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 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, as expected from the higher Q of the evanescent waveguide modes.

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 $.08\lambda$, where λ is the wave length at mid band, has established the validity of normal combline theory [1]-[4]. The unloaded Q of the resonator is given by:

$$Q = K\, b\sqrt{f} \qquad (1)$$

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

However another large group of filters have 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]. This has been known for many years, but apparently has not been previously reported in the literature.

The bandwidth ratio BWR is defined as

$$\text{BWR} = \text{Measured bandwidth/TEM bandwidth} \qquad (2)$$

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

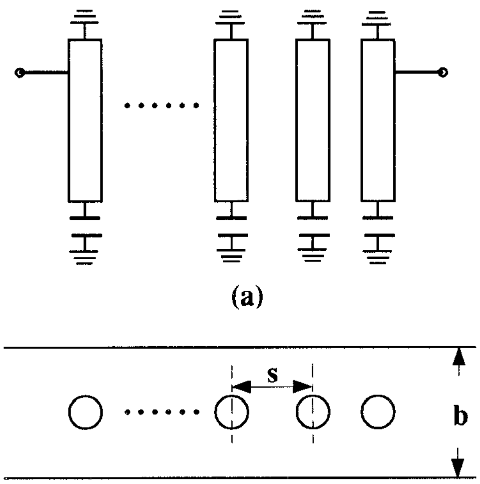

Fig. 1 Combline filter with (a) plane view and (b) cross section.

The increase of the 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 as much as 3500 for $b/\lambda = 0.2$. This increase in K has obvious important economic implications, and implies that combline filters may be designed with as little as half the insertion loss predicted by standard combline theory.

II. COMBLINE VS. EVANESCENT MODE THEORY

Evanescent mode filters described in the literature have assumed that the input and output ports are terminated in waveguides , e.g. [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

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as a coaxial-to- waveguide transition, which is usually the case. Actually the one situation which 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 superseded by direct tap onto the end resonators or by same-sided transformers.

There has been some controversy on the validity of the two theories with some proponents for the evanescent mode approach [5, p.43] and others for the combline theory [6]. However, it is interesting that the combline filter shown in [6, Fig. 1] indicates a BWR of approximately 1.6, 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 a combination of TEM and evanescent waveguide modes, and the filter may be regarded as a transitional combline/evanescent mode structure.

On the other hand it is noteworthy that the interdigital filter of [6, fig. 3] shows good agreement with TEM theory, which is precisely because such filters do not exhibit the BWR increase of combline filters. The alternating of the grounded ends in interdigital filters suppresses at least some of the waveguide modes. Interdigital filters have normalized unloaded Q, given by $K = 2300$, as defined in (1), which is higher than TEM combline filters where K equals 1600. The values quoted here are average approximations for practical silver plated conductors. Above a certain ground plane spacing, the evanescent mode Q enhancement results in combline filters having higher Q than interdigital filters, experimental results indicating a crossover value of b/λ of approximately 0.13.

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.

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 not calculated using the available mode matching program , and only measured results have been available at this time. The graph of Fig. 2 is a composite of measured results of normalized Q for several transitional combline/evanescent mode filters. Since practical Q is dependent on many factors, such as surface finish, quality of the plating, and contact problems, this is intended only to represent the general trend.

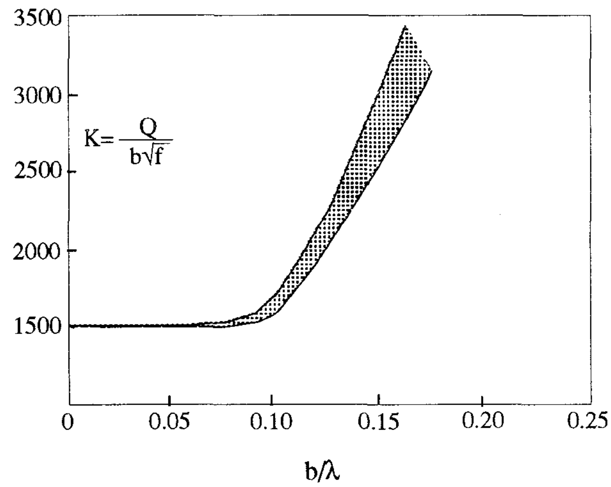

Fig. 2 Measured variation of unloaded Q with b/λ (b: inch; f: GHz).

One experimental observation which has yet to be explained theoretically is an apparent variation of the BWR with degree N of the filter. Thus a simple two-cavity filter appears to show little if any BWR increase above the TEM value. Initially this might appear to be in contradiction with the mode matching results of Section **IV** which are based on two resonators, but in this theory the boundary values are assumed to be that corresponding to those existing at the center of a multi-cavity filter, i.e. corresponding to a situation where the evanescent mode are established. It seems that in a two cavity filter with transformer or direct-tap couplings the coupling is largely TEM, and several cavities are required to establish the evanescent modes. This has been confirmed both by measurements of 2 and 3-cavity filters which show low value of BWR, and also by coupling coefficient measurements on high degree filters. Here probing into a pair of cavities to measure the coupling coefficient with other cavities shorted gives coupling coefficients in accordance with TEM theory which are much less than those present in the actual filter when the other resonators are present.

Obviously this represents a major difficulty if it is desired to tune the filter using measured inter-resonator couplings, and it is necessary to have rather accurate

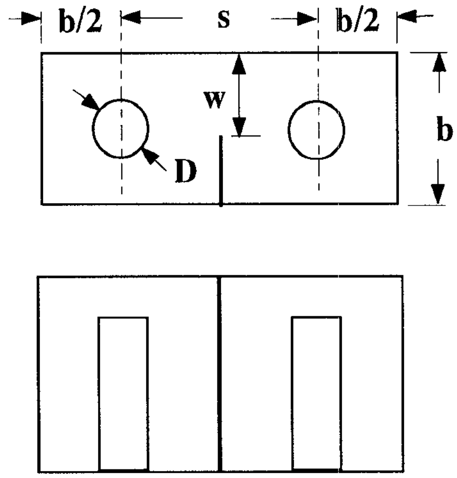

Fig. 3 Combline filter with thin asymmetric decoupling iris.

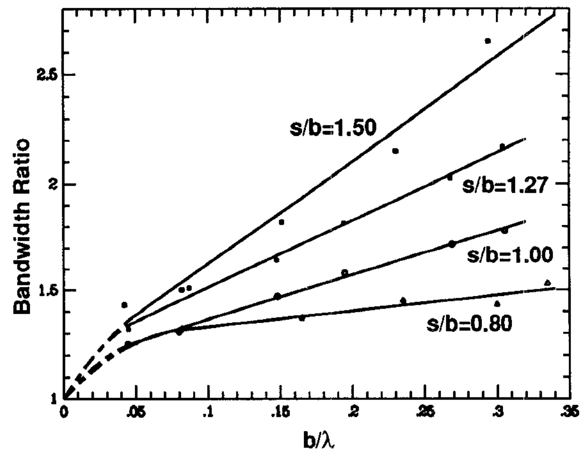

Fig. 4 Bandwidth ratio BWR vs. b/λ derived from mode matching theory.

design procedures in order to produce these filters without undue effort.

IV. MODE MATCHING RESULTS

In order to test the increase in coupling with 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 the 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, e.g. [8]. Values of b/λ varying between .04 and .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 $s/b = 0.80$, 1.00, 1.27, and 1.50. In addition the $s/b = 1$ case was calculated with a thin asymmetric iris having $w/b = .5913$ as shown in Fig. 3.

The results for the two non-iris cases are shown in Fig. 4. The results for the asymmetric iris showed very little difference from the $s/b = 1$ case and is not plotted. It is seen that the observed BWR increase is confirmed theoretically.

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 2-cavity filter.

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

V. 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. 4 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 has been found that the filters may be designed using 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

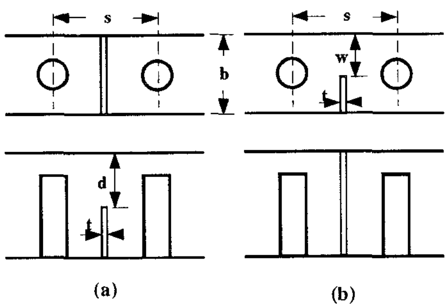

Fig. 5 (a) Decoupling iris with longitudinal dependence, and (b) decoupling iris with uniform longitudinal dependence.

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 practice, 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 re-manufacturing.

The form of the coupling iris appears to have a major effect, with irises which have a longitudinal dependence (Fig. 5(a)) tending to suppress the evanescent mode, whereas those having a uniform longitudinal cross section as in Fig. 5(b) have a minimal effect. The reason for this may be that the broad dimension of the waveguide corresponds to the ground plane spacing or b dimension. The irises of Fig. 5(a) correspond to inductive irises in the waveguide which have large susceptances. On the other hand the irises of Fig. 5(b) are capacitive susceptances of much smaller value, and therefore inhibit the evanescent mode much less.

As confirmation, a pair of filters made to the same electrical design, one with irises as shown in Fig. 5(a) and the other as shown in Fig. 5(b), demonstrated much higher Q for the (b) case in accordance with the Q-enhancement observed in the transitional filters.

An attempt was made to confirm the different effects of the two types of de-coupling irises using the mode matching program, but they each demonstrated similar theoretical BWR curves, so that more work on this aspect of the theory is required. The practical difference observed could possibly be due to the fact that the partial height irises inhibit the generation of the evanescent modes at the source end of the filter, and the assumed fields in the mode matching model are not present. It would seem that there are several possible combinations of TEM and evanescent modes which satisfy the boundary conditions, and the particular situation is dependent on the initial conditions at the source and load. This apparent discrepancy is similar to the situation of having only two coupled resonators as discussed in Section III.

VI. CONCLUSIONS

The observed bandwidth expansion factor of combline filters having ground plane spacings of a significant fraction of a wavelength in the range 0.08 - 0.35 has been confirmed using a mode matching program. There is still much research work required to confirm or refute other aspects of measured results on these transitional combline/evanescent mode filters, such as the large increase in normalized Q, the apparent variation with number of coupled resonators, and the variation with different types of de-coupling irises. However design theories are sufficiently advanced so that the filters may be easily designed, including those having cross couplings between non-adjacent resonators.

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