Groove- and *H*-Waveguide Design and Characteristics at Short Millimetric Wavelengths

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***Abstract*—The design of the *H* guide and groove guide for use in the short millimetric range with relatively low-loss, low-dispersion, and single-mode operation is considered. Measurements at 40 and 100 GHz show encouraging characteristics. It is considered feasible to construct components to form complete systems in these guides.**

I. Introduction

THE USE OF the short millimetric wavelength range has been inhibited, apart from a number of specialized applications, by the absence of convenient sources, waveguides, and components. Solid-state sources are now readily available at the lower frequency end of the spectrum; however, backward wave oscillators can cover the range, and recent advances in high-power electron-tube technology have made available CW power levels in excess of a 1-kW mean at about 300 GHz. The use of a normal rectangular TE_{10} dominant-mode guide presents difficulties. The dimensions become very small (maximum transverse dimension $<$ wavelength), and the attenuation becomes exceedingly large (e.g., measured attenuation [1] at 200 GHz over 40 $dB \cdot m^{-1}$). An overmoded rectangular guide gives lower losses but a higher order mode propagation, while the low-loss circular-guide mode gives very low attenuation but allows transmission only with no components for signal manipulation.

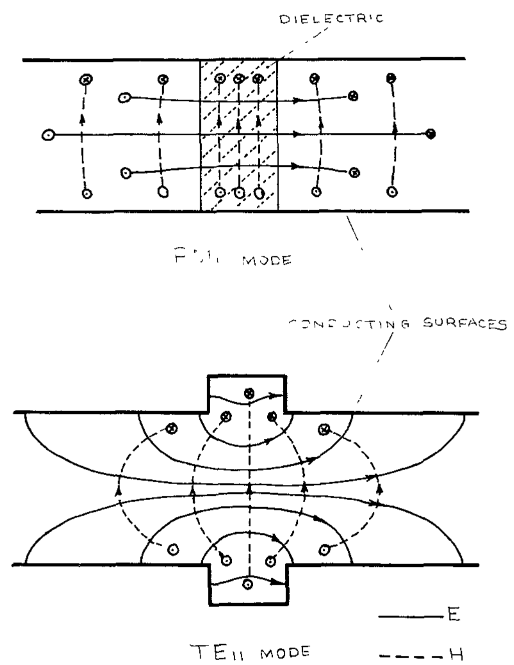

Fig. 1. Cross sections and transverse field distributions.

Both the *H* guide and groove guide could provide alternative waveguide systems which are advantageous for this frequency range. The basic guide forms and field distributions are shown in Fig. 1. The energy is concentrated in the transverse direction by the dielectric sheet and by the grooves for the two guide types. The *H* guide supports a hybrid mode, with much of the electric field in the form of closed loops, while the groove-guide mode is transverse electric. The field distributions and characteristics have been analyzed by several authors [2]–[6]. The losses in the guides can be readily computed, and typical characteristics are shown in Figs. 2 and 3, for various guide dimensions in the frequency range of interest. It is clear that for low losses, the plane separation must be considerably greater than the wavelength in each case, and for the *H* guide the dielectric film thickness must also be very small. Guide dimensions in excess of the wavelength normally lead to the possibility of overmoded guide propagation, and there is the added problem of supporting a very thin film across the guide width. It is shown, however, that these problems can be overcome, and that both guide types can be used with essentially single-mode propagation.

II. Design of the *H* Guide

Support of the thin dielectric film and higher mode suppression can be achieved by the guides shown in Fig. 4. Suppression of the higher order modes depends upon the dimension d_1 or d_2 for the two possibilities shown. Since the fields decay rapidly in the direction away from the dielectric sheet, the guide can be conveniently constructed from two *U* channels clamping the dielectric sheet to support it across the guide.

The behavior of such a guide can be measured by obtaining the resonance characteristic for a short-circuited length, with both ends being closed by conducting plates with a coupling aperture. The resultant resonance spectrum yields the dispersion, the attenuation, and the moding behavior. If the frequency of the source can be

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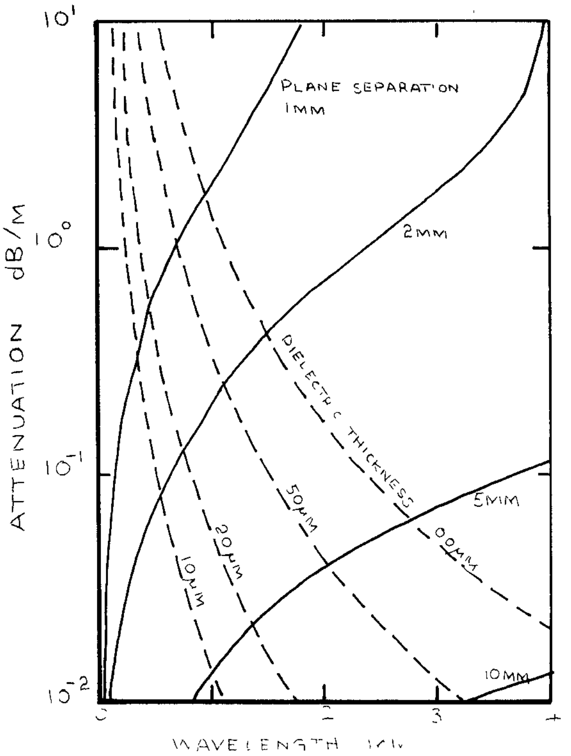


Fig. 2. *H*-guide attenuation. Conductor loss ($\sigma_m = 5.8 \times 10^7$ S·m^{-1}). Dielectric loss ($\epsilon_r = 2.1$, $\tan\delta = 0.001$).

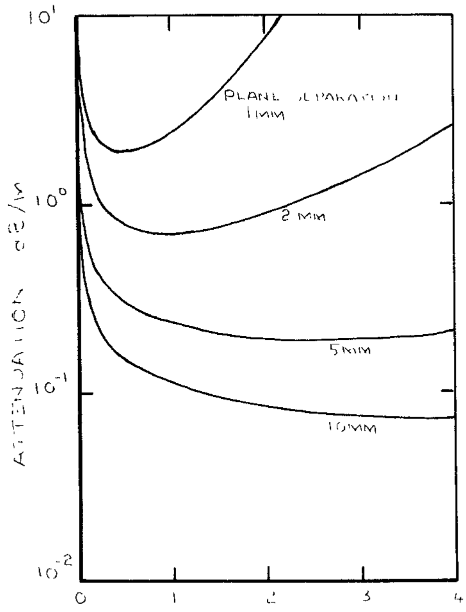


Fig. 3. Groove guide attenuation. Groove depth = 0.25 plane separation. Groove width = 0.5 plane separation ($\sigma_m = 5.8 \times 10^7$ S·m^{-1}).

changed over an appreciable range, the dispersion is obtained by measuring the number of half-guide wavelengths using a perturbation technique at each resonant frequency, the attenuation is measured from the half-power frequency values for each resonance and measurement of the coupling coefficients, and the moding spectrum can be displayed directly using an oscilloscope or *xy* plotter.

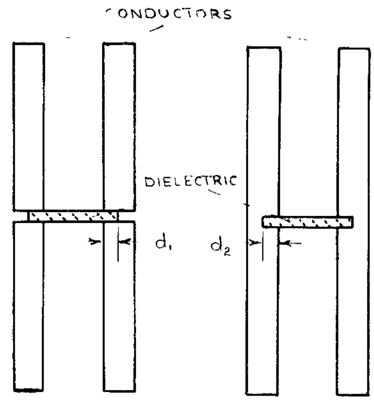


Fig. 4. Modified *H*-guide cross sections.

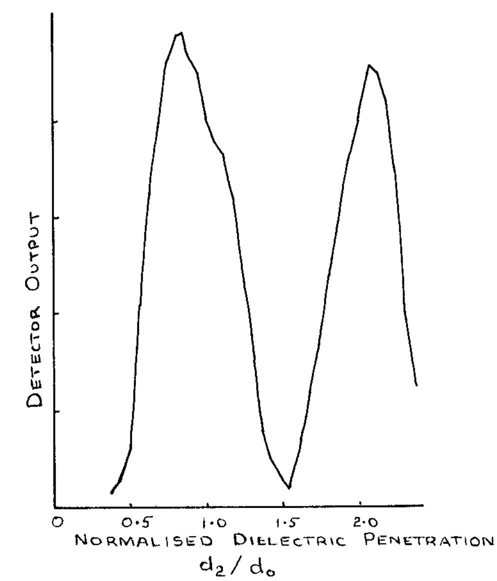


Fig. 5. Effect of dielectric penetration on main-mode transmission in the *H* guide.

The effect of the distance d_2, the penetration of the dielectric into the conducting surface, on the propagation of the first-order mode has been measured in the 26–40-GHz region. With a plane separation of 35 mm, the magnitude of the signal transmitted through the resonant section was measured for a number of incremental values of d_2. One such measurement is shown in Fig. 5. The penetration depth is normalized to d_2/d_0, where d_0 is equal to the broad dimension of the dielectric-filled rectangular guide with the TE_{10} mode having the same phase velocity as the simple *H* guide. Similar curves were obtained for a number of frequencies across the measurement spectrum. Good transmission is obtained for $d_2/d_0 \simeq 1.0$ and 2.0, but there is suppression for $d_2/d_0 \simeq 0.5$ and 1.5. Since phase velocities are a function of mode number, higher order mode suppression can occur for the optimum d_2/d_0 condition for the first-order mode. The technique has the disadvantage of requiring a slot depth with a dimension critical to a fraction of a wavelength and therefore of being frequency sensitive. The guide has been made with a plane separation of 35 mm but devoid of measurable higher order modes [7] over a frequency range of 7 GHz centered on 34 GHz; clearly, however, the constructional problems will increase for very short millimetric wavelengths.

Since the plane separation is large compared with the wavelength, e.g., 4λ in the above example, the dispersion and the attenuation are both very low, but accurate measurements have not been made in the short millimetric range. Clearly the attenuation is reduced further for wider plane separations and thinner dielectrics, but the possibility of higher mode propagation then increases, and the dielectric becomes more difficult to support. A plane separation of about 4λ and a dielectric thickness to give comparable attenuation would seem about optimum.

III. Groove-Guide Design

The interesting feature of the groove guide of allowing only single-mode propagation even with plane separations large compared with the wavelength has been remarked by Nakahara and Kurauchi [6], although experimental verification of its validity at short millimetric wavelengths has not been previously reported. A series of measurements similar to those for the *H* guide as outlined above have been made in the 26–40-GHz range. The moding spectrum has been investigated using a resonant length of guide having a variable groove depth. The plane separation was 30 mm, and the mode for each resonance was identified by a perturbation technique. The mode magnitude variation as the groove depth was increased is shown in Fig 6, where it can be seen that when the groove depth is about a quarter of the plane separation, the higher order modes are effectively suppressed. By combining the wave equations for the groove and outer regions, with the outer region wave number less than that for the groove region, it can be shown that the energy in the outer region can propagate transversely out of the guide rather than being evanescent in the transverse direction. Thus, provided that there is effective coupling between the two modes, e.g., between the third-order mode in the groove region and the first-order mode in the outer region, the higher order mode energy will leak out of the guide, and the mode will be suppressed. A simple Fourier analysis of fields at the groove–outer region interface shows that for this groove-depth condition there is good coupling between the first few higher order modes in the groove region and the appropriate leaky mode in the outer region.

Theoretical analyses of the guide lead to series solutions, but measurements at 3-cm wavelength confirm the adequacy of these expressions using only the first term of the series for practical applications with plane separations which are large relative to the wavelength.

A wide range of measurements has been carried out at 3-mm wavelength [8], [9] using the guide cross section of Fig. 7(a). A typical resonance spectrum is shown in Fig. 7(b). The lossy polystyrene is to absorb unwanted modes. The 3-mm source in an IMPATT (Plessey ATO 271), and the spectrum is obtained by varying the resonant guide length with an appropriate short circuit. The detail of the spectrum can also be investigated using the electronic tuning of the IMPATT. The plane separation of 10 mm is greater than 3 λ, but only first-order mode resonances are significant with a groove depth of 2.5 mm. The unloaded *Q* factor was obtained from measurements on two different lengths of an otherwise similar guide. These guides were constructed from aluminum by conventional machining techniques, and a guide attenuation of 0.6-dB $\cdot$ m^{-1} was measured. This is a factor of 4 greater than the theoretical value but a factor of 10 less than the attenuation of the corresponding single-mode rectangular guide.

An important feature of the guide is that mode suppression results from the geometry of the guide. It does not depend upon critical constructional dimensions that are a

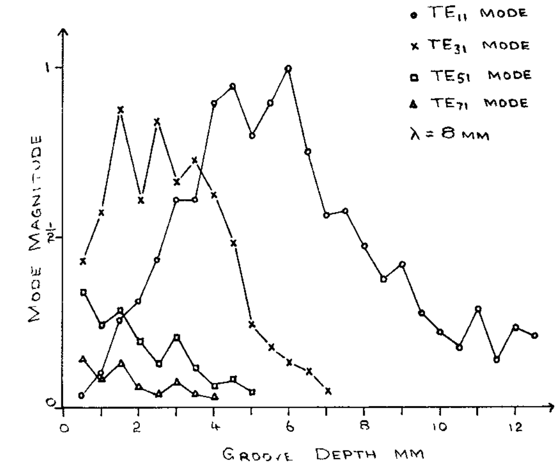
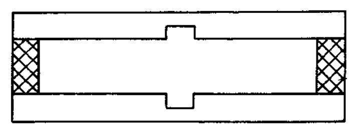
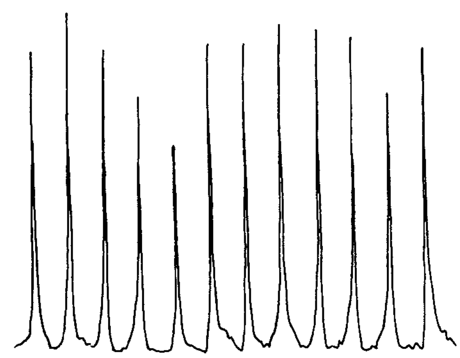


Fig. 6. Relative groove-guide-mode magnitudes. Plane separation: 30 mm.



(a)



(b)

Fig. 7. (a) Guide cross section. Plane separation : 10 mm. Groove: 2.5 mm ×5 mm. (b) Resonance spectrum. Guide length: 95–115 mm. Frequency: 96 GHz.

fraction of a wavelength or require great precision in manufacture. The guide, therefore, should be simple to construct even into the submillimeter region. So far preliminary measurements only have been made at such short wavelengths [10]. The relationship of the groove depth equal to a quarter of the plane separation is now used for most of our measurements. The attenuation can be reduced somewhat by an increase of the groove width, but the improvement is marginal and can lead to the possibility of transmission of additional unwanted modes. The wide plane separation and absence of wavelength-related dimensions should lead to a very wide operating frequency range. The cutoff wavelength for the guide used for 3-mm wavelength measurements is about 2 cm, and the short-wavelength limit will be set by the increasing possibility of higher mode transmission. We have not investigated the extent of the effective frequency range for a particular guide, but it is clearly going to be very large.

IV. General Characteristics of the *H* and Groove Guide

Both the *H* guide and groove guide of a suitable design have the attractive features of convenient cross-sectional dimensions, relatively simple construction, low dispersion, effective single-mode operation, and losses considerably less than that of an equivalent dominant-mode rectangular guide. Additional advantages of the *H* guide are that the wall currents are entirely transverse and, therefore, connections between separate lengths of the guide are simplified; the presence of the dielectric could be valuable as a support, but the main disadvantage relative to the groove guide is the requirement of a critical depth of slot for the dielectric in the conducting planes. The groove guide is easier to construct and will have a wider frequency range for given guide dimensions, but there is a component of current in the direction of propagation, and connections may be more difficult.

For both guides, the attenuation can be reduced by increasing the plane separation to give low-loss transmission sections. The transitions from such sections to more tightly coupled and controlled sections for signal manipulation would be simple. The field distributions in the guides are such that the construction of components directly in the guide should be feasible. Some initial work on a double-groove guide has shown that both symmetrical and nonsymmetrical modes can exist with different phase velocities, and a similar result would be expected for a double-dielectric *H* guide. This should form the basis of directional couplers. It should be possible to mount devices such as IMPATT's directly in modified sections of these guides to provide energy sources and high-frequency diodes to form detectors. Since access is readily achieved through the outer edges of the guides and there is an exponential decay of fields in the transverse direction, components such as attenuators and phase shifters should be straightforward. A complete system may thus be envisaged with generation, transmission, and reception in the *H* or groove guide; alternatively, these guides may replace the rectangular guide and be used in conjunction with the circular guide by development of a suitable transition. It is envisaged that the groove guide in particular should be readily extended into the submillimeter-wave region.

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