

(Scientific Note)

Leaky Mode Perspective on Printed Antenna

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ABSTRACT

This paper confirms that the guided-wave approach for effective integrated antenna design is applicable by exploring the various aspects of the propagation characteristics of the leaky modes. The (suspended) microstrip line is investigated throughout the paper because of its simplicity and popularity. The first category of leaky modes stems from the higher-order modes on microstrip discovered by Oliner *et al.* Careful analyses show that these higher-order leaky modes are periodical and coincident with the patch antenna's resonant frequencies. When multiple leaky-mode lines are employed to form an array, the circuit model based on the mode-coupling of the leaky modes can result in very accurate assessment of the far-field radiation pattern. The leaky modes carrying dominant-mode-like currents and displaying very similar transverse field patterns surrounding the (suspended) microstrip belong to the second category. These newly found modes are experimentally proved to coexist simultaneously with the dominant, bound mode. Differential TDR (time-domain-reflectometry) experiment on the leaky line shows excellent agreement with the time-domain step response obtained by invoking the transmission line model characterized by complex propagation constant and complex characteristic impedance using the power-current definition, thus confirming the applicability of complex characteristic impedance of a leaky line. Throughout the paper, printed antennas are either viewed as waveguides or designed by the corresponding guided, complex, leaky modes.

Key Words: leaky-mode integrated antenna, mode coupling, surface wave, space wave, complex wave

I. Introduction

Fact that printed antenna and printed microwave circuit are two entities whose operational principles are distant to each other is now severely challenged by the recent advance in search of the new leakage effects in planar or quasi-planar guiding structures since 1986. Oliner and Lee (1986a) discovered the leaky mode from higher modes on microstrip and later reported such leaky mode could be employed for designing microstrip antenna that radiated predominantly the space wave (Oliner and Lee, 1986b; Menzel, 1979).

In an open guiding structure, the leaky mode with phase constant β leaks away in the form of surface wave when

$$\beta < k_s, \quad (1)$$

where k_s is the surface wave number, and of space wave and/or surface wave when

$$\beta < k_0, \quad (2)$$

where k_0 is the free-space wave number.

Although numerous papers have reported the peculiar power leakage behaviors of leaky modes for a variety of printed transmission lines (Tsuji *et al.*, 1997; Nghiem *et al.*, 1993), a growing interest in utilizing the leaky mode's space-wave radiation properties has emerged; not only for the fact that the agreement between the theoretical design and measured performance has been better for leaky wave antennas (Oliner, 1984), but the antenna design based on the dispersion characteristics of leaky mode has generally yielded very good performance (Chou and Tzuang, 1996a, 1996b). The recently proposed micro-slotline (a uniplanar guiding structure combining microstrip and slotline) (Chou and Tzuang, 1996a, 1996b) and micro-coplanar waveguide (CPW) (a uniplanar guiding structure combining microstrip and cpw) leaky-wave antennas (Tzuang and Lin, 1996) have demonstrated their effectiveness for exciting first, second, third, etc., higher-order leaky modes with alternating odd and even field symmetries. Extensive measurements show that the properly designed leaky-mode

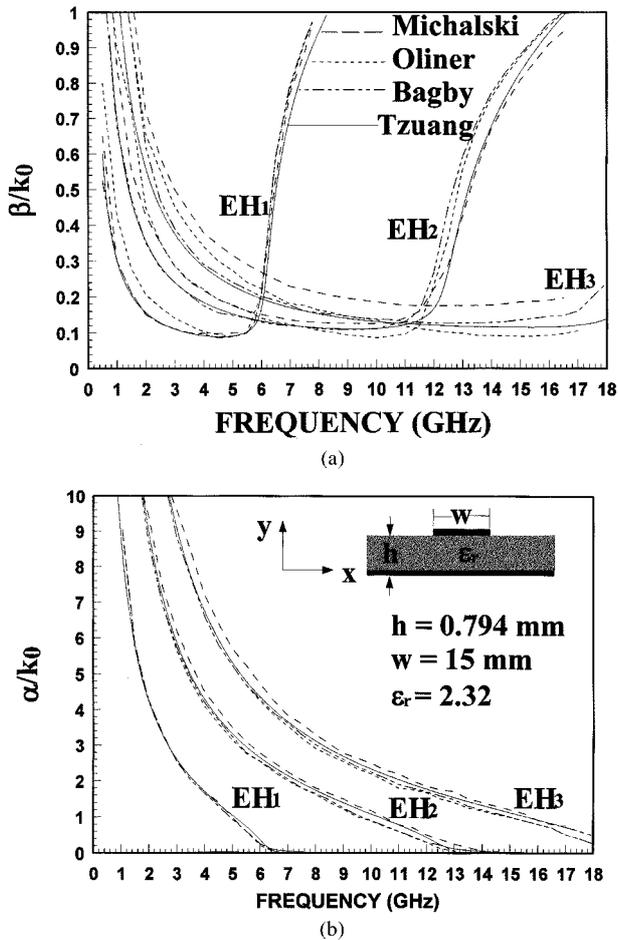


Fig. 1. (a) The normalized phase constants of the higher-order leaky modes, EH_1 , EH_2 , and EH_3 , calculated by four groups: Michalski, Oliner, Bagby, and Tzuang. (b) The normalized attenuation constants of the higher-order leaky modes, EH_1 , EH_2 , and EH_3 , calculated by four groups: Michalski, Oliner, Bagby, and Tzuang. [Data from Michalski and Zheng (1989), Oliner (1987), and Bagby *et al.* (1993)].

antenna radiates most electromagnetic energy into space with hardly detectable surface wave leakage. Furthermore, these antennas can easily achieve antenna efficiency higher than 80%, and in some cases even much higher.

Contrary to the seemingly promising progress on the leaky-mode integrated antenna, our knowledge about the leaky mode propagation on printed lines is still very limited. This paper aims to report the leaky modes of distinct natures that share one physical property in common: they all radiate effectively into free space in a predictable fashion. Mastering these leaky modes, we enter the era when the printed antenna design has never been so close to the microwave circuit design like now.

II. Leaky Modes from Higher-Order Microstrip and Mode-Coupling of the Complex Waves

Even the simplest guiding structure like wire or metal strip, suspended above or attached to a substrate, carries the leaky modes pertinent to space-wave radiation. The first category belongs to the leaky modes which are essentially the higher-order modes of the guiding structure. The mode chart as shown in Fig. 1 consists of the first three higher-order leaky modes, namely, EH_1 , EH_2 and EH_3 . The normalized phase constants (β/k_0) and normalized attenuation constants (α/k_0) of the EH_1 leaky mode reported by various research groups, e.g., Michalski and Zheng (1989), Oliner (1987), Bagby *et al.* (1993) and us, are in excellent agreement. As for the higher EH_2 and EH_3 leaky modes, all the solutions still agree well within the acceptable design tolerance. Our leaky mode solutions are closer to the Michalski's on the high side near the onset frequency of the leaky mode and closer to the Bagby's on the lower region of the leaky mode. One important observation made from these solutions is the knee-frequencies (the points where β/k_0 curves bend sharply) or the onset frequencies (the locations where α/k_0 curves are about to take off) are periodical.

Applying the cavity model proposed by Lo *et al.* (1979) to the patch antenna of perimeter equal to the width of leaky-mode microstrip line, we immediately notice that the patch resonant frequencies are very close to the knee-frequencies. This implies that the patch resonator must radiate leaky modes! But how much amount and in what level does the electromagnetic field get radiated? What shown in Fig. 2 are the measured results carried out for a two-port diagonally fed patch

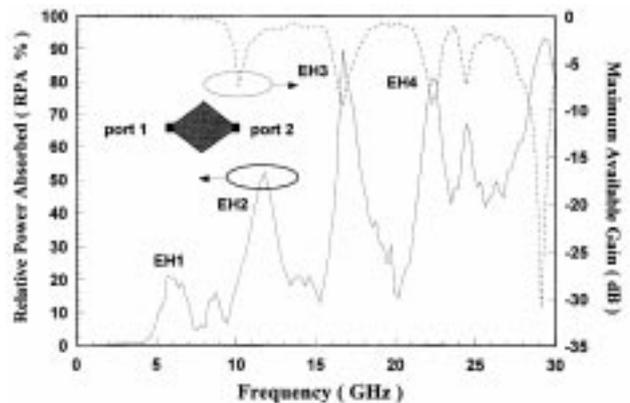


Fig. 2. The relative power absorbed (RPA) and the maximum available gain of the two-port diagonally fed square patch of perimeter equal to 16 mm, $\epsilon_r=2.55$ and substrate height 0.762 mm.

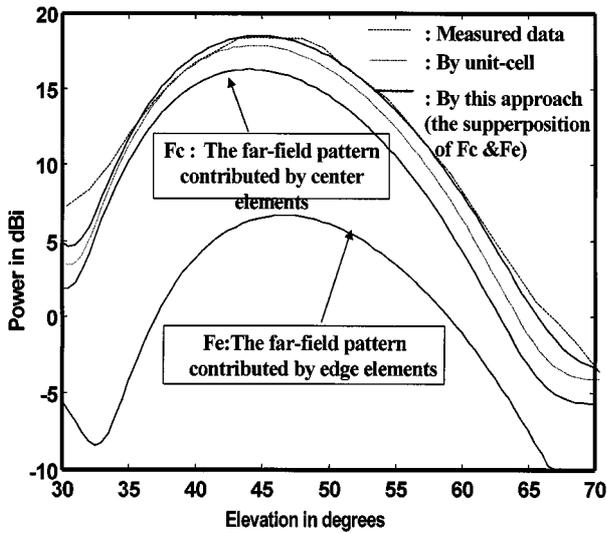


Fig. 3. The far-field radiation pattern of a linear leaky-mode array. Here an 8-element array can be obtained very accurately and understood with great physical insight by applying the mode-coupling solutions of the leaky modes.

circuit of perimeter equal to 16 mm, relative permittivity $\epsilon_r=2.55$ and substrate height 0.762 mm. The dimensions and material constant of this patch circuit are slightly different from the data shown in Fig. 1. Nevertheless we observe the same periodicity of the RPA (relative power absorbed, $1-|S_{11}|^2-|S_{21}|^2$) plot for all leaky modes as well as the maximum available gain of the passive two-port (Gonzalez, 1984) for EH_3 and EH_4 higher modes. We recognize that, through this particular two-port measurement, the leaky modes are susceptible to be excited, thus carrying a substantial portion of energy into free space.

An advantageous application of leaky mode is the linear N-element antenna array, producing a pencil beam that otherwise must be realized by a two-dimensional array of cumbersome feeding network. Figure 3 plots the antenna pattern against the elevation angle along the y-z plane (parallel to the microstrips and normal to the substrate surface of an eight-element microstrip leaky-mode array), comparing the results obtained by measurement and by theoretical calculations using a unit-cell, single leaky-mode approximation and the more accurate approach incorporating multiple leaky modes. Since the EH_1 leaky mode is employed for designing the corporate-fed linear array (Hu and Tzuang, 1997) and the individual array element is excited by an in-phase input signal of equal amplitude, the majority portion of the array can be divided into several single-element radiating sources with electric walls separating them except for the two edge elements on both ends of the array where the

periodicity ends. This suggests the radiation patterns obtained by a single leaky mode approximation (or the unit-cell approach) must deviate from the measured data. Indeed Fig. 3 shows such discrepancy for the elevation angle larger than the main beam and it becomes slightly worse as the elevation angle increases. The problem can be remedied by acknowledging the existence of the mode-coupling of the leaky modes on the array. Figure 4 plots the eight leaky modes obtained by the combination of the coupled-mode approach and full-wave method (Tzuang and Hu, 1998). Each leaky mode solution corresponds to a particular eigenvector (state) carrying distinct modal current distributions along each microstrip. Therefore the input in-phase excitation can be expressed uniquely by the linear combination of the eight eigenvectors (states) associated with the eight coupled leaky modes. After a series of analyses, we obtain equivalent leaky modes which respectively represent the propagation characteristics of center elements (for elements 2 to 7) and edge elements (for element 1 and 8). The former carries the current distributions similar, but not identical, to the unit-cell, single-mode modal current distribution. The latter reflects the fact that the edge elements at both ends shall carry the modal current distributions different from the unit-cell approximation, since the boundary conditions for the individual in the array can be different. The far field radiation pattern obtained by the superposition of the two equivalent leaky modes agree very well with the measurement.

III. Space-Wave Leaky Modes Carrying Dominant-Mode-Like Currents

The second category consists of leaky modes like

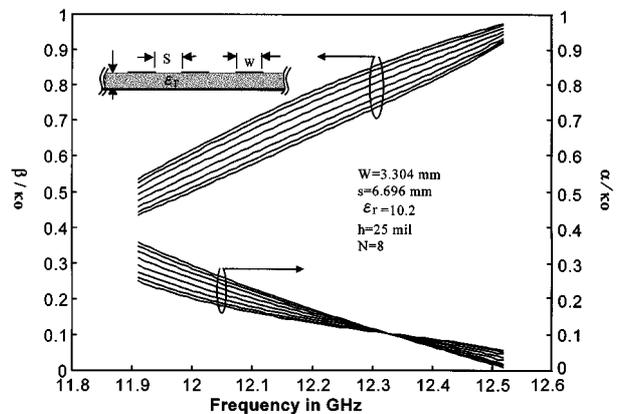


Fig. 4. Coupled-mode solutions for the complex leaky modes of first order. [Data from Tzuang and Hu (1998)].

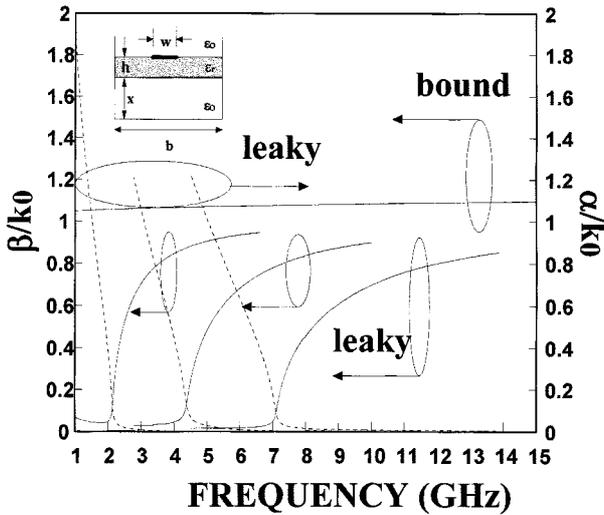


Fig. 5. Leaky modes carrying dominant-mode-like currents on suspended microstrip; substrate thickness $h=0.762$ mm, $\epsilon_r=2.1$, strip width $w=1.6$ mm, $x=b=1$ m. [Data from Tzuang and Lin (1998)].

a phantom accompanying the dominant, bound mode but responsible for space-wave radiation. The discovery of this type of leaky modes is very recent (Tzuang and Lin, 1998). Figure 5 shows three space-wave-type leaky modes for a suspended microstrip of width 1.6 mm integrated on a 0.762 mm thick dielectric substrate of relative permittivity 2.1. Although only three leaky modes are present in the figure, there should have infinitely many of these modes. Investigating these modes on their modal current distributions and transverse fields, we notice that these modes carry very similar modal currents to those of bound mode and possess very close resemblance of the transverse fields surrounding the strip. Partly for such reason this type of leaky modes was never discovered before.

The above-mentioned two kinds of similarities between bound mode and leaky mode make us conjecture that we can not possibly exclude the excitation of the accompanying leaky mode when intending to use the bound mode only. A simple measurement setup can prove our guess. Connecting a wire of diameter 1.6 mm to both ends of the cables tied to a vector network analyzer, simulating the case of suspended wire resonator above the ground plane, we measure the two-port scattering parameters and extract the resonant frequencies. By changing the lengths of wire resonator, we may deduce the phase constants of the resonant modes. Figure 6 plots the results, showing that two modes, both bound and leaky modes, are simultaneously present and their phase constants agree excellently to those of the theoretical bound mode and leaky mode, respectively.

Notice that the normalized phase constant of the suspended strip immersed in the air must be equal to one. The measurement confirms this and shows that the fast-wave resonance caused by the leaky mode is essentially a wire antenna best viewed as a waveguide.

Naturally the question of characteristic impedance of the leaky mode arises. Following the definition proposed by Das (1996), the complex characteristic impedances of the dominant-mode-like leaky mode are obtained and plotted in Fig. 7. If we simplify the physical conditions by assuming that only the leaky mode is present in the wire, we may compute the two-port scattering parameters for the wire resonator by

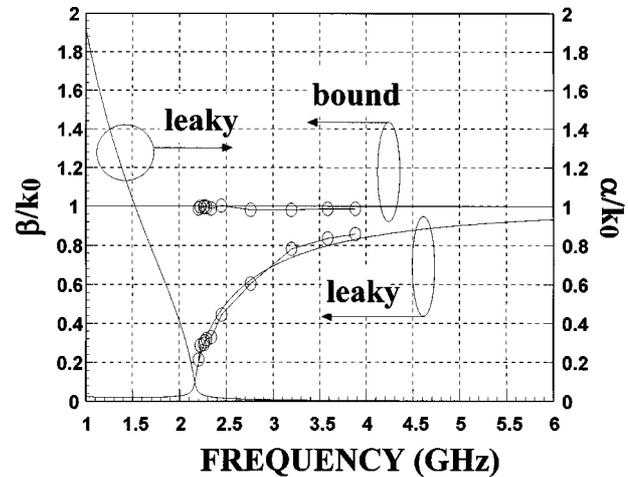


Fig. 6. Simultaneously extracted normalized phase constants of a suspended wire in the air with diameter equal to 1.6 mm. Circle: measurement. Solid: theory.

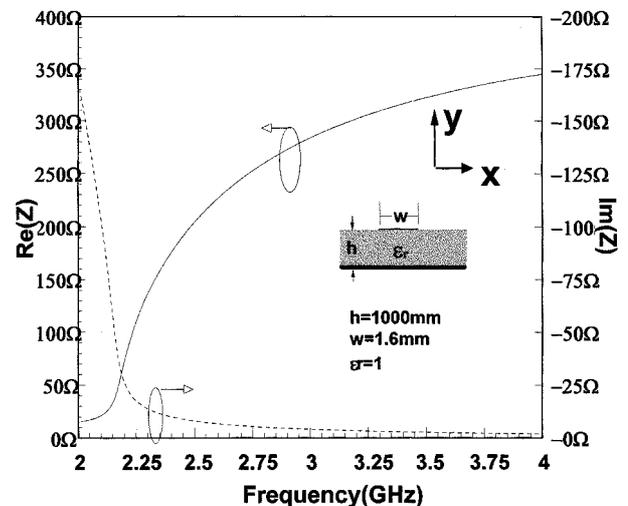


Fig. 7. The complex characteristic impedance of the domain-mode-like leaky mode.

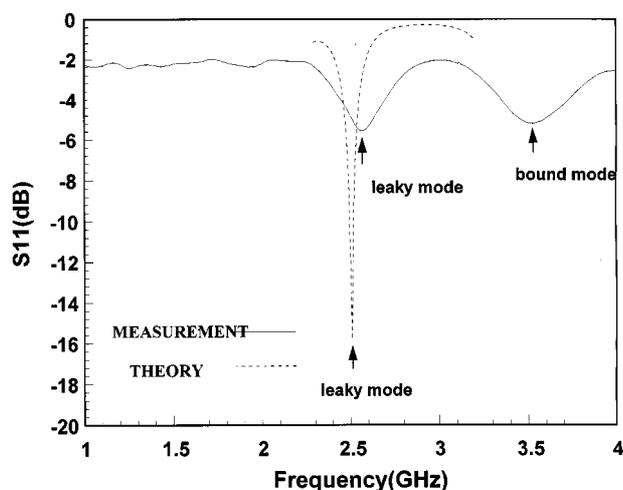


Fig. 8. The measured S_{11} parameter of a wire resonator, compared with the transmission line model needing the complex propagation constant, complex impedance and the wire length (118 mm). We assumed that only the leaky mode is present in the wire and obtained the leaky mode resonant frequency (2.51 GHz) in good agreement with the measurement (2.57 GHz).

invoking the well-known transmission line model needing only the complex propagation constant, the complex characteristic impedance, and the wire length. Figure 8 compares the S_{11} plots obtained by the simple model and the measurement, illustrating fairly good agreement is achieved. It is highly likely the leaky-mode antenna can be described more accurately by a better waveguide equivalent circuit model.

IV. Conclusion

The supposedly most simplest and best known (suspended) microstrip line is shown to possess rather complicated power leakage properties which are very useful for printed-circuit integrated antenna design. The sources of free-space radiations may stem from two distinct types of leakage: higher-order modes on microstrip and the companion leaky modes carrying dominant-mode-like currents. The antenna design based on both categories, either implicitly or explicitly, is best viewed as waveguide, manifesting the powerfulness of mastering the leaky modes.

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References

- Bagby, J. S., C. H. Lee, D. P. Nyquist, and Y. Yuan (1993) Identification of propagation regimes on integrated microstrip transmission lines. *IEEE Trans. Microwave Theory Tech.*, **41**, 1887-1894.
- Chou, G. J. and C. K. C. Tzuang (1996a) An integrated quasi-planar leaky-wave antenna. *IEEE Trans. Antennas Propagat.*, **44**(8), 1078-1085.
- Chou, G. J. and C. K. C. Tzuang (1996b) Oscillator type active integrated antenna – the leaky-mode approach. *IEEE Trans. Microwave Theory Tech.*, **44**(12), 2265-2272.
- Das, N. K. (1996) Power leakage, characteristic impedance, and leakage-transition behavior of finite-length stub sections of leaky printed transmission lines. *IEEE Trans. Microwave Theory Tech.*, **44**(4), 526-536.
- Gonzalez, G. (1984) *Microwave Transistor Amplifiers Analysis and Design*, Chapter 3. Prentice-Hall, Upper Saddle River, NJ, U.S.A.
- Hu, C. N. and C. K. C. Tzuang (1997) Microstrip leaky-mode antenna array. *IEEE Trans. on Antennas and Propagation*, **45**(11), 1698-1699.
- Lo, Y. T., D. Solomon, and W. F. Richards (1979) Theory and experiment on microstrip antennas. *IEEE Trans. Antennas Propagat.*, **27**(2), 137-145.
- Menzel, W. (1979) A new traveling wave antenna in microstrip. *ARCHIV FUR ELEKTRONIK UND UBERTRAGUNGSTECHNIK*, Band **33**, 137-140.
- Michalski, K. A. and D. Zheng (1989) On the leaky modes of open microstrip lines. *Microwave Opt. Tech. Lett.*, **2**(1), 6-8.
- Nghiem, D., J. T. Williams, D. R. Jackson, and A. A. Oliner (1993) Proper and improper dominant mode solutions for a stripline with an air gap. *Radio Science*, **28**(6), 1163-1180.
- Oliner, A. A. (1984) Historical perspectives on microwave field theory. *IEEE Trans. on Microwave Theory and Techniques*, **32**(9), 1022-1045.
- Oliner, A. A. (1987) Leakage from higher modes on microstrip line with application to antennas. *Radio Sci.*, **22**(6), 907-912.
- Oliner, A. A. and K. S. Lee (1986a) The nature of the leakage from higher modes on microstrip line. *IEEE MTT-S Digest*, pp. 57-60. Baltimore, MD, U.S.A.
- Oliner, A. A. and K. S. Lee (1986b) Microstrip leaky wave strip antennas. *IEEE Int. Antennas Propagat. Symp. Dig.*, pp. 443-446. Philadelphia, PA, U.S.A.
- Tsuji, M., H. Shigesawa, H. Sannomiya, and A. A. Oliner (1997) The spectral gap when power leaks into more than one type of surface wave on printed-circuit lines. *IEEE MTT-S International Microwave Symp. Digest*, pp. 483-486. Denver, CO, U.S.A.
- Tzuang, C. K. C. and C. C. Lin (1996) Millimeter wave micro-CPW integrated antenna. *Proc. SPIE Conf.*, pp. 513-518. Denver, CO, U.S.A.
- Tzuang, C. K. C. and C. N. Hu (1998) The mutual coupling effects in large microstrip leak-mode array. *IEEE MTT-S Int. Microwave Symp. Dig.*, pp. 1791-1794. Baltimore, MD, U.S.A.
- Tzuang, C. K. C. and C. C. Lin (1998) Space-wave-type leaky mode carrying dominant-mode-like current distributions. *IEEE MTT-S Int. Microwave Symp. Dig.*, pp. 643-646. Baltimore, MD, U.S.A.

洩漏波模於印刷電路天線之展望

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摘要

本文敘述如何藉著深入瞭解洩漏波模波導的各種傳播方式可有效地設計積體電路天線。由於構造簡單的（懸空）微帶線廣泛地被積體電路採用，本文即對微波線作討論。本文探討的第一種類型的洩漏波模係由A. A. Oliner教授研究群所發現的。經過仔細的研究這種洩漏波模呈現週期性現象且和平面方形天線（patch antenna）的共振腔頻率一致。本文進一步報導如何利用波導之模與模之間的耦合現象來建立電路模型，方便大型陣列天線的設計，同時取得非常準確的遠場場型。本文探討的第二種類型的洩漏波模係本人和學生所發現的洩漏波模—這種模在微帶線所傳播的電流分布及微帶線附近的近場場形皆和習知且不會輻射的微帶模非常近似。藉著微帶線的共振實驗，我們可以證明習知的微帶模和新發現的洩漏波模同時存在—然而後者產生快速波（fast wave；phase velocity高於光速）共振且把能量傳播至大氣中。這一類洩漏波共振現象可使用含複數型的傳播常數及複數型的特性阻抗的微波傳輸線電路模型來計算。總之，本文視某些印刷型天線為一種波導並利用複數模，即洩漏波模來設計天線。