A History of Microwave Filter Research, Design, and Development

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Abstract—An account of the development of microwave filters is surveyed, commencing from 1937. Much of the foundation of modern filter theory and practice took place during the period of World War II and the years immediately following, especially by such pioneers as the late P. I. Richards, whose subsequent career is briefly described. Filter topics discussed include low-pass, bandpass, high-pass, and multiplexers constructed in a variety of media, such as waveguide, coaxial line, microstrip, and stripline, as well as dielectric resonators. All types of filter characteristics are surveyed, such as Chebyshev, elliptic and pseudo-elliptic function, Achieser-Zolotarev, and a variety of generalized designs, including linear phase.

I. World War II and Earlier

WORK ON MICROWAVE filters commenced prior to the war, a particularly significant early paper being published in 1937 by W. P. Mason and R. A. Sykes [1]. They used A, B, C, D parameters, although not in matrix form, to derive the image impedance and image phase and attenuation functions of a rather large variety of useful filter sections.

Major advances and applications mainly using image parameters were made at various laboratories in the United States during the World War II years of 1941 to 1945 (for example, at the M.I.T. Radiation Laboratory, the Harvard Radio Research Laboratory, Bell Laboratories, NRL, etc.). At the Radiation Laboratory, emphasis was on waveguide cavity filters, while at the Radio Research Laboratory, work was concentrated on broad-band low-pass, bandpass, and high-pass coaxial filters for ECM applications and also on narrow-band tunable coaxial resonator filters for search receivers. Much of this work is described in the M.I.T. Radiation Laboratory Series by Fano and Lawson [2]. Even though the work reported is about 40 years old, it still retains a modern character. The scientists and engineers who worked in the Rad.Lab. and in associated microwave laboratories both in the U.S.A. and in the U.K. were among the best in the world, including such well-known names as H. A. Bethe, N. Marcuvitz, E. M. Purcell, and J. Schwinger. Some of their work at this time is still unsurpassed, particularly in the area of field theory. The chapter on the theory of microwave filters in [2] is superb, and remains one of the clearest introductions to the topic to this day. Network theory was probably the most advanced topic in engineering at that time, S. Darlington having published his famous cascade synthesis theory as far back as 1939 [3]. Fano and Lawson [2] succeeded in writing a very clear and concise summary of Darlington's theory.

Chapter 10 of [2] on the design of microwave filters contains some surprisingly modern designs, e.g., describing filters with finite frequency attenuation poles and dual-mode cavities. The section on the theory of direct-coupled cavities gave the solution to the narrow-band case, but is not easy to understand. However, it can be said that much of the work of later authors was concerned with deciphering some of the less clear aspects of Fano and Lawson [2], making their work comprehensible to the specialist filter designer, and enabling designs to be produced.

II. Direct-Coupled Cavity Filters

In the case of the direct-coupled filter, examples of which are shown in Fig. 1, the Fano and Lawson theory was based on a low-pass prototype, but the implementation was far from obvious, requiring a difficult synthesis procedure, and this in the days before computers were either available or had the required accuracy. The main problem was the lack of specific formulas for the low-pass prototype element values. Such formulas, at least for the important Chebyshev case, did not appear until several years later [4], [5]. A short time after, the first really comprehensive theory appeared, supplying the "missing parts" of the Fano and Lawson theory [6]. This paper also extended the range of applicability to much broader bandwidths, i.e., about 20 percent in terms of guide wavelength, and was exceptionally easy to apply by any engineering specialist, requiring only the solution of very simple specific equations.

One of us (RL) was working on multicavity waveguide filters when this paper appeared, and indeed had submitted a contribution to the Institution of Electrical Engineers, which appeared in the same year [7]. The purpose of this was to extend the existing narrow-band design theories, restricted then to Butterworth designs [8], to so-called "generalized" microwave filters, which could be designed to have Chebyshev-like characteristics. Design formulas were derived up to six cavities, and were based on analysis by transfer matrix multiplication. The first reaction of this author to the appearance of [6] was one of disbelief, because how could a symmetrical cascade of an even number of cavities give the predicted ripple at midband? Evidently, the mysteries of intercavity coupling by means

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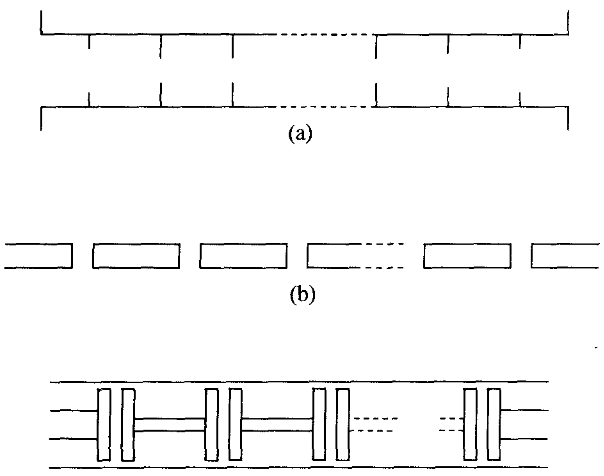

Fig. 1. Direct coupled resonator filters. (a) Waveguide. (b) Stripline. (c) Tubular.

of impedance inverters were not entirely elucidated at this time! Fortunately, this omission was remedied in due course [11], while practical application of [6] to (typically) 8-cavity filters clearly demonstrated its validity.

The direct-coupled cavity filter theory was one of the first great contributions from the group formed at Stanford Research Institute, among whose workers was Leo Young. He became interested in extending the bandwidth of direct-coupled filters beyond 20 percent, and succeeded in doing so by using a *distributed* rather than a lumped-element prototype filter. Naturally, a distributed prototype could be expected to match the broad-band characteristics of a filter better than a lumped-element one. The distributed prototype used was the multisection low-pass filter or quarter-wave multisection transformer (these two prototypes are closely related, and give identical results). The series or shunt reactances of the bandpass filter were matched to those of the prototype at the midband or "synchronous" frequency, and the response of the filter compared with that of the prototype [9]. There were significant differences which could be predicted in advance using correction factors which were plotted in the paper. The distributed prototypes were derived using an exact synthesis technique published in 1957 [10].

This theory did not seem to represent a final answer because of the amount of theoretical empiricism involved. Then, in 1966, a connection between the Cohn [6] and Young [9] papers was established, leading to a design which is quite direct in its application [11]. Given the desired parameters of the filter, i.e., number of cavities, ripple level, and band edges, a simple formula is used to derive the correct distributed prototype. This may be synthesized exactly using standard commensurate-line synthesis techniques, and the element values of the filter derived. A simple analysis is then used to determine the stopband attenuation properties of the filter. The theory is good to bandwidths of about one octave in terms of guide wavelength.

In this sense, the theory was not completely satisfactory because it could not predict extremely broad-band filters, where, in the case of inductively coupled waveguide structures, the upper stopband practically disappears, and a high-pass filter results. This is an example of a mixed-lumped and distributed structure, the subject of much work on the part of circuit theorists from the mid-1960's until quite recently, when apparently they gave up. No less an expert than Herbert Carlin was forecasting this outcome many years ago. Microwave people knew that the exact solution of such a problem is hardly likely, and have concentrated on developing approximations which have become more and more exact. Such an approximation was developed in the late 1960's which solved the very broad-band filter problem to all intents and purposes [12].

III. P. I. Richards and Distributed Circuit Theory

It would be interesting to describe the latter theory, but we have bypassed a major development of 1948 upon which it was based. Modern distributed-circuit theory may be considered to have begun when Paul I. Richards published his comprehensive theory of commensurate line circuits [13]. This established a simple relationship between lumped and distributed circuits, which enabled the entire well-developed lumped theory to be applied to distributed circuits using a simple transformation

$$\omega \rightarrow \tan(k\omega). \qquad (1)$$

In other words, an inductor of reactance ωL would become a short-circuited stub of reactance $L\tan(k\omega)$, with a similar result for capacitors. For the transformation to apply, all line lengths in the distributed circuit would have to be of electrical length $k\omega$, with lengths of $nk\omega$ also allowable (n: integer), a so-called commensurate network. However, the most significant result was the appearance of a new distributed-circuit element having no counterpart in lumped-element theory. This is the length of transmission line, which Richards showed could be extracted at any stage of a cascade synthesis, leaving a remainder guaranteed to be realizable. Indeed, it was possible to form commensurate networks consisting entirely of unit elements, terminated in resistors. A typical example of this would be the multisection quarter-wave transformer [10].

Personal Remarks by S. B. C.

"I joined the Radio Research Laboratory at Harvard immediately after graduating from Yale with a bachelor's degree in electrical engineering, but with negligible knowledge of transmission lines, filters, and waveguides. On my first day at RRL, I was handed the Mason and Sykes *BSTJ* article [1] and was directed to learn how to design coaxial-line filters.

"At this point I want to digress by mentioning Paul I. Richards. Although Richards' theorems have served as the basis of rigorous TEM-line circuit synthesis for about 35 years, very few microwave engineers know anything about him. Richards joined RRL in 1943 after dropping out of

Harvard at the end of his junior year. In 1944 and 1945, Richards and I shared the same office, both of us working on filters, but usually on different topics. I worked on such items as waveguide corrugated filters, ridge waveguide for very wide bandwidths, very broad-band coax to waveguide transitions, methods of improving the VSWR of image parameter filters, and methods of designing octave-tuning-range narrow-band coaxial resonator filters having almost constant bandwidth. Paul Richards extended the A, B, C, D matrix analysis method in a number of ways, including very general insertion-loss formulas. Also, he derived the image parameters of many kinds of TEM filter sections composed of equal line lengths, and in some cases of unequal lengths, but all integer factors of the same length. Although he did not talk about his hopes for synthesis then, this is evidently the time when his thoughts on that subject started. He began studying Darlington's paper on synthesis of L, C, R circuits [3], and talked about the importance of that work. At this point, the war ended, and he left RRL to reenter Harvard.

"Meanwhile, some months earlier, I needed help on aperture coupling between tunable coaxial resonators. Therefore, I rode the Mass Ave. streetcar to M.I.T. one day to visit the theoretical group at the Radiation Laboratory. I found it populated by very, very young men. After learning that Julian Schwinger (later a Nobel prize winner) worked at night and seldom was there during the day, I spoke to David Saxon (recent Chancellor of the seven University of California campuses). He directed me to Nathan Marcuvitz (author of the *Waveguide Handbook*, of course) who gave me several reports by H. A. Bethe (another Nobel Laureate, whose distinguished career intersected our microwave field for just a few weeks, leaving his aperture theory for our lasting benefit). Marcuvitz assured me that with Bethe's reports I could easily derive the formula I needed by myself. I doubted this, but left. Fortunately, Marcuvitz phoned me the next morning and gave me the formula after deriving it in minutes.

"On the subject of Paul Richards again, he saw no point in wasting time by returning to Harvard as a senior. The graduate school dean agreed, and accepted him directly as a graduate student. Two years later he received his Ph.D. degree without ever receiving a bachelor's degree. His dissertation covered the mathematically rigorous set of proofs and theorems for the synthesis of circuits containing commensurate lines and resistors to yield prescribed performance versus frequency (subject to necessary and sufficient realizability conditions that he specified). After publishing a small blizzard of papers in 1947 and 1948 on the mathematics and synthesis aspects of his Ph.D. thesis, he left microwave engineering for other fields of applied mathematics and physics. Since then, many other people have applied his theorems to achieve exact synthesis of numerous kinds of filters, directional couplers, matching transformers, etc.

"I last saw Richards in 1947, but while working on this article I decided to track him down to renew our acquaintance and learn about his subsequent career. I was shocked to learn that he died in 1979 while still in his fifties. I still see him as a young man, almost a boy, but intellectually highly mature. He once influenced me strongly by telling me that if you do something worthwhile you should publish it. I took his advice seriously, and tried to follow it for a long time afterward."

R. L. Writes as Follows

"Seymour called me to say that Paul Richards had worked in Massachusetts for his entire career, and that it would be easier for me to elucidate further details in my home state. From the 1979 edition of the IEEE Directory, I discovered that Paul Richards' last position was with Arcon Corporation in Waltham, where, according to Chief Scientist Dr. Norman Friedman, he had worked for about 11 years. Evidently, he had a brilliant career both as an engineer and as a physicist, and was well known for many fine contributions in the fields of physics and applied mathematics. His main work was in the hydrodynamics of fireballs, optimization methods (a solution of the "nesting" problem), and in physical optics. He also wrote a book on English Usage and a Handbook of Physics.

"Dr. Friedman referred me to Dr. Stanley Woolf, who had worked with Richards since 1964. Dr. Woolf told me that Richards had spent a year at Brookhaven National Laboratory with Goudschmitt before joining Tech. Ops. of Boston as a Corporate Fellow in 1947. They had both transferred to Arcon Corporation at the same time. Both Drs. Woolf and Friedman expressed the opinion that Richards was one of the most brilliant physicists that they had known. Dr. Woolf wrote an obituary for *Physics Today* in 1979."

Most of the work on distributed-circuit theory in the first few years following Richards' paper [13] was carried out in Japan. Among the most versatile and useful contributions was the set of transformations discovered by K. Kuroda, first published in 1955, in a Japanese thesis. Their first appearance in English appears to be in a remarkably advanced paper published in 1958 by Ozaki and Ishii [14]. The four basic Kuroda transformations are shown in Fig. 2. Here the lumped inductors and capacitors are actually symbols for short- or open-circuited stubs of length commensurate with the unit elements. These transformations enable unit elements of characteristic impedance equal to that of the load or generator to be introduced into a network in order to separate the stubs physically. This procedure is referred to as the introduction of degenerate unit elements into the network. Although still very useful, it is being superseded in many instances by a nondegenerate synthesis procedure which involves "contributing" unit elements, often a more efficient process which gives both improved performance and more convenient impedance levels.

IV. Compact Coaxial Bandpass Filters

The direct-coupled cavity filters of Fig. 1 have excessive length in coaxial or stripline form. This dimension was reduced by a factor of 2 with the introduction of parallel-

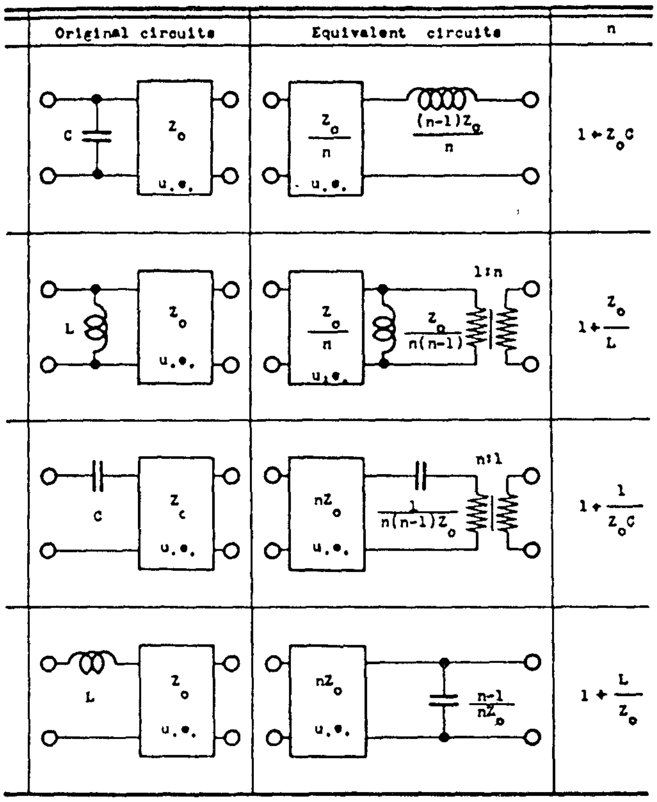

Fig. 2. Kuroda's transformations.

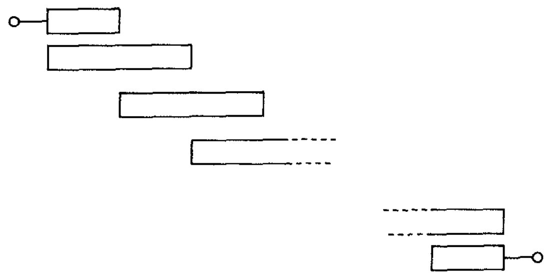

Fig. 3. Parallel-coupled line filter.

coupled lines [14], [15], as indicated in Fig. 3. Parallel coupling is much stronger than end coupling, so that realizable bandwidths could be much greater.

This advance was the precursor of the interdigital and combline filters developed by the extraordinary S.R.I. group. The prime mover here was George Matthaei, who published the theory and practical realizations of interdigital filters in 1962 [16] and the combline filter in the following year [17]. Schematics of these filters are shown in Figs. 4 and 5.

The interdigital filter theory was conceived from the parallel-coupled-line-type by imagining the resonators to be folded into two, forming parallel-coupled resonators which are short circuited at one end and open circuited at the other. The resulting equations were thought originally to be rather approximate, but later work based on an exact analysis of the interdigital structure showed that Matthaei's results are very accurate, holding to bandwidths as large as one octave.

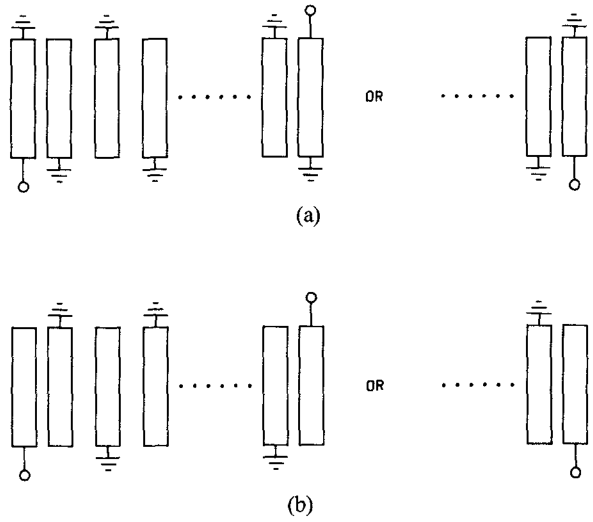

Fig. 4. Interdigital filter. (a) Short-circuited transformer coupling. (b) Open-circuited transformer coupling.

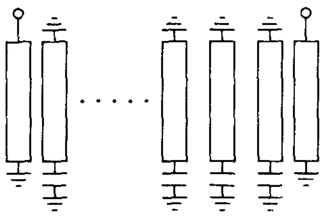

Fig. 5. Combline filter.

The exact analysis of the interdigital filter was really a giant step in the history of filter theory, and was taken by R. J. Wenzel in 1965 [18]. The result was quite unexpected in terms of its great simplicity. Commencing from a vast $n \times n$ admittance matrix and then applying the boundary conditions, one would hardly expect that the final two-port network bears a precise one-to-one relationship to the static capacitance matrix of a cross section through the interdigital structure! (See Fig. 6.) A similar result applies to combline structures where the coupled lines are shorted at the same end. The only difference is that the coupling between the parallel shorted stubs is by means of other shorted stubs in series, replacing the unit elements shown in Fig. 6.

Bob Wenzel was also instrumental in developing the very broad-band combline filter [19]. This 1971 paper is to be regarded as a classic, and is of lasting tutorial value.

V. Bandstop, Low-Pass, and High-Pass Filters

Turning to other types of filters, waveguide *bandstop filters* were described by Fano and Lawson [2, p. 704]. Apart from comparatively minor design improvements, they look basically the same today as in the 1940's. On the other hand, coaxial and TEM bandstop filters have undergone some useful developments as the result of the coupled-line circuits developed in Japan, and independently by the S.R.I. and Bendix (Horton and Wenzel) groups. References [20] and [21] show improvements given by

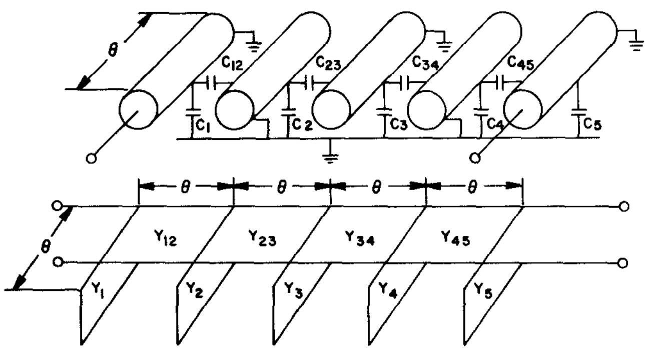

Fig. 6. Exact equivalent circuit of an interdigital filter. $Y_i = vC_i$, $Y_{ij} = vC_{ij}$, where v is the wave velocity.

parallel-line coupling in terms of compactness and in ease of realization.

Low-pass filters in both waveguide and coaxial form are very important components in microwave systems, being used to reject unwanted harmonics in both high- and low-power systems. A very good account of the early development is given in the classic volume of Matthaei, Young, and Jones [22, ch. 7]. Incidentally, the publication of this book was another milestone in the history of microwave filters. Although many of the theories and techniques are somewhat dated, it contains a large amount of valuable reference material, which more than justified a recent reprinting. However, the theory of both semi-lumped coaxial filters and waveguide corrugated low-pass filters has undergone major improvements since 1964. The invention of distributed low-pass filters took place before World War II, and the design techniques described in [22] are of that vintage, with some detailed improvements. These are tedious to apply, and can give poor performance, especially close to the cutoff frequency. Empirical design techniques of this nature have been (or should be) discarded in favor of the "almost exact" synthesis techniques for mixed-lumped and distributed structures alluded to earlier in Section II.

Here, it is appropriate to mention the Leeds group, formed at the University of Leeds, England, in 1963 by Peter Clarricoats. He was soon joined by J. O. Scanlan and R. Levy, and with graduate research students, including J. D. Rhodes, T. E. Rozzi, L. Lind, and I. Whiteley, a very productive period ensued in the history of distributed network theory. (Several other research students whose names are not mentioned made significant contributions in other microwave areas.)

One of the first developments arising from this group was a precise design for coaxial low-pass filters [23]. Based on the multisection commensurate low-pass prototype [24], the fringing capacitances at the junction of the high- and low-impedance sections were compensated exactly at the cutoff frequency of the filter, and low-pass filters having a VSWR <1.05 were demonstrated, both in theory and in practice. However, it is not generally realized that this technique was later made obsolete by the mixed-lumped and distributed method [26], [27], which has superior skirt attenuation and a wider stopband. The key to the mixed-

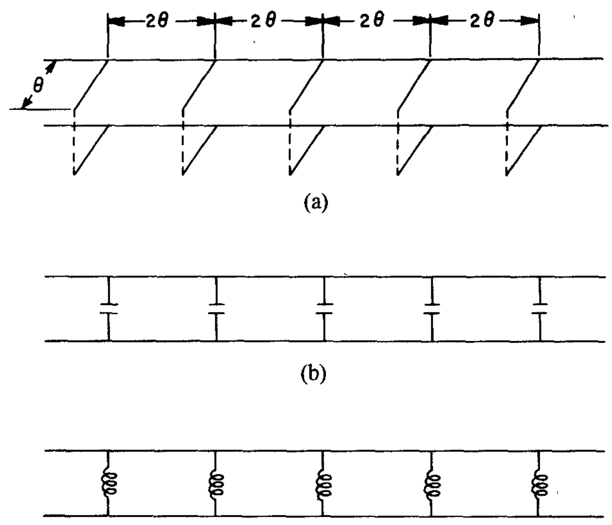

Fig. 7. (a) Distributed prototype filter, (b) converted to a mixed lumped and distributed low-pass filter, or (c) to a high-pass filter.

element theory was discovered during a train ride from London to Leeds in January 1966, although the discoverer was not aware of the fact until a few years later. Initially, the idea was used for the exact synthesis of branch-guide couplers. This required synthesis of a network consisting of a cascade of stubs of length θ separated by unit elements of length 2θ, as shown in Fig. 7. It was necessary for the filter network to be matched over some broad passband when the stubs were changed from open to short circuits. It was recognized that the double-length unit element had the property of being invariant (apart from an unimportant phase change) to the low- to high-pass transformation

$$S \to 1/S \tag{2}$$

where S is the Richards' variable as in (1), i.e.,

$$S = j \tan k\omega. \tag{3}$$

Thus, if the filter in Fig. 7 is a low-pass filter having a passband from electrical lengths 0° through 60° when the stubs are open circuited, it becomes a high-pass filter with a passband extending up from 30° when the stubs are short circuited, and the filters are each matched in a common band extending from 30° to 60°. Hence, followed the design of a branch-guide coupler, where the two filter conditions represented the even and odd modes of the four-port network.

The problem of how to synthesize the filter of Fig. 7 with double length unit elements of uniform impedance was quickly solved. The work of Riblet [25] and others (particularly that of Herbert Carlin and co-workers at the Polytechnic Institute of Brooklyn in numerous internal reports and published papers) had established the fact that the circuit of Fig. 7 could be reduced to a cascade of $2n$ unit elements plus a *single* stub. Actually, it was possible to synthesize the known insertion-loss function in an infinite number of ways, with stubs distributed arbitrarily between the $(2n+1)$ junctions. It was realized that one unique circuit consisted of $(n+1)$ stubs separated by n

double length stubs of uniform impedance. This was achieved by "partial extraction" of a stub of impedance such that two unit elements could then be extracted successively of equal impedance.

It was not until 1969 that the realization came that this low-pass structure could be converted to a mixed-lumped and distributed filter by replacing the shunt open-circuited stubs by lumped capacitors [12]. Since the distributed stubs are of half the length of the unit elements, the filter remains extremely well matched in the low-pass region when the substitution is carried out. The only other problem was how to realize the structure in either waveguide or coaxial form, using thick irises or discs having fringing capacitance, while taking mutual interactions between neighboring capacitors into account. This problem was solved in a very general way [26], and, as with the previous technique [23], gave a perfect result at the cutoff frequency, yet deteriorating negligibly from the ideal in the low-pass region. Now, however, the method had improved convergence, and gave much more compact designs with far superior stopband performance. An example of a coaxial low-pass filter is given in [26], and the synthesis of waveguide low-pass filters having the same highly predictable characteristics in [27]. The waveguide versions could eliminate the impedance transformers required in the old designs given in the "big black book" [22], and, hence, the filters could be designed in as little as one-third of the length. This is because the impedance tapering is incorporated into the filter itself.

The designs given in [27] describe how the waveguide narrow dimension is stepped to give a desired low average impedance in the main central region of the filter. In later unpublished work, the broad dimension has been stepped also, giving a structure which is relatively free from spurious transmissions in the stopband. This requires no new theory apart from a model of the step discontinuities, since the general theory of [26] remains valid. Hence, the synthesis of mixed-lumped, distributed, and *inhomogeneous* low-pass filters has been accomplished.

The theory of these networks makes extensive use of an unusual class of equi-ripple functions, the history of which dates back to the 19th century [28], [29]. Achieser-Zolotarev functions (let us abbreviate this to A-Z functions) are classes of symmetrical rational functions which are equiripple for values of x in the regions $-1, -\lambda$ and $\lambda, 1$ (Fig. 8). They may have poles located where $|x|>1$, and degenerate to Chebyshev rational functions for certain values of the parameter λ. In the general case, however, the first ripple near the origin is larger than any of the others.

R. L. Writes as Follows

"The existence of the A-Z functions was brought to my attention by Henry Riblet, who presented me with a copy of an obscure 1928 survey paper (in German) of N. I. Achieser. Knowledge of the existence of this was due to Dr. Riblet's continued interest in mathematical publications, but when he walked into my office with a copy of the paper in 1969 I don't think he was aware of its many

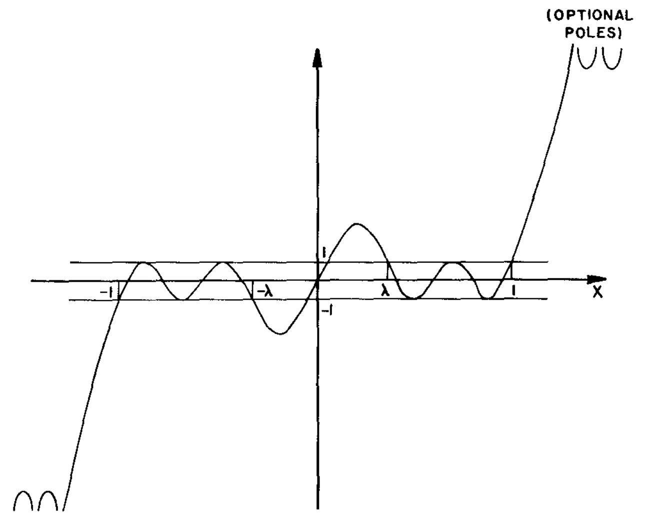

Fig. 8. Achieser-Zolotarev functions.

applications in our field, any more than I was at that time. I was able to work out the rational functions from the elliptic function representation of the A-Z functions, and synthesized a variety of both lumped and distributed networks having the peculiar A-Z response. It was immediately evident that the impedance levels within the networks were very sensitive to small changes in the amplitude of the first ripple. Actually, this was suspected in advance by reason of previous observations, otherwise I doubt whether I would have possessed the incentive to complete the complicated mathematical work. In addition to filter theory, the main application of A-Z functions has been to overcome the problem of difficult impedance levels in branch-line couplers."

An alternative to these types of analytical methods is to use computer-aided design by iterative processes. There have been many papers on this approach [30], [31], from which it is evident that the most important general rule is to commence from a prototype or approximately synthesized design which is as close as possible to the desired final result.

There remains only high-pass filters to be described in this section, but they are less important economically, and tend to be designed as very broad-band high-pass filters, e.g., as described in [11] and [12]. Commensurate-line versions are obviously possible, and are described, for example, in [21]. The main interest in high-pass filters is as an essential component of diplexers, and further comments are deferred to Section X.

VI. Generalized Filter Designs Using Cross Coupling

In the previous sections, we have omitted reference to more complex and generalized filters, both to keep the description simple and to recognize the fact that most such developments took place after 1965 or so. But, actually, the recognition and indeed the implementation of many "advanced" ideas occurred much earlier. We have already mentioned descriptions of elliptic function filters by Fano

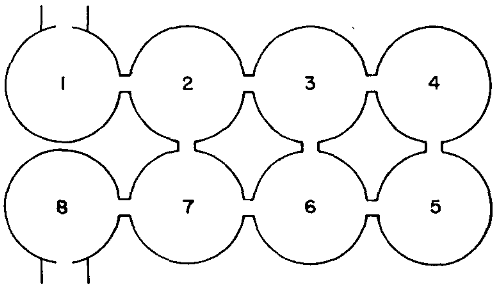

Fig. 9. Illustrating cross coupling between electrically nonadjacent cavities.

and Lawson [2], who described cascade realizations. These types of filters are coming into vogue once more, but historically have been difficult to design. The favored method has utilized generalized filters having cross couplings between nonadjacent resonators (see Fig. 9). These cross couplings give a number of alternative paths which a signal may take between the input and output ports. The multipath effect causes transmission zeros to appear in the transfer function, which, depending on the phasing of the signals, may cause attenuation poles at finite frequencies or group delay flattening, or even both simultaneously. These types of filters are nonminimum phase filters since they have transmission zeros located in the right-half complex frequency plane.

The first description of such a multipath filter appears to be by J. R. Pierce in 1948 [32]. The structure described consisted of two short-circuited manifolds transversely coupled by means of cavity resonators at several points. He showed that it was possible to obtain a linear-phase passband characteristic. Since the equivalent circuit is a cascade of lattices, then any known transfer function could, in theory, be realized. The reason why the invention was not widely utilized at the time is due perhaps to its relative complexity, and to the fact that the cavities are located only in the transverse paths and not in the manifolds, so that it is probably difficult to obtain steep rejection characteristics. The paper is nevertheless quite remarkable, and even gives an approach to the design of contiguous manifold multiplexers, many years before their actual implementation!

A slightly later invention showing elliptic function bandpass filters using generalized coupling was patented by microwave filter pioneer Milton Dishal in 1951 [34]. Here, a quite "modern" approach is taken, and this patent surely invalidates many later patents which look all too similar! The main contribution from later workers consists of design theories, and descriptions of other types of coupling arrangements.

Meanwhile, similar developments were taking place in the field of mechanical filters. A patent by L. L. Burns filed in 1956 [35] is the exact mechanical analog of the Pierce transversal filter [32], and describes filters with elliptic function characteristics having flattened group delay in the passband! Other generalized mechanical filters similar in most respects to their electrical counterparts were developed by R. A. Johnson at Collins Radio Company in the 1960's [36]. Here, the most modern sophisticated network design theories were used, and it must be admitted that the mechanical filter people were years ahead of the microwave fraternity, where interest in the field appeared to lapse between 1956 and 1963.

An awakening came with the work of E. C. Johnson [37] and R. M. Kurzrok [38], [39] in 1963–1966. These papers describe cross couplings in filters consisting of three or four cavities, with the object of producing finite frequency attenuation poles, which they accomplished very successfully. It is interesting that both authors stressed the importance of having negative cross coupling to obtain these poles, stating that positive coupling deteriorates the skirt selectivity. The use of the latter type of coupling to obtain improved group delay was not indicated.

The impetus for synthesis of filters having equalized delay characteristics arose from satellite communications requirements of the late 1960's. Self-equalized filters are smaller and potentially superior to their externally equalized counterparts. One would expect that making use of extra degrees of freedom in a network (i.e., cross couplings) should lead to a more efficient structure.

A major step in the development of linear-phase filters was taken at the University of Leeds in 1966, when the European Office of Aerospace Research of the U.S. Air Force placed a contract entitled "Microwave Networks with Constant Delay." Some of the results were published in the following year [40]. The same issue of the IEEE TRANSACTIONS ON CIRCUIT THEORY contained a significant contribution by Abele [41], while both papers were built to some extent on a previous contribution by Carlin and Zysman [42]. This work was not directly applicable to practical microwave filter problems because it was not possible to control both amplitude and delay simultaneously.

A solution to the problem requires the analysis and synthesis of generalized filters, as indicated in Fig. 9. These networks are nonminimum-phase, and result in transfer functions having right-half plane transmission zeros. The first type of filter to be studied was the generalized interdigital filter, initially by C. L. Ren [43], who derived equivalent circuits in the form of networks connected in parallel. A much more comprehensive study was carried out by Rhodes [44], who formulated the type of transfer functions which could be realized by the generalized interdigital network. By carrying out a variety of matrix operations (scaling and rotations) which are invariant on the transfer function, it was shown that most of the cross couplings could be eliminated, and in particular a two-layer structure with coupling only between nearest neighbors would generally suffice.

A synthesis technique used to design the first linear-phase generalized interdigital filters was published in 1969 [45], and was the first in a series of such papers dealing with interdigital and waveguide realizations. The early theories have been made obsolete by later techniques which combine synthesis with computer-aided optimization, but it is

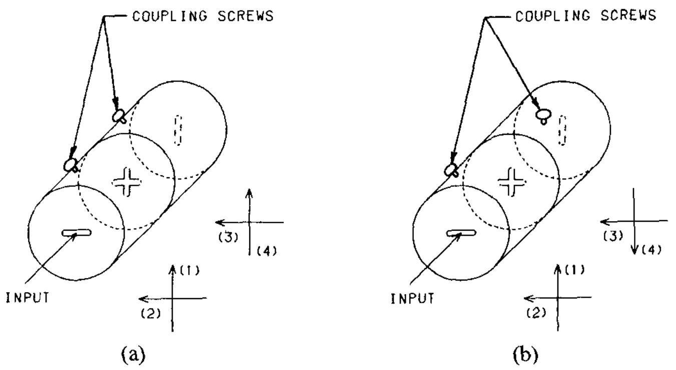

Fig. 10. Two-cavity four-resonator waveguide filter with (a) positive or (b) negative cross coupling.

worth mentioning the best of the early methods, which has a good deal of design flexibility [46]. Its disadvantage is that the stopband characteristics are very sensitive to tiny changes in the specified phase characteristics. The theory allows specification of an arbitrary phase characteristic, but the amplitude must then be determined by analysis, and is often unsatisfactory. Later workers, e.g., [47], [48], have found that the opposite procedure (specify amplitude and vary the phase) is much preferable.

The technique described in [47] is useful for generalized filters having just one extra cross coupling. This gives a filter with vastly improved delay characteristics, particularly over the central 50 percent of the passband, but with little extra complexity (and, hence, cost) compared with a conventional minimum-phase filter.

Linear-phase combline filters were described in 1974 [49], and the problem of dispersion and its solution was discussed. This topic received a more thorough treatment by Wenzel in 1976 [48].

Significant new developments took place in the 1970's in laboratories concerned with satellite communications, particularly at COMSAT by Atia and Williams [50]–[52], and at Siemens, Munich, by Pfitzenmaier and colleagues [53]. The COMSAT work on elliptic function and linear-phase waveguide filters using dual-mode cavities with cross couplings was particularly noteworthy and significant. The combination of high-Q factor, elliptic function response, delay equalization (when desired), and small size (due to the dual-mode cavities) has lead to the virtual standardization of these designs for satellite transponders. A schematic of a four-resonator filter consisting of two TE_{111} dual-mode cavities is shown in Fig. 10. It is seen that modes 1 and 4 may be coupled to each other either in-phase or out-of-phase using a suitable coupling screw arrangement.

VII. Filters Using Other Higher Order Modes

Prior to the introduction of filters using somewhat exotic higher order modes, the most commonly used waveguide modes were, of course, the TE_{101} rectangular and TE_{111} circular, which are dominant modes, and the TE_{011} low-loss circular electric mode. With the advent of 12–14-GHz satellite communications in the mid-1970's, it became necessary to use high-Q cavities. The TE_{011} mode gives very low loss, but it may be used only in single-mode cavities since it is circularly symmetric, and, hence, leads to rather bulky filters compared with dual-mode structures. A second disadvantage is that the Q of the cavity is reduced substantially when it is heavily loaded, a condition that occurs for surprisingly small relative bandwidths of the order of 0.2 percent or greater. This filter has the considerable advantage that it may be tuned over a wide frequency band, unlike the dual-mode filters. However, the disadvantages of using the TE_{011} mode stimulated investigation of several alternatives, as outlined by Griffin and Young [54]. These included the square cavity TE_{103} and TE_{105} modes, and the cylindrical TE_{113} mode. In dual-mode configuration, it was reported that the later mode represents the best choice, giving an unloaded Q of about 16000 at 12 GHz, yet having almost the smallest volume of any of the alternatives considered. Similar results were obtained independently by workers at Com Dev. Ltd. [55]. Another recent promising development from Com Dev. is a triple-mode elliptic function filter [56], which promises still further reductions in size and weight. Even further advances in this direction are available using dielectric resonator loaded cavity filters [57].

VIII. Dielectric Resonator Filters

The previous reference leads naturally to the examination of the history of dielectric resonator filters. Most of the early work was carried on in the early 1960's, as summarized in [58]. These filters consist of a number of coupled dielectric disks mounted in a waveguide beyond cutoff. In order to give important size reduction, a high dielectric constant must be used, but originally such dielectrics possessed excessive temperature sensitivity, e.g., 500×10^{-6} per °C, compared with 25×10^{-6} per °C for aluminum or 1×10^{-6} per °C for invar. Now this drawback has been overcome with the development of high-Q ceramics with temperature coefficients of expansion comparable to those of invar.

One of the first dielectrics having improved frequency stability was reported by workers at Raytheon [59]. Considerable improvements carried out at Bell Telephone Laboratories and Murata Manufacturing Company of Japan were reported at the Workshop on Filter Technology during the 1979 MTT-S International Microwave Symposium. Bell uses a barium titanate ceramic ($Ba_2Ti_9O_{20}$) having a relative permittivity of 40, and achieves resonator Q's of between 5000 and 10000 in the 2–7-GHz frequency range [60], [61]. Filters may be constructed in all the common transmission media ranging from waveguides to microstrip, and the technique is, therefore, quite versatile. Moreover, filters are now being produced in substantial quantities for Bell System Microwave links. Substantial size reductions have been made, particularly in the 3.7–4.2-GHz and 5.9–6.4-GHz waveguide bands, and the filters are stated to have low cost.

The Murata workers have used other dielectrics, such as $(ZrSn)TiO_4$ and $MgTiO_3$–(Ca La) TiO_3. At low microwave frequencies, temperature-stable filters and multiplexers have been built with such fine tolerances that tuning mechanisms are not required, even in production [62].

Mention has been made of dual-mode dielectric resonator loaded cavity filters [57], another indication of the considerable potential for reduction in size and weight of high-Q waveguide filters.

IX. Coaxial and Stripline Elliptic, Pseudo-Elliptic, and Miniature Filters

In Section VI, we traced the development of elliptic function and linear-phase filters using the principle of cross coupling between nonadjacent resonators. Now, we must return to outline the development of other types of elliptic function filters.

We have seen that although the synthesis of the lumped-element elliptic function filter dates back to 1939 [3], it was not applied directly to a cascade synthesis of microwave filters until the 1960's (cascade synthesis does not use cross coupling between nonadjacent resonators). One of the earliest procedures of Ozaki and Ishii [63] underlined the mathematical difficulties. In an attempt to overcome this, the Leeds group worked on a technique based on transforming lumped-element low-pass prototypes into distributed elliptic function filters, and derived several forms of low-pass, high-pass, bandstop, and bandpass filters [64]. The technique involved the introduction of redundant unit elements into the Richards-transformed lumped prototype, and was quite successful in many instances. However, other examples, particularly for bandpass filters, showed up problems in realizing the impedance levels. It is known now that these difficulties may be greatly alleviated by the use of *contributing* unit elements, so that the type of structures described in [64] are becoming feasible, e.g., [65].

Another way of overcoming the problem is to abandon the unit element in favor of other distributed cascade elements. Essentially, this was the approach taken by Horton and Wenzel [66] in the wide-band elliptic filter (Fig. 11) and in the narrow-band stepped digital elliptic filter of Rhodes [67] (Fig. 12). However, both of these filters are quite difficult to construct and tune. In fact, the narrow bandwidth design has been superseded by the conceptually similar combline elliptic filter [67], [68], which, although often difficult to construct, is comparatively easy to tune, since high-Q lumped capacitors may be used in the design (Fig. 13). The technique is useful when it is required to locate poles in a nonsymmetrical manner to obtain more general characteristics (see, e.g., [48]).

The use of printed-circuit technology to obtain miniature, and possibly low-cost filters, has been available for many years. Thus, stripline parallel-coupled line filters were described in the earliest papers on such developments. There is little difficulty in constructing broad-band filters in printed-circuit form, because the problem of low Q of this medium is not too serious (insertion loss being inversely proportional to bandwidth). The problem concerns narrow-band filters, and here dielectric resonator filters may come into their own. The other problem is the use of microstrip with substrates of high permittivity, e.g., 10.

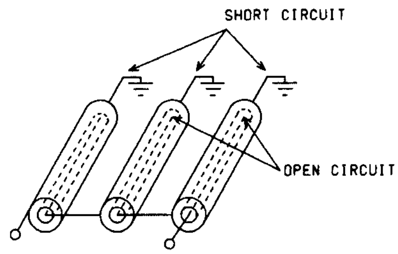

Fig. 11. Bandpass digital elliptic filter.

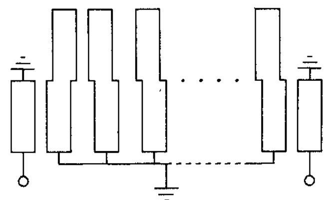

Fig. 12. Stepped digital elliptic filter.

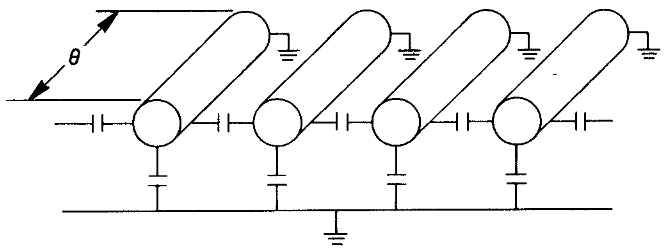

Fig. 13. Combline elliptic filter. $\theta < 60°$.

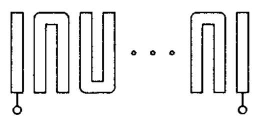

Fig. 14. Hairpin-line filter.

Inevitably, these have very poor Q, and even broad-band filters become quite lossy. Moreover, surface waves and non-TEM modes introduce spurious responses, and make achievement of high stopband rejection quite difficult. A useful discussion of these problems is given in the well-known paper by Cristal and Frankel [70], which introduced the hairpin-line filter shown in Fig. 14. This paper was a valuable addition to the art of printed-circuit filters, and an improved design procedure was given later by Gysel [71].

Difficulties encountered in inhomogeneous coupled line filters have been overcome very successfully by later workers. Thus, Easter and Merza [72] showed that addition of short uncoupled line sections at each port of a parallel-coupled line section equalizes the even- and odd-mode characteristics over a very broad frequency range, and demonstrated very good predictable microstrip filters. Another technique by Wenzel and Erlinger uses a computer-aided design approach, with accurate modeling of the inhomogeneous structure [73].

It seems, however, that the optimum solution to the problems of printed-circuit filter design is not only the use

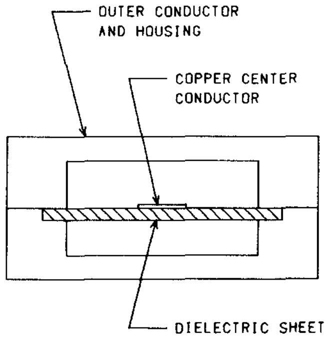

Fig. 15. Suspended substrate stripline.

of dielectric resonators but also the adoption of suspended substrate stripline (SSS) as shown in Fig. 15. The substrate dielectric material may be quite thin, so that the electromagnetic field is mainly in the air region. Hence, the unloaded Q may approach that of air–dielectric stripline, while the advantages of printed construction are retained. An account of the development of many different types of filters in this medium has been given by Rooney and Underkofler [74]. Unlike microstrip, a wide range of impedance values is achievable in SSS, while the filters may be easily integrated with other components, such as switches, mixers, and amplifiers. An intriguing idea is the use of the clamped circuit board itself to form a gasket-tight EMI and moisture seal. Grounding, higher order mode suppression, and isolation are accomplished by use of plated-through holes. It is reported that isolations of greater than 80 dB are realized. Filters with center frequencies as high as 34 GHz have been fabricated with reasonable Q of about 200, adequate for broad-band filters. The superiority of this medium compared with microstrip is evident from this result, since scarcely higher Q values are reported at 3 GHz in that medium!

Recently, SSS has been applied to the design of multi-octave bandwidth multiplexers [75], [76], which is the topic of the next section.

X. Multiplexers

Multiplexing provides a means of sub-dividing a wide frequency band into a number of narrower bands, or, reciprocally, of combining frequency bands at a common port. They are of two types: contiguous and noncontiguous. In a noncontiguous multiplexer, the passbands are separated in frequency, whereas in the contiguous type, the passbands are adjacent, with no intervening guard bands. If a contiguous multiplexer is of the substantially lossless type making use of complementary filters, the insertion loss at the crossover frequencies must be a minimum of 3 dB, the power being split equally between adjacent channels at this frequency. In common with many other filter developments, the first description of multiplexers was given by Fano and Lawson [2], while J. R. Pierce described an approach for contiguous designs in 1948 [32], [33]. These papers discuss multiplexing of the modern sophisticated type, and do not invoke the use of circulator or hybrid-coupled filters. This statement is not intended to denigrate the latter techniques, which are still of great importance (especially in communications systems, millimeter-wave multiplexing, and high-power multiplexing) but rather to emphasize the advanced thinking of the early workers. The simpler techniques will not be discussed further here, since they involve sub-assemblies of conventional filters and other components.

The art of multiplexing consists of combining several filters in such a way that undesirable mutual interactions are eliminated. Additionally, in most applications, the overall size of the assembly must be minimized.

One of the earliest multiplexing techniques used directional filters, which are four-port devices combining the properties of a filter and a hybrid. A good summary of coaxial and waveguide directional filters, which were invented in the 1950's (this early work being due to Seymour Cohn and Frank Coale) is given in [22, chs. 14, 16]. The technique is no longer popular, some of the difficulties associated with it being mentioned in the reference. It is difficult to use modern filter techniques in the directional mode. Hence, workers turned their attention to combining nondirectional filters.

After this intermediate development, the next major advance was made by the S.R.I. group, with most of the work being due to Cristal and Matthaei [77], [78]. Here, filters were connected in series or parallel, and the mismatched immittance compensated by means of an additional network at the common junction. An alternative procedure is to eliminate the first resonator of each standardly designed filter, which also has the effect of canceling the junction susceptances, while causing the real part of the immittances to add to near unity on a normalized basis.

Although techniques such as immittance compensation are still used occasionally, they are being or have been replaced by more precise and certainly more canonic (i.e., efficient and nonredundant) synthesis methods, in which the constituent filters are specifically designed to match when multiplexed. In the case of a diplexer, the two filters are termed *complementary*, since each compensates the other, providing a good match over their combined passbands. The first person to point out that filters complement one another if designed on a singly terminated (rather than doubly terminated) basis was R. J. Wenzel [21], [79], who obtained his basic information from the well-known book by Guillemin on circuit theory [80]. However, this concept was new for microwave engineers at that time, the existing basic circuit theory being written in a somewhat formalized and obscure form. Bob Wenzel had attended Professor Guillemin's lectures at M.I.T. in 1961–1962, and consequently was very familiar with this work! His initial papers were soon followed by others giving designs for broad-band [81] and narrow-band [82] situations.

Meanwhile, very important work on multichannel multiplexers, particularly for multi-octave band applications, was being carried out by Harold Schumacher at Microphase Corporation [83]. The same issue of *Microwave Systems News* contains an interesting article on other current multiplexer developments [84].

A second and completely different approach to the multi-octave contiguous multiplexer problem was taken by P. LaTourrette [85], [86]. Based on the very broad-band combline filter theory pioneered by Bob Wenzel [19], he discussed practical means for multiplexing these miniature filters, and in later developments included finite frequency attenuation poles to steepen rejection characteristics [87].

Returning to basic multiplexer theory, more recent work has shown that contiguous as well as noncontiguous multiplexers may be designed by modifying the first few elements (i.e., those closest to the common junction) of standard doubly terminated filters. The impetus for this work seems to have derived from an experimental discovery by E. J. Curley of Microwave Development Laboratories, probably around 1968. While tuning a noncontiguous diplexer consisting of two interdigital filters having a common transformer, he noticed that the first resonator of the lower frequency filter should be tuned to a lower frequency than normal, and vice versa. Computer simulation showed that this was indeed the case in theory, and was a viable alternative to an additional immittance compensation network. Later, this idea was both formalized and extended by J. D. Rhodes [88], who had worked with E. J. Curley and R. Levy during the late 1960's. An extension to the general multichannel case was published in 1979 [89]. Of even greater interest, however, is the companion paper [90], which gives the general solution for the design of manifold multiplexers. The lengths of transmission line which separate the filters along the manifold are used as additional immittance compensation networks, resulting in a considerable improvement over the simpler directly connected case [91]. The theory works well for both contiguous and noncontiguous, narrow- to medium-band waveguide or coaxial multiplexers, and has given excellent results for such complicated cases as a 10-channel contiguous manifold multiplexer. More recently, other workers have achieved comparable results using computer-aided design techniques, which, however, provide less insight into the design process.

One of the most recent advances is in the area of multi-octave band contiguous multiplexers constructed in suspended substrate stripline [75], [76] rather than solid coaxial line [83]. Here is a third multi-octave multiplexer technique, competitive with those discussed earlier in this section, and features cascaded diplexers consisting of pseudo-elliptic low- and high-pass filters. The pseudo-elliptic filter is one having its finite frequency attenuation poles at a single frequency (just outside the edge of the passband) rather than distributed freely throughout the stopband. This has the advantage of leading to a more manageable range of impedance levels in the filters. The most interesting development reported in [75], [76] is the inhomogeneous high-pass filter, a complex and fascinating component for those with an interest in advanced filter theory. It is interesting to observe that Lamar Allen had pointed out some of the peculiar and intriguing properties of inhomogeneous coupled line sections some years earlier [91].

The main advantage claimed for printed-circuit filters and multiplexers is in cost, achieved by having fewer machined parts, less assembly time, and simpler tuning. Disadvantages include higher insertion loss and lower power handling capability compared with solid coaxial construction. From an academic point of view, it is unfortunate that commercial considerations inhibit immediate publication of the advances which have been made in overcoming such disadvantages!

XI. Some Closing Remarks

This is an historical paper and as such we have tried to concentrate on early work in the field. However, in attempting to place these developments in historical perspective, it has been necessary to refer to much recent work. In this sense, the paper may resemble a review paper, but this has not been the intention. Therefore, we are not including such comparatively recent topics as, for example, millimeter-wave filters, involving finline and other techniques. These developments should be left for a sequel by some future historian(s) who will no doubt possess the hindsight necessary to place them in proper perspective. Inclusion of many other topics would have caused this paper to become even longer than the original guideline, which it has far exceeded, as well as trying the endurance and patience of its authors, who are located apart by a distance of 2650 miles!

Finally, one can only repeat here the plaintive statement by one of us in a previous publication that a good deal of excellent work by many workers has not been mentioned here, if only for reasons of perspective or mere abbreviation. Another reason is the fact that much of it remains unpublished for proprietary or security considerations.

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