Single-mode Limits for Shielded Microstrip

The use of microstrip transmission lines has been steadily increasing over the last three decades. One reason is that microstrip is a planar transmission structure, so can be easily fabricated even down to minute sizes with photolithography, and can be incorporated into microwave integrated circuits (MICs). Placing microstrip in a rectangular shield eliminates unwanted coupling between strips, also simplifying analysis, and can reduce attenuation and dispersion. Care must be taken, however, in the proper design of a microstrip shield to avoid allowing higher order modes to propagate which can use the shield and strip as a waveguide. These higher order modes will limit the performance of a microwave circuit by allowing power to by-pass part of the circuit. It is desirable, therefore, to know how the geometry of a shielded microstrip structure determines the frequency limits for single-mode operation.

A cross-section of a shielded microstrip transmission line (fig.1) shows the complexity involved in solving for the exact electromagnetic fields in the structure. The tangential electric field must be zero on both the metal shield and the strip, and the fields must match across the dielectric/air interface.

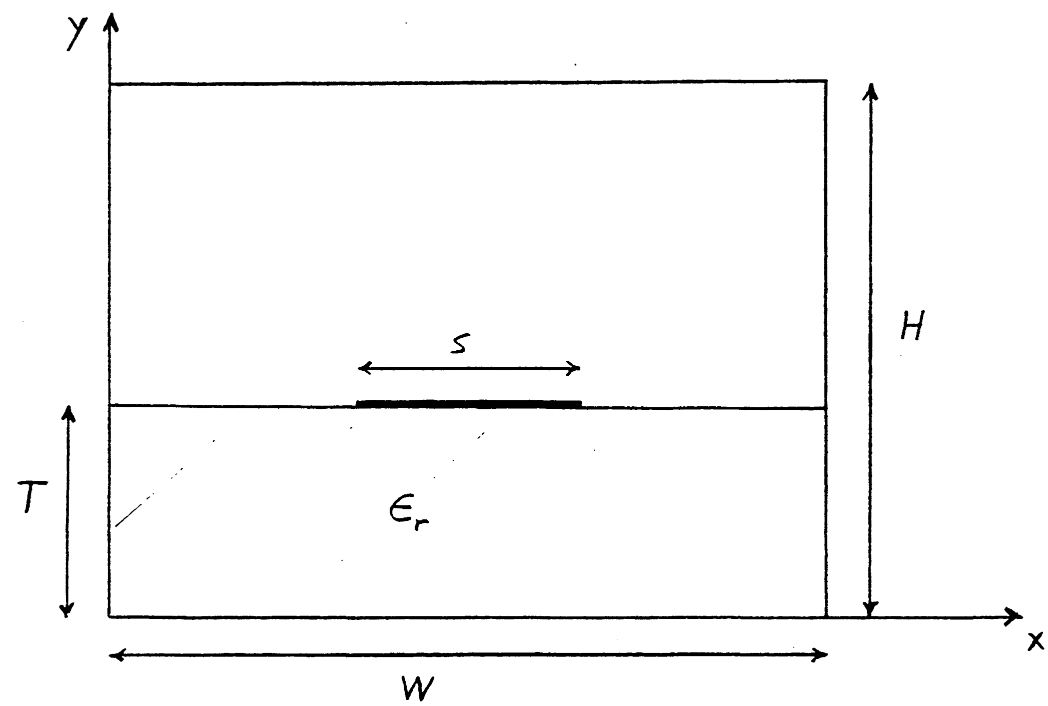


Figure 1
Cross-section of shielded microstrip waveguide

A much easier problem to solve is to find the cut-off frequencies for this structure without a strip present, ie, finding cut-off frequencies for a dielectric-loaded waveguide. As long as the strip width and thickness is small, the presence of the strip should be a small perturbation from the stripless case, still exhibiting approximately the same mode cut-off frequencies. The extreme case of this perturbation is for the strip to completely cover the substrate, dividing the structure into two waveguides, which can be easily analyzed.

The modes in a rectangular dielectric-loaded waveguide can be divided into two types; longitudinal-section electric (LSE) modes which have no electric field component normal to the dielectric/air interface, and longitudinal-section magnetic (LSM) modes which have no magnetic field component normal to this interface. The lowest order of each of these modes are the LSE_{01} mode and the LSM_{11} mode. To keep all waveguide modes from propagating, the operating frequency must be maintained below the cut-off frequency for both of these modes.

Collin [1] shows how to find the propagation constant for each of these modes by matching boundary conditions across the air/dielectric interface for the electric and magnetic fields. Assuming the waveguide walls to be perfectly conducting, the propagation constant, γ , will be zero at cut-off. For the LSE_{01} mode the cut-off frequency must satisfy the transcendental equation,

$$\tan(k_o*\sqrt{\epsilon_r}*T) = -\sqrt{\epsilon_r}*\tan[k_o*(H-T)] ,$$

and for the LSM_{11} mode,

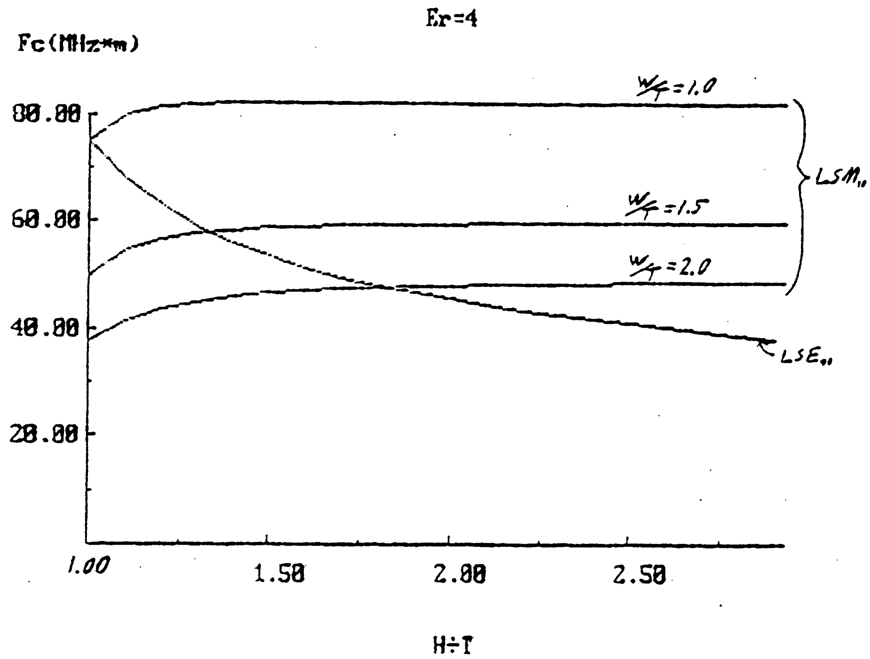
$$\epsilon_r*\sqrt{k_o^2-(\pi/W)^2}*\tan[\sqrt{k_o^2-(\pi/W)^2}*(H-T)] = -\sqrt{\epsilon_r*k_o^2-(\pi/W)^2}*\tan[\sqrt{\epsilon_r*k_o^2-(\pi/W)^2}*T]$$

where

$$k_o = 2*\pi/\lambda_o = (2*\pi/c_o)*f_{co}$$

Note that the LSE_{01} mode cut-off has no guide width dependence.

Holding the substrate thickness constant at a normalized value of a meter, figure 2 shows how the cut-off frequencies for these modes change with shield geometry. The LSM_{11} mode will limit the operating frequency for low height and wide width microstrip shields ($H_y = 0$), while the LSE_{01} mode will limit the operating frequency for high height and narrow width microstrip shields ($E_y = H_x = E_z = 0$). For a particular thickness the height which gives the highest cut-off frequency is about 90% of the width for quartz ($\epsilon_r = 4$) and about 84% for silicon or GaAs ($\epsilon_r = 12$).



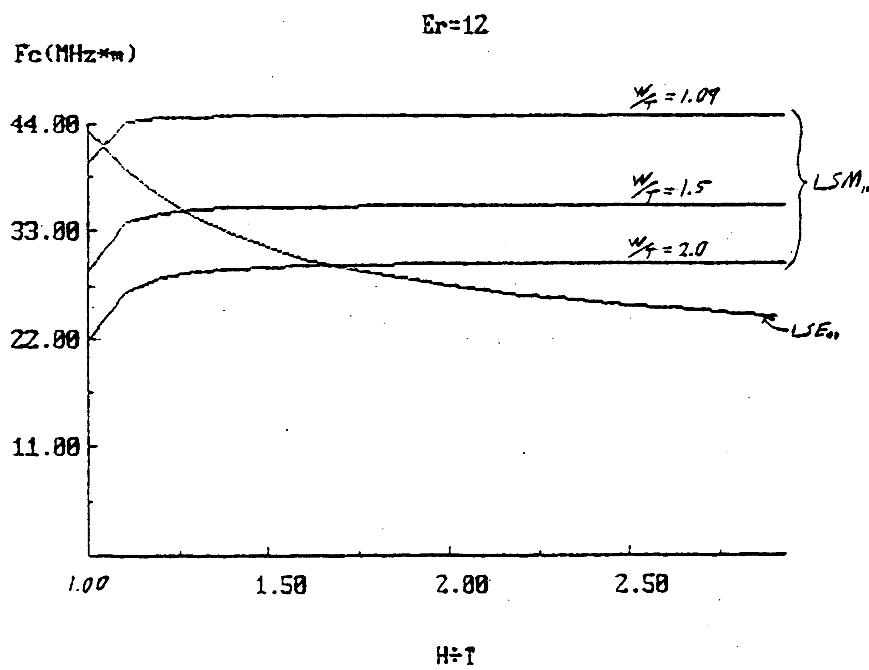


Figure 2
Cut-off frequencies for dielectric-loaded waveguide

To generally analyze the case of a structure with a microstrip present, we should consider the extreme case of a strip extending completely across the substrate, dividing the shield into two filled waveguides. The cut-off frequency for a filled rectangular waveguide will either be dictated by the cut-off frequency of the E_{11} mode, which is,

$$f_c = (c_o*\sqrt{W^2+H^2})/(2*\sqrt{\epsilon_r}*W*H)$$

or will be dictated by the cut-off frequency for the H_{10} mode, which is,

$$f_c = c_o/(2*\sqrt{\epsilon_r}*X)$$

where,

$$X = \begin{cases} W & W>H \\ H & H>W \end{cases}$$

The waveguide filled with dielectric will nearly always have the lower cut-off frequency and the H_{10} mode will usually dictate what this cut-off is. The intersection of the LSM_{11} mode cut-off frequency line with the H/T = 1.0 axis in figure 2 gives the cut-off frequency for the bottom waveguide when the strip completely crosses the substrate.

The presence of a microstrip will have less effect on the LSM_{11} mode because this mode has most of its electric field directed normal to the strip. It will have a stronger effect on the LSE_{01} mode, which has all of its electric field directed tangential to the strip, with a maximum at the strip location. We can therefore expect that as the strip width is widened, the cut-off frequency will lower more slowly for those geometries which are dominated by the LSM_{11} mode when no strip is present than for those dominated by the LSE_{01} mode when no strip is present. In order to exactly find the highest frequency for single-mode operation for a shielded microstrip configuration, a more rigorous analysis is called for, such as the spectral domain method of analysis.

Stripline Modes

For enclosed microstrip, the waveguide analysis used previously is no longer strictly valid. To find the cutoff frequencies of the higher order stripline modes (the dominant mode has no cutoff), the spectral-domain method can be used.

In the spectral-domain method, the strip current is approximated by a summation of basis functions. The amplitudes of these basis functions are computed by using the appropriate Green's function to associate a field with the strip current, and enforcing boundary conditions on the strip for this field. The phase constants for the propagating modes are those values that make the determinant of the system vanish.

Spectral-domain formulations are efficient because the use of spatial Fourier transforms converts all convolution math to algebraic math. Well-chosen basis functions (that match the strip current within the first few terms) also help by reducing the size of the matrix to solve.

A spectral-domain program, written by Chi Chan of Ohio State University, was used to find the region of single-mode propagation for enclosed microstrip on GaAs ($_r$=12). The input consisted of the height H and width W of the waveguide, the thickness T of the substrate and the width S of the strip conductor, as well as the frequency f (See Fig. 1). To reduce the number of variables to handle, all variables were scaled by T:

T -> 1 (meter)
H -> H/T
W -> W/T
S -> S/T
F -> F*T

The results are plotted in Fig. 3, with scaled cutoff frequency fc*T (MHz*m) for the first higher order mode on the left vertical scale, and strip width in terms of S/W (0 to 1) on the horizontal scale. Three families of curves were generated for H/T = 1.2, 1.5 and 2.5, and in each family there are three curves for W/T = 1.0, 1.5, and 2.0. As an illustation of the generality of the results, the right vertical scale indicates where a cutoff frequency of 135 GHz would be located on the graph for several values of T.

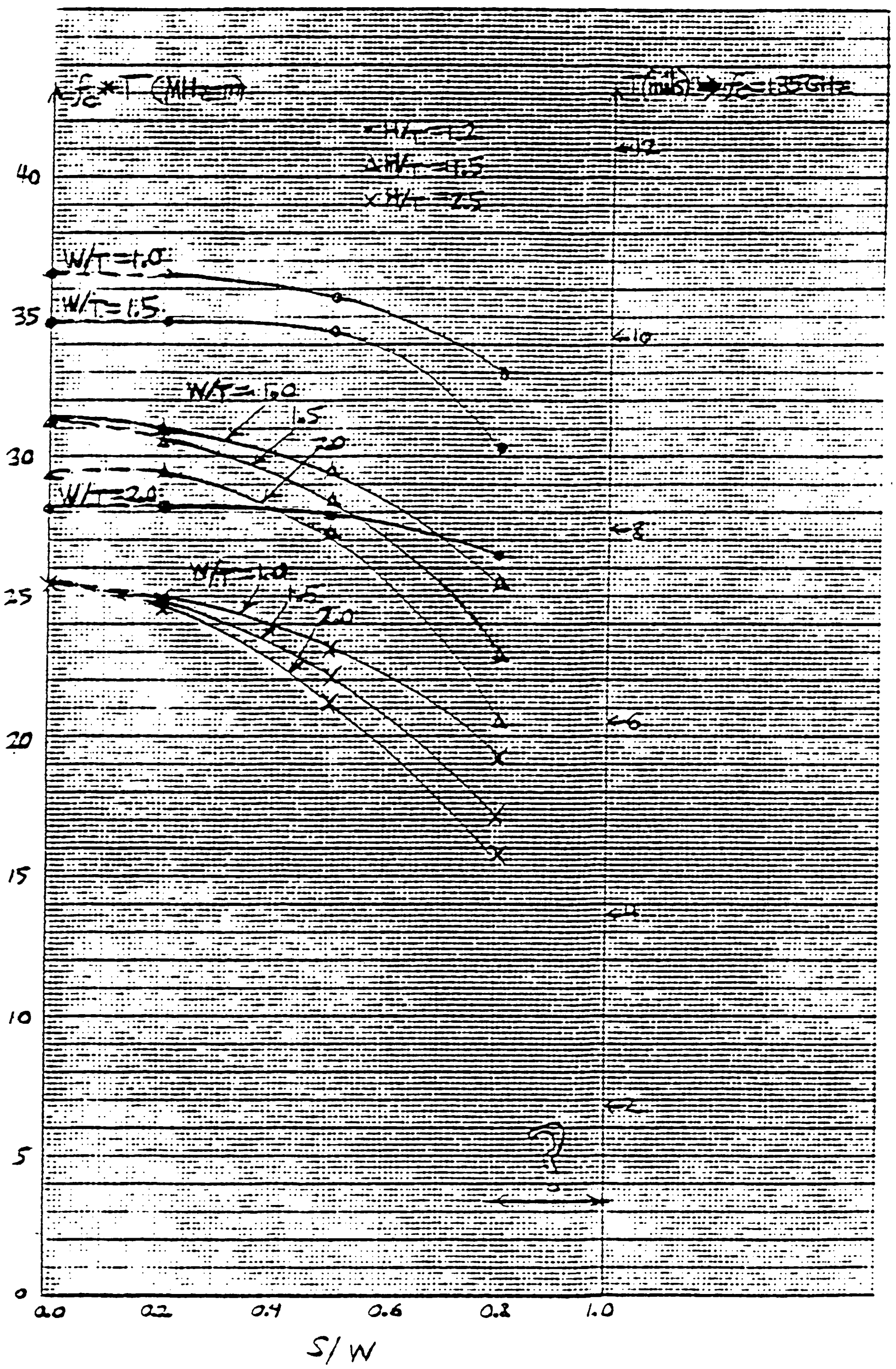


Fig. 3: Scaled analysis of single-mode propagation limits for enclosed microstrip on GaAs. Right vertical axis indicates T required for all points above it to satisfy minimum 135 GHz limit.

Note that the curves extrapolate to the lowest order waveguide cutoff frequencies (S/W = 0). The appearance of the strip (S/W small) has a negligible effect at first, but as the strip widens the cutoff frequency drops, due to the lowest order odd (asymmetrical) mode [2]. As suspected, the only curve that remains relatively flat is the only configuration dominated by the LSM_{11} mode when no strip is present--the H/T=1.2, W/T=2.0 case. Consequently, spurious moding may result from enclosed microstrip circuit design based on a waveguide analysis, particularly those cases where wide strips are required (e.g., choke filter) or where the waveguide mode is the LSE_{01} mode.

There is some question about the accuracy of the program in the limit S/W->1, because the calculated fc is different from the value expected for a filled waveguide of the dimensions of the substrate. However, it is assumed that as long as the fields in the air and the dielectric are coupled (S/W<1), the program results hold.

References

1. Collin,R.E., Field Theory of Guided Waves. York,PA:McGraw-Hill Co., 1960.
2. Yamashita,E. and Atsuki,K., "Analysis of Microstrip-Like Transmission Lines by Nonuniform Discretization of Integral Equations," IEEE Trans. Microwave Theory Tech., vol. MTT-24, pp. 195-200, 1976.