Transitional Combline/Evanescent-Mode Microwave Filters

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***Abstract*— Traditional combline-filter theory based on TEM-mode coupling results in bandwidths which are too large—the increase being a function of the ground-plane spacing to wavelength ratio b/λ. As the b/λ ratio increases from 0.05 to 0.35, the bandwidth ratio (BWR), defined as actual bandwidth/TEM bandwidth, increases from unity to over 2:1. This bandwidth increase has now been confirmed by calculation of the coupling coefficient between combline resonators using mode matching. Accompanying the increased bandwidth is a considerable increase in the unloaded Q in accordance with the higher Q of the evanescent waveguide modes. A similar study carried out in the case of interdigital filters shows that these effects are much less significant.**

***Index Terms*—Bandpass filters, coaxial filters, combline filters, microwave filters, mode matching.**

I. Introduction

A SCHEMATIC of a combline filter is shown in Fig. 1. A large number of filter designs with the ground-plane spacing b made less than 0.08λ, where λ is the wavelength at midband, has established the validity of normal combline theory [1]–[4]. The unloaded Q of a combline resonator is given by

$$Q = Kb\sqrt{f} \tag{1}$$

where K is a constant approximately equal to 1600 for practical silver-plated filters, b having units of inches, and f of gigahertz.

However, another large group of filters has been made having b/λ ratios between 0.08 and 0.3, resulting in bandwidths up to 2.8 times that given by TEM theory [3], [4]. The bandwidth ratio (BWR) is defined as

$$\text{BWR} = \text{Measured bandwidth/TEM bandwidth} \tag{2}$$

and appears to be dependent on several factors, in particular varying with fractional bandwidth as well as the b/λ ratio.

The increase of unloaded Q with b/λ is equally dramatic, and has the effect of making the K in (1) no longer constant, but a function of the various parameters, and increases to over 2500 for $b/\lambda = 0.18$. This increase in K has obvious important economic implications, and implies that combline filters may be designed with much lower insertion loss than predicted by combline theory based on K experienced at small values of b.

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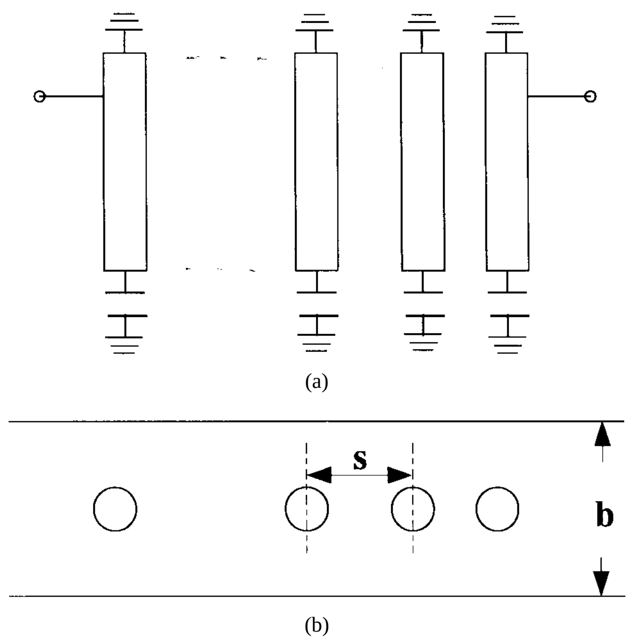


Fig. 1. Combline filter. (a) Pan view. (b) Cross section.

The discrepancy between normal TEM combline theory and practice has been known to many filter engineers since at least the early 1980's, but apparently has not been previously reported.[1]

It is interesting to observe that other workers attributed the bandwidth expansion to different factors, most commonly to TEM-mode coupling between nonadjacent resonators, which is almost certainly not the case. The effect of variable end loading of the resonators is an example of yet another explanation, which is discussed further in Section IV.

II. Combline versus Evanescent-Mode Theory

Evanescent-mode filters described in the literature have assumed that the input and output ports are terminated in waveguides, [5], but rather obviously this is not necessary, and coaxial terminations are equally likely to set up waveguide modes if the coaxial junction to the first resonator or transformer element acts as a coaxial-to-waveguide transition, which is usually the case. Actually, the one situation which

[1] For example, J. A. Duncan of Racal-MESL, Edinburgh, Scotland, described his discovery of the effect in 1984, in a recent private communication to one of the authors (R.L.), who coincidentally had discovered the effect at about the same time. Duncan had come to the independent conclusion that the cause was evanescent moding. It is also noteworthy that some commercially-available combline-filter design programs have incorporated empirical bandwidth correction factors to give good results (but others have not)!

inhibits the waveguide mode is the opposite-sided transformer having grounded ends on opposite sides, as described in [1], but such transformers are now rarely used, having been largely superseded by direct tap onto the end resonators or by same-sided transformers.[2]

There has been some controversy over the validity of the two theories with some proponents for the evanescent mode approach [5, p. 43] and others for the TEM combline theory [6]. However, it is interesting that the combline filter shown in [6, Fig. 1] was designed for a bandwidth of 4%, but measured approximately 6.2%, i.e., a BWR of approximately 1.55, which is far from good agreement with TEM combline theory.

It appears that the inter-resonator couplings in a general combline filter are due to evanescent waveguide modes, the TM_{11} and TE_{10} modes being dominant, and these are similar to TEM modes when b/λ is small. Hence, the filter may be regarded as a transitional combline/evanescent mode structure. Further discussion of this point is presented in Section IV.

On the other hand, it is worth noting that the interdigital filter of [6, Fig. 3] shows good agreement with TEM theory, which is precisely because, theoretically, such filters exhibit much less dramatic BWR increase than combline filters, as discussed further in Section VI. The alternating of the grounded ends in interdigital filters appears to suppress the evanescent-mode effects to a large extent.

Interdigital filters have normalized unloaded Q, defined in (1), given by $K = 2300$, which is higher than TEM combline filters of small ground-plane spacing ($b/\lambda < 0.08$) where $K = 1600$. The values quoted here are average approximations for practical silver-plated conductors. Above a certain ground-plane spacing corresponding to $b/\lambda = 0.15$, the evanescent mode Q enhancement results in combline filters having Q comparable to, or even higher than, the value for interdigital filters.

The deviation of TEM combline theory from experiment for large b/λ is not too surprising if one realizes that the standard methods for the calculation of self and mutual capacitances between rectangular [3] or circular [4] bars fail to consider higher order modes, unlike early work on the high-frequency dependence of coaxial line fringing capacitances [7]. On the other hand, simple extension of the theories would be expected to give some, but not a complete, improvement in filter prediction, since the BWR is dependent on other factors unrelated to the cross section through the filter.

An additional feature of the transitional filters concerns the out-of-band rejection, which in comparison with standard TEM theory is steeper on the low side and less steep on the high side of the passband. This effect may be predicted by a suitable mapping function such as given in [5, eq. (3.1)]. In physical terms, the filter behaves more like a TEM filter at low frequencies where b/λ is less, and the looser inter-resonator couplings necessary to give the correct bandwidth produces steeper rejection. On the high side, the coupling coefficients increase since b/λ becomes even larger, and the rejection is reduced.

Alternatively, the transitional filter may be regarded as intermediate between a TEM combline filter and a waveguide filter. The waveguide has much steeper low-side rejection, the inverse of the combline situation.

[2]However, opposite-sided transformers are often useful as common transformers in the design of combline duplexers.

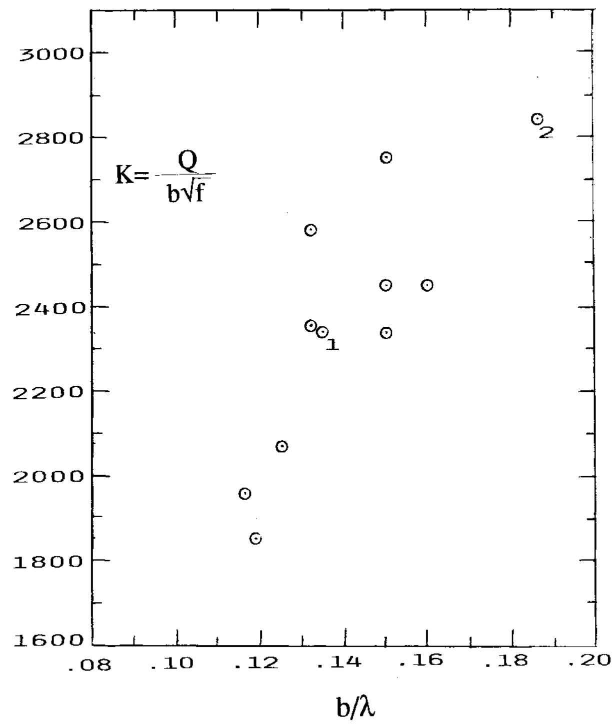


Fig. 2. Measured variation of normalized unloaded Q with b/λ (b: inches, f: gigahertz).

III. Experimental Results

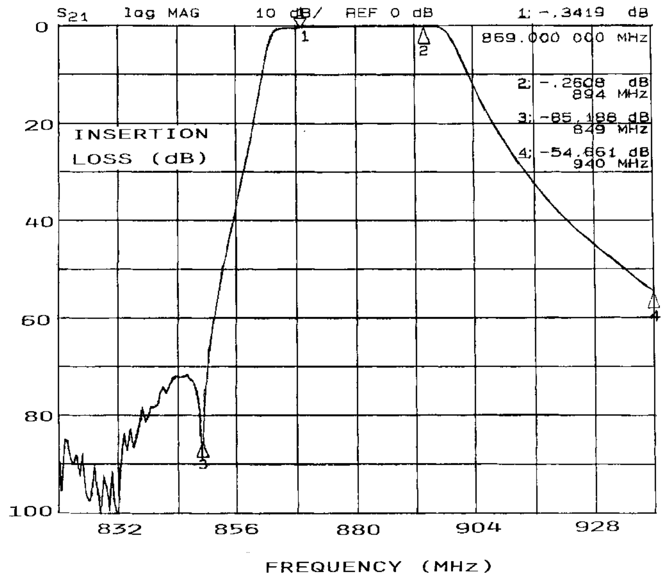
As stated earlier, the increase of BWR with increasing b/λ is a well-established fact, and the results are in reasonable agreement with the mode-matching predictions of Section IV.

The Q is difficult to calculate using the mode-matching program, and only measured results are presently available. Fig. 2 shows measured results of normalized Q for eleven transitional combline/evanescent mode filters having b/λ values ranging between 0.12 and 0.185. Practical Q is dependent on many factors, such as surface finish, quality of the plating, and possible contact problems, which are reasons for the spread in the K values, but the trend of increasing K with increasing b/λ is well established.

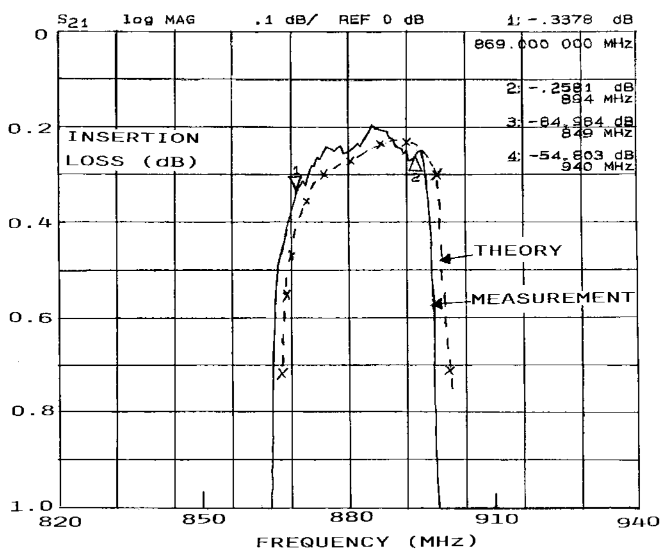
More detailed description of two of the results plotted in Fig. 2 are as follows.

A. Example 1: $b/\lambda = 0.1345$, $K = 2367$ (Point 1 of Fig. 2)

This is a six-section filter designed basically for the 869–894-MHz band having two cross couplings across nodes 1–3 and 4–6, forming a pair of cascaded trisection or CT sections. The designed equiripple bandwidth is 31 MHz centered at 881.5 MHz, and the rejection poles are both placed on the low side of the passband to give >70-dB rejection at 850 MHz. The measured insertion loss of the filters showing the detailed rejection characteristics is given in Fig. 3(a). The ground-plane spacing b is 1.8 in and the filter has decoupling irises with resonator spacings of 1.95 in. The insertion loss near midband is 0.25 dB and is in almost exact agreement with theory across the entire passband when the Q in the analysis portion of the synthesis program is set at 4000, as shown in Fig. 3(b). This corresponds to a K value of 2367. Note that

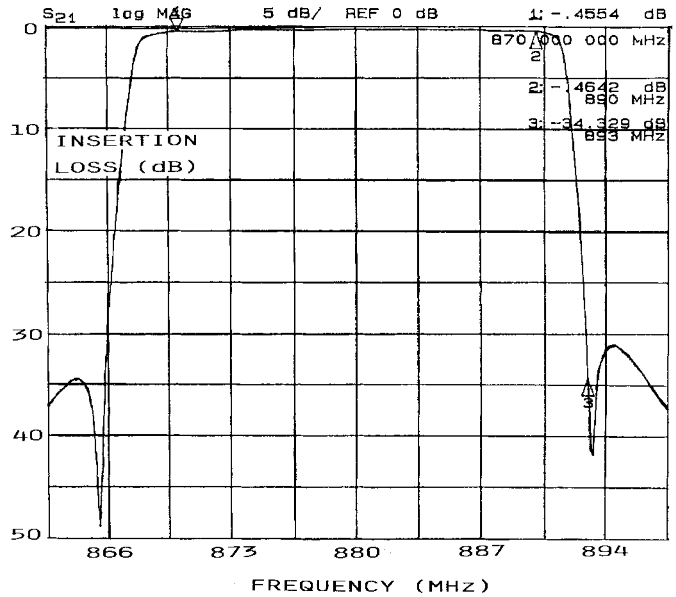


(a)

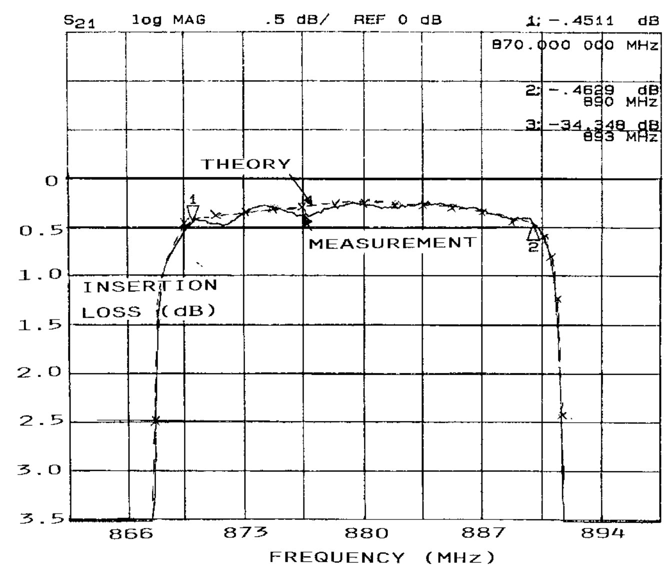


(b)

Fig. 3 Example one. (a) Rejection characteristic and (b) theoretical and measured passband insertion loss.



(a)



(b)

Fig. 4. Example two. (a) rejection characteristic and (b) theoretical and measured passband insertion loss.

the result is based on the total filter loss including connectors, and the Q of the resonators is probably slightly higher.

B. Example 2: $b/\lambda = 0.1864$, $K = 2824$ (Point 2 of Fig. 2)

This is an eight-section filter designed for the 870–890-MHz band having one 3–6 cross coupling (i.e., a cascaded quadruplet (CQ) section) to give >30 rejection at 865 and 893 MHz. The equiripple bandwidth for 25 dB return loss was 22.9 MHz, and the rejection poles were placed at 865.3 and 893.1 MHz, corresponding to a ratio of pole bandwidth to equiripple bandwidth of 1.21. The measured results are shown in Fig 4. The ground-plane spacing b was chosen to be 2.5 in and the resonator spacing is 2.75 in. The measured results for passband insertion loss are reproduced very well by assuming a Q of 6624, as shown by the comparison of Fig. 4(b). The K value is then derived as

$$K = Q/(b\sqrt{f}) = 6624/(2.5 \times \sqrt{0.88}) = 2824.$$

IV. Mode-Matching Results

In order to test the increase in coupling with the increase in ground-plane spacing dimension b, the coefficient of coupling between pairs of combline resonators was calculated using a mode-matching field theory program. The coupling coefficient was determined by calculation of the resonant frequencies for the cases of electric and magnetic walls along the symmetry plane, between the cavities as discussed in previous papers [8]. Values of b/λ varying between 0.04-0.35 were selected, and four values for the spacing s between the center lines of the resonators were chosen, given in relationship to b as $s/b =$ 0.80, 1, 1.27, and 1.50. In addition, the $s/b = 1$ case was calculated with a thin asymmetric iris having $w/b = 0.5913$, as shown in Fig. 5.

The results for the four noniris cases are shown in Fig. 6. The result for the asymmetric iris showed very little difference

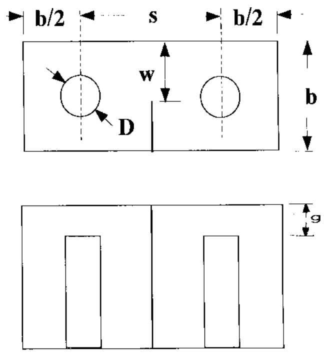


Fig. 5. Combline filter with thin asymmetric decoupling iris.

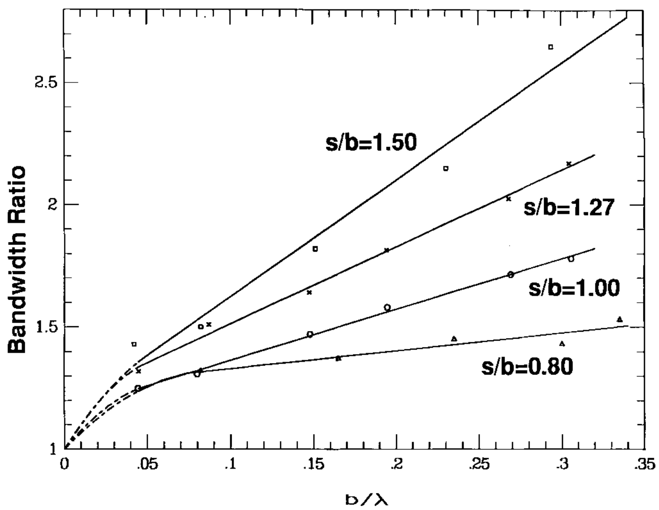


Fig. 6. BWR versus b/λ derived from mode-matching theory.

from the $s/b = 1$ case with no iris and is not plotted. It is seen that the observed BWR increase is theoretically confirmed. The slight deviations of the results from smooth curves is thought to be due to the effect of different end loadings of the resonators. This is due to the necessity to have differing end gaps to obtain the appropriate resonant frequency at the various b/λ values (see also, Section V).

The calculated coupling of the baseline TEM theory uses conventional combline theory [1] to design a two-section Butterworth filter. The g values are $g_1 = g_2 = 1.4142$, and the coupling coefficient between the resonators is

$$k_{12} = \frac{w}{\sqrt{g_1 g_2}} \tag{3}$$

where w is the fractional 3-dB bandwidth of the complete two-cavity filter.

The dimensions were obtained using the TEM theory, actually based on [9], [10], which gives results in close agreement with those of [4] for coupled bars without irises. The dimensions for the iris-decoupled filters were obtained using the general approach outlined in [9], [10].

Some physical understanding of the reason for the large variation in the BWR factor may be obtained by considering the waveguide field in the region between the resonators, specifically at the symmetry plane between a pair of identical resonators. Inspection of the amplitudes of the coefficients of the terms in the modal expansion has established that most of the energy is contained in the TM_{11} and TE_{10} modes.

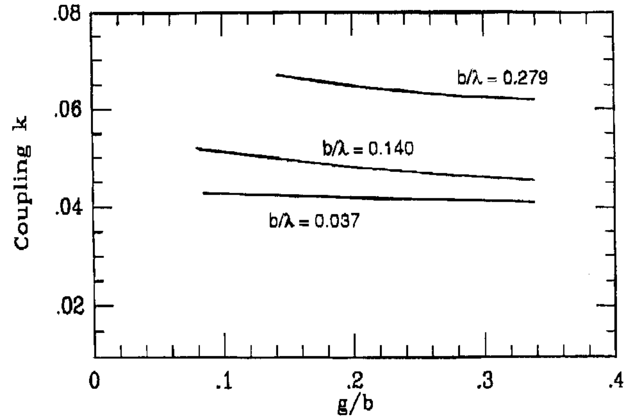


Fig. 7. Coupling-coefficient variation as a function of loading gaps with b/λ as a parameter. ($s/b = 1$, $d/b = 0.380$).

Note that there is no TEM mode, which can not exist in a waveguide. Inspection of the field pattern of the TM_{11} mode [11, Fig. 2.2] indicates that it most closely approximates the static field of the odd TEM mode since it has a strong electric field in the direction of propagation between the resonators. On the other hand, the TE_{10} mode has a component of the magnetic field in the direction of propagation and takes the place of the even mode of the TEM static-field theory.

The cutoff wavelength for the TE_{10} mode is given by

$$\lambda_{c10} = 2b. \tag{4}$$

Note that the broad dimension of the waveguide corresponds to the ground-plane spacing in accordance with the literature on waveguide evanescent-mode filters [5]. The cutoff wavelength of the TM_{11} mode is given by

$$\lambda_{c11} = \frac{2b}{\sqrt{1 + (b/a)^2}} \tag{5}$$

with a being the housing dimension in the axial direction of the resonator. Both cutoff wavelengths tend to zero as b tends to zero. Hence, as b increases, the waveguide modes become less attenuated and the inter-resonator coupling increases. Significantly, the amplitudes of the two waveguide modes on the symmetry plane are equal for small b, but deviate as b increases.

V. Effect of Varying the End Loading in Combline Resonators

There has been some suggestion that the bandwidth expansion may be due to the effect of the tuning arrangements and on the magnitude of the gap g between the open-circuited end of the resonator and the end wall [12]. This was investigated by using the mode-matching program to calculate the coupling coefficient between a pair of resonators with variable b/λ and g/b ratios. For a given b dimension, the end gap was varied between normalized values of $g/b = 0.1$ and $g/b = 0.35$. The resonance was kept tuned to the same frequency, corresponding to an electrical length of 60.4°, by adjusting the depth of a tuning plunger from the end wall, which is modeled within the program, as in [8].

The results are summarized in Fig. 7, which plots the coupling coefficient between a pair of resonators as a function of g/b with b/λ as a parameter. Clearly, the coupling coefficient

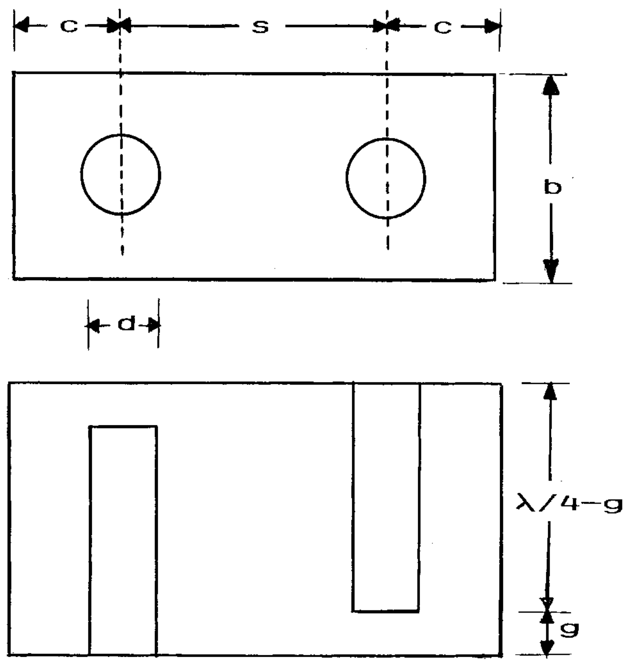


Fig. 8. Two-cavity interdigital filter analyzed using the mode-matching program.

is hardly affected by the end loading, whereas the coupling coefficient shows large increases with increasing b/λ.

VI. Interdigital Filters

As stated earlier, numerous results for interdigital filters have shown very close agreement with standard TEM theory. It is interesting to carry out a theoretical study, similar to that for combline filters, of the coupling between a pair of interdigital resonators in order to ascertain if this is supported by theory. To this end, several interdigital pairs of resonators were analyzed using the mode-matching program [8].

The configuration is shown in Fig. 8 and the dimensions are listed in Table I. They correspond to two-cavity Butterworth interdigital filters with resonance close to 1 GHz and inter-resonator coupling coefficient derived from standard TEM theory of 0.0636. In all five cases, we have $d/b = 0.396$ and $s/b = 1.0$. The distance between the end walls of the cavity (i.e., along the axis of the resonators) was made one quarter-wavelength at 1 GHz, and estimates of the end gaps g were made so that the end capacitance maintained resonance close to 1 GHz. In practice, using an approximate theory to calculate the gap, the resonance varied from 1.015 GHz at $b/\lambda = 0.04$ to 1.052 GHz at $b/\lambda = 0.3$.

The results from the mode-matching analysis are given in the last column of Table I, rounded to three decimal places. Evidently there is much less variation of coupling coefficient with variation in b/λ compared to the case of combline filters.

Practical results for interdigital filters with b/λ values as high as 0.3 have demonstrated a small bandwidth expansion factor of this order accompanied by a correspondingly slight improvement in normalized $Q/(b\sqrt{f})$.

VII. Design of Transitional Combline/Evanescent Mode Filters

It has been observed that the evanescent-mode coupling is considerably weaker for broader bandwidth combline filters, and this is confirmed by the results of Fig. 6 where the BWR is less for more closely spaced resonators. This is a complication in the design of the transitional filters since the end resonators are more strongly coupled than the central resonators, and the BWR factor will be lower for these. Ideally it will be useful to develop a complete mode theory for inter-resonator coupling, or perhaps a simple correction factor to the TEM theory may be found to enable filters to be designed.

However, the situation is quite manageable at present since it is possible to measure or otherwise determine the coupling coefficients between adjacent resonators, which are then set to the required values. A rapid design method is to use conventional TEM theory with a bandwidth correction factor, i.e., design for a smaller bandwidth. Since the bandwidth is determined by the central couplings and only the end couplings are somewhat tighter, this gives acceptable results and, in practice, the filters tune very well. It is usually necessary to include tuning screws between the resonators, and these are adequate to compensate both for imperfections in the theory and for tolerances. It has been observed that the couplings between the end pair of resonators do need to be tightened in practiced, as stated above.

The correct bandwidth may not be obtained in the initial design, but by using inter-resonator tuning and perhaps also in the case of narrower bandwidth filters using decoupling irises which are easily adjusted, the design can be changed to give the required bandwidth, usually without remanufacturing.

TABLE I
Parameters of Interdigital Filters Shown in Fig. 6

b/λ	b	d	s	c	g	k_{12}
0.04	0.472	0.187	0.517	0.236	0.137	0.063
0.08	0.944	0.374	1.034	0.472	0.274	0.063
0.15	1.770	0.701	1.939	0.885	0.514	0.063
0.20	2.360	0.936	2.585	1.180	0.684	0.063
0.30	3.540	1.402	3.877	1.770	1.027	0.069

VIII. Conclusions

The observed bandwidth expansion factor of combline filters having ground-plane spacings equal to a significant fraction of a wavelength in the range 0.08–0.35 has been confirmed using a mode-matching program. The bandwidth expansion factor is accompanied by an increase in the normalized Q, a fact which is demonstrated by measurements, but which has still to be theoretically confirmed. Design theories are sufficiently advanced so that the filters may be easily designed, including those having cross couplings between nonadjacent resonators.

It was also shown that interdigital filters demonstrate much less dramatic effects.

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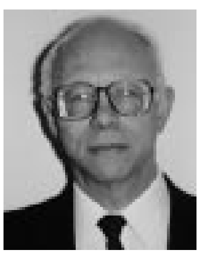

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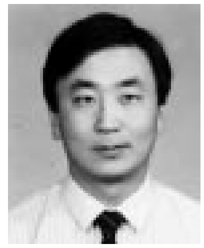

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