Experimentally Determined Equivalent Network Scattering Parameters for Edge Slots in Rectangular Waveguide for Use as Reference Data

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Abstract— **Tabulated, experimentally determined, scattering parameters for edge slots in the narrow wall of rectangular waveguide are given over a range of frequencies. The suggestion is that these tabulated results be used instead of graphs (extant in the literature since the 1940's) from which it is difficult accurately to read off slot properties for comparison with theoretical techniques which may be proffered in future work by others.**

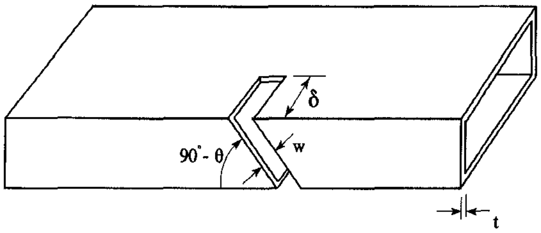

Fig. 1. Inclined slot in the narrow wall of rectangular waveguide.

I. Introduction

Arrays of longitudinal or transverse slots in the broadwall, or edge slots in the narrow wall, of rectangular waveguide continue to be used in many applications. Theoretical computation of the properties of the broadwall slots has reached the point [1]–[3] where agreement between computed and experimentally determined properties is well within the (very small) measurement uncertainty of properly used modern microwave instrumentation. Important in achieving the latter level of maturity has been the availability of a set (albeit restricted) of *tabulated* experimentally determined values of the slot properties for comparison with theoretical results. Recently there has been some renewed interest in dealing with the edge slot problem theoretically using both integral equation moment method formulations [4] and differential equation based finite-difference time-domain techniques [5]. However, in [4], [5], and other published work on edge slot properties, computations have been compared to values taken from curves of measured data [6]. The preciseness with which such values can be read off a somewhat compact graph does not match the kind of accuracies already achieved with broadwall slots, and which accuracies are indeed a requirement for the design of high-performance arrays [7], [8]. The reliability of the measurements in [6] is not being questioned here; only the ability to read-off values with sufficient accuracy. In [9] it was indicated that some *tabulated* measurements for edge slots, over a range of frequencies, could be obtained on request. The response to this offer prompted the present letter.

It is worthwhile to add some further comment on the history of the widely used data [6, Figs. 9–12] mentioned above; unless otherwise stated we comment on the *single slot data* only (labeled "ordinary" in [6]). It was apparently first measured and published in [10], but was not given in [11], as implied in [4]. This information was then republished in [12], [13], and [6], and then again in [14] (the updated edition of [6]). In [6, Figs. 9–12] and [14, Figs. 9–12] the maximum value indicated on the vertical scale is 0.4, whereas it should [10], [12] read 0.2. This correction has been implied in [13, Figs. 9–21] where the "0.4" has simply been omitted without being replaced by any other number. In [4, Fig. 5] and [15, Fig. 3] it would seem that in comparing their computations to the above data the necessary change in the scale has been accounted for.

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II. Measurement Procedure

Measurements were performed on an HP8510 vector network analyzer over the frequency range from 8–11 GHz. The complex S-parameters of individual edge slots were obtained, treating each slot in a waveguide module (shown in Fig. 1) as a two-port device, hereafter referred to as the test section. There is also a reference section of the same length as the test section, but without a slot. This length was made sufficiently long (0.5 m) to allow unwanted reflections to be properly gated out, as discussed below. The values of the elements of the equivalent networks of these slots are then easily determined from their S-parameters. We provide these results *in tabular form*, along with complete details of the slot/waveguide dimensions (see Fig. 1) in the next section; the details of the measurement procedure are first described here.

1. The network analyzer is switched on and left for 2 hours. It is then calibrated using two offset shorts and a matched load over the frequency range 7 to 12 GHz in order to have as wide a calibrated bandwidth as possible for good resolution in the time-domain.

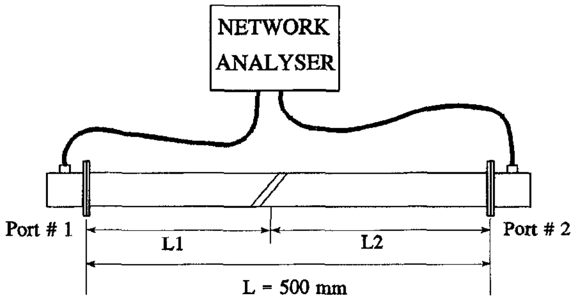

Fig. 2. The measurement setup for measuring the scattering parameters of an edge slot cut in a 500-mm-long waveguide section.

2. The test section is then connected and left for 2 hours. Measurements are examined in the time domain. The time gating is adjusted to allow the slot-scattering parameters to be determined on their own, with the contributions due to the coax-to-waveguide adapters and test section flanges eliminated. This fixes the time-domain gating's center position and span. With the above-mentioned frequency range and test section length, we here used t_{center} = 2.545 ns, and Δt_{span} = 2.11 ns; these were checked to ensure that slight changes in their values did not alter the measurements (i.e., the gate was sufficiently wide).
3. The test section is then removed and replaced by the reference section. Using the gating settings as above, the scattering parameter s_{21} is measured in amplitude and phase and stored in the network analyzer as $s_{\text{ref}}^{(2)}$, and the scattering parameter s_{12} is measured in amplitude and phase and stored as $s_{\text{ref}}^{(1)}$. The reference section is then removed.
4. The test section is then connected and s_{21} is measured in amplitude and phase. A table of normalized data is output as $s_{21}/s_{\text{ref}}^{(2)}$ versus frequency. Thereafter s_{11} is measured, and a table of normalized data $s_{11}/s_{\text{ref}}^{(2)}$ is output. The reason for the above normalizations is to reduce any effects due to losses in the waveguide walls and flanges on the measurement; the s_{21} and s_{11} measurements use signals that have traveled through the same length of waveguide and number of flanges, the s_{21} case through the full section just once and through each of the two flanges, while the s_{11} through the input half-section of the waveguide twice and twice through the input side flange. Then s_{12} and s_{22} are measured in amplitude and phase, and a table of normalized data is output as $s_{12}/s_{\text{ref}}^{(1)}$ and $s_{22}/s_{\text{ref}}^{(1)}$.
5. Clearly, for the ideal situation we should have $s_{21}/s_{\text{ref}}^{(2)} = s_{12}/s_{\text{ref}}^{(1)}$ and $s_{11}/s_{\text{ref}}^{(2)} = s_{22}/s_{\text{ref}}^{(1)}$ for the case of the edge slot discontinuity. In practice there are differences (albeit small), due principally to slight differences between L_1 and L_2 (see Fig. 2). We therefore take the arithmetic average of $s_{21}/s_{\text{ref}}^{(2)}$ and $s_{12}/s_{\text{ref}}^{(1)}$, and of $s_{11}/s_{\text{ref}}^{(2)}$ and $s_{22}/s_{\text{ref}}^{(1)}$. This serves to subjugate the effect of the slot perhaps not being precisely at the center of the test section.

TABLE I
METROLOGY DATA OF THE TWO FABRICATED EDGE SLOTS WHOSE SCATTERING PROPERTIES WERE MEASURED

	Slot # 1	Slot # 2
θ (deg)	24.6	14.8
w (mm)	1.6	1.6
δ (mm)	3.6	3.5
t (mm)	1.27	1.27

TABLE II
MEASURED SCATTERING PARAMETERS (MAGNITUDE AND PHASE) FOR SLOT # 1 AT A NUMBER OF DISCRETE POINTS IN THE FREQUENCY RANGE 8–11 GHz

Frequency	s_{11}		s_{21}	
[GHz]	Magnitude	Phase	Magnitude	Phase
8.0	−23.62	−127.8	−0.34	−6.1
8.2	−23.54	−134.4	−0.40	−5.6
8.4	−23.42	−141.9	−0.48	−4.8
8.6	−23.51	−151.6	−0.54	−4.1
8.8	−23.90	−162.1	−0.56	−3.1
9.0	−24.69	−172.2	−0.53	−2.2
9.2	−25.66	178.1	−0.47	−1.5
9.4	−26.67	169.2	−0.40	−0.9
9.6	−27.82	161.9	−0.33	−0.5
9.8	−29.10	156.5	−0.26	−0.3
10.0	−30.22	151.8	−0.22	−0.2
10.2	−31.63	147.1	−0.17	−0.2
10.4	−32.96	144.0	−0.15	−0.1
10.6	−33.93	143.6	−0.12	−0.1
10.8	−34.61	142.0	−0.10	−0.1
11.0	−35.77	138.4	−0.09	−0.1

TABLE III
MEASURED SCATTERING PARAMETERS (MAGNITUDE AND PHASE) FOR SLOT # 2 AT A NUMBER OF DISCRETE POINTS IN THE FREQUENCY RANGE 8–11 GHz

Frequency	s_{11}		s_{21}	
[GHz]	Magnitude	Phase	Magnitude	Phase
8.0	−32.90	−107.3	−0.06	−2.1
8.2	−33.12	−113.2	−0.08	−1.9
8.4	−33.00	−117.5	−0.10	−1.7
8.6	−33.19	−123.7	−0.11	−1.5
8.8	−33.29	−130.3	−0.13	−1.3
9.0	−33.59	−136.8	−0.15	−1.1
9.2	−34.02	−145.4	−0.16	−0.9
9.4	−34.45	−154.4	−0.16	−0.6
9.6	−35.04	−161.8	−0.15	−0.3
9.8	−35.87	−170.1	−0.13	−0.1
10.0	−36.93	−177.3	−0.12	0.1
10.2	−38.34	175.2	−0.10	0.3
10.4	−39.81	169.8	−0.09	0.4
10.6	−40.67	168.4	−0.07	0.5
10.8	−41.16	166.5	−0.06	0.5
11.0	−42.49	162.6	−0.05	0.5

III. EXPERIMENTALLY DETERMINED PROPERTIES OF TWO EDGE SLOTS

As an additional comment, we note that we have just for the sake of interest compared the results given in this paper with measurements in [14] and [15]. For instance, for slot # 2 (see Table I for relevant dimensions) the data in [14], valid only at 9.375 GHz, gives the slot conductance as 0.047 as best we were able to read off the published curve. The data in [15], also valid only at 9.375 GHz, gives it as 0.032 from a similar curve. The measurements reported here give this conductance as 0.036 at 9.4 GHz.

TABLE IV
EQUIVALENT NETWORK SHUNT ADMITTANCE (REAL AND IMAGINARY PARTS) CALCULATED FROM THE MEASURED SCATTERING PARAMETERS FOR BOTH SLOTS AT A NUMBER OF DISCRETE POINTS IN THE FREQUENCY RANGE 8–11 GHz

Frequency	Shunt admittance: Slot # 1		Shunt admittance: Slot # 2	
[GHz]	G	B	G	B
8.0	0.074	0.167	0.013	0.059
8.2	0.089	0.154	0.017	0.054
8.4	0.108	0.135	0.021	0.050
8.6	0.123	0.112	0.024	0.045
8.8	0.130	0.080	0.029	0.040
9.0	0.124	0.050	0.033	0.034
9.2	0.111	0.026	0.035	0.028
9.4	0.095	0.007	0.036	0.019
9.6	0.079	−0.005	0.034	0.011
9.8	0.064	−0.009	0.031	0.005
10.0	0.054	−0.012	0.028	−0.001
10.2	0.042	−0.011	0.024	−0.006
10.4	0.036	−0.012	0.021	−0.009
10.6	0.030	−0.011	0.017	−0.011
10.8	0.026	−0.010	0.015	−0.011
11.0	0.023	−0.009	0.013	−0.011

IV. CONCLUDING REMARKS

A detailed set of tabulated, experimentally determined values of the equivalent network parameters of two different edge slots has been given here. Care has been taken accurately to measure these properties using modern microwave instrumentation. We wish respectfully to suggest that these results may be used in future papers for comparison with theoretical results instead of the graphs in [6]—for reasons stated earlier—if alternative measurements are not readily available.

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