Frequency Dependent Behavior of Microstrip

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Recently there has been considerable interest in the use of the open microstrip geometry as a transmission line in microwave integrated circuits. This form of propagating structure is applicable to a monolithic approach on a semiconductor substrate as well as to a hybrid approach using a ceramic substrate. In order to choose suitable materials, we have investigated the basic properties of microstrip and its interactions with the substrate. A detailed experimental investigation has brought to light two important aspects of circuit design with microstrip. First, microstrip has an upper frequency limit and second, it is dispersive.

Measurements of the attenuation constant[1], α, and phase constant, β, were made on substrates of rutile and alumina by resonating open end lengths of line and correcting for the effects of the end and the transition.[2] Ceramic rutile as prepared in our own laboratory was measured[3] and has a dielectric constant, $\kappa = 104$, and loss tangent, $\tan\delta \sim 8 \times 10^{-4}$ at f = 9.90 GHz. The alumina used was Wesgo AL-995[4] which was measured and has $\kappa = 9.7$ and $\tan\delta < 10^{-4}$ at f = 9.87 GHz.

It is well known that the dielectric-covered ground plane, used to support the microstrip transmission line, is also capable of propagating plane-trapped surface waves.[5,6] The propagation constant is plotted against frequency for the two lowest order surface waves in Figure 1 along with the hypothetical β-ω line of a TEM mode as described by Wheeler.[7] The lowest order mode is the TM_0 which has a zero frequency cutoff. The next higher order mode is a TE wave which has a finite "divergence" frequency, below which frequency it cannot exist, unlike waveguide modes. It is not surprising that these modes couple to the microstrip and alter its behavior at elevated frequencies.

1) Upper Frequency Limit - The most vivid effect is the coupling to the higher order TE surface wave. At and above f_c, the divergence frequency, determined by the dielectric constant and thickness of the substrate, the propagation of energy cannot be confined to the microstrip configuration. Experimentally, it is observed that energy propagates on the substrate, independent of the microstrip line and radiates from the edges of the substrate. Above f_c transmission can be observed across a substrate with no microstrip line. As indicated in Figure 2, this limit has been observed on rutile substrates at 5.8 GHz for a 0.050" thickness and at 14.6 GHz for 0.020" thickness. Likewise, it would occur on alumina at 20.1 GHz on a 0.050" thickness and at 50.2 GHz on 0.020".

2) Dispersion - Because the "TEM mode" and the TM surface wave β-ω curves cross, one should expect a synchronous coupling of modes

as indicated by curves (2) and (3) of Figure 1. Experimentally, we find it convenient to describe curve (2) by an apparent dielectric constant, κ_{eff}, similar to that of Wheeler[7] and given by the square of the ratio of the velocity of light in free space to phase velocity on microstrip, $(c_o/v)^2$. An expression has been derived from coupled mode theory[8] for κ_{eff} in terms of the low frequency κ, κ_1, the surface wave κ_{eff}, κ_2 and a coupling coefficient ξ. κ_{eff}, as described in Figure 3, has been fitted to data on rutile and alumina substrates, Figures 3 and 4, respectively. Theoretical calculation of ξ is not possible without an explicit description of the electric and magnetic fields of the assumed "TEM mode." However, qualitatively it is expected that ξ should increase with frequency as energy in the surface wave is drawn into the dielectric.

3) Radiation - The remaining wave, curve (3) of Figure 1, is often observed indirectly as a source of radiation. Earlier investigations[9] have indicated that a small dipole, close to the surface of the dielectric, can radiate into the TM_o surface wave with greater than 95 percent efficiency.

Conclusions - Although boundary conditions on the surface waves have been neglected, the simple mode behavior described above provides a workable model to describe the frequency limitation, dispersion and radiation to be expected with microstrip on a ceramic substrate. Dispersion implies that the characteristic impedance, Z_o, decreases with increasing frequency. This has been observed by measurement of mismatch on a 50 ohm line on alumina at high frequencies. For the reasons described, it is necessary that the substrate thickness, h, be much less than a quarter wavelength in the dielectric. Radiation can be minimized by avoiding all leads which project above the surface of the substrate.

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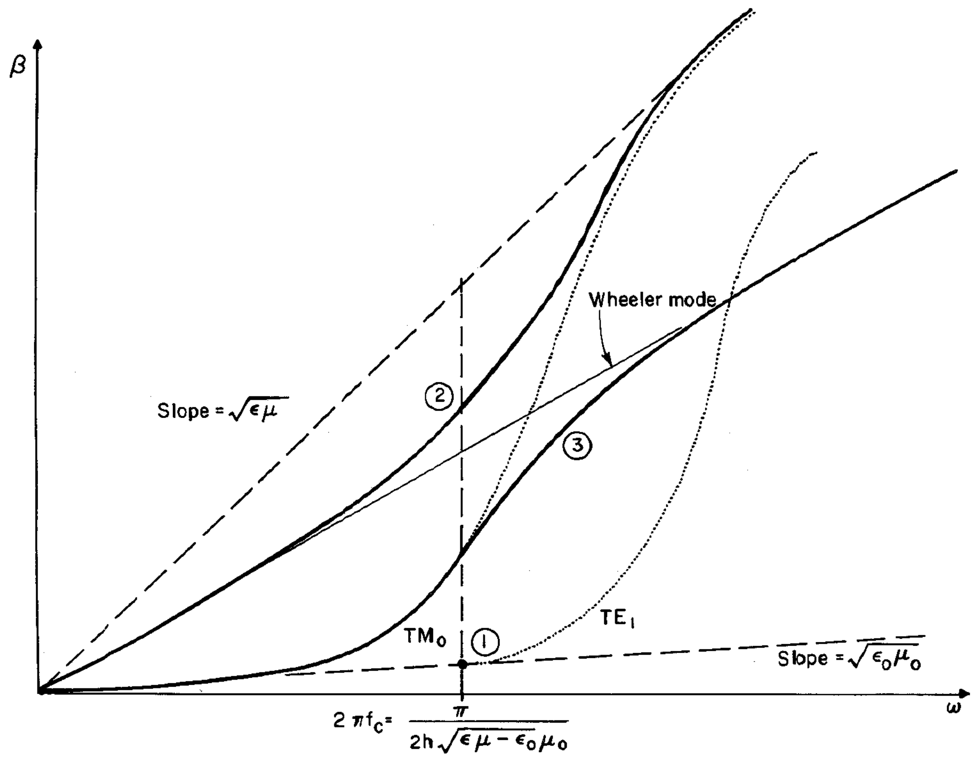

Figure 1 β-ω Diagram for Microstrip and Surface Wave Modes.

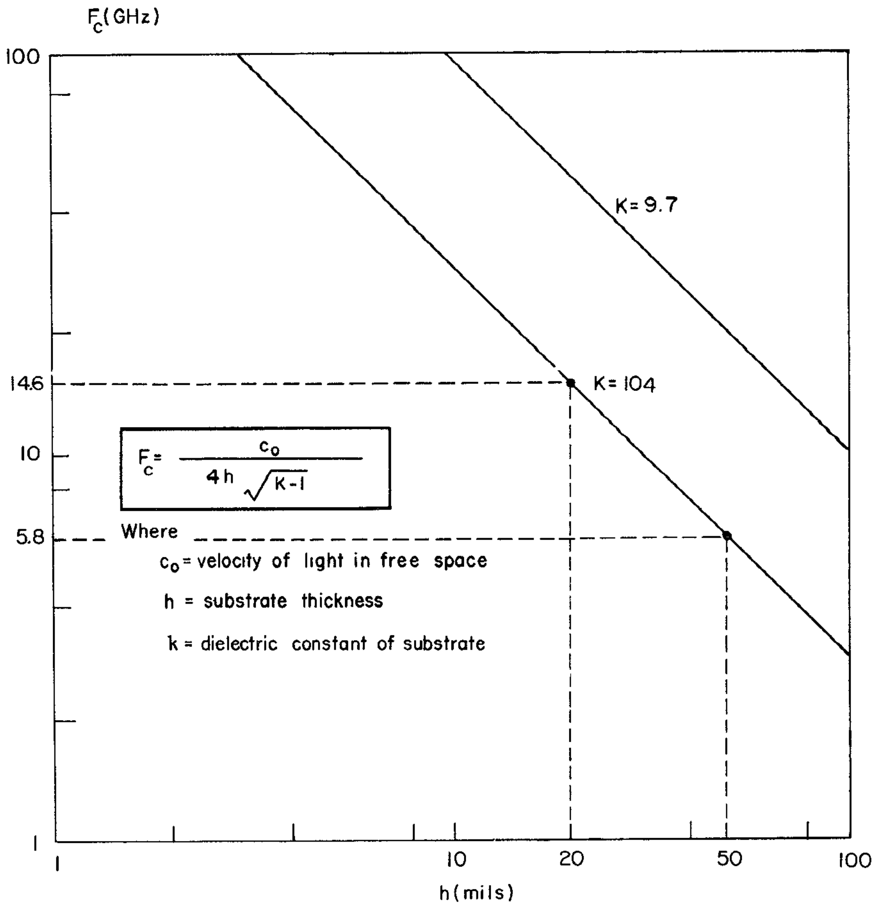

Figure 2 Divergence Frequency of Lowest Order TE Surface Wave versus Dielectric Thickness.

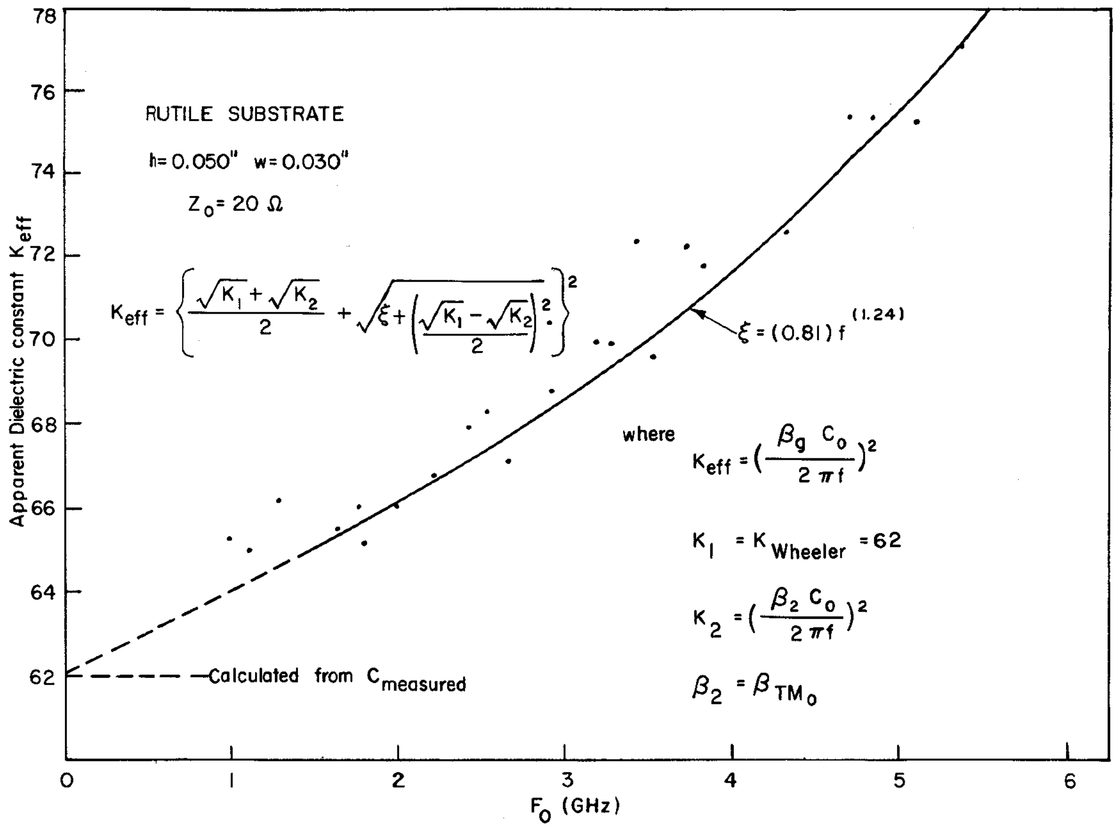

Figure 3 Apparent Dielectric Constant versus Frequency for a Rutile Microstrip.

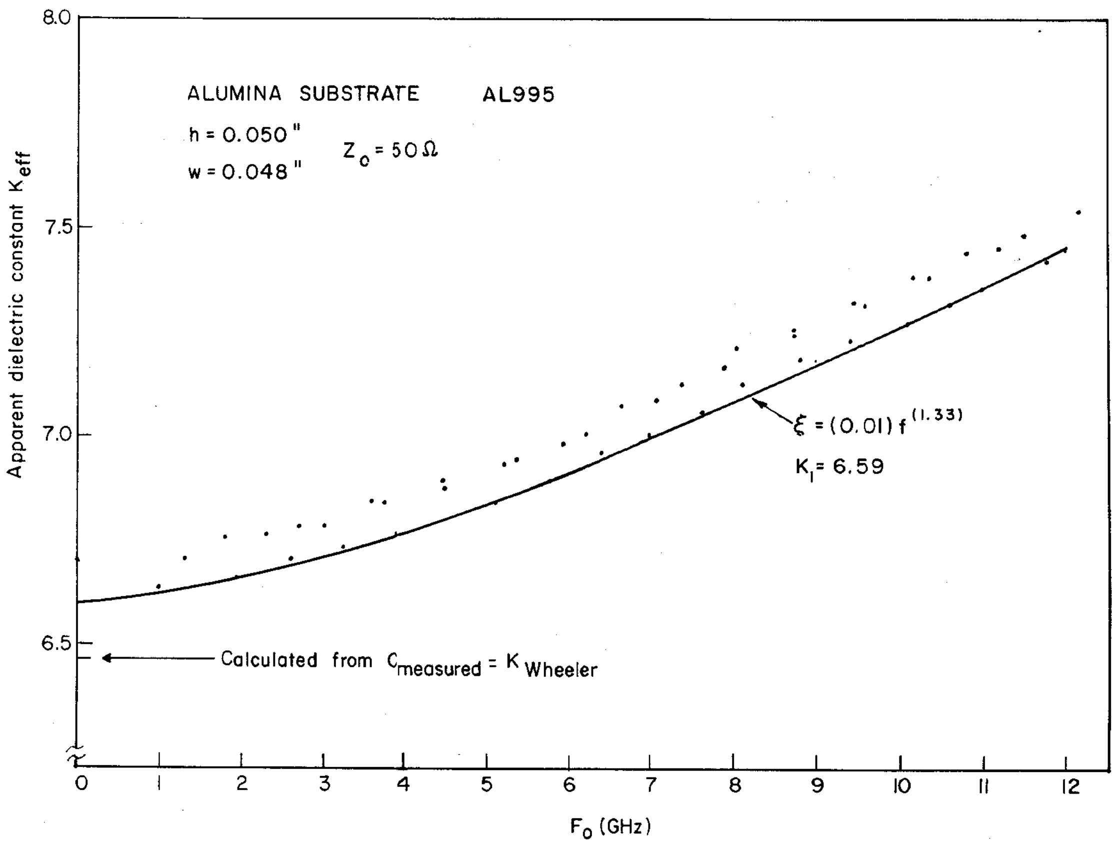

Figure 4 Apparent Dielectric Constant versus Frequency for an Alumina Microstrip.