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Experimental Studies of the Peak Power-Handling Capacity of Finlines at Centimeter and Millimeter Wavelengths

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Abstract **—The microwave and millimeter-wave field breakdown in various unilateral finlines is investigated experimentally. First, experiments in the *X*- and *Ka*-band are described to study the breakdown phenomenon and its effects on the structure. Then, experimental values of the maximum transmissible peak power are compared with the theoretical predictions.**

Experimental results confirm the validity of the theoretical model, within a reasonable limit, when the uncertainties produced by the various parameters pertaining to the electric breakdown phenomenon are taken into account.

I. Introduction

In a recent paper [1], a theoretical model of the electric breakdown phenomenon that occurs in a class of *E*-plane transmission media transmitting pulsed signals was presented. The peak power-handling capacity could be theoretically determined, knowing the geometry and the atmospheric conditions, for frequencies up to 140 GHz. In order to validate the theoretical model, it was necessary to compare the theoretical predictions with measurements.

Unfortunately, very few experimental data are available for *E*-plane structures. Measurements were performed on finline structures (without the waveguide enclosure), in order to verify the accuracy of the finite element method used for field computations [2]. To avoid dissipation and to provide a real quasi-static condition, they were performed at very low frequency. Regarding measurements at higher frequencies, maximum peak power levels for pulsed signals in the *X*-band were recently presented [3]. Unfortunately, no data are available in the *Ka*-band. In the present paper, experiments carried out at 35 GHz (*Ka*-band) are described, the effects of the electric breakdown on the finline structure are examined, and the maximum power that can be transmitted in pulse signal operation is determined. Experimental results in both the *X*- and the *Ka*-band are then discussed and compared with the theoretical predictions.

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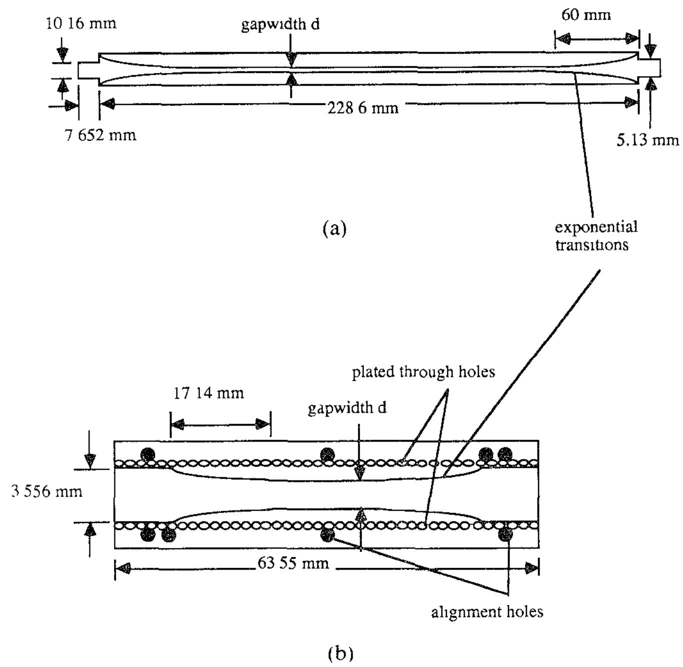

Fig. 1 Finline sample used for experiments at (a) 9 6 GHz and (b) 35.5 GHz.

II. Experimental Procedure

Unilateral finlines with gap widths varying from 0.5 to 2.5 mm and 34 μm metallization thickness were prepared and mounted in a WR-90 waveguide enclosure. For measurements in the *Ka*-band, the gap widths varied from 0.2 to 2 mm, the metallization thickness was 9.9 μm, and the unilateral finlines were mounted in a WR-28 waveguide enclosure. The fins were etched on a 762-μm-thick dielectric substrate (RT/duroid, $\epsilon_r = 2.22$) for the *X*-band measurements. Transitions from finlines to empty waveguide consisted of single exponential tapers. Quarter-wave stubs were cut in the dielectric substrate in order to match it to the empty waveguides (see Fig. 1(a)) [4]. The fins for the *Ka*-band measurements were deposited (plated) on a 254 μm dielectric substrate. Plated holes in the fins prevented leakage to the side ends of the substrate (see Fig. 1(b)).

The block diagram of the measurement system is shown in Fig. 2. A radar station which transmitted a 0.8 μs pulse width signal, with a repetition rate of 1000 pulses/s (0.001 duty cycle) was used for the *X*-band measurement. The generator (magnetron) could produce an adjustable peak power up to a maximum of 300 kW at a fixed frequency of 9.6 GHz. A built-in circulator and a Teflon window prevented damage due to reflections. In order to read the transmitted power level, a power meter calibrated in terms of peak power was connected in front of the test unit. An oscilloscope was connected, through a detector, at the end of the test unit, to observe any sudden change of the signal envelope level which would indicate a breakdown occurrence. For *Ka*-band measurements, the experimental arrangement was the same as for *X*-band measurements, except that a klystron generator was used. Also, the duty cycle was different with a pulse width of 16.6 μs

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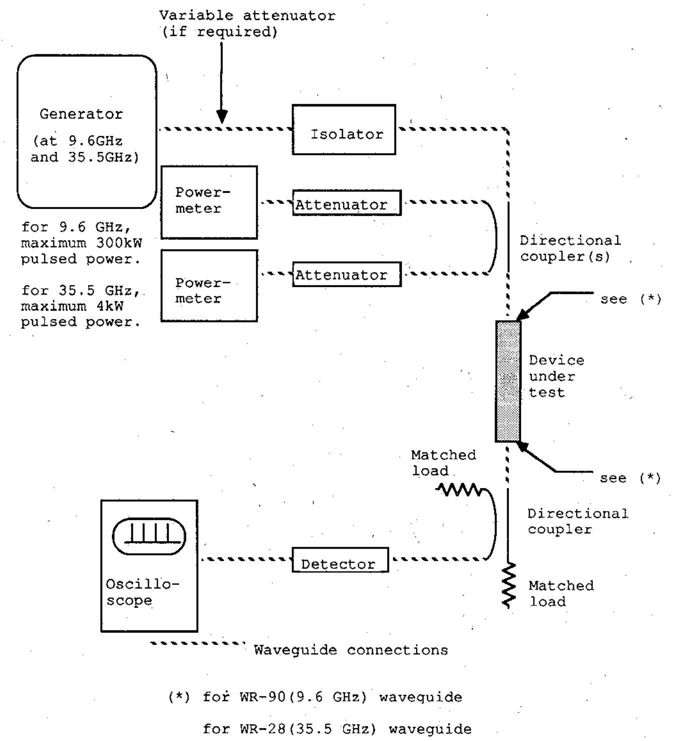


Fig. 2. Experimental arrangement for measurements at 9.6 GHz and 35.5 GHz.

and a repetition rate of 60 Hz. The available equipment did not permit any adjustment of the pulse width. This parameter also affects the breakdown value of the electric field [9]. The output power could be adjusted to a maximum of 4 kW at a fixed frequency of 35.5 GHz.

III. Results

As a first result, experiments confirmed that the breakdown occurred in the gap (air) and not in the dielectric substrate. Indeed, theoretical predictions [1] showed that the maximum field strength occurs at the edges of the conducting strips. The samples under test did not display any noticeable increase in temperature just after electric breakdown occurred. This confirms the validity of the assumption that for narrow pulsed signals, the limitation of the power level is dictated by the electric field strength in the structure at which breakdown occurs. A decrease of about 20 percent of the power transmitted through the test line was observed, just after the breakdown started. The power was then rapidly decreased, in order to avoid a complete destruction of the structure. This would have resulted in large reflections that may have damaged the generator.

Fig. 3 shows interesting facts concerning the breakdown phenomenon occurring in a finline structure. First of all, due to the irregularities in the gap width, the breakdown does not occur simultaneously along the whole structure but only at locations where these irregularities make the gap narrower, as it is revealed by the micrography of Fig. 3(a). The sketch in Fig. 3(b) shows the location of a large number of breakdown regions. During the experiment, the line broke down first in the narrow gap, provoking a mismatch of the line. Thus a standing wave built up and electrical arcs started to appear in front of the initial breakdown and moved towards the generator, until the gap was sufficiently wide to reduce the field strength to a value below the breakdown level. In addition, the marks that can be seen in the X-ray micrography of Fig. 3(c) show the superficial destruction of the

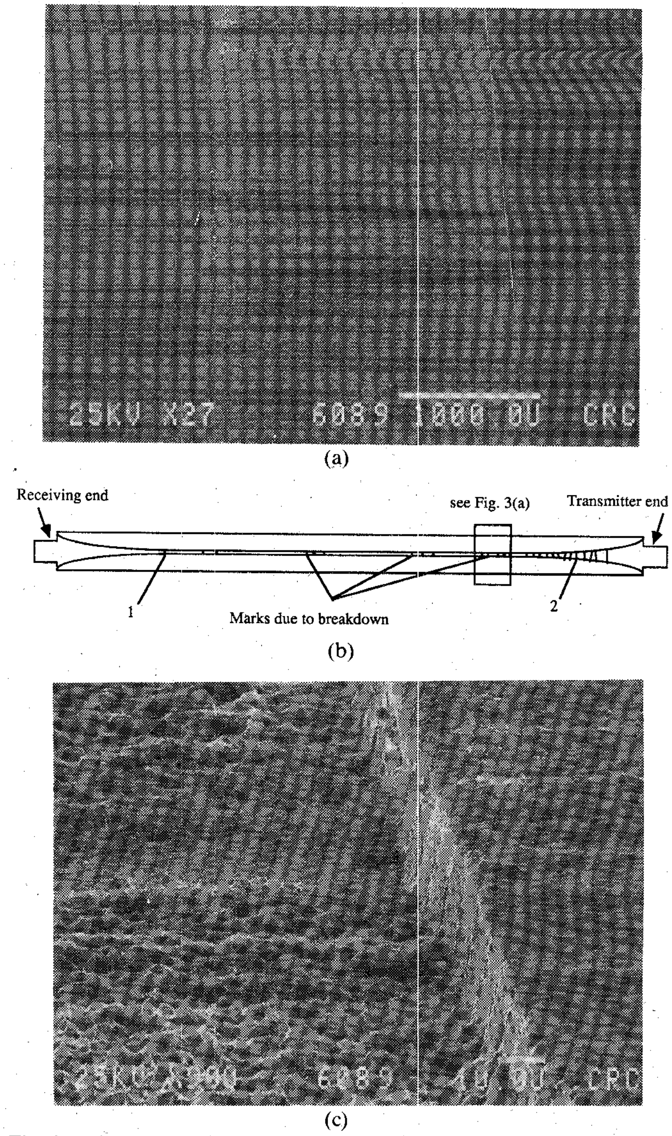
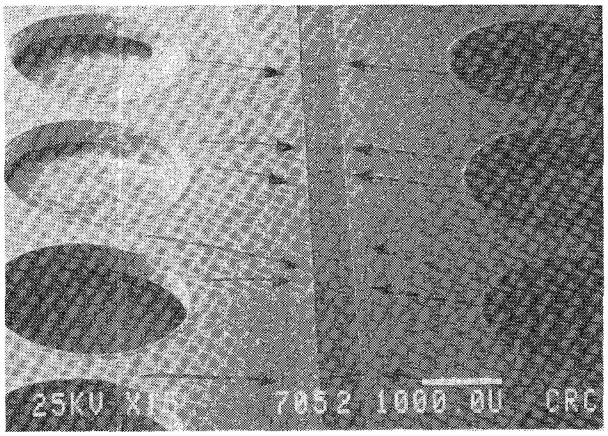


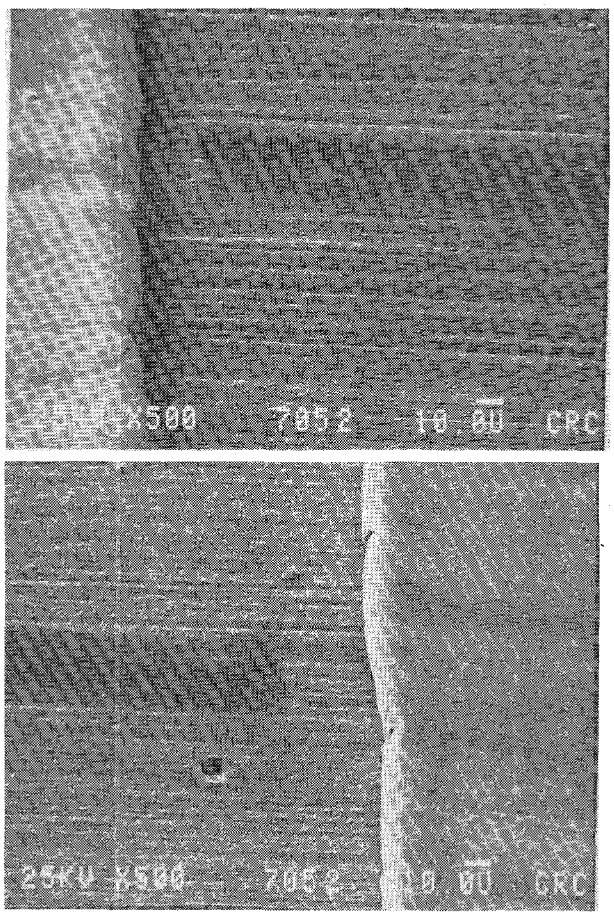
Fig. 3. Finline structure after testing at 9.6 GHz. Conductor thickness $g = 34$ μm and substrate thickness $s = 762$ μm with etched fins. (a) Electron micrograph showing the breakdown locations (magnification 333 μm/cm). (b) Sketch of breakdown occurrence. (c) Electron micrograph of the location where breakdown occurred (magnification 10 μm/cm).

dielectric substrate due to the intense localized heat provoked by the electric arc. Also, except for a slight erosion, the conducting strips did not suffer from the breakdown. To confirm this, subsequent trials did not change significantly the value of the maximum power transmitted before the breakdown occurred. Had the power been kept at the breakdown limit, strips and the substrate would have been severely damaged and the power would be reflected back to the generator. At 35.5 GHz, the electric breakdown mechanism was similar to that in X-band, except that the superficial destruction of the dielectric substrate did not occur over the whole length of the gap, as shown in Fig. 4(a). This can be explained by the fact that the power was reduced immediately after the breakdown occurred. For the same reason, the conductors did not suffer significantly from the breakdown, as shown in Fig. 4(b) and (c).

The values of the transmitted peak power at which breakdown occurred are shown in Tables I and II for X- and Ka-band measurements, for different gap widths. As expected, the maximum power that can be transmitted increases with the gap width value. The values after a subsequent trial are shown in order to



(a)



(b)

Fig. 4. Finline structure after testing for measurement at 35.5 GHz. Conductor thickness $g = 9.9\ \mu m$ and substrate thickness $s = 254\ \mu m$ with deposited (plated) fins. (a) Electron micrograph showing the breakdown locations at the tip of the arrows (magnification 667 $\mu m/cm$). (b) Electron micrograph of the location around the lower mark of Fig. 4(a) for both sides of the gap (magnification 20 $\mu m/cm$).

confirm that the structure did not suffer significantly from a short breakdown condition, at both frequencies.

IV. Theoretical Model

In order to predict the maximum peak power that E-plane structures can handle, a theoretical model of the breakdown phenomenon [1] was used. The maximum field strength in the E-plane structure was evaluated with a quasi-static approach, using a realistic geometry for the conducting strip profile. The

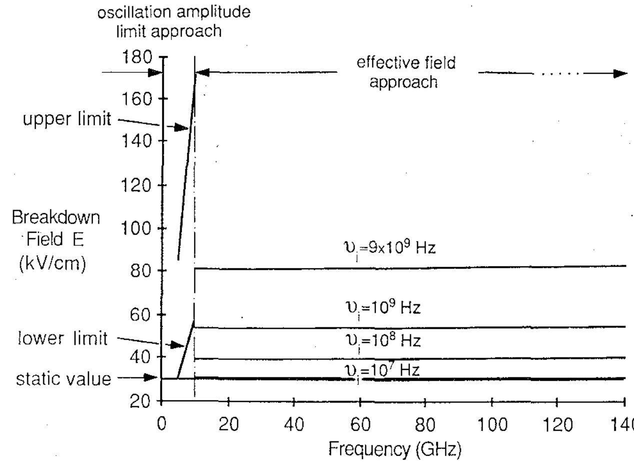


Fig. 5. Breakdown field values in the air versus frequency (theoretical prediction). Pressure $p = 760$ mmHg. ν_i = ionization rate (from [1]).

power transmitted under dynamic conditions was computed using the relation

$$P_{\max} = \frac{V_{\max}^2}{2Z_0} \tag{1}$$

where $V_{\max}$ is the voltage across the gap under breakdown condition and Z_0 is the power–voltage impedance of the line computed with a fast spectral domain algorithm [5]. For the impedance calculation, only infinitely thin conductors were assumed, since it was found that the impedance values are affected by only a few percent when the metallization thickness is taken into account, except for extremely narrow gap widths [6].

The breakdown field value depends on various parameters such as the geometry (inhomogeneous fields), the frequency, and environmental conditions. Under normal atmospheric conditions, with samples free of dust, the breakdown field value is shown in Fig. 5 as a function of frequency for different parameters pertaining to breakdown conditions. Two different models, namely the oscillation amplitude limit [7] and the effective field approach [8], cover a frequency range from a few GHz to 140 GHz. For the oscillation amplitude limit, the upper and lower curves, which depend on the geometry, correspond to a breakdown occurring simultaneously along the whole structure (ideal model) and over a short distance of a few μm (as observed in the experiments), respectively. Note that both the oscillation amplitude limit and the effective field approach are valid around 10 GHz. This yields the ionization rate from the intersection of the corresponding curves, and consequently the theoretical breakdown field value at higher frequencies.

V. Comparison Between Theory and Experiments

Tables III and IV compare the theoretical and experimental values of the peak power-handling capacity of unilateral finlines with comparable characteristic impedance values, in both the X- and the Ka-band. Only values corresponding to samples with characteristic impedances below 500 Ω are shown. It can be seen that theoretical values compare fairly well with the experiments for characteristic impedances above 200 Ω in the X-band, and for all values in the Ka-band. For lower impedance values in the X-band, the difference between the predicted and experimental values is quite large in terms of percentage, but still well in the same order of magnitude. These discrepancies can be explained by the fact that the parameters pertaining to the geometry of the volume, in which the ionization process takes place, are difficult

TABLE I
PEAK POWER-HANDLING CAPABILITY OF WR-90 WAVEGUIDE HOUSING FINLINES WITH DIFFERENT GAP WIDTHS AT 9.6 GHz (X-BAND)

d (mm)	Z_0(ohms)	1st trial (kW)	2nd trial (kW)	Average (kW)
0.5	145 6	5.60	5 43	5 51
1.0	188.4	9.50	8.38	8 94
1 5	213.7	10 75	10 75	10 75
2 0	238 3	12 00	11 50	11 75
2 5	261 2	19 06	18 02	18.54

Repetition of pulse is 1000 pulses/s with pulse duration of 0.8 μs. Conductor thickness $g = 34$ μm and substrate thickness $s = 762$ μm.

TABLE II
PEAK POWER-HANDLING CAPABILITY OF WR-28 WAVEGUIDE HOUSING FINLINES WITH DIFFERENT GAP WIDTHS AT 35.5 GHz (Ka-BAND)

d (mm)	Z_0(ohms)	1st trial (kW)	2nd trial (kW)	Average (kW)
0 2	168.5	0.94	0 96	0 95
0 5	217 5	3.80	3.15	3 48

Repetition of pulse is 60 pulses/s with pulse duration of 16.6 μs. Conductor thickness $g = 9.9$ μm and substrate thickness $s = 254$ μm.

TABLE III
COMPARISON BETWEEN THEORETICAL AND EXPERIMENTAL RESULTS FOR UNILATERAL FINLINE STRUCTURES AT 9.6 GHz

d (mm)	Peak power (kW) lower limit	Expt (kW)	% error	Peak power (kW) upper limit
0 5	2 125	5.510	61 4	49 95
1 0	5 349	8 938	40 2	125 7
1 5	8.830	10 75	17 9	207 6
2 0	11 76	11.75	00 0	276.4
2 5	14.25	18 54	23 1	335 0

WR-90 waveguide is used with conductor thickness $g = 34$ μm and substrate thickness $s = 762$ μm.

TABLE IV
COMPARISON BETWEEN THEORETICAL AND EXPERIMENTAL RESULTS FOR UNILATERAL FINLINE STRUCTURES AT 35.5 GHz

d (mm)	Peak power (kW)	Expt (kW)	% error
0 2	1 002	0 950	5 47
0.5	3.240	3.475	6.76
1 0	6 109	—	—
2.0	9 663	—	—

WR-28 waveguide is used with conductor thickness $g = 9.9$ μm and substrate thickness $s = 254$ μm.

to determine accurately, especially when the electric field becomes highly inhomogeneous, which is the case for narrow gaps. The calculated maximum power values correspond to the model that assumes the breakdown to occur only over the short distance observed on the samples after experiments. This value is about 12 μm and depends on the size of the irregularities of the profiles. The theoretical upper limit for which the electric breakdown would occur along the entire structure is about one order of magnitude above the experimental values, but does not correspond to a realistic situation.

VI. CONCLUSION

The theoretical model to predict the peak power-handling capacity of finline structures was verified by an experimental procedure carried out at 9.6 GHz (X-band) and 35.5 GHz (Ka-band). Theoretical and experimental values compare fairly well, especially for structures with gap widths larger than 1.5 mm. The best prediction is made when it is assumed that the breakdown occurs only over a small distance along the line, which corresponds to the size of the irregularities of the profiles (about 12 μm). This value can be used to determine the ionization rate for extrapolation to higher frequencies.

The analysis of the samples after breakdown showed that, for pulsed operations, no significant heat is produced due to the relatively low average power involved in this case. It is found that at 35.5 GHz (Ka-band), the maximum peak power that can be handled by a unilateral finline of 220 Ω characteristic impedance is about 3.5 kW under narrow pulse signal operation.

In conclusion, the theoretical breakdown model developed and presented previously by the authors [1] is appropriate for predicting the peak power-handling capability of finlines for the purpose of establishing limits of safe operation under laboratory conditions.

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An Evanescent-Mode Tester for Ceramic Dielectric Substrates

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***Abstract*—The TE_{01} mode in a cylindrical waveguide at a frequency below cutoff is used to probe a ceramic dielectric substrate located on the central plane between input and output coupling loops. Maximum transmission occurs at a frequency determined by the waveguide radius, the substrate thickness, and the dielectric constant. The dielectric constant and**

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