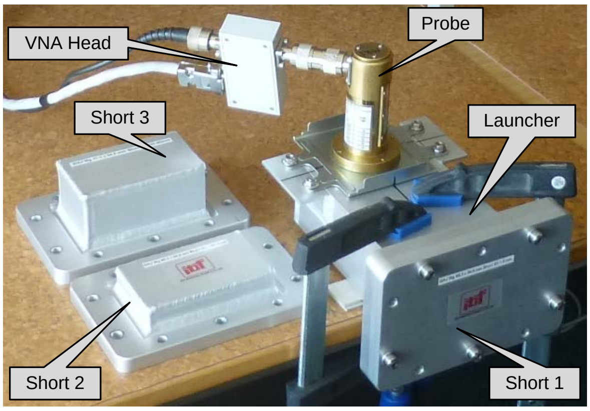

Figure 6. Calibration setup.

After completing the calibration, a variety of loads were measured in the 2.2 – 2.7 GHz band. A representative case is illustrated in Fig. 7. The true Rieke reflection coefficient obtained by the VNA calibration is Γ_R. The reflection coefficient measured at the probe input is Γ_p. The conventional procedure should ideally transform Γ_p to Γ_R. However, using the original table, the result is Γ_1. The discrepancy is mainly caused by the incorrect phase angle $2\varphi_{21}$ deduced from the probe data table. This suggests that the data accompanying probes may not always be reliable. Γ_1 is additionally subject to an error due to the probe input mismatch, expressed by the uncertainty circle with radius $|S_{11}|$.

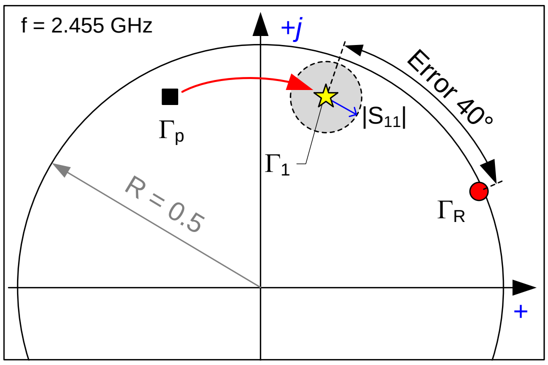

Figure 7. Antenna probe application comparison.

As an illustration of practical use, a calibrated probe was installed in a commercial microwave oven in place of the magnetron (Fig. 8).

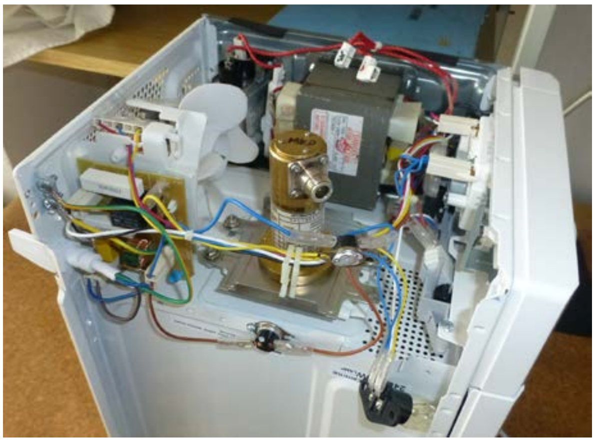

Figure 8. Antenna probe in a domestic microwave oven.

Swept Γ_R for this arrangement was observed in the 2.5 – 2.6 GHz band for various loads. An example is shown in Fig. 9. The magnetron would oscillate at a frequency for which the point at the measured trace touches the Rieke contour for the same frequency (f = 2454.6 MHz)[1]. The magnetron would deliver then about 815 W of microwave power.

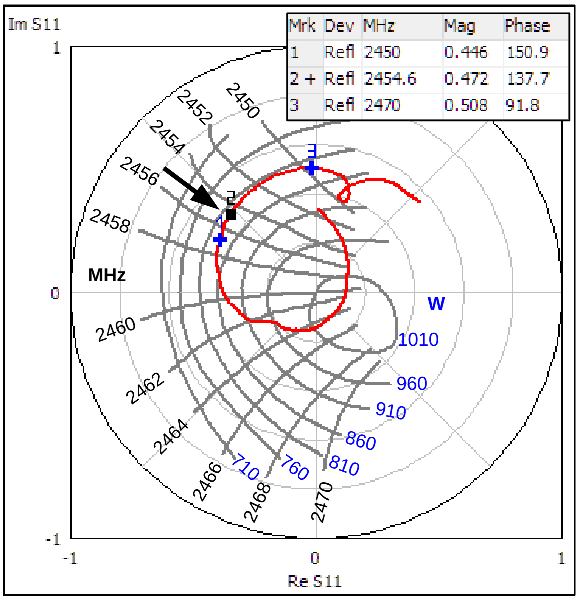

Figure 9. The Rieke reflection coefficient in 2.5 – 2.6 GHz band of a teacup with 200 ml of cold water centered in the oven.

Conclusions

Using a magnetron antenna probe with a properly calibrated vector network analyzer (VNA) provides significant advantages compared to the conventional usage of the probes. The principal benefits are (a) the direct display of the reflection coefficient related to Rieke diagram on the VNA screen, (b) high-speed sweeping in arbitrary frequency range of interest, and (c) high measurement accuracy.

For further reading:

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About the Author

Dr. Vladimir Bilik graduated in Radio-Electronics from the Faculty of Electrical Engineering of the Slovak University of Technology at Bratislava in 1972, where he also received his PhD degree in 1979, and for more than two decades lectured courses on microwaves.

Currently, Dr. Bilik is responsible for R&D in S-TEAM company, which he co-founded in 1990, and still holds a part-time research fellowship with the University. His main professional interests have included automated scattering parameters measurement, implementations of six-port reflectometers, and automatic impedance matching of industrial microwave systems.