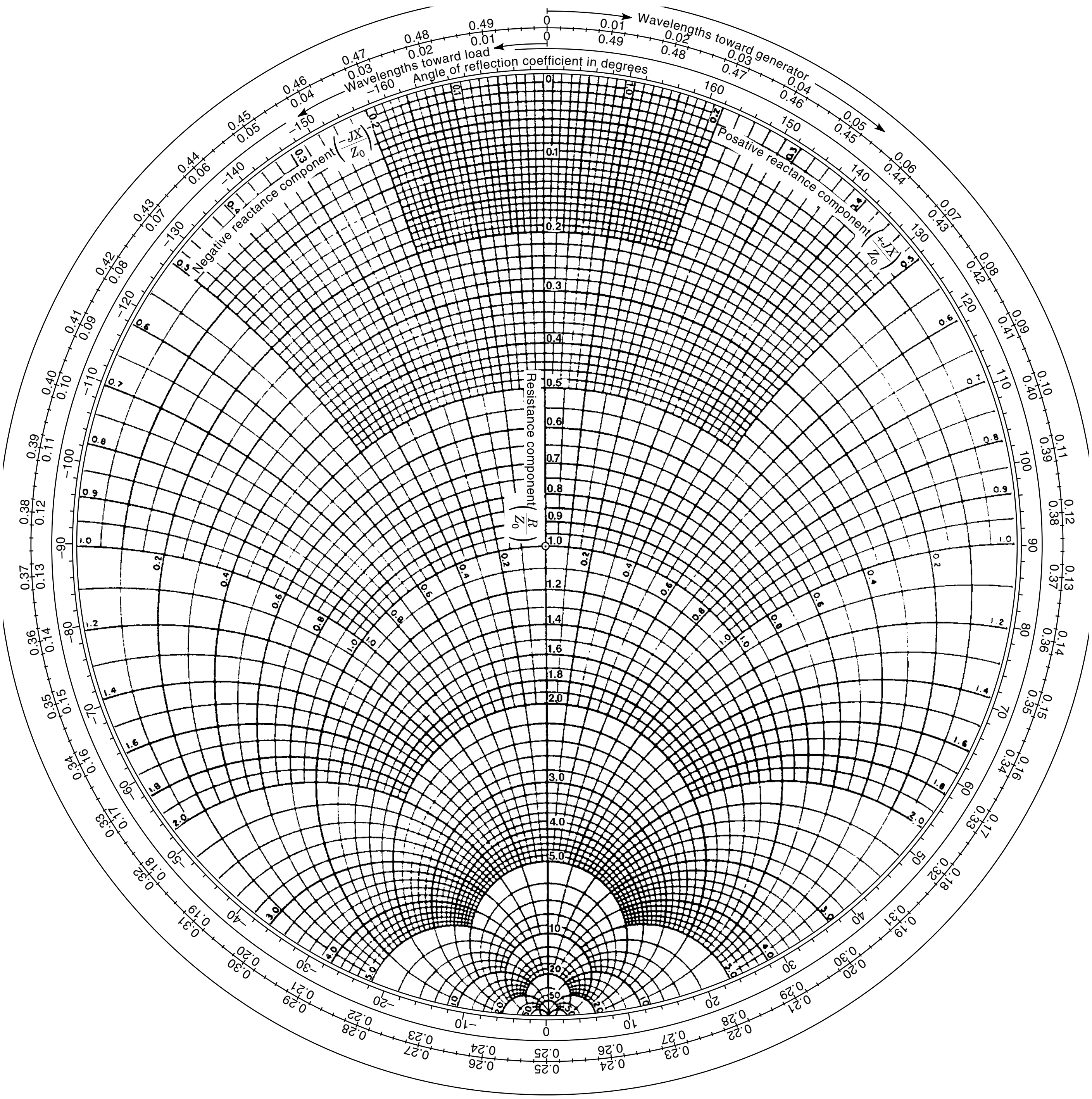
SMITH CHART

The origin of the Smith Chart as a fast and accurate graphical design tool is rooted in the predigital computer era of the 1930s. The original paper chart format was routinely used to solve difficult transmission line matching problems in a variety of broadcasting, microwave, circuit design, and telecommunications applications. While it has since evolved almost exclusively into a software format, the original paper forms remain a convenient detailed medium for print output of finished work from software implementations of Smith's graphical method.

Phillip H. Smith, inventor and developer of the Smith Chart, was affiliated with Bell Telephone Laboratories for his entire engineering career after graduating from Tufts College in 1928. At Bell Labs, Smith repeatedly demonstrated his incisive, pragmatic, problem-solving abilities on a variety of technical problems. In his first decade on the job he developed the Chart to its common present form through an iterative trial process of several more rudimentary forms. Smith's original intended application was to simplify the tedious work of installing and matching open wire transmission lines for antennas. During this period he almost single-handedly developed and proved the concept of using a graphical chart as a viable solution method. One can certainly appreciate his desire to minimize tedious slide-rule calculations required to solve transmission line equations involving hyperbolic functions. Smith (1) cited his routine need to obtain impedance solutions using Fleming's (2) telephone equation as a driving force to consider a graphical solution alternative. [Readers interested in greater detail on the life of Phillip Smith are referred to the Foreword section of Ref. 3 for a written transcript of the memorial session in Phillip Smith's honor presented at the 1990 IEEE MTT/S Symposium. An on-line IEEE source (4) also provides good detail on Smith's background.]

The Chart was first published in a usable developmental form in 1939 by Smith (5). A subsequent publication (6) in 1944 described the refined form known and used today. A standard preprinted paper Chart in this format is shown in Fig. 1(a), and Fig. 1(b) shows only the enlarged central portion around the normalized point $z = (1 + j0)$. In each of Smith's publications the fundamental equations and methods



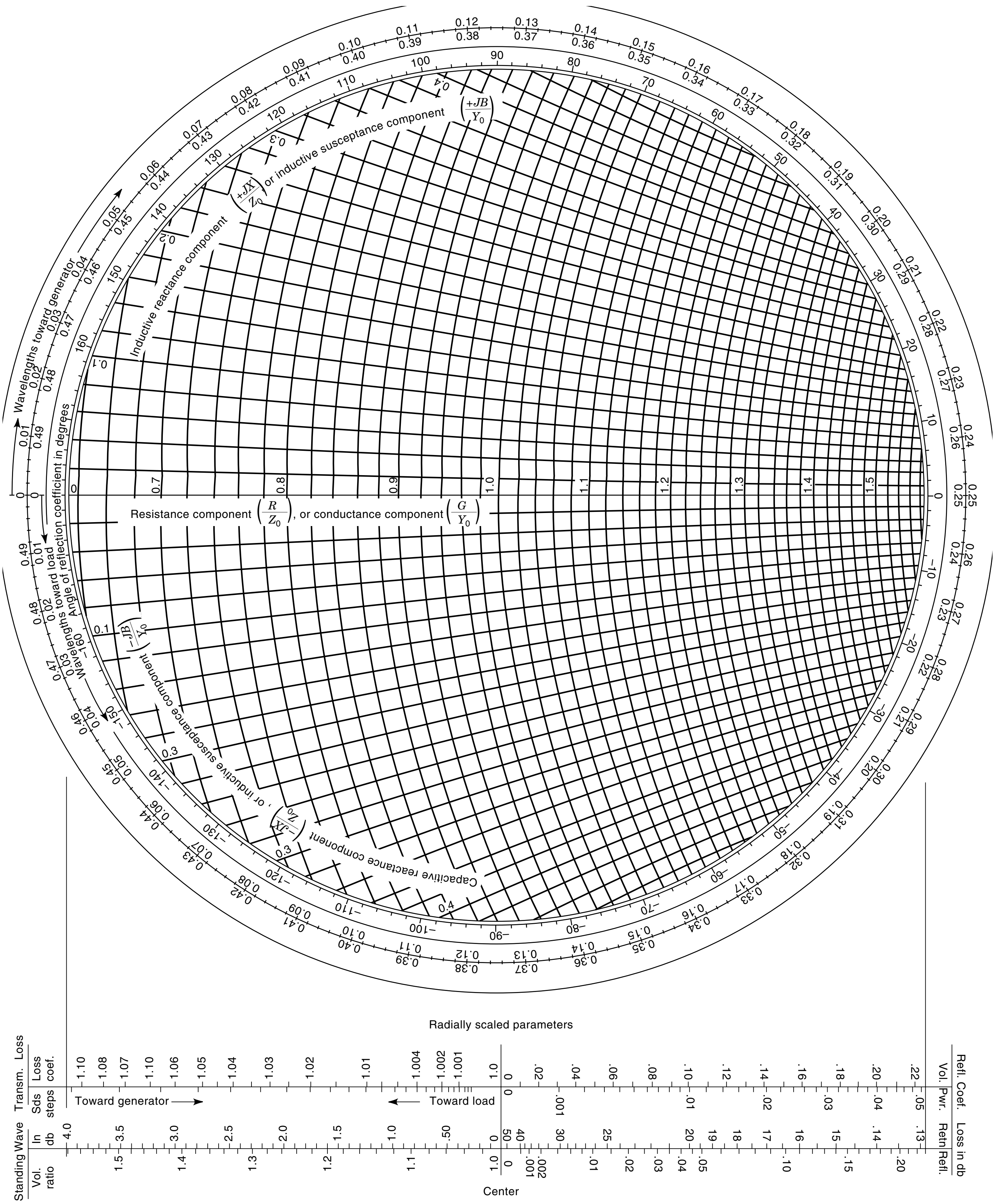
(a)

Figure 1. Full-size Smith Chart grid. (b) Enlarged center portion of the chart.

are provided along with demonstrations of the utility of the Chart method. Certainly the ability to represent and mathematically manipulate a complete impedance data vector on a single compact graphical paper chart was a significant step forward at the time for the telecommunications and emerging electronics industries at the onset of World War II.

THE ATTRACTION OF A GRAPHICAL SOLUTION METHOD

The essential objective in using the Smith Chart is stated simply: An impedance (or equivalent admittance) locus over a frequency range is systematically repositioned on the Chart in well-defined ways by the progressive effects of series or



(b)

Figure 1. (*Continued*)

shunt elements, thereby placing the passband portion of the impedance vector in the central area of the Chart and the stop-band portion at the outer periphery of the Chart. The circuit elements commonly used include distributed elements such as transmission lines and quarter-wave stubs, discrete elements such as inductors and capacitors, and any combination of these and related elements. Resistance elements are seldom intentionally used.

There is no need for a graphical method as an aide to solve a straightforward equation such as Ohm's law. However, the more difficult general equation for the input impedance ("sending impedance" in early 20th century publication parlance) of a transmission line with an arbitrary value of load impedance ("receiving impedance") is another matter. The presence of multiple hyperbolic functions in Fleming's equation is shown in Table 1, line 1. Figure 2(a) illustrates the concentric circular arc movement on the interior of the chart for a value of load impedance, Z_L, connected to a length, l/λ, of transmission line to produce an input impedance of Z_i. The input impedance equations for transmission line stubs (i.e., lengths of line typically less than a half-wavelength, with short-circuit and open-circuit load impedance values) are given by the equations of Table 1, lines 2 and 3 respectively. Figure 2(b) illustrates the concentric circular arc movement along the periphery of the chart for a value of load impedance ($Z_L = 0$ for the short-circuit stub and $Z_L = \infty$ for the open-circuit stub), connected to a stub with length l/λ, to produce an input impedance of Z_i.

The equation of Table 1, line 2 shows the effective parallel L-C circuit tuning effect for a short-circuit stub, and line 3 illustrates the effective series L-C circuit tuning effect for the case of an open-circuit stub. At relatively higher frequencies for which the length of the stub is greater than a half-wavelength, these tuning effects repeat unlike the effect of discrete (lumped element) parallel or series L-C circuits.

The repetitive nature of these three equations when line length exceeds a half-wavelength is evident when one looks at them plotted on the Chart. Likewise, the tuning effects of discrete elements is also calculable and treated on the Chart. The inductor and capacitor are especially used in typical equalizer, filter, and matching circuits. The resistor element, while it can also be treated on the Chart, is seldom used except in cases such as ultra-broadband (i.e., multi-octave to decade bandwidth) tuning of electrically short antennas to meet a VSWR specification. The equations for the discrete elements and the relative motion of their locus on the Chart is given in Table 1, lines 4, 5, and 6. Figure 2(c) illustrates the movement on the chart along arcs of constant-resistance for some load impedance, Z_L, when a capacitance or inductance is placed in series.

The Smith Chart's power as a graphical solution method comes from its versatility to design cascade and parallel circuits made up of any combination of distributed and lumped circuit elements defined by the equations given in Table 1. In addition, algorithmic methods such as the design of transmission line impedance transformers can also be implemented directly on the Chart. Design aids such as a voltage standing wave ratio (VSWR) goal plotted as a circle concentric to the center of the Chart, and other geometric constructs such as forbidden areas and boundary circles make the design process straightforward. These design aids as well as the line entries in Table 1 are discussed in greater detail in subsequent sections.

MATHEMATICAL STRUCTURE OF THE CHART

The mathematical basis of the Smith Chart is a conformal bilinear transformation for which all data values approaching infinitely large values on the $\{(R,X)$ or $(G,B)\}$ complex plane map to a single uniquely defined finite point. In implementing the transformation, the simple, familiar, straight-lined, rectangular, impedance grid with resistance (or conductance) on the positive abscissa and reactance (or susceptance) on both positive and negative axes of the ordinate map into two families of circles that intersect orthogonally to one another. This holds true for charts scaled for impedance or admittance.

The equations which uniquely define the bilateral transformation between complex normalized impedance and complex reflection coefficient are given as

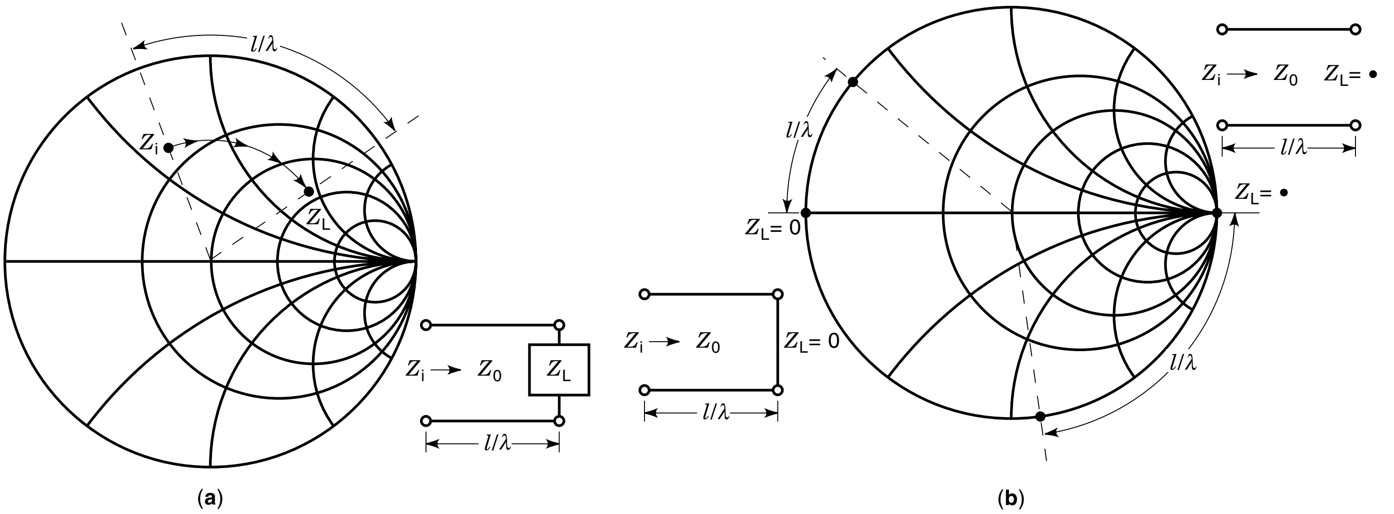
$$z = \frac{1+k}{1-k} \quad \text{and} \quad k = \frac{z-1}{z+1} \tag{1}$$

where z represents normalized impedance (Z/Z_0), k is the complex reflection coefficient at the point where z is measured, and Z_0 is the reference or normalizing value of impedance.

The generality of the underlying bilinear transformation is seen by plotting normalized impedance values (or analogously admittance values) on the right half of a Cartesian coordinate plane and evaluating the paired Eq. (1) for reflection coefficient loci which have constant values of magnitude with varying modulus as well as constant modulus (angle) values with varying magnitudes. Figure 3(a) illustrates normalized impedance plotted in a Cartesian frame, with the dashed lines indicating constant-resistance and constant-reactance values

Table 1. Distributed and Lumped Element Components Commonly Used in Smith Chart Analysis and the Direction of Progression with Frequency on the Chart

Element Type	Defining Equation	Motion on the Smith Chart
Transmission line	$Z_{in} = Z_0(Z_L + Z_0 \tanh \gamma l)/(Z_0 + Z_L \tanh \gamma l)$	CW along a circle centered at $Z_0 = 1 + j0$. See Fig. 2(a).
Short-circuit stub	$Z_{in} = jZ_0 \tan \gamma l$	CW along chart perimeter with region near ∞ especially useful ($l = \lambda/4$). See Fig. 2(b).
Open-circuit stub	$Z_{in} = -jZ_0 \cot \gamma l$	CW along chart perimeter with region near 0 especially useful ($l = \lambda/4$). See Fig. 2(b).
Inductance	$E = IX_L$; $X_L = j\omega L$	CW along constant-R circles. See Fig. 2(c).
Capacitance	$E = IX_C$; $X_C = 1/j\omega C$	CCW along constant-R circles. See Fig. 2(c).
Resistance	$E = IR$	To right along constant-X arcs toward $R = \infty$.



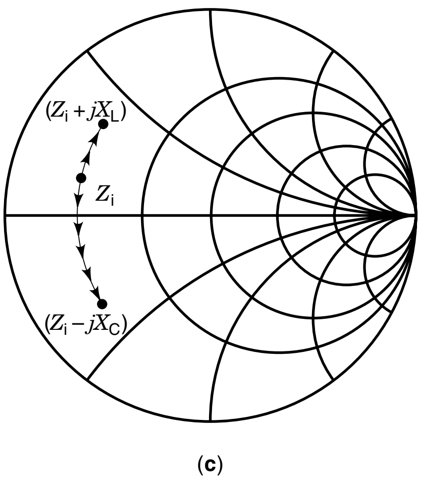


Figure 2. (a) Concentric circular movement along the chart interior to a value of input impedance, Z_i, resulting from addition of a transmission line to a load impedance Z_L. (b) Concentric circular chart movement along the chart periphery for the input impedance of a short-circuit ($Z_L = 0$) and an open-circuit ($Z_L = \infty$) stub. (c) Movement along circular arcs of constant-resistance for addition of a capacitance (downward) and inductance (upward) to a load impedance Z_L.

(hereafter referred to as constant-R and constant-X, respectively). Figure 3(b) uses the same frame to depict loci of constant-k values as solid lined full circles, and it uses loci of constant phase angle values for variable-k magnitudes as solid lined partial circles. The constant angle value loci all intersect at the single point $z = (1 + j0)$ for which $k = (0 + j0)$.

Alternately, one can plot the complex reflection coefficient $[k = K\exp(j\phi)]$ in two-dimensional cylindrical (i.e., polar) coordinates as shown in Fig. 4(a), with $k = (0 + j0)$ located at the center and cylindrical angle representing the reflection coefficient angle ϕ. Then the transformation to complex normalized impedance using Eq. (1) results in loci for constant-R and constant-X values which are again full circles and partial circles, respectively, as illustrated in Fig. 4(b). These circles and circular arcs have progressively offset centers located along the orthogonal axes defined by the horizontal line at $x = 0$ and the vertical line tangent to the outer circle at the right side point. Figure 4 illustrates the orthogonality features in both domains of (a) reflection coefficient and (b) normalized impedance. The latter grid of circles and circular arcs represent exactly the Chart solution method first proposed by Smith to the radio engineering community.

The radii and centers of the constant-R circles and constant-X circular arcs of Fig. 4(b) are derived relative to the center of the cylindrical coordinate plot of complex reflection coefficient. The radii are given by Eq. (2), where the value of either r or x is held constant. The geometric locations of the centers of the constant-R circles are given by Eq. (3), and the positions of the centers of the constant-X circular arcs are given by Eq. (4).

$$r_k = \frac{[(r^2 - 1 + x^2)^2 + 4x^2]^{1/2}}{(r+1)^2 + x^2} \tag{2}$$

$$(k_R^x, k_R^y) = \left(\frac{r}{r+1}, 0\right) \tag{3}$$

$$(k_X^x, k_X^y) = \left(1, \frac{1}{x}\right) \tag{4}$$

where the subscripts R and X denote constant-R circles and constant-X arcs, respectively, and the superscripts x and y denote the directional components.

NORMALIZATION OF THE CHART

For commonality and other reasons it is useful to deal with normalized rather than unnormalized Charts. Both full-size and enlarged central area Charts are normalized by dividing

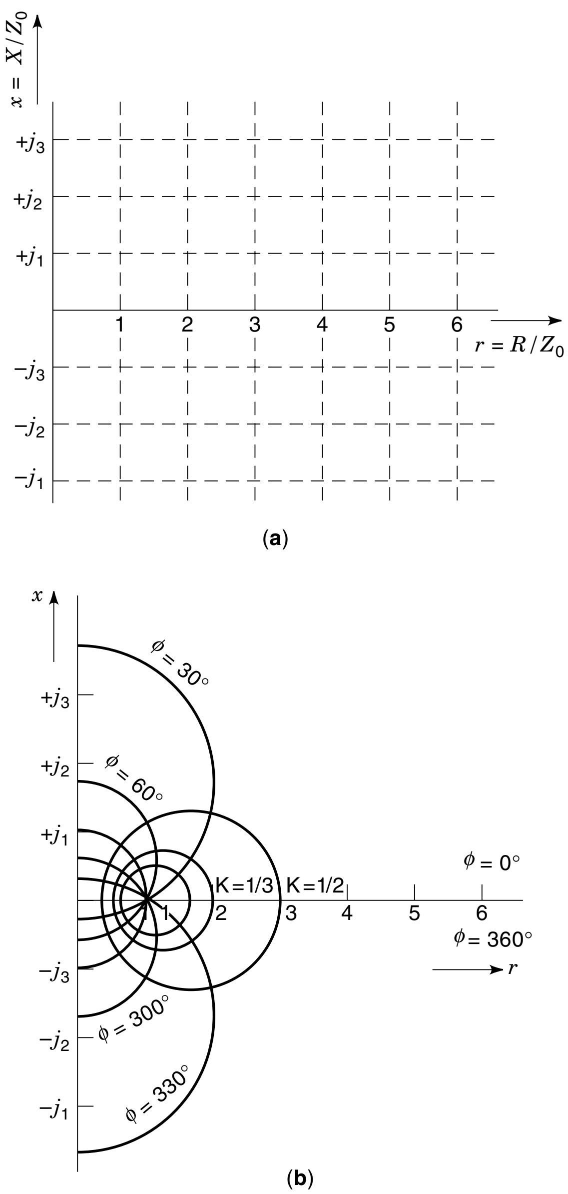


Figure 3. (a) Plots of normalized constant-R and constant-X on a Cartesian frame. (b) Loci of constant-k (full circles) and constant-ϕ angle (circular arcs).

values of resistance (R) and reactance ($\pm X$) by the real reference value (Z_0). This scaling results in all real axis values to the left of the center point having values between 0 and 1, and all real axis values to the right of the center point represent values between 1 and infinity. Charts which plot admittance values are analogously normalized using the reference value $Y_0 = 1/Z_0$. The usage of normalized impedance values on the Smith Chart grid facilitates the computation of reflection coefficient, VSWR, and return loss from the chart. Design examples given in subsequent sections for transmission line problems illustrate the advantage of using normalized values for chart-based computation.

GRID-BASED FEATURES OF THE SMITH CHART

A number of useful design features result from the final form of the Chart grid as derived by Smith. In addition to the interrelation of VSWR, return loss, and reflection coefficient, one is also able to read length (l/λ) along a transmission line segment from the rim of the chart and use boundary circles as a design aid. These features are reviewed below, but the reader is referred to Smith's seminal text (7) for added detail on these and other features. This reference also contains an exhaustive bibliography on publications related to the Smith Chart through 1969.

VSWR Circles

The relationship between VSWR and reflection coefficient is given by Eq. (5), where K is the magnitude of the complex reflection coefficient written as $k = K\exp(j\phi)$.

$$\text{VSWR} = \frac{1+K}{1-K} \tag{5}$$

On the Smith Chart, loci of constant VSWR are concentric circles with all centers located at $K = 0$, and radii are nonuniformly distributed between unity and infinity for values of K ranging from 0 to 1.

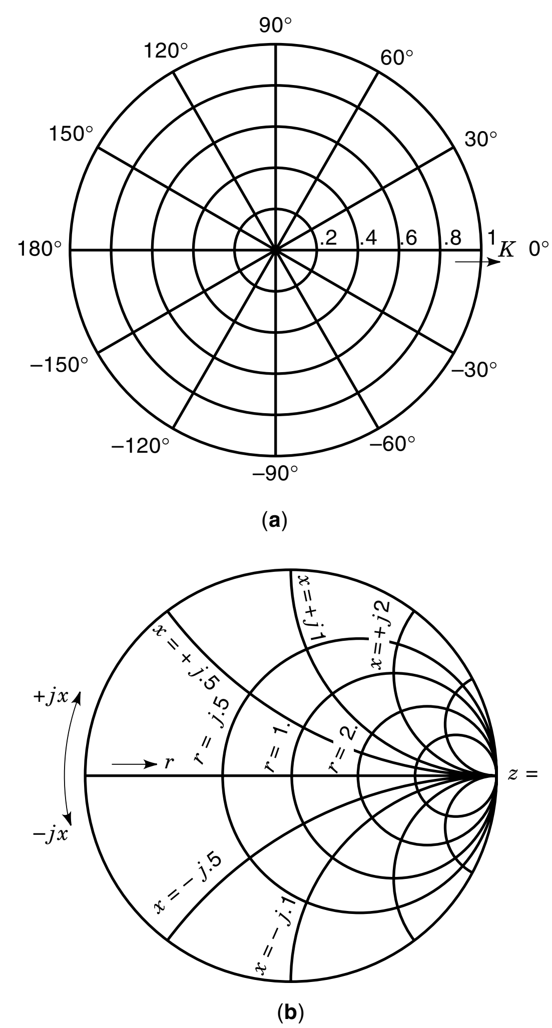


Figure 4. (a) Two-dimensional cylindrical coordinate plot of loci of constant reflection coefficient magnitude and constant reflection coefficient angle. (b) Loci of constant-R circles and constant-X circular arcs scaled to fit on the reflection coefficient loci plot of part (a).

Chart Perimeter as Transmission Line Length

The classical transmission line equation (see Table 1, line 1) clearly illustrates that impedance, and hence VSWR, varies in a repetitive fashion every half-wavelength in distance along a lossless line. On the Smith Chart this is equivalent to repeated values for reflection coefficient with every complete rotation around the chart relative to the center of the chart. The entire perimeter of the Smith Chart calibrates uniformly as a $\pm$ quarter-wavelength distance relative to a reference location. Clockwise rotation around the Chart's periphery is equivalent to moving along the line in a direction toward the source (generator), and counterclockwise rotation around the Chart is equivalent to moving toward the load.

Impedance and Admittance Locus Movement for Discrete Circuit Elements

Electronic circuit impedance matching is easily performed utilizing the Smith Chart. Typically one desires to use only lossless components to accomplish a match. The addition of a discrete circuit element such as a capacitance or an inductance in a matching circuit has a well-defined effect on moving the locus of a load impedance vector on the Chart grid. The four key discrete circuit elements commonly used in circuit matching are given as follows along with their effect on motion of an impedance locus (for series elements) or an admittance locus (for shunt elements):

- Series inductance rotates an impedance locus CW on a constant-R circle
- Series capacitance rotates an impedance locus CCW on a constant-R circle
- Shunt inductance rotates an admittance locus CCW on a constant-G circle
- Shunt capacitance rotates an admittance locus CW on a constant-G circle

Here CW and CCW denote clockwise and counterclockwise motion, respectively, on the specified circles.

Boundary Circles

The Chart-centered circle for a finite value of VSWR leads directly to the useful design construct known as boundary circles. They serve as a visual aid to determine the correct value of a circuit element which will cause the proper amount of rotation of an impedance or admittance locus for acceptable matching (i.e., which meets the VSWR requirement).

For a specified VSWR there are two related pairs of boundary circles. Each pair consists of two circles which are centered on the $x = 0$ line and which are doubly tangent to both the VSWR circle and the periphery of the Chart where the magnitude of the reflection coefficient is unity. Figure 5 shows the combination of a VSWR = 1.25 circle along with its associated pair of boundary circles. Knowing the directions of rotation for an impedance or admittance locus caused by the addition of series or shunt elements, respectively, one immediately determines that impedance values over a very large portion of the Chart—namely, the interior portions of both small boundary circles, as well as the upper and lower exclusion areas outside both of the larger boundary circles—

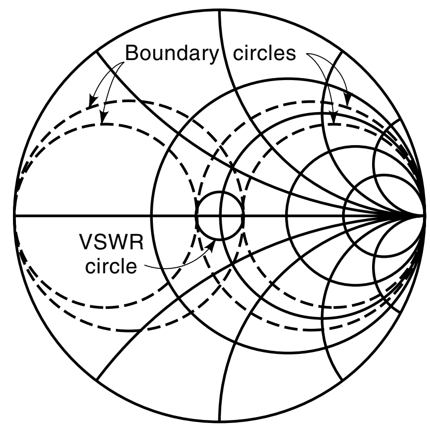


Figure 5. VSWR circle and its associated boundary circle pairs for a value VSWR = 1.25.

cannot be matched to within a specified value of VSWR with a single matching element.

OTHER IMPORTANT OPERATIONS EXECUTABLE ON THE SMITH CHART

Two Element Matching Over the Entire Chart

In contrast to the case just shown where impedance values over much of the Chart area cannot be matched with a single element, it can be shown that all single-frequency impedance values anywhere on the Chart exclusive of the outer rim circle ($r = 0$) can always be perfectly matched to a value of $r = (1 + j0)$ by use of a two-element circuit. Smith (8) and a current software Chart implementation (9) provide overlay diagrams of the eight possible ell-type circuits (four L-C, two L-L, and two C-C), each with its associated allowed area and supplementary forbidden area on the Smith Chart. (The same diagrams are also illustrated in Ref. 10, p. 40.) Any point within an allowed area can always be perfectly matched using the associated ell-circuit.

Transmission Line Transformers

Frequently the design of an impedance matching circuit must be implemented using distributed parameter elements such as transmission lines. Somlo (11) has shown how a single-frequency design for a transmission line transformer is graphically implemented using a Smith Chart. Narrow bandwidth matching designs are also achievable using the same method. The Somlo technique is implemented as a utility tool in the software implementations of Refs. 9 and 12.

The ability to graphically analyze the matching effects of a variety of transmission line circuit elements (e.g., open or short-circuit stubs as well as transmission line sections and impedance transformers in both series and shunt configurations) gives the Smith Chart more versatility than software synthesis tools that are typically unable to treat a full array of transmission line elements.

EXAMPLE

A circuit matching design exercise is described here to illustrate the methods used in obtaining a solution on the Smith

Table 2. Load Impedance Values for Example Matching Problem

Frequency (MHz)	Load Impedance (Ω)
850	$15.0 - j250$
875	$19.0 - j227$
900	$21.5 - j192$
925	$25.0 - j180$

Chart. To keep the Charts visually succinct, each of the intermediate plotting steps including $Z \rightarrow Y$ and $Y \rightarrow Z$ inversions as well as the effects of individual branch-by-branch circuit constructions are presented on a set of individual Charts. The traces plotted on the Charts use the convention of Z_N or Y_N for the driving point impedance or admittance when looking toward the load from branch N. Readers who wish to study a variety of antenna matching problems executed in step-by-step detail can consult Ref. 13.

In this problem a device, such as an antenna, has a highly capacitive input impedance vector as given in Table 2 for the range of 850 MHz to 925 MHz. The objective is to produce a matching circuit which meets a VSWR requirement of 2.5 : 1 over the reduced frequency range of 855 MHz to 920 MHz with the restriction that no lumped circuit inductors be used in the matching circuit.

The bandwidth requirement of about 8.5%, the highly capacitive values, and the implementation restriction of no lumped inductors all imply that additional elements beyond a simple two-element L configuration will be required to implement a satisfactory matching circuit. The two solutions derived by use of a software chart method are described in Table 3, giving all the circuit element parameter values. The first solution uses transmission lines and short-circuit stub elements exclusively and is illustrated in the set of successive charts in Fig. 6. The second solution requires fewer elements but includes a capacitance and a short-circuit stub having a low value of Z_0 which is virtually impossible to implement. It is presented in the second part of Table 3 for purposes of contrast only.

Table 3. Component Types and Values for the Solutions of Example Problem

Element No.	Element Type	Parameter Values (v/c = group velocity)
		Primary Solution[a]
1	Transmission line	$Z_0 = 234\ \Omega$, 2.60 cm, $v/c = 0.69$
2	Shunt short-circuit stub	$Z_0 = 10.1\ \Omega$, 4.84 cm, $v/c = 0.69$
3	Transmission line	$Z_0 = 76.22\ \Omega$, 0.70 cm, $v/c = 0.69$
4	Shunt short-circuit stub	$Z_0 = 6.53\ \Omega$, 6.25 cm, $v/c = 0.69$
		Contrasting Solution
1	Transmission line	$Z_0 = 100\ \Omega$, 4.91 cm, $v/c = 0.69$
2	Shunt capacitance	9.4 pF
3	Transmission line	$Z_0 = 42.8\ \Omega$, 5.84 cm, $v/c = 0.69$
4	Shunt short-circuit stub	$Z_0 = 3.12\ \Omega$, 5.91 cm, $v/c = 0.69$

[a] See Fig. 6 for associated chart traces.

The first element in the matching circuit must be either of the two inductive types: either a short-circuit stub or a transmission line of sufficient length to rotate the load impedance trace toward the inductive reactance portion (i.e., upper half), of the Chart. There is, however, a distinct observable difference in how the two candidate initial elements cause the load impedance trace to rotate on the chart. A series wired short-circuit stub will move the load trace CW and upward along constant-R grid lines, causing the rotated impedance vector to lie closer to the center of the Chart, but extending it over the Chart to a greater degree than would be caused by a series transmission line. Conversely, the series transmission line keeps the rotated load trace further out toward the chart periphery. A compromise for the initial element is to use a short length of transmission line with high Z_0. This has an impedance transforming effect in bringing the load trace toward the center of the chart, but the short length keeps the trace located mostly on the capacitive side of the chart. In this case the characteristic impedance and length of the transmission line element are selected to rotate the impedance locus such that it approximately straddles the lower-left crescent of the boundary circles associated with the specified VSWR.

The second element, a shunt position short-circuit stub, rotates the Y_1 trace CCW and downward to position the ends of the Y_2 trace on the inductive susceptance side of the chart with the trace approximately surrounding the center of the chart. This begins the process of pulling the ends of the trace inward toward accomplishing the ultimate goal of collapsing the final trace into a loop configuration and positioning it inside the 2.5 : 1 VSWR circle.

The third element, a length of transmission line, rotates the Z_2 trace CW to an approximately vertical orientation with about half of the trace in each of the top and bottom halves of the chart. With the central portion of the Z_3 locus inside the VSWR circle, the sole purpose of the fourth and final element will be to complete the process of collapsing the trace into the needed loop and place it inside the VSWR circle.

The fourth element, a shunt wired short-circuit stub, adds sufficient compensating susceptance (inductive susceptance at the low frequencies and capacitive susceptance at the high frequencies) to further close the loop. To provide the necessary magnitude of compensating susceptance given by $B_{\text{stub}} = -(\cot \gamma l / Z_0)$, the characteristic impedance required for the shunt short-circuit stub element is a small value. This also keeps the Y_4 trace tightly looped. In practice, this low value of Z_0 is typically accomplished with four equal-length stubs wired in parallel and each having a Z_0 of about 25 Ω, which is a practical physical lower limit. Frequency interpolation is used to confirm that the VSWR specification is met for the frequency range of 855 MHz to 920 MHz.

The contrasting solution listed in Table 3 follows much the same sequence used in the first solution. The primary difference in the two methods is that use of a capacitance for the second element places its associated Y_2 trace in a more vertical orientation with the extremes of the trace spread further out from the VSWR circle. That causes the value of characteristic impedance for the short-circuit stub used for the fourth element to be much lower than that for the first solution method where more of the admittance locus for the third element is already within the VSWR circle. This second solution is clearly not a physically realizable situation. Hence, the associated chart traces are not shown.

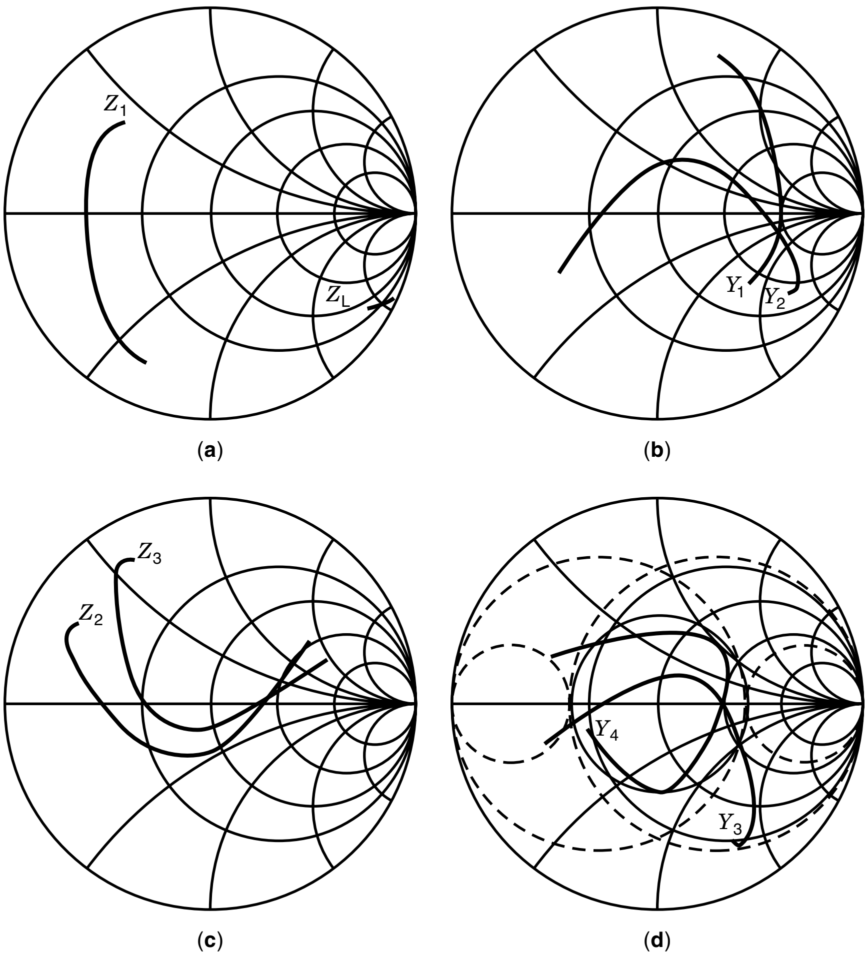


Figure 6. Solution to the example impedance matching problem requiring no lumped element inductors. (a) Z_{Load} trace and Z_1 trace after adding series transmission line section. (b) Y_1 trace and Y_2 trace after adding shunt short-circuit stub. (c) Z_2 trace and Z_3 trace after adding series transmission line section. (d) Y_3 trace and Y_4 trace after adding shunt short-circuit stub.

REVITALIZATION OF THE SMITH CHART IN SOFTWARE

The original printed paper versions of the Smith Chart were primarily used in industrial research and World War II development efforts through the 1940s. For the following three decades, these paper Charts became a mainstay tool in every transmission lines course in academia as well as a broad-based industry design tool. Beginning about 1980 with the onset of a variety of numerical design tools such as the real-frequency method pioneered by Yarman and Carlin (14) and implemented in commercial software (15), the paper version of the Smith Chart fell into relative disuse. However, beginning about 1990, a number of software tools (9,10,12,16,17) became available which implemented the core operations of the Smith Chart on a computer screen.

These software implementations of the Smith Chart alleviated most or all of the key difficulties encountered with manual use of the paper charts. These advantages include (1) elimination of math errors since the software internally performs all the background calculations of branch impedance or admittance values including normalization, (2) elimination of errors due to using an incorrect rotation direction on the chart, (3) elimination of interpolation errors when plotting data onto or reading values off of the chart, (4) requiring the user to select a proper value of group velocity for a transmission line ($v/c < 1$), (5) having the software internally perform spline calculations to plot smoothly contouring line vectors on the chart, (6) the dramatic speed improvement factor over hand-drawn Smith Charts, and (7) toggled screen presentation of VSWR and boundary circles as convenient design aids. In addition, an attractive feature of the software versions is their ability to plot the finished work in excellent detail on a preprinted paper Smith Chart form for delivery or publication purposes.

With the availability of software-based Smith Chart programs, the professional circuit designer, student, and researcher can take full advantage of the clarity and simplicity of graphical methods with a minimum investment of labor and time to obtain the needed solution. More important, one gains the value of personal insight into the process of design of a matching circuit when using this graphical method.

The value of the Smith Chart as a potent graphical design tool was well stated by Carlin (18) at a 1983 IEEE MTT/S professional workshop on broadband matching: "So far the 'best' transfer functions analytic theory has to offer are based on Chebyshef polynomials and almost invariably these yield matching structures which can be surpassed in performance by significantly simpler equalizers. In effect the old-fashioned procedure of 'playing around' on the Smith Chart may produce better results than sophisticated theory."

As software-based Smith Chart tools evolve to include additional capabilities such as built-in circuit optimization functions and IEEE-488 interfaces to port measured impedance data from network analyzers, it is expected that they will enjoy continued future usage by a variety of technical practitioners and students

BIBLIOGRAPHY

1. P. H. Smith, Introduction section, *Electronic Applications of the Smith Chart,* New York: McGraw-Hill, 1969; subsequent reprints Malabar, FL: Krieger Publishing, 1983, and Tucker, GA: Noble Publishing, 1996.
2. J. A. Fleming, *The Propagation of Electric Currents in Telephone and Telegraph Conductors,* New York: Van Nostrand, 1911.
3. L. M. Schwab, *Advanced Automated Smith Chart, Version 2,* Boston: Artech House, 1995.
4. Available on line: http://www.ieee.org/history_center/oral_histories/abstracts/smith3_abstract.html
5. P. H. Smith, Transmission line calculator, *Electronics,* January, 29, 1939.
6. P. H. Smith, An improved transmission line calculator, *Electronics,* January, 130, 1944.
7. P. H. Smith, *Electronic Applications of the Smith Chart,* New York: McGraw-Hill, 1969; subsequent reprints Malabar, FL: Krieger Publishing, 1983, and Tucker, GA: Noble Publishing, 1996.
8. Ref. 7, pp. 116–117.
9. L. M. Schwab, *Automated Smith Chart, Version 3* (MS Windows 95/NT), Boston: Artech House, 1998.
10. L. M. Schwab, *Automated Smith Chart* (DOS), Boston: Artech House, 1991.
11. P. I. Somlo, A logarithmic transmission line chart, *IRE Trans. Microw. Theory Tech.,* **8**: 463, 1960.
12. L. M. Schwab, *Advanced Automated Smith Chart, Version 2,* (MS Windows 3.1), Boston: Artech House, 1995.
13. W. N. Caron, *Antenna Impedance Matching,* Newington, CT: Amer. Radio Relay League, 1989.
14. B. S. Yarman and H. J. Carlin, A simplified "real frequency" technique applied to broadband multistage microwave amplifiers, *IEEE Trans. Microw. Theory Tech.,* **30** (12): 2216–2222, 1982.
15. *Complex Match II,* synthesis software by Compact Software, Inc. Paterson, NJ, 1988.
16. W. Hayward, *MicroSmith* (DOS), Newington, CT: American Radio Relay League, 1992.
17. Eagleware, *winSMITH* (MS Windows), Tucker, GA: Noble Publishing, 1995.
18. H. J. Carlin, Keynote speech: That perennial problem of broadband matching, *1983 IEEE MTT/S Symp. Workshop:* Broadband matching and design of microwave amplifiers.

LEONARD M. SCHWAB
Germaine Development Corp.