NOVEL CONTRIBUTIONS TO MICROWAVE CIRCUIT DESIGN

J. K. Hunton

G.T.E. Government Systems

Mountain View, California

ABSTRACT

Dr. S. B. Cohn's work in two areas is described. One is slot line which he introduced in 1968. The other is circuit design by equal ripple optimization which appeared in a 1974 paper.

INTRODUCTION

Dr. S. B. Cohn's contributions to the microwave art - both in theoretical and in practical design have been very numerous and have covered a wide range of circuit forms. This presentation is an attempt to describe and set in perspective two significant contributions. One is the introduction in 1968 of a new concept for a microwave transmission line which Dr. Cohn called Slot Line [48]. A complete analysis followed in 1969 [50] and other papers [51, 53, 54] in the next two years. The other is the development of a computer optimization technique for networks such as filters or couplers that have a pass band response differing from the ideal by an equal ripple error [55]. In later papers on filter design [56] and coupler design [59] he used the optimization technique for the design of the circuits discussed.

Although this paper is mainly concerned with these important contributions themselves, the presentation will attempt to show some of the later applications of slot line in microwave components as well as some of the later applications of the equal-ripple optimization algorithm to the design of various microwave circuits.

SLOT LINE

Slot line was proposed by Dr. S. B. Cohn in 1968 [48] and his analysis was published in 1969 [50]. Dr. Cohn introduced the concept with the idea that it would be very useful for microwave integrated circuits in conjunction with microstrip line which can occupy the other side of the dielectric substrate. Slot line is quite similar to fin line that was introduced in 1972 by P. J. Meier as a medium primarily useful for integrated circuits at millimeter wavelengths. (See - P. J. Meier, "Two new integrated circuit media with special advantages at millimeter wavelengths", IEEE 1972 G-MTT Symposium Digest, pp 221-223). It is interesting to note that Dr. Cohn's analysis which included only two of the four waveguide walls needed to enclose fin line can be extended to include this case if the fin line gap is small enough relative to the waveguide height for certain assumptions, about the nature of the fields in the gap to be valid.

Dr. Cohn analyzed slot line by a resonance method wherein a section of slot line on dielectric is arranged to extend across a rectangular waveguide in the manner of a capacitive iris. This is depicted in Figure 1 reproduced from his paper. Here the y axis is vertical, the z axis is in the direction of normal wave propagation in the waveguide and the x axis is perpendicular to the page. In all regions the fields can be determined by summing the infinite set of known rectangular waveguide modes. In particular the fields at the center of the slot line section (z=0, y=0, x = a/2) were determined in terms of the fields in the full height regions on either side of the metalization. This was done by application of the metallic wall boundary condition above and below the slot. Also the approximation was made that the E field has only a y component which has a constant value within the slot region (from y = -w/2 to +w/2). The admittance at the center of the slot line section was determined in terms of the infinite summation of wave admittances of all the full height waveguide modes calculated at the plane of the slot line metalization.

The waveguide mode admittances were calculated looking in both directions down the rectangular waveguide (i.e., in the plus and minus z direction). The standard transmission line impedance transforming equations were used to take account of the dielectric / air interface at z = d. A metal wall beyond this point and a metal wall to the left could be taken into account in the same manner, in which case, the results could be applied for unilateral fin line. The approximation regarding the fields in the slot would have to be valid for the fin line. Although this additional step was not taken in Dr. Cohn's original work, he added it to his analysis on May 18, 1970 and it appears in his unpublished notes of that date.

Having computed the total admittance at the center of the slot line section (x = a/2, y = 0, z = 0), the condition was then found for which it is zero. This is the resonance condition at which a standing wave exists on the slot line with exactly one half a slot line wavelength occupying the distance between waveguide side walls. In other words, at resonance, the slot line wavelength λ' is equal to 2a. For a given set of dimensions the equation which sets susceptance equal to zero is solved (by iteration) for the frequency. This determines the wavelength ratio λ'/λ for that frequency (here λ is the free space wavelength). To find a set of values over a range of frequencies the slot line length, a, is varied over a wide range, repeating the solution process. Dr. Cohn showed how the slot line impedance could be computed by finding, in addition, the derivative of the susceptance with respect to the wavelength ratio at resonance.

In a 1969 paper [51] a set of very useful slot line design graphs was published. These are plots of the slot line wavelength ratio λ'/λ and the characteristic impedance, Zo, against the normalized frequency variable d/λ for different values of w/d (see Figure 1 for dimensions). Design graphs were made available for dielectric constants of 9.6, 11.0, 13.0, 16.0, 20.0. This paper also provided results of a number of measurements on a number of slot lines of different dielectric constants indicating good agreement with the theory. Transitions from microstrip to slot line were also tested. These showed that for a 50 ohm microstrip the theoretical slot line impedance as defined earlier should be 75 ohms for a low SWR transition. This has been confirmed by other workers and the discrepancy may be largely a result of the choice of impedance definition. In 1971 and 1972 Dr. Cohn published extensions of his earlier analysis. One was sandwich slot line [53] which contains dielectric on both sides of the slot plane. In the other [54] all of the fields at x = a/2, y = 0 were computed for different values of z. A number of plots of H_x and H_z against z were shown. These showed elliptical polarization of the magnetic field to exist outside the metalized substrate on both sides with best circularity close to the surface. This paper also dealt with the problem of the approximations made in the earlier slot line analysis in which the assumption was made that the E field in the slot plane was all in the y direction and was constant across the slot. In this paper a new result just for fields very close to the slot was derived from a low frequency approximation involving a conformal transformation.

Dr. Cohn's work on slot line was a significant contribution in the field of MIC component design. It has found its major use as a balanced transmission line in all kinds of balanced microwave circuits, such as mixers, frequency multipliers and dividers, push-pull amplifiers. In combination with microstrip and coplanar waveguide it has been used in various forms of planar hybrid junctions. In a symmetrical housing when excited by a microstrip or coaxial transition it forms an excellent balun. In this case the signal is accurately balanced through symmetry a short distance from the transition. The elliptical polarization of the magnetic field near the slot has possible applications for coupling to ferrites and also to dielectric resonators.

CIRCUIT DESIGN BY EQUAL RIPPLE OPTIMIZATION

Most optimization techniques use general forms of error minimization algorithms (see, for example, reference 2 in [55]) which generally do not allow all of the information known about a very specific network like a filter to be utilized. Usually the response of an optimizable network is sampled at a number of equally spaced frequencies and the error between this sampled response and the desired response is computed at each frequency. The optimization program, through an iterative process, reduces this error to a minimum, arriving at a final network design in terms of the optimized circuit parameter values. In a filter, whose response is expected to have an equal ripple error (vs. frequency) the frequencies at which the peaks of the error will occur are either known exactly or to a close approximation prior to optimization. This information can be used to advantage.

An important contribution in this field was made by Dr. S.B. Cohn in 1974 [55]. In this paper he describes a very efficient optimization process in which all known information about the filter is fully utilized. The types of filters considered in the paper are those which are not directly synthesizable by the methods of modern network theory but do closely resemble them. Examples are filters in which lumped circuit elements are mixed with distributed elements and filters that have distributed elements that are non-commensurate. As in the case for direct synthesis the optimized filter circuit has to be non-dissipative.

In Dr. Cohn's algorithm the equal ripple error function is required to have equal amplitude peaks which alternate in sign from one frequency sample to the next as shown in Figure 2(b). The reason for this is that the algorithm forces only the peaks and, if they alternate in sign, the zero crossings are assured. With some network functions, such as the input susceptance of a singly terminated filter or the coupling of a directional coupler, the error does have alternating sign because it oscillates about a non-zero value. For a matched filter, however, this is not the case for either the transmission or reflection coefficient magnitudes.

Fortunately, as pointed out in Dr. Cohn's paper [55] and in his reference number 4, a function exists which has the same magnitude as the reflection coefficient but does alternate in sign. In terms of A B C D matrix parameters this function is E/jF where $E = B-C$ and $F = |A+B+C+D|$. It applies only to lossless symmetrical networks (where A and D are real, A=D, and B and C are both imaginary).

Referring again to Figure 2, reproduced from Dr..Cohn's paper, the final result of an optimization is shown. The upper plot is the actual reflection coefficient magnitude while the lower one is the corresponding alternating sign function peculiar to symmetrical lossless networks. At the start of the optimization process a set of estimated peak frequencies is supplied to the program. These do not have to be exactly where the final peaks appear but they have to be close enough to be within the space between the appropriate final zeros. These starting sample frequencies are computed from an approximation function which suits the particular type of filter - much the same as would be used in a synthesis problem. Also supplied to the program are starting parameter values for all the filter equivalent circuit elements.

The procedure next involves the computation of function values and derivatives (with respect to all optimizable parameters) at the sample frequencies. For m sample frequencies a set of m simultaneous equations is solved. Each of these relates the required change in function value at that sample frequency to the changes required in all the parameter values through the derivatives (as in a Taylor series representation). Since the process is non-linear the solution of these linearized equations does not give the final correct answer but only a local direction to proceed in changing the parameter values by some fraction of what the solution predicts. The process is repeated with successively new sets of parameter values.

As the process continues peaks form at frequencies slightly different from the ones initially chosen. Dr..Cohn developed, in his algorithm, a method of correcting for this along the way. It is depicted in Figure 3, reproduced from his paper. In 3(b) the sample frequency, Fi, is a little off, so the function is sampled at frequencies slightly higher and lower. By finding an equivalent parabola passing through the three points a correction is derived which can then be applied to the frequency Fi to bring it closer to the peak. At successive iterations of the process parameter values and sample frequencies are changed until a final equal ripple result is achieved with the specified amplitude, within a specified accuracy.

In the paper Dr. Cohn provides formulas for the starting sample frequencies for interdigital and combline filters and shows results for a 15-element combline filter with lumped capacitors at the rod ends and tapped input and output couplings - an example of a non-synthesizable filter.

Other authors have described equal ripple optimization algorithms somewhat similar to Dr. Cohn's (see references 3 and 4 in [55]). The most important differences are in the way in which they handled the selection and updating of the sample frequencies during the iterative optimization process, and in the increased number of equations needed for the solution. Dr. Cohn's method, in this regard, is unique and is very reliable as can be confirmed by this author who has used it in a number of applications. Actually, all the peaks of the error function do not have to be present at the start of optimization. Several iterations of parameter changes can be made and the peaks will gradually form. The sample frequency correction process can then be started.

It has been pointed out by Dr. Cohn that the restriction requiring an alternating sign error function, which limits optimization to symmetrical filters, can be removed. This can be done by making the optimization algorithm force the zeros as well as the peaks of the equal ripple error function. If N peaks are present an additional set of (N-1) sample frequencies will be needed for the zeros and this same number of additional equations will be required. Fortunately the unsymmetrical network has the same number of additional optimizable parameters.

Dr. Cohn used the alternating sign algorithm in other published work, dealing with filters [56] and couplers [59].

An interesting point about optimization can be made here. The general literature on optimization is extensive. Although the equal ripple process is briefly mentioned as the Remez Method dating back to 1934 (see reference 1 in [55]), it is really a special case of the general class of "minimax" algorithms in which the minimum value of the maximum (peak) error is sought. In the general case, the number of peaks in the optimum result and their locations are not known ahead of time and the optimization process is quite different from the equal ripple algorithm just described. Another point about band pass filters, in particular, is that optimization is usually only required for the pass band. Fixing the ripple amplitude and the resonant frequencies of resonators assures the stop band performance, as predicted by an approximation function.

CONCLUSION

Dr. S. B. Cohn's work in two unrelated areas - slot line, and computer optimization - has been described. The contributions in these two areas are significant. Spurred by his introduction of slot line, a number of microwave integrated circuit components using it have been developed. His equal ripple optimization method, used by him as well as by others has led to the development of useful new microwave circuits. In the presentation emphasis will be on applications both for slot line and for equal ripple optimization.

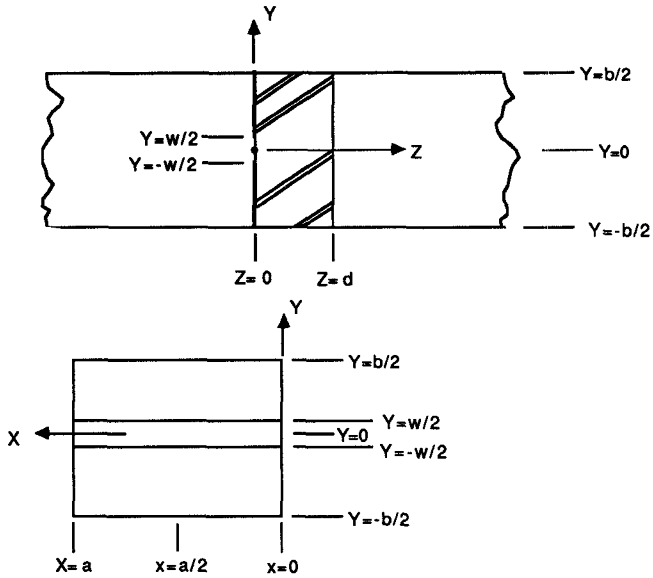

Fig.1 Waveguide Model Containing Capacitive Iris and Dielectric Slab

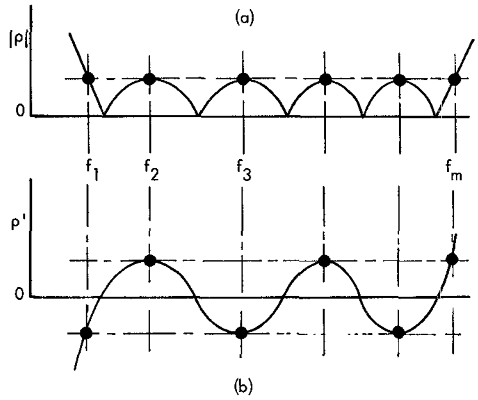

Fig. 2 Equal-ripple response functions

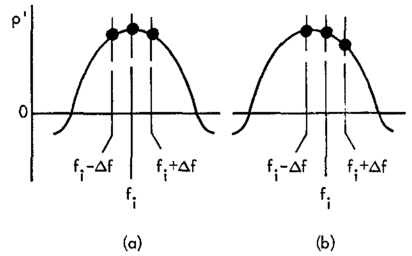

Fig. 3 f_i on maximum at (a), off maximum at (b)