Space-Wave-Type Leaky Mode Carrying Dominant-Mode-Like Modal Current Distributions

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Abstract

A recently explored non-zero cut-off leaky mode is reported to coexist with the well-known bound mode in a suspended microstrip placed in a large U-shaped conducting container to suppress any surface wave leakage. This new space-wave-type leaky mode is confirmed by rigorous full-wave modal investigations and three-dimensional scattering analyses. The new leaky mode bears strikingly similar modal current distributions and near-strip transverse electric field patterns to the bound mode. Thus, the new type of leaky mode is an indispensable companion to the bound mode for a suspended microstrip.

I. Introduction

Leaky mode displaying its cross-sectional current distributions and field patterns bearing close resemblance to those of the familiar bound mode is important for microwave circuit design. This belongs to a class of leaky mode known as leaky dominant mode, which has been identified for a number of guided structures, namely, microstrip [1], stripline with air gap [2], coplanar strips [3]-[5], etc. These leaky modes often and easily create undesired coupling in the microwave circuits, resulting in unexpected circuit performance [6],[7].

The above-mentioned leaky dominant modes have been reported to leak predominantly in the form of surface waves, thereby affecting the neighboring circuit via substrates coupling. This paper, on the other hand, presents a new evidence that leaky mode can indeed propagate into free space with its modal current distribution remarkably similar to the dominant mode, which is commonly known as a bound mode.

The new finding emerges from the suspended microstrip line modeled in Figure 1, which shows a metalized strip laid on top of the substrate partially enclosed by a U-shaped electric container of infinite conductivity, that is also large enough causing little influence on the leaky-mode propagation, if it exists. The side walls associated with the U-shaped container exclude any possibility of exciting the surface waves. Should a leaky mode exist in this guided structure, it must radiate into space. The theoretical results have been validated by numerical studies, followed by three-dimensional scattering analyses of exciting the suspended microstrip. The results show that a non-zero cut-off space-wave-type leaky dominant mode is present and likely one of the major causes responsible for the radiation of suspended printed wires.

II. The Non-Zero Cut-off Leaky Mode

By moving the two side walls and the bottom ground plane to a distance approximately a few wavelengths away from the suspended metalized strip, these conducting side walls would have negligible effects on the dispersion characteristics of the suspended microstrip. Figure 2 plots the mode chart of the suspended microstrip as the results of applying the full-wave integral equation method [8], showing the well-known bound mode and the newly found leaky mode. The former, the loss-free mode, has zero attenuation constant and the phase constant slightly higher than the free-space wavenumber. The latter is a complex wave with non-zero cut-off frequency, i.e., the leakage covers the entire spectrum. (Not shown in Figure 2 are the asymptotic curves of the leaky mode at much higher frequencies). This is by no means similar to any leaky dominant mode reported to date. As mentioned in Section 1, all the reported leaky dominant modes are basically the surface wave type [1]-[5]. However, the leaky mode reported here is certainly not a surface wave in view of its guided structure that has a U-shaped electric container. Furthermore, the leaky mode with a non-zero cut-off is a rare circumstance. One best known example is the conductor-backed CPW (coplanar-wave-guide) with the side plane extended to infinity [9]. The newly found leaky mode has polarization opposite to the channel-guide modes which are normally found in

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partially open, asymmetric waveguides with opening smaller than the wavelength [10]. When the suspended microstrip is offset from center, the dispersion curves in Figure 2 show negligible change. Thus, the space-wave leaky mode is indeed insensitive to the side walls.

III. Fundamental Properties of the New Leaky Mode

It is of great interests to examine the normalized modal current distributions of the new leaky mode reported in section II. Parts a and b of Figure 3 plot the transverse and longitudinal modal currents, respectively, for both bound mode and leaky mode of Figure 2.

It is important to observe the two sets of normalized current distributions are almost identical for both bound and leaky modes. This observation is significant in that 1) the newly found leaky mode is even-symmetric, 2) the leaky mode is liable to the electromagnetic radiation or undesired coupling to the nearby circuit. Therefore, we are not surprised to see that the transverse electric fields near the suspended strip are almost identical for both bound mode and leaky mode as shown in Figure 4 and Figure 5, which plot the transverse electric fields for the two modes at distances 0 λ_0, 0.85 λ_0 and 2.91 λ_0 away from the strip. As the distance measured from the strip increases, the bound mode's transverse electric field decays to almost a negligible extent. The leaky mode, on the other hand, increases exponentially in magnitude as expected. Notice that both Figure 4 and Figure 5 exhibit excellent field matching near the suspended strip.

IV. Frequency-Scanning Property of the New Leaky Mode

The validity of the newly found leaky mode has been established by plotting the transverse fields that satisfy the boundary conditions, e.g., Figure 5, or by examining the frequency-scanning behavior of the suspended microstrip. Figure 6 shows the far-field E-plane radiation patterns obtained by the scattering analyses of the suspended microstrip using the three-dimensional space-domain integral equation method [11]-[12]. What shown in Figure 6 are the radiation patterns for three frequencies at 2.25 GHz, 2.55 GHz, and 2.75 GHz, respectively, with cross-section parameters identical to those listed in Figure 2. At 2.75 GHz the length of the suspended microstrip is approximately 1.0 λ_0 and the input reflection coefficient ($|S_{11}|$) is approximately -9.3 dB. This suggests a fair input matching is achieved for the relatively short leaky line without any matching circuit. Two main beams point to two angles, θ_m and 180°-θ_m, symmetric about the horizon, since no ground plane is assumed in the simulation. Two important facts are observed. First, as expected, the main beam's angle (θ_m) decreases as frequency decreases, since the normalized phase constant of Figure 2 decreases when frequency is reduced from 2.75 GHz. Second, as an example, θ_m estimated from the phase constant of Figure 2 at 2.75 GHz is 45.1°. Figure 6, however, shows θ_m of 45° at 2.75 GHz, about 0.1° difference from the previous estimation. Thus, the validity of the new leaky mode is confirmed again by examining the main beam's angle and the applicability of the large U-shaped container is established.

V. Conclusion

A new type of leaky mode is explored and confirmed to coexist with the bound mode in the suspended microstrip, showing non-zero cut-off dispersion characteristics, even symmetry field patterns, bound-mode-like modal current distributions and similar near-strip transverse electric field patterns to the bound mode.

Detailed scattering analyses suggest that the new leaky mode can be easily excited with low input reflection while its frequency scanning characteristics are in excellent agreement with the prediction carried out from the leaky mode's complex propagation constants.

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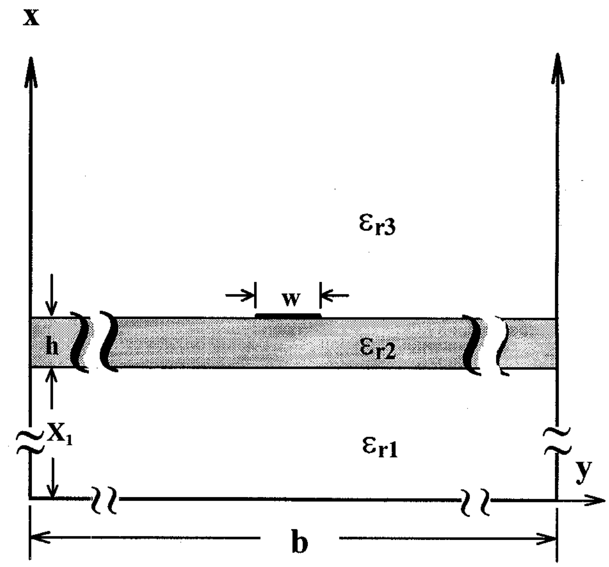


Fig. 1 Geometry of a suspended microstrip line partially enclosed by a large U-shaped electric container of infinite conductivity.

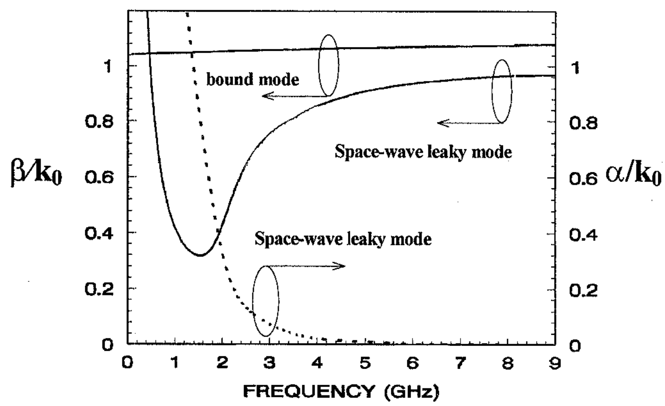
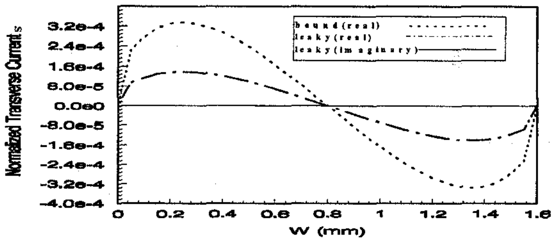
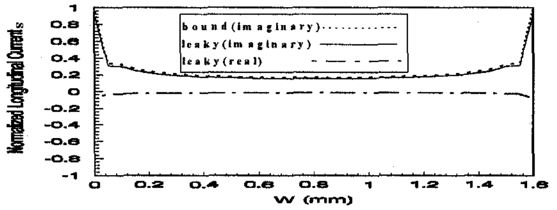


Fig. 2 The dispersion characteristics of the suspended microstrip line with dimensions of x_1 = 300 mm, x = ∞, b = 421.6 mm, w = 1.6 mm, h = 0.762 mm; ε_{r1} = 1.0, ε_{r2} = 2.1 and ε_{r3} = 1.0.



(a)



(b)

Fig. 3 Normalized current distributions of the suspended microstrip of the bound and leaky modes at 2.25 GHz: (a) the transverse currents; (b) the longitudinal currents.

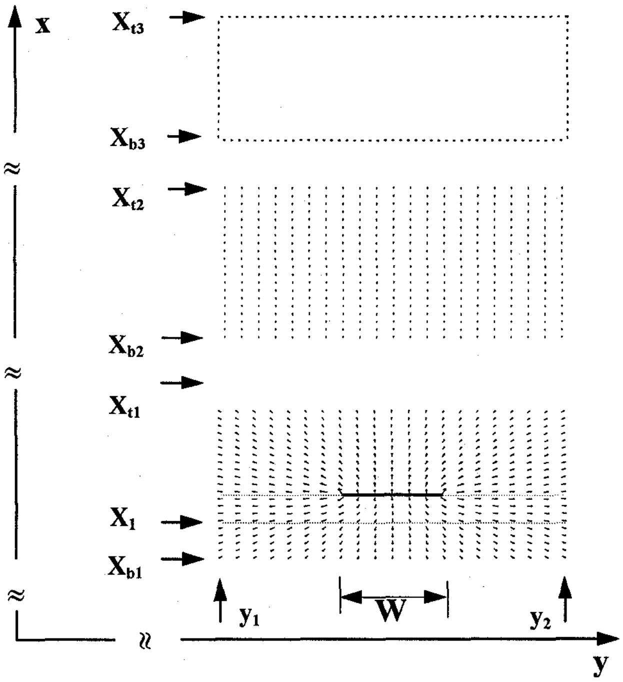


Fig. 4 The transverse electric fields of the ***bound mode*** of the suspended microstrip at 2.25 GHz at the locations (1) x_{b1} = 299 mm, x_{t1} = 303 mm, (2) x_{b2} = 408 mm, x_{t2} = 412 mm, (3) x_{b3} = 677 mm x_{t3} = 681 mm; x_1 = 300 mm, y_1 = 208.3 mm, y_2 = 213.3 mm.

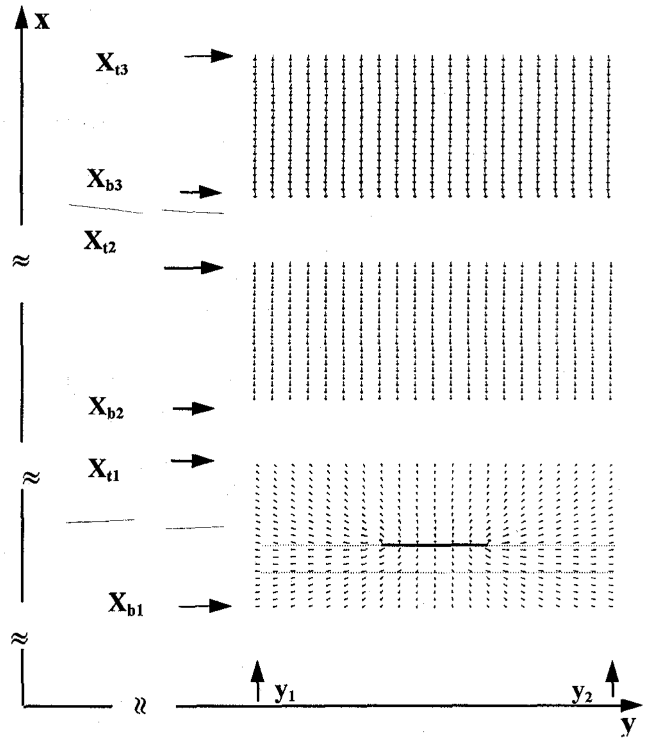


Fig. 5 The transverse electric fields of the ***leaky mode*** of the suspended microstrip at 2.25 GHz at the locations (1) x_{b1} = 299 mm, x_{t1} = 303 mm, (2) x_{b2} = 408 mm, x_{t2} = 412 mm, (3) x_{b3} = 677 mm x_{t3} = 681 mm; x_1 = 300 mm, y_1 = 208.3 mm, y_2 = 213.3 mm.

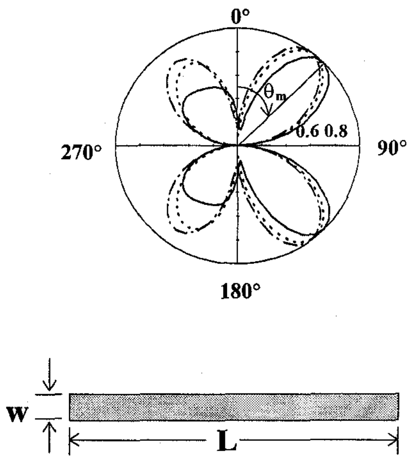


Fig. 6 The far field E-plane radiation patterns of the suspended microstrip line of length L = 107 mm. The rest of the parameters are shown in Figure 2.
The broken line (-·-·-·-·-): 2.25 GHz.
The dotted line (··············): 2.55 GHz.
The solid line (————): 2.75 GHz.