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Experimental and Theoretical Characterizations of Very Thin Coplanar Waveguide and Coplanar Slow-Wave Structures

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Abstract

A very thin coplanar waveguide and a slow-wave structure using a very thin coplanar strip have been characterized in a wide range of field penetration by comparing the measured transmission characteristics with the theoretical data calculated by the phenomenological loss equivalence method. The measured transmission characteristics show very good agreement with the calculated ones. It is shown that the effect of field penetration into the thin coplanar lines is significant over a wide range of frequency and must be included in the design of monolithic microwave integrated circuits.

Introduction

Coplanar lines are suitable for monolithic millimeter-wave integrated circuits due to the easy mounting of components without via holes[1]. However, high frequency and high integration of the circuits require very thin and narrow coplanar lines in which field penetration into the conductors results in high conductor loss and affects the transmission characteristics. Therefore, the thin coplanar lines must be characterized by taking the field penetration into account over a wide range of frequency. DC calculation at complete penetration and the incremental inductance method at shallow penetration[2], however, cannot be used directly in the wide range of field penetration.

This paper shows experimental and theoretical characterizations of a very thin coplanar waveguide and a slow-wave structure using a very thin coplanar strip. The phenomenological loss equivalence method[3] is used to calculate the internal impedance due to the field penetration. The measured transmission characteristics show very good agreement with the calculated ones and the importance of the field penetration for the thin conductor structures.

Characterization of a thin coplanar waveguide

As shown in Fig.1, a thin (1.25 μm) coplanar waveguide using silver is fabricated on a very thick (1270 μm) quartz substrate. Total length of the coplanar waveguide is 9.5 mm: one end is shorted using silver paste and S_{11} is measured through the other end using a coplanar waveguide probe. The measured conductivity of the evaporated silver is 61S/μm which has the skin depth of about 2μm at 1 GHz. Therefore, the field penetration effect can be observed clearly in the wide frequency range from 1 to 40 GHz.

The internal impedance(Z_i=R+jωL_i) of the coplanar waveguide due to the field penetration has been calculated using the phenomenological loss equivalence method[3] in a wide range of field penetration. In the method, the coplanar waveguide is transformed to an equivalent single strip based on the property of electromagnetic fields which always penetrate into a good conductor in the normal direction of the surface. The width(W_e=1/G) of the equivalent strip of uniform surface current is obtained from the geometric factor(G) of the coplanar waveguide at shallow penetration which is related to the quasi-static surface current distribution. The equivalent strip thickness(t_e) is calculated by equating the distributed resistances of the coplanar waveguide and the equivalent strip at complete penetration. The moderate field penetration is incorporated into the finite strip thickness(t_e) of the equivalent strip based on the vertical field distribution in the equivalent strip. Since the surface current is assumed to be uniform within the equivalent strip width(W_e=1/G), the total internal impedance(Z_i) can be simply expressed by $Z_s^t/W_e=Z_s^tG$ using the surface impedance of the equivalent strip(Z_s^t) for the finite thickness. Finally, in order to calculate the transmission characteristics of the coplanar waveguide, the total internal impedance is incorporated into the circuit model of transmission line where the distributed capacitance and the external inductance are calculated using the empirical formulas[4].

The calculated and measured S_{11} data shown in Fig.2(a) are in very good agreement in the wide frequency range. The field penetration effect is important below 10GHz at which the skin depth is about half of the conductor thickness and the incremental inductance method is no longer valid. The slight discrepancy at low frequencies is considered due to the imprecise measurements of the conductor thickness and conductivity or small calibration error. Radiation and substrate mode generation at input discontinuity can also result in slight deviations at the resonant dips in Fig.2(a). Calculated distributed resistance and conductor loss are shown in Fig.2(b) in which the resistance and the attenuation become saturated below 10 GHz due to the field penetration.

Characterization of a thin coplanar slow-wave structure

A 4mm-long cross-tie slow-wave structure using a thin coplanar strip[5] shown in Fig.3 and Fig.4 has been built on a (100) face LEC-grown semi-insulating GaAs substrate which has a 500 μm thickness and a resistivity > 10^7 Ωcm. A GaAs

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ridge is located between two coplanar strips and periodic cross-tie overlays spaced by a silicon nitride layer are on top of the wider strip section A. The strip widths are modulated to reduce the conductor loss in the slow-wave structure by reducing the current density in section A. The actual thicknesses of the gold strip and the silicon nitride measured using Dektek are 0.9 μm and 0.48 μm, respectively, and the measured ridge height is 0.75 μm. The strip width (W=3.7 μm) and gap (S=4.3 μm) are measured using a microscope. The conductivity of the evaporated gold (σ=35 S/μm) is obtained from the total DC resistance (R=64 Ω). The resistance measured between two coplanar strips is almost infinite showing very high resistivity and negligible dielectric loss of the pure GaAs substrate.

The S_{11} has been measured using a coplanar waveguide probe for the slow-wave structure terminated by a short. Fig.5 shows the impulse response in time domain. High reflection comes from the probe point corresponding to marker-1 due to the mode mismatch between the coplanar waveguide probe and the coplanar strip. The slow-wave structure is between marker-2 and marker-3, and marker-3 corresponds to the short termination. Using the quasi-static analysis and the phenomenological loss equivalence method[5], the S_{11} has been calculated and compared with the measured data in Fig.6. The equivalent shunt capacitance (C=0.037 pF) associated with the mode mismatch at the probe point has been obtained from the measured data. Since the skin depth becomes comparable to the conductor thickness below 30GHz, the field penetration effect is importance in the almost entire frequency range. The measured conductor loss as well as the slow-wave factor are in good agreement with the calculated ones. The slow-wave factor is also important to characterize the slow-wave structure since the high conductor loss increases the slow-wave factor especially at low frequencies. The slight discrepancy mainly comes from the discontinuity capacitance between the cross-tie section A and the normal coplanar strip section B which enhances the slow-wave factor but is not included in the quasi-static analysis.

Conclusion

For a very thin coplanar waveguide and a slow-wave structure using a very thin coplanar strip, the transmission characteristics have been experimentally characterized in a wide range of field penetration and compared with the theoretical data calculated by the phenomenological loss equivalence method. The measured and calculated transmission characteristics are in very good agreement. The effect of the field penetration is observed to be significant for the thin coplanar structures in a wide range of frequency. The field penetration must be taken into account for the design of monolithic microwave integrated circuits using thin conductors.

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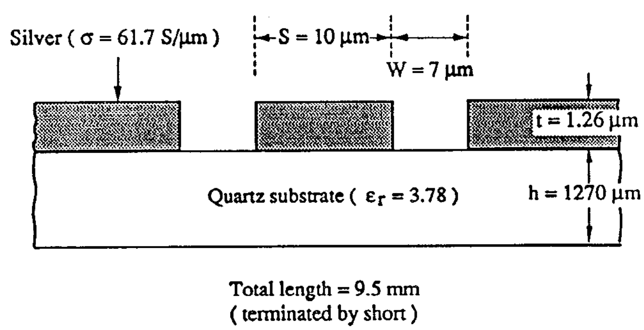
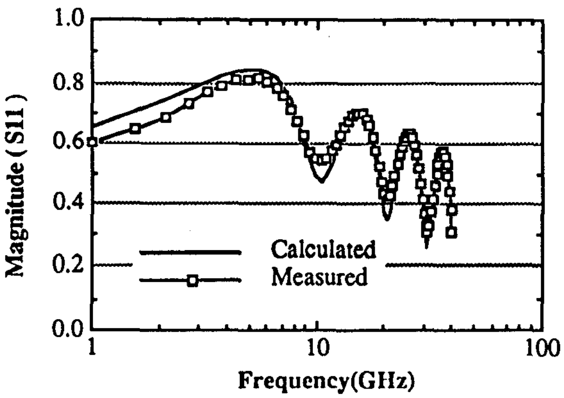
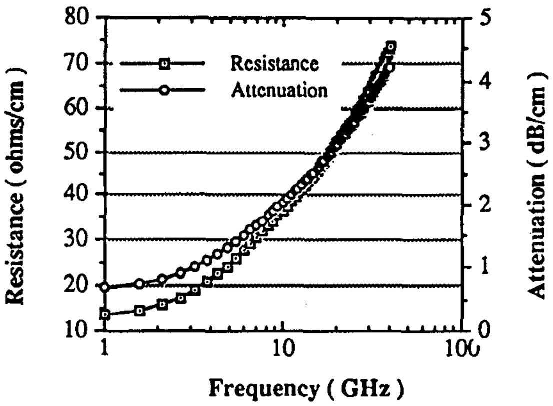


Fig. 1. Thin coplanar waveguide on a quartz substrate



(a)



(b)

Fig. 2. (a) S_{11} and (b) Distributed resistance and attenuation of the coplanar waveguide with short termination shown in Fig. 1.

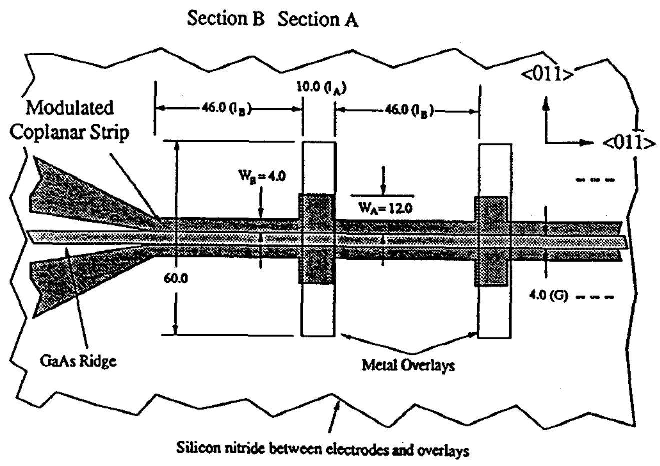


Fig. 3. Cross-tie slow-wave structure using a thin modulated coplanar strip

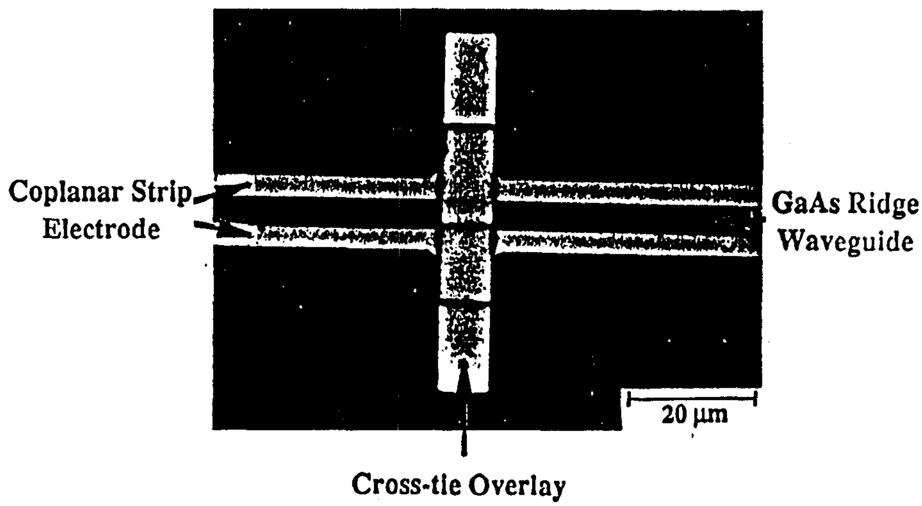


Fig. 4. Photograph of the slow-wave structure on GaAs substrate

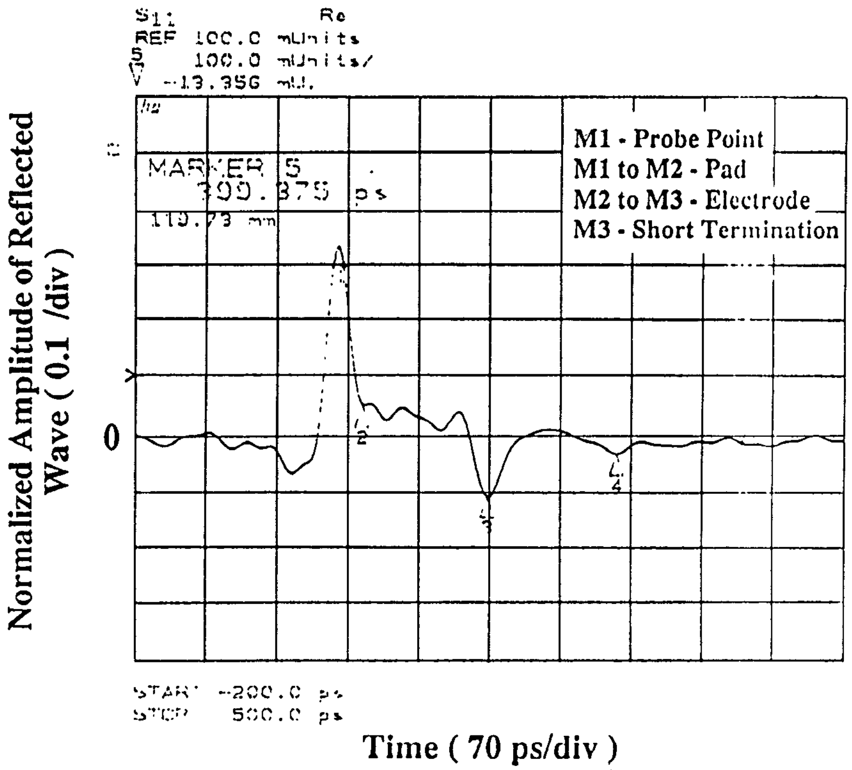


Fig. 5. Time-domain impulse response of the slow-wave structure

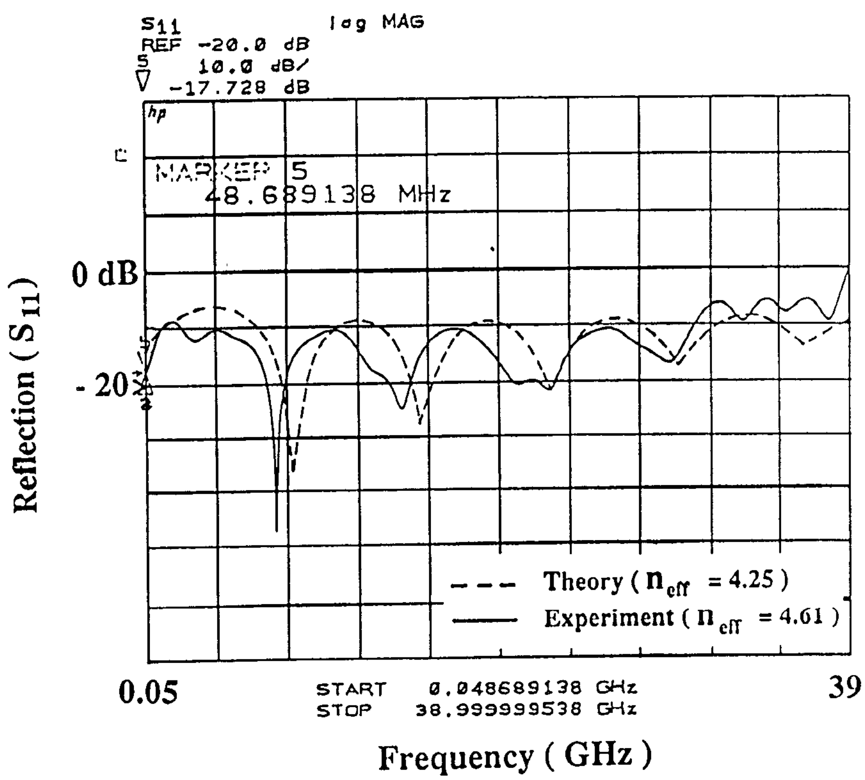


Fig. 6. Frequency response (S_{11}) of the slow-wave structure with short termination