QUASISTATIC AND FULLWAVE ANALYSES OF CONDUCTOR-BACKED EDGE-COUPLED COPLANAR-WAVEGUIDE STRUCTURES

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A new conformal-mapping quasistatic-approximation model is developed to supplement the spectral-domain fullwave approach in characterizing the edge-coupled coplanar-waveguide (CPW) structure with finite-extent backed conductor. In this study, the theoretical results based on spectral-domain approach and quasistatic model are compared, and the effect of backed-conductor width on the coupling coefficient is examined.

1 Introduction

Conventional edge-coupled coplanar-waveguide (CPW) structure was proposed in 1970 to implement a CPW directional coupler [1]. However, the coupling effect is relatively weak due to its edge-coupled configuration. The coupling coefficient of edge-coupled CPW structure can be enhanced by adding an extra floating conductor on the another side of the substrate [2]. The coupling phenomenon associated with this conductor-backed edge-coupled CPW structure was characterized by the conventional spectral-domain approach in [2], but the fullwave approach needs a lot of computer resources and the fullwave results were still lack of validation. For design purpose, a fast computational tool is also required to calculate the characteristic impedances of transmission lines, including the CPW structures with or without the backed conductor.

In this study, a new conformal-mapping quasistatic-approximation model will be developed to calculate the odd-mode capacitance of the edge-coupled CPW structure with finite-extent backed conductor. This quasistatic model is useful in supporting the spectral-domain approach [2], in addition to providing analytical expressions for designing the conductor-backed edge-coupled CPW structures.

2 Quasistatic Model

Consider the edge-coupled CPW structure with finite-extent backed conductor of width L as shown in Fig. 1(a). The odd and even CPW modes of this structure are defined by introducing the electric wall and magnetic wall on the plane $x = 0$, respectively.

For the odd mode, the electric potential on the backed conductor is nearly grounded as suggested by the field distributions [2]. To apply the quasistatic method, two extreme cases must be considered first. As the width L of the backed conductor tends to zero, the structure Fig. 1 (a) would become the conventional edge-coupled CPW structure with finite substrate thickness. Alternatively, as the width L becomes very large, the

structure Fig. 1 (a) would approach the edge-coupled structure with infinite-extent backed conductor. In this study, the capacitances corresponding to the odd CPW mode of these three structures are denoted by C^{odd} , $C^{odd}(L = 0)$, and $C^{odd}(L = \infty)$, respectively. The quasistatic formulas for computing the capacitances $C^{odd}(L = \infty)$ and $C^{odd}(L = 0)$ are available in [3],[4]. The capacitance C^{odd} of the structure Fig. 1 (a) for the odd CPW mode must be between these two extreme values and may be expressed as

$$C^{odd} = u \cdot C^{odd}(L = \infty) + u' \cdot C^{odd}(L = 0). \quad (1)$$

The parameters u and u' are determined by the successive conformal-mapping steps as shown in Fig. 1 (b). Since the upper region to the signal lines of the structure Fig. 1(a) is filled with air, one needs to consider only one half of the lower region in the z -plane by symmetry. The mapping functions from z -plane to t -plane and then to ω -plane are defined by

$$t = \sinh^2\left(\frac{\pi z}{2h}\right), \quad \omega = \int_{t_a}^t \frac{dt}{\sqrt{(t-t_a)(t-t_b)(t-t_c)(t-t_e)}}. \quad (2)$$

By the above mapping functions, one may determine the lengths of P , Q , and R in the ω -plane (Fig. 1(b)). Note that as $L = 0$, $P = R$, $C^{odd} = C^{odd}(L = 0)$, and the parameters $u = 0$, $u' = 1$. Alternatively, as $L = \infty$, $P = Q$, $C^{odd} = C^{odd}(L = \infty)$, and the parameters $u = 1$, $u' = 0$. By these considerations, the desired values u and u' may be chosen as

$$u = \sin\left(\frac{P-R}{Q-R} \cdot \frac{\pi}{2}\right), \quad u' = 1 - u. \quad (3)$$

The related parameters are

$$\begin{aligned} \frac{P}{W_m} &= \frac{F(\arcsin \sqrt{\frac{-t_e(t_c-t_a)}{t_c(t_a-t_e)}}, k_o)}{K(k_o)}, & \frac{Q}{W_m} &= \frac{F(\arcsin \sqrt{\frac{t_c-t_a}{t_c}}, k_o)}{K(k_o)} \\ \frac{R}{W_m} &= \frac{F(\arcsin \sqrt{\frac{t_c-t_a}{t_c(t_a+1)}}, k_o)}{K(k_o)}, & \frac{W_m}{H_m} &= \frac{K(k_o)}{K'(k_o)}, \quad k_o = \sqrt{\frac{t_c(t_b-t_a)}{t_b(t_c-t_a)}} \end{aligned} \quad (4)$$

where $K(k)$ and $K'(k)$ are the complete elliptic integral of the first kind and its complement, and $F(\phi, k)$ is the incomplete elliptic integral of the first kind.

From (1) and (3), one can compute the capacitances of the odd CPW mode from which the effective dielectric constants and characteristic impedances may be derived.

The even CPW mode of the structure Fig. 1 (a) is difficult to handle by the quasistatic technique. When the width L of the backed conductor is narrow, the electric potential on the backed conductor is different from zero. The potential depends on the width of the backed conductor and the thickness of the substrate in a complicated manner. The quasistatic formulas are not available for the capacitances of the even CPW mode, neither the effective dielectric constants and characteristic impedances.

3 Numerical Results

To ensure the accuracy of the theoretical analysis models, both the quasistatic model (QM) and spectral-domain approach (SDA) [2] are used to characterize the finite-extent

conductor-backed edge-coupled CPW structure (Fig. 1(a)). Figs. 2–3 show the corresponding effective dielectric constants ϵ_{eff}^{odd} and characteristic impedances Z_o^{odd} for the odd CPW mode calculated by the QM and SDA methods. The ϵ_{eff}^{odd} will become larger as the backed-conductor width L is increased, and Z_o^{odd} will be reduced when the line spacing d or substrate thickness h is reduced. Good agreement among the results from both methods for various structure parameters (L, d, ϵ_r, h) supports the accuracy of the SDA method and quasistatic model.

Fig. 4 shows the fullwave results for the characteristic impedances Z_o of odd and even CPW modes and the associated coupling coefficient C ,

$$C = 20 \cdot \log \frac{Z_o^{even} - Z_o^{odd}}{Z_o^{even} + Z_o^{odd}}, \quad (5)$$

of the structure shown in Fig. 1(a). As the backed-conductor width L is increased, the difference between the two characteristic impedances is increased, which makes the coupling coefficient also enhanced.

4 Conclusion

In this study, a new conformal-mapping quasistatic-analysis model has been developed to supplement the conventional spectral-domain approach in handling the finite-extent conductor-backed edge-coupled CPW structure. The effect of backed-conductor width L on the characteristics of the conductor-backed edge-coupled CPW structure (Fig. 1 (a)) has been examined, which shows that the coupling coefficient may be improved by an increase of backed-conductor width.

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Fig. 1 (a) Cross section of finite-extent conductor-backed edge-coupled CPW structure, (b) conformal mappings for quasistatic analysis of odd CPW mode of the CPW structure in (a).

Fig. 2. Comparison of quasistatic results and fullwave results for odd CPW mode with different dielectric constants ($w = 200\mu m$, $s = 160\mu m$, $d = 240\mu m$, $h = 100\mu m$, $f = 1GHz$).

Fig. 3. Comparison of quasistatic results and fullwave results for odd CPW mode with different substrate thickness ($w = 200\mu m$, $s = 160\mu m$, $L = d + w$, $\epsilon_r = 12.9$, $f = 1GHz$).

Fig. 4. Mode characteristic impedances and coupling coefficient of conductor-backed edge-coupled coplanar-waveguide structure ($w = 300\mu m$, $s = 240\mu m$, $d = 360\mu m$, $h = 200\mu m$, $\epsilon_r = 12.9$, $f = 3GHz$).