The Interdigital Coplanar Waveguide: A New Low-Impedance Micromachinable Planar Structure

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***Abstract*—This letter describes a new type of coplanar waveguide (CPW) which we call interdigital coplanar waveguide (ICPW). ICPW has three advantages over CPW. First, ICPW can have a lower characteristic impedance for the same minimum feature size and overall line width. Second, at low impedances it can obtain reduced high-frequency resistive loss. Finally, thickening the conductor reduces the ohmic losses more rapidly in the ICPW than in the CPW. This letter presents an analysis comparing CPW and ICPW assuming a TEM mode of propagation. Calculations are performed using finite-element analysis, and volume filament and surface ribbon methods.**

***Index Terms*— Coplanar waveguides, interdigital coplanar waveguide, millimeter-wave waveguides, planar transmission lines, planar waveguides.**

I. Introduction

Micromachined membrane suspended coplanar waveguides (CPW's) have been discussed by a number of authors [1]–[4]. These lines have very thin low-permitivity substrates that make attaining low impedances difficult. For a given line width, the minimum feature size of the micromachining process sets a lower limit on the gap width and therefore the characteristic impedance. This CPW already has large resistive losses due to thin aluminum conductors. As the impedance decreases, smaller gap sizes increase loss at high-frequency through greater current crowding. In many cases thickening the conductors lowers the attenuation of the line.

This letter presents a new micromachinable planar transmission line, the interdigital coplanar waveguide (ICPW) shown in Fig. 1, and compares it to CPW of the same cross-sectional extents d and w_g, conductor and substrate thicknesses t and h, respectively, and dielectric constant ε_r. Under this basis of comparison the ICPW can obtain lower characteristic impedances for a given minimum feature size, and at low impedances, it can have lower high-frequency losses. The ICPW also shows greater improvement over CPW when the conductor thickness is increased.

Current crowding due to skin and proximity effects causes a rise in ohmic losses at high frequencies. The skin effect is intrinsic to the conductor material. The proximity effect, however, depends on the cross-sectional geometry of the line. An ICPW line reduces the losses due to proximity effects at high frequencies by breaking the positive conductor into two pieces and placing a third ground in-between the split conductor. This geometry requires larger gaps in order to obtain the same characteristic impedance as a CPW with the same cross-sectional extent.

At low frequencies current spreads almost uniformly across the conductors' cross section, and the resistance is approximately the dc resistance of the waveguides. The small positive conductor widths of the ICPW give it a dc resistance that is almost twice that of the CPW and therefore has twice the losses. In the mid-frequency range, ohmic losses in both lines begin to increase due to crowding. The skin effect forces current to concentrate along the metals' surfaces. If the conductors were isolated from one another, the ICPW would have larger series resistance due to the smaller perimeter of its positive conductors. With no isolation, however, the proximity effect caused by the currents in the different conductors increases the current density near the gaps. The narrower the gap, the more pronounced the crowding. The two effects together cause a redistribution of current to the surface of the conductors near the gaps. The ICPW has more vertical conductor surface along its wider gaps so that it is more suited for this. At low impedances the gaps of the CPW are small enough to give it higher series resistance at some point within the mid-frequency range. Once this occurs the CPW will remain more lossy at higher frequencies, where both waveguides' resistances become dependent on the square root of the frequency.

II. Numerical Calculations

A quasi-TEM mode is assumed to be the only mode to propagate down the waveguides [6], and the dielectric is assumed to have negligible losses. These assumptions allow the waveguides to be modeled as transmission lines with per-unit length series resistance, series inductance, and shunt capacitance. A finite-element (FEM) program [7] found the capacitances C of the waveguides using biquadratic elements that geometrically grew in size away from the conductor corners at a rate of 1.2 times the next closest element. The minimum element dimension was 0.1 μm, and the capacitances found for the CPW lines agree to with in 4% of the conformal map predictions [8]. Volume filament method (VFM) [9] and surface ribbon method (SRM) [10] programs determined the frequency-dependent resistances and inductances R and L, respectively. The VFM program split the conductors into filaments with a minimum dimension of 0.1 skin depths, and the filaments grew geometrically at a rate of 1.5 from the conductor corners. The SRM ribbons used the same geometric increase in size and had minimum ribbons sizes less than 0.1 skin depths. The attenuation and impedance were calculated

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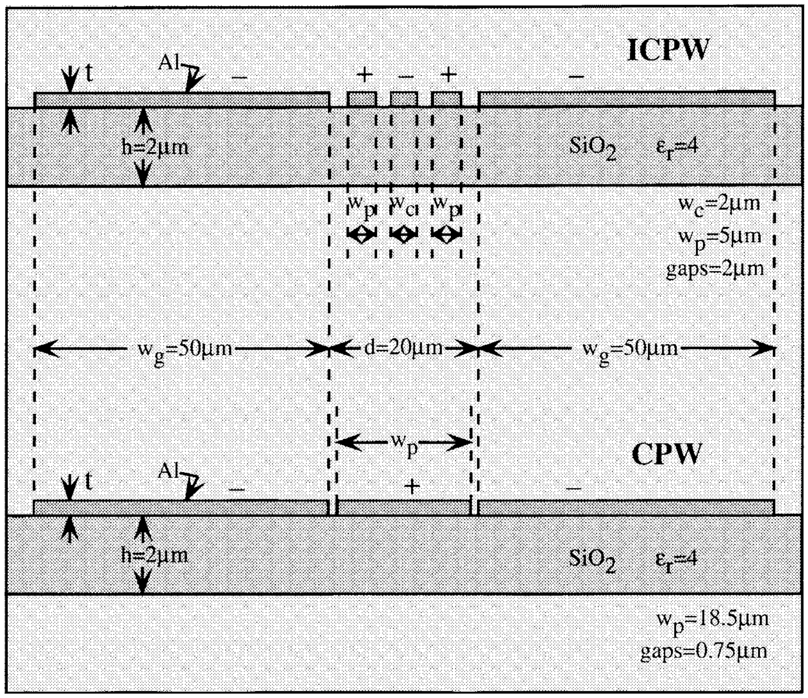

Fig. 1. Comparison of ICPW and CPW showing dimensions used in calculations.

using the transmission line parameters given by the FEM, VFM, and SRM programs, and the following formulas:

$$\begin{aligned} \text{impedance:} \quad & Z_C = \mathrm{Re}\left\{\sqrt{\frac{R+j\omega L}{j\omega C}}\right\} \\ \text{attenuation:} \quad & \alpha = \mathrm{Re}\left\{\sqrt{(\mathrm{R}+\mathrm{j}\omega\mathrm{L})(\mathrm{j}\omega\mathrm{C})}\right\}. \end{aligned} \tag{1}$$

Fig. 1 gives the dimensions and materials of the lines examined with the assumption that the silicon wafer has been etched sufficiently away from underneath the SiO_2 substrate so that it does not affect the line parameters. To show that the ICPW lines can achieve lower impedances than the CPW lines for a given minimum feature size, the ICPW lines were confined to a minimum feature size of 2 μm. This forced the CPW lines to have gaps that break this rule in order to obtain the same impedance as the ICPW.

Figs. 2 and 3 give the attenuation and impedance calculated for conductor thicknesses of 0.6 and 2.4 μm. In each case both waveguides' high-frequency impedance are approximately equal. The ICPW's attenuation starts greater and becomes smaller than CPW's as the frequency increases. With an increase in conductor thickness (decrease in impedance) the frequency at which the ICPW attains lower attenuation decreases and the attenuation for CPW actually increases. Fig. 4 shows the ratio of the ICPW's to CPW's resistances calculated using the VFM for three thicknesses. At dc the three curves have the same value of approximately 1.7. As current crowding effects take over, the ICPW's resistance becomes smaller and the curves drop below one. Each of the curves asymptote to different values as the resistances become dependent on the square root of the frequency. The lower the impedance of the lines the greater the improvement in ohmic losses over CPW.

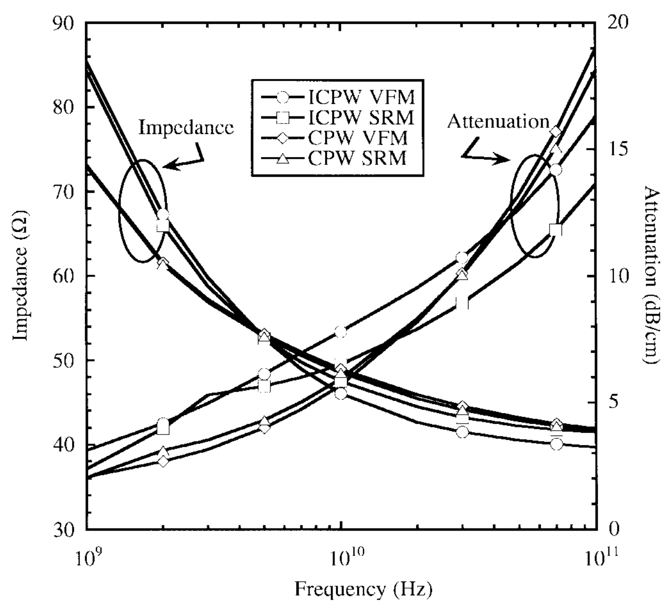

Fig. 2. VFM and SRM impedance and attenuation calculations of ICPW and CPW with $t = 0.6$ μm.

III. Resonator Measurements

Micromachining capabilities were not available to us. In order to gain confidence in the calculations, measurements were made on a through-line resonator constructed from an 18-in unloaded ICPW. The fabricated line differed from the nominal dimensions due to asymmetries in the gaps and positive conductors. The positive conductors differed in width by 0.6 mils, and the average value of the two was 17.8 mil. The middle ground was also 17.8 mil. The gap widths varied by a maximum of 1.0 mil with an median value of 11.9 mils. The average values were used in the calculated results. This line was fabricated on a 125-mil-thick $\varepsilon_r = 2.2$ Rogers

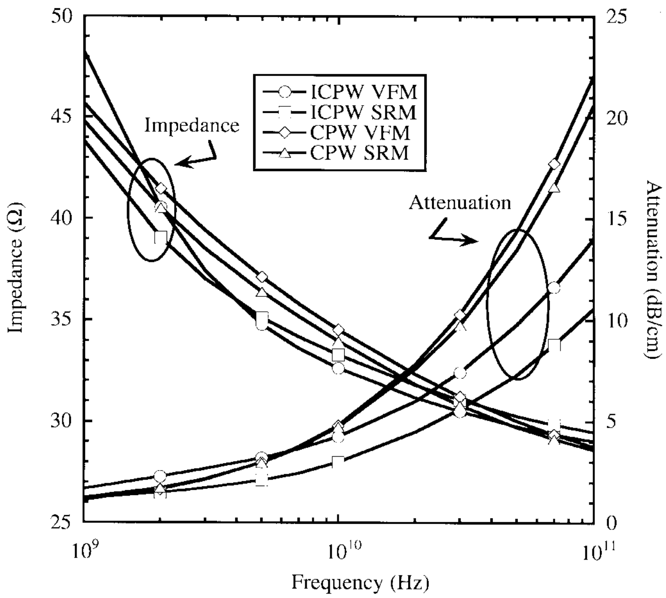

Fig. 3. VFM and SRM characteristic impedance and attenuation calculations of ICPW and CPW with $t = 2.4$ μm.

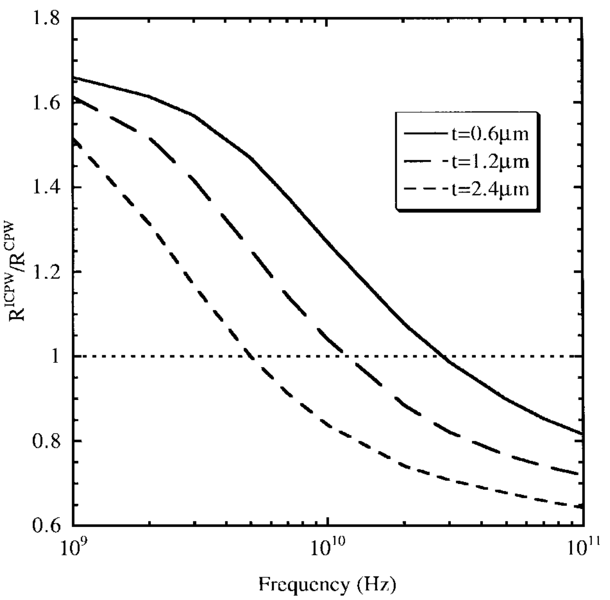

Fig. 4. Ratio of the frequency dependent ICPW and CPW resistances.

5880 RT-duroid substrate with half-ounce copper cladding. The nominal impedance was 52 Ω. Straps connecting the two positive conductors as well as ground straps prevented spurious modes. The coupling to the resonator was made as small as possible. The Q's of the resonator were measured repeatedly until reducing the coupling had no measurable effect on the results. The measured and calculated resonant frequencies and Q's are shown in Table I.

TABLE I
Q MEASUREMENTS OF SIX RESONANT PEAKS OF AN UNLOADED LENGTH OF ICPW

Resonant Peak	Resonate Frequency (GHz)		Q	
	Calculated	Measured	Calculated	Measured
1	0.259	0.258	60	53
2	0.521	0.518	83	76
3	0.783	0.781	100	92
4	1.045	1.037	116	102
5	1.306	1.303	130	112
6	1.567	1.562	143	122

IV. CONCLUSION

The calculations show that the characteristic impedances of ICPW can be lower than CPW for the same cross-sectional dimensions and minimum feature size. ICPW has a higher dc resistance but comparable or lower high-frequency resistance. At low impedances on low dielectric-substrates, the ICPW is a lower loss high-frequency transmission line. It also gains more benefit from the thickening of conductors than the CPW. This new line may be suitable for high-frequency MMIC lines especially microchannel lines where the dielectric has been removed. Because ICPW has larger gaps than CPW at the same impedance, the maximum transverse electric fields should be less. Therefore, ICPW may also have applications in radio frequency power and resonator circuits where breakdown due to high fields on the transmission lines are important.

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