Properties of CPW in the Sub-mm Wave Range and Its Potential to Radiate

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Introduction

In recent years, new technologies of monolithic integrated circuits have been pushing utilization of the CPW as far as the sub-mm wave range [1-3]. Additional new findings on CPW characteristics and behaviour have in this way been revealed step by step. Our paper contributes to this process.

Detailed investigation of possible higher order leaky waves that may occur on the CPW has allowed us to make a new interpretation of the measured dispersion characteristics [2] of the CPW, made on a high resistivity Si substrate, in the frequency range up to 700 GHz. For a microwave designer, it is very important to know the frequency up to which the line transmits only the bound wave. This upper cutoff frequency has been determined, and data are available for a wide range of line cross-sectional dimensions and substrate permittivities. CPW also has the potential to radiate space leaky waves. We report theoretical identification of the space leaky waves on the CPW. Tzuang and Lin discovered, and later experimentally verified, this type of leaky wave two years ago on the suspended microstrip line [4,5].

Dispersion characteristics of CPW and comparison with experiments

The coplanar waveguide, the cross-section of which is shown in the inset of Fig. 1, can leak power at high frequencies. Tsuji, Shigesawa and Oliner investigated leaky waves on this open unboxed line in [6]. In [7] we identified higher order leaky waves on the slotline, which represent the simultaneous power leakage into the corresponding number of surface waves. Two adjacent leaky waves may exist in a quite wide overlapping frequency band. As for the CPW, we have shown that on this line higher order surface leaky waves can occur successively. However, the frequency band of simultaneous propagation of two adjacent waves is now relatively narrow. These conclusions result from spectral domain analysis (SDA) of the CPW, assuming infinite conductivity and zero thickness of the conductors. Ground strips are laterally infinitely wide.

Pfeifer et al [2] measured at frequencies ranging up to 670 GHz the propagation constant of the CPW, with finite but sufficiently wide ground strips, fabricated on a silicon substrate. The measured data are plotted in Fig. 1 and 2, and compared with our calculated values. Heinrich´s model [8] provides a good description of the effective permittivity, which is equal to the square of the normalized phase constant, at frequencies lower than 80 GHz, as follows from [2]. At higher frequencies, Frankel´s semiempirical analytic dispersion formula [1] fits well with the measured record [2]. Interpretation of the measured dispersion characteristic based on our leaky wave concept is as follows. Bound wave propagation stops and 1st leaky wave excitation starts in the vicinity of 81 GHz. This wave is replaced by the 2nd leaky wave in the vicinity of 129 GHz, etc. The 8th leaky wave is substituted for the 7th wave around 700 GHz. This means that the field propagating over the CPW in the sub-mm wave range consists of consecutive higher order surface leaky waves, complemented probably by residual waves [9], depending on the source.

Besides attenuation due to leakage and the lossy substrate, we also have to account for conductor losses. For a 0.4 μm thick electroplated Au conductor with conductivity of 3.10^7 S/m, the CPW attenuation constant was calculated according to [8], assuming a lossless substrate. In leakage constant computation (SDA), the imaginary part of the silicon frequency dependent permittivity [10] was used. After adding to the leakage constant, including substrate lossess, the attenuation constant raised due to metallization losses, the total attenuation constant compares well with the measured data. Apparently the main component of the losses is the leakage of power, followed by the influence of metallization, and finally the dielectric losses are negligible.

Upper cutoff frequency of bound wave propagation on the CPW

The bound wave and the 1st leaky wave can propagate simultaneously on the CPW in a relatively narrow band. The frequency at which the 1st leaky wave sets in determines f_C, the upper cutoff frequency of pure bound wave propagation. We have computed f_C for a set of w/h, s/h, ε_r combinations when w/h, s/h $\in$ (0.1, 1.9) and ε_r=2.25, 3.75, 5, 7, 9.8, 11, 15. The normalized upper cutoff frequency $h/\lambda_C=f_C h/c$ is plotted in Fig. 3 for selected permittivities. When, e. g., ε_r=15, a function

$$\left(h/\lambda_C\right) = A_1 + \left[A_2 + A_3\left(w/h\right)^{-A_4}\right]^{-A_5} - A_6\, e^{-A_7\left|\left(w/h\right)-A_8\right|^{A_9}}$$

where A_1, A_2, ... A_9 are simple functions of s/h, fits such set of curves with an error of less than 0.65% at all one hundred calculated points. Knowledge of this frequency cut down facilitates CPW design.

Space leakage from CPW

We have investigated the properties of the CPW by the method of moments in the spectral domain. Analysis in the source-free region provides particular components of the total field propagating over the line. First, we recalculated the dispersion characteristics of a slotline with infinite wide conductors, in order to assure ourselves that the integration being conducted to the space leaky wave is right. It turned out that our values differ negligibly from those published in Fig. 3 of [11]. We therefore applied the same procedure in the CPW analysis.

The dispersion characteristics of the independent space leaky waves on the CPW are shown in Fig. 4. All curves were computed with the same number of basis functions. A number of branches were found subsequently along the frequency axis, but only five of them are plotted in Fig. 4. These characteristics correspond to the simultaneous space and surface leakage, since the branch cut and the pole corresponding to the TM_0 surface wave were taken into account in their calculation. We believe that waves corresponding to the characteristics quoted here are an analogy of the space-leaky modes carrying dominant-mode-like currents on suspended microstrip revealed by Tzuang and Lin in [4]. The electric field within the slots of the CPW for those space leaky waves greatly resembles that of the dominant bound wave.

Conclusions

We have shown that the main part of the field propagating over the CPW in the sub-mm wave range consists of consecutively excited higher order surface leaky waves. In addition, residual waves and/or space leaky waves may accompany them, depending on the source. If we exclude space leaky waves, the frequency band of pure bound wave propagation is determined by the frequency at which the 1st surface leaky wave sets in. We have provided this frequency for a wide range of line dimensions and substrate permittivities. We have found a new solution of the dispersion equation for the CPW that is relevant for a space leaky wave with a field distribution within the slots, as is the case for the dominant bound mode. As we know, waves of this type have already been discovered in [4] on a suspended microstrip line. We consider that our findings contribute to the general discussion on leakage effects on open transmission lines.

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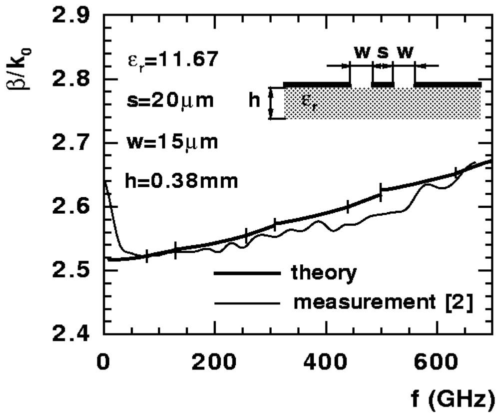

Fig. 1 The calculated and measured normalized phase constant of the CPW as a function of frequency

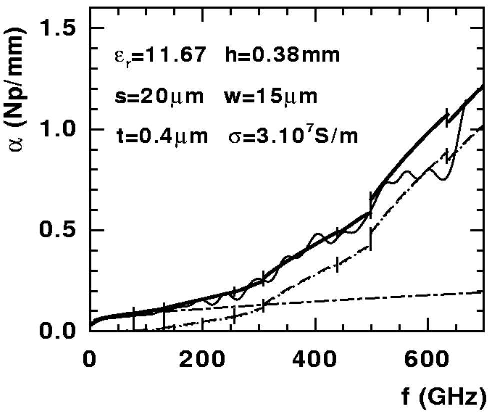

Fig. 2 The attenuation/leakage constant of the CPW: measured [2] ————;
calculated:
only leakage from the lossless line ·········· ,
leakage and losssy substrate – – – – – – ,
only lossy metallization [8] – · – · – · ,
total losses ▬▬▬ .

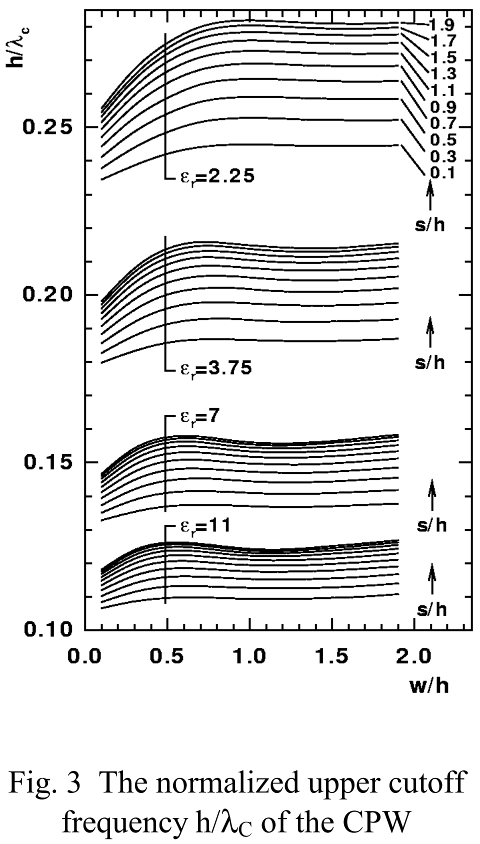

Fig. 3 The normalized upper cutoff frequency h/λ_C of the CPW

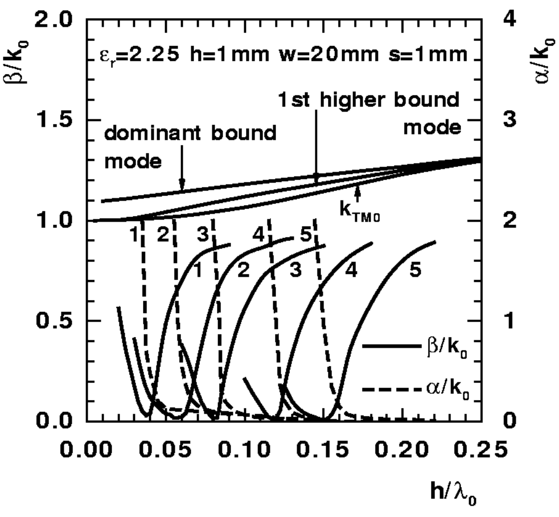

Fig. 4 Dispersion characteristics of the CPW