THE SLOT LINE IN UNIPLANAR MMIC'S: PROPAGATION CHARACTERISTICS AND LOSS ANALYSIS

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ABSTRACT

Slot-line structures as used in uniplanar MMIC's are analyzed including a full-wave description of conductor loss. It is found that such lines support a fundamental wave mode that differs basically from the conventional slot-line type. Results on propagation characteristics are presented studying also the influence of metallization thickness.

INTRODUCTION

In the design of MMIC components the "uniplanar" concept gains more and more importance, particularly when regarding applications for the mm-wave frequency range [1]. Instead of the well-known microstrip, coplanar waveguide and slot line are used as standard transmission-line elements. Their fields are orientated in the surface plane and, therefore, they prove to be well suited for the implementation of FET elements.

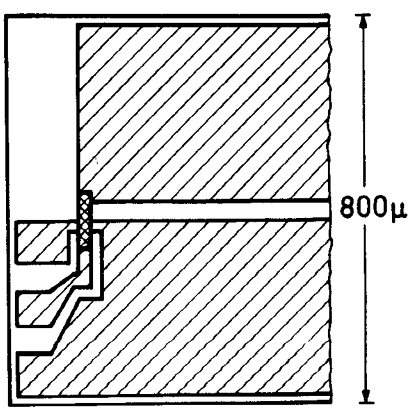


Fig. 1: Slot-line structure in uniplanar MMIC [2] (top view)

The slot line represents one basic element in such MMIC's which, for instance, is used to provide simple balancing circuits. Fig. 1 illustrates an example (see [2]).

With regard to slot-line *analysis*, on the other hand, one encounters problems, since it is known to support a non-TEM mode [3] which causes difficulties, e.g. when applying Wheeler's method for loss evaluation.

Our investigations are based on a mode-matching approach [4] that includes conductor loss rigorously without relying on any perturbation or skin-effect approximation. Compared with the state-of-the-art, the paper contributes new results in mainly two ways:

- The propagation behaviour of the MMIC slot-line and the differences compared with conventional slot line are clarified.
- Full-wave results on slot-line conductor loss are presented the first time.

THE MMIC SLOT-LINE

Studying slot-line configurations as used for MMIC's one finds that their geometry differs basically from that of the conventional slot-line (see Fig. 2): Firstly, the substrate extends over the whole lower portion of the cross-section and is backed by an metallic plane which introduces an additional microstrip-like wave mode. This aspect has been pointed out already by Oliner [5].

There is a second essential difference, however, which, to the knowledge of the author, has not been considered in theory so far: The *characteristic dimensions* (i.e. slot and metallization widths S and W, respectively) are *small compared to the wavelength* λ, whereas the conventional slot line requires W values greater than λ.

As a consequence, in MMIC's the fundamental wave mode exhibits *quasi-TEM* properties. It resembles the odd-mode excitation of closely spaced microstrips more than the conventional slot-line case.

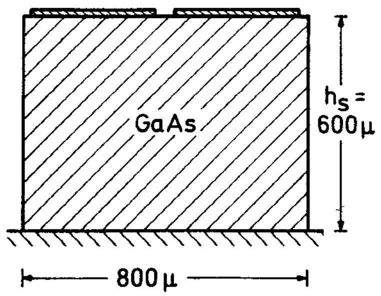
Fig. 4 demonstrates the principal propagation behaviour with growing frequency of operation. For frequencies with W in the order of the wavelength the nature of the mode changes towards a purely non-TEM one and a strong interaction with substrate and package geometry can be observed. No direct transition occures from the quasi-TEM mode to the conventional slot-line one when increasing the frequency. The latter wave seems to emerge from one of the higher-order modes.

In contrast to the conventional slot-line geometry the MMIC substrate fills the whole lower part of the waveguide cross-section. Therefore, the higher-order modes cover the complete ε_{reff} range up to $\varepsilon_r = 12.9$ (see Fig. 4). This prevents application as MMIC waveguide because in practice one is not able to separate a single mode.

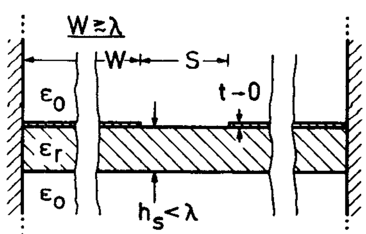
Hence the usefulness of the MMIC slot-line is restricted to the quasi-TEM range with $W \ll \lambda$. This also offers advantages with regard to MMIC modelling and design. One, therefore, has to ensure that the metallization widths of such slot lines are small enough. Empirically, a maximum width

$$W_{max} + \frac{S}{2} \approx \frac{\lambda_0}{4 \cdot \sqrt{\varepsilon_r}} \tag{1}$$

is found, which corresponds to the cut-off wavelength of the first higher-order substrate mode (λ_0 denotes the free-space wavelength, S the slot width, and ε_r the substrate permittivity).



a) MMIC slot-line of Fig. 1
(cross-sectional view)



b) Conventional slot line (see [3])

Fig. 2: Comparison of slot-line geometry

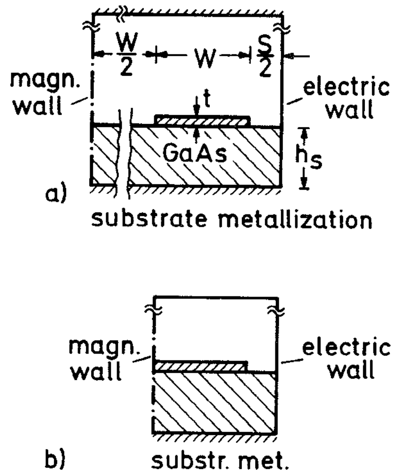


Fig. 3: The 2 models for the MMIC slot-line used here (Fig. 3(b) is identical to Fig. 3(a) except for the magnetic wall being shifted to the left hand side of the metallization).

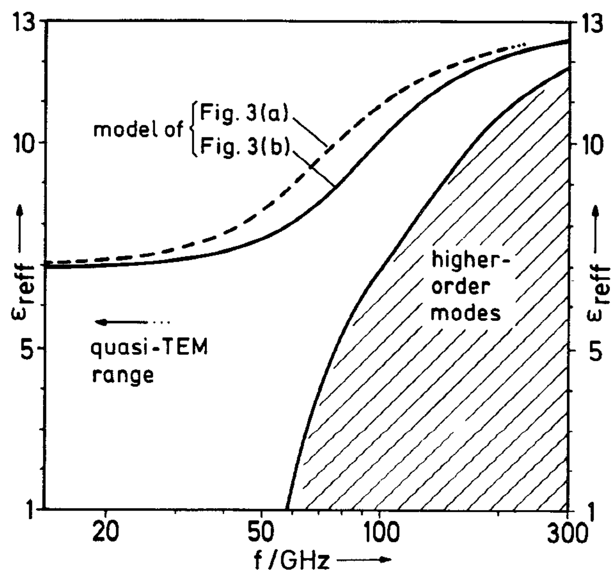


Fig. 4: Effective relative permittivity $\varepsilon_{reff} = (\beta/\beta_0)^2$ of a typical MMIC slot-line against frequency (transition region quasi-TEM → non-TEM).

Model of Fig. 3(a) (dashed curve) and (b) (solid curves), respectively, with $S = 40\mu$, $W = 400\mu$, $h_s = 600\mu$, $t = 3\mu$, conductivity κ of the metallizations: $\kappa = 3 \cdot 10^7\,(\Omega m)^{-1}$, GaAs: $\varepsilon_r = 12.9$, $\tan\delta_\varepsilon = 3 \cdot 10^{-4}$.

Accordingly, one derives a maximum frequency f_{max}:

$$f_{max} \approx \frac{1}{\sqrt{\mu_0 \varepsilon_0 \varepsilon_r}} \cdot \frac{1}{4 \cdot (W + S/2)} \tag{2}$$

Assuming a slot line with $S = 40\mu$ and $W = 400\mu$, for instance, $f_{max} \approx 50$ GHz is obtained (see Fig. 4).

RESULTS

Fig. 5 presents data on the propagation quantities of typical MMIC slot-lines using the model of Fig. 3(b) and the parameters given in Fig. 4. The characteristic impedance Z_W is calculated following the voltage-power definition $Z_W = 0.5 \cdot |U|^2/P_z^*$ with U being the voltage across the slot and P_z^* the complex conjugate of the power flowing in z direction.

As discussed before, the metallization width W causes a limitation in frequency for the quasi-TEM range (see eqn. 2). This effect can be observed also in Fig. 5: The larger W the lower the frequency at which the quasi-TEM regime ends and ε_{reff}, α, and Z_W show fundamental changes.

Below that frequency, the MMIC slot-line exhibits favourable low-dispersive characteristics with ε_{reff} values of about $(\varepsilon_r + 1)/2$, nearly independent of slot width S.

The attenuation increases when reducing slot width S. With regard to metallization width W, only a slight influence can be observed.

As well kown the characteristic impedance Z_W depends strongly on slot width S. In contrast to the conventional slot line case, however, the metallization width W influences Z_W equally, also in the low-frequency range. Z_W varies by about 20% for $W = 200 \ldots 400\mu$. This can be explained by the field distribution. Because it is similar to the odd-mode excitation of coupled strips, a considerable part of the fields extends over the whole strip.

The imaginary part of Z_W is found to be negligible.

Fig. 6 illustrates in which way the phase and attenuation constants change when varying the metallization thickness t. Due to the field concentration in the slot, ε_{reff} decreases considerably for large values of t, in particular when applying small slot dimensions. For comparison, also the curve $\varepsilon_{reff} = (\varepsilon_r + 1)/2$ is drawn in Fig. 6. This value corresponds to the zero strip-thickness approach. Varying t from 1.5μ to 6μ results in a 10% ε_{reff} decrease for the 10μ slot.

The attenuation constant α, on the other hand, remains approximately constant with t as long as $t \geq 3\delta$ holds (δ denotes the skin depth).

At low frequencies the phase constant is affected by the conductor losses, too, which explains the negative slope of the ε_{reff} curves towards the left hand side of the diagrams in Figs. 5 and 6.

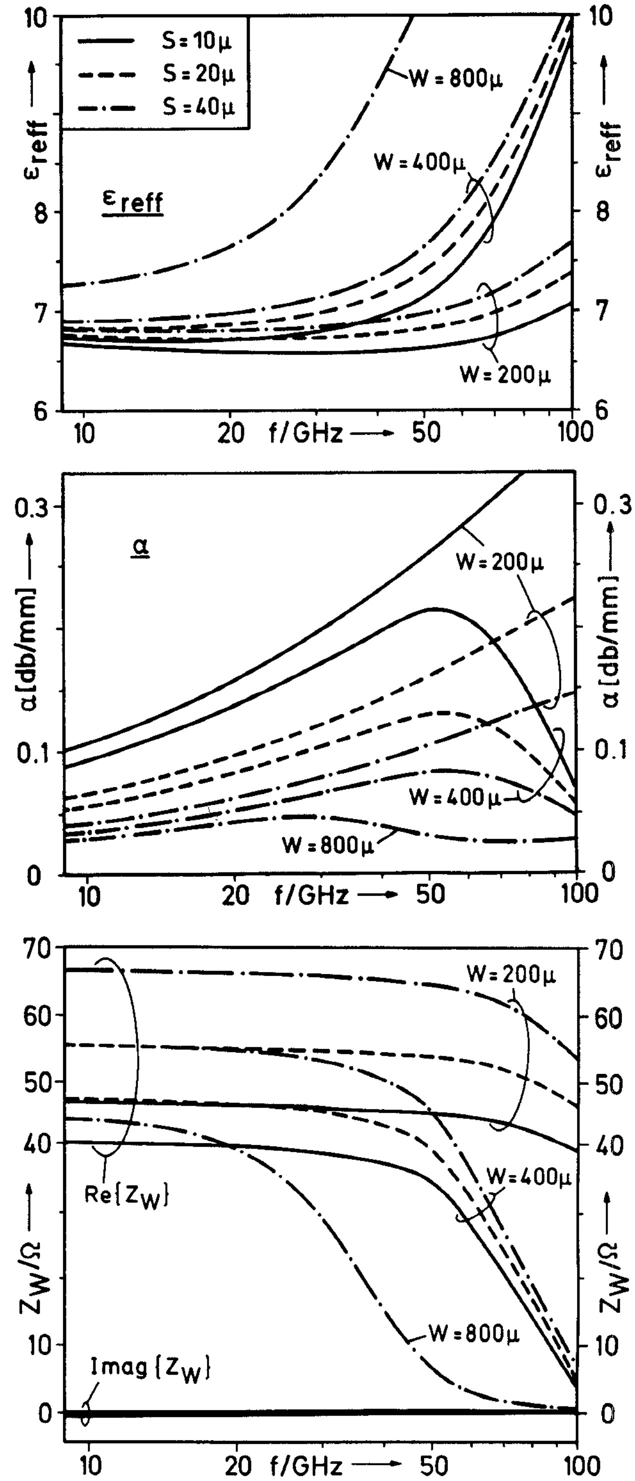


Fig. 5: Propagation characteristics as a function of frequency for different metallization widths W and slot dimensions S.
Model and data according to Fig. 3(b) unless otherwise specified, $S = 10\mu$ (solid lines), $S = 20\mu$ (dashed), and $S = 40\mu$ (chain-dotted).

CONCLUSIONS

Regarding the design of slot lines in uniplanar MMIC's and their modeling, the following conclusions can be drawn:

- In contrast to the conventional type the MMIC slotline supports a quasi-TEM fundamental wave mode similar to the odd-mode excitation of coupled strips.
- It offers advantageous low-dispersive properties, even at mm-wave frequencies. The attenuation ranges at values about 2...3 times larger than those of a comparable microstrip line.
- The widths W of the side metallizations have to be kept small enough compared with the wavelength in order to exclude parasitic non-TEM phenomena (see eqns. 1 and 2). W also exerts a significant influence on Z_W, which is nearly equal to that of the slot width S.

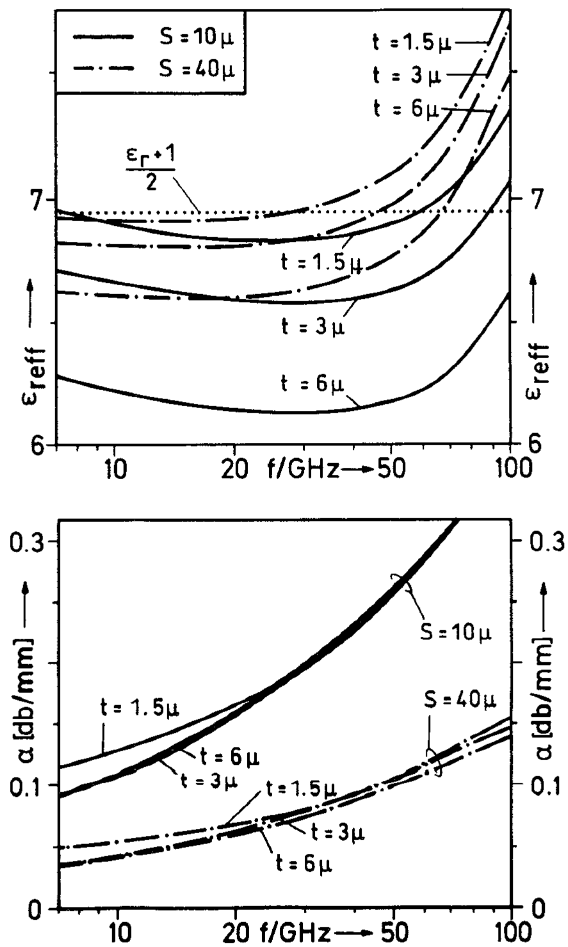


Fig. 6: Influence of metallization thickness t on ε_{reff} and α (model of Fig. 3(b)).

- The metallization thickness t has to be accounted for in two ways. It affects particularly the phase constant. Varying t in the range $1.5\ldots6\mu$, a deviation of $5\ldots10\%$ in ε_{reff} was found. On the other hand, t must be chosen larger than 3δ in order to avoid excessive losses (δ – skin depth).

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