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Channel Expansion and Tolerance Analysis of Waveguide Manifold Multiplexers*

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***Abstract*—A computer aided optimization procedure is introduced to enable the addition of extra channels to an already existing waveguide manifold multiplexer, without changing any of the existing multiplexer elements. The process provides the important advantage of the ability to expand the number of channels as required, a property which was only feasible before for channel dropping type multiplexers. The process is illustrated by practical examples that show its validity. Analysis of the effect of mechanical tolerances on the multiplexer performance is also presented to provide guide lines for the tolerance ranges in manifold multiplexer fabrication.**

I. Introduction

Waveguide manifold multiplexers have been widely used in communication satellite applications requiring high quality, low loss, high power handling capability, small size and mass [1]-[6]. Their applications cover bands from *S* [7], Ku [8] to millimeter wave [9] frequencies. Due to the structure complexity, experimental adjustment and optimization of initial designs was always needed to obtain satisfactory performance [1]-[5]. Recently in reference [7], precise computer modeling techniques of waveguide T-junctions and filters have been developed to a degree that the design and construction are allowed to practically achieve the final desired response without any adjustments.

Manuscript received August 20, 1991; revised December 18, 1991. This work was supported in part by Diversified Communication Engineering, Inc., Austin, TX.
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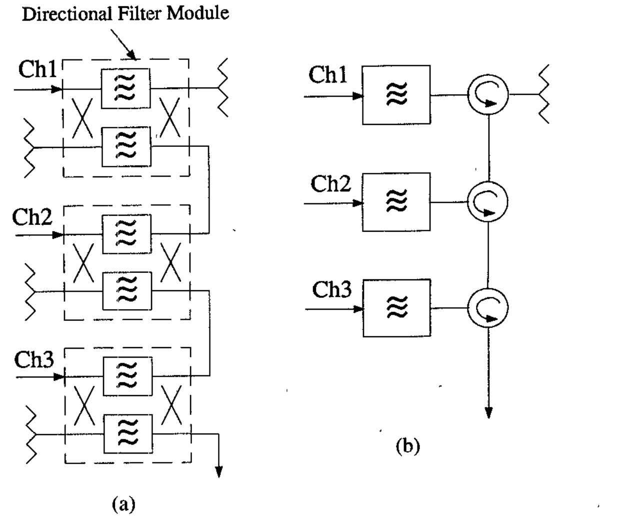

Fig. 1. Channel dropping multiplexers using directional filters. (a) Two filters and two hybrids per module. (b) One filter and one circulator per module.

Despite their desirable characteristics, waveguide manifold multiplexers have not been used in applications where the flexibility of adding channels to an existing multiplexer is required, such as in satellite earth stations, *S*-band TV distribution systems and cellular radio base stations. These applications have been typically served using channel dropping techniques that allow the simple cascading of "modules." Each module typically requires directional filters consisting of the equivalent of a pair of band pass filters and a pair of hybrids for each channel, or a single filter and circulator per channel, as shown in Fig. 1. Although these techniques have the advantages of eliminating interactions among channels, their performance is generally inferior to well designed waveguide manifold type multiplexers, (e.g. larger in band insertion loss, gain slope and group delay variations).

The objective of this paper is to present a computer-aided design procedure that enables the simple expansion of the number of channels of an already existing manifold multiplexer, without changing any of the elements of the existing multiplexer. Unlike the procedure described in [12], in the present paper, the original multiplexer parameters are all fixed and not allowed to change. As a result, it is now possible to expand an already deployed multiplexer in the field by adding to it new properly designed modules.

II. Modeling and Optimization

A manifold multiplexer, shown in Fig. 2, is a combination of several separated devices (T-junctions and filters) and the connecting pieces of waveguide. The multiplexer model can be built up by modeling each device, separately, to determine its scattering parameters, and then combining the scattering matrices together to obtain the scattering parameters of the $n + 1$-port multiplexer.

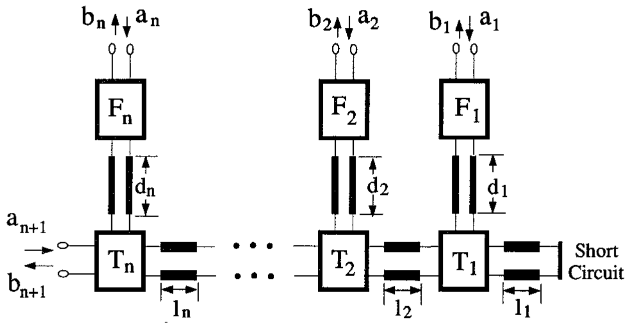

Fig. 2. N-channel multiplexer configuration.

Filter modeling has been reported before for both Chebyshev and elliptic function [1], [10]; and T-junction modeling has also been reported recently in [7]. Once the S-parameters of T-junction and filters are produced, all the S-parameters of the multiplexer can be obtained.

Using this network model, all multiplexer responses of interest can be computed. The accuracy of the modeling process has been verified by experiment in [7]. It is important to note that the higher order mode interaction between devices is not taken into account by this network model. Therefore, some minimum limitation for the lengths of waveguide is required. Experience shows that the minimum length of each piece of waveguide can be $0.17\lambda_g$, λ_g is the guide wavelength at the center frequency of the multiplexer frequency band.

A waveguide manifold multiplexer cannot be designed by arbitrarily selecting the lengths of the spacings and stubs in the manifold and using well designed doubly terminated channel filters. Optimization of all parameters is always necessary to make the multiplexers satisfy the specification. The error function to be minimized is developed using the multiplexer specifications. It is usually sufficient to take the common port return loss as the measure of the multiplexer response.

Assume the required specification for common port return loss in dB is

$$20\ lg\,|S_{n+1,n+1}| \le R_i (\le 0) \tag{1}$$

in ith frequency pass-band, and the computed value from the network model is

$$D_i = D_i(l_j, d_j, r_j, m_j \,|\, j = 1, 2, \cdots, n) \tag{2}$$

where l_j and d_j are the lengths of the spacings and stubs in manifold, r_j is the input impedance of each filter to the manifold, and m_j is the coupling matrix of each filter. The error function can be defined as

$$\overline{ER} = \sqrt{\sum_i^n \Delta_i^2} \tag{3-1}$$

$$\Delta_i = \begin{cases} D_i - R_i, & D_i - R_i > 0; \\ 0, & D_i - R_i \le 0. \end{cases} \tag{3-2}$$

By varying the values of l_j, d_j, r_j and the elements of m_j ($j = 1, 2, \cdots, n$), the value of error function $\overline{ER}$ can be minimized.

The multiplexer response optimization problem is complicated by the fact that there are relatively large number of variables to be optimized [12]. For example, in a four channel multiplexer there are 48 parameters to be determined. Although there are several general optimization subroutines available [11], experience has shown that these subroutines need the initial values of the variables to be chosen close to their optimum values. For multiplexer optimization, it is not possible to guarantee the initial variable values are close to their optimum values, especially for large numbers of channel multiplexers [12]. Therefore, attempts have been made to study the behavior of the error function as a function of the multiplexer variable parameters. This study led to the adoption of a relatively simple, yet very effective optimization procedure, i.e. minimizing the error function by varying the parameters one variable at a time. This approach leads to an acceptable design, which may not be the optimal design. Results of the one variable at a time optimization could be used as the starting point for reoptimization by a multi-variable algorithm (e.g. [13]) although this was not found to be necessary in the cases treated here.

TABLE I
S-Band 4-Channel Multiplexer Specifications

	Ch.1	Ch.2	Ch.3	Ch.4
Center Frequencies (GHz)	2.647	2.659	2.671	2.683
Band Width (MHz)	6	6	6	6
Return Loss In-Band (dB)	−20	−20	−20	−20

As an example for the optimization process, an S-band 4-channel multiplexer with the specifications given in Table I is considered. The requirements for a single channel can be met by an isolated four pole doubly terminated elliptic function filter, with 0.05 dB pass-band ripple and 30 dB minimum out-of-band rejection. The response of such filter is shown in Fig. 3(a). When four channel filters of this type are connected to waveguide manifold, the initial response obtained is shown in Fig. 3(b). The multiplexer response and a typical single filter response after optimization are shown in Fig. 3 too.

The initial individual filters parameters are made based on the multiplexer specifications, and are determined on a doubly terminated design satisfying the separate channel requirements. The choice of the initial manifold dimensions is somewhat more critical. The variation of the error function with the short spacing (the spacing between the first T-junction and the short circuit at the end of the manifold) is shown in Fig. 4. The error function varies almost periodically with the short circuit spacing with a period of $\lambda_g/2$ at approximately the midband frequency of the multiplexer. The error function variation with the other variables, (spacings and stubs), has very similar behavior. The minimum value of the error function at each local minimum is increasing with the increase of the short spacing. Therefore, the first minimum is always expected to be the best choice and the initial value of each spacing or stub can be $\lambda_g/2$ or less. However, the first minimum typically results in some spacings or (stub lengths) which are very short. For such close spacings, in practice, the higher order modes excited by the discontinuities will not be negligible. Because the network model neglects the higher order mode interaction between elements, the optimized design will not be reliable, even not correct. In order to avoid this problem, the second minimum should be chosen, and the initial value of the spacing (stub) can be around one guide wavelength (λ_g).

The selection of the first minimum as the initial value has other advantages. Considering the total frequency band covered by the multiplexer, the longer the spacing (or stub length), the more sensitive the response is to the spacing (or stub length). This will be shown by the tolerance analysis given later. On the other hand, whatever the initial values are chosen for manifold dimensions, local minimum can always be reached. And the solution satisfying the specification is not unique.

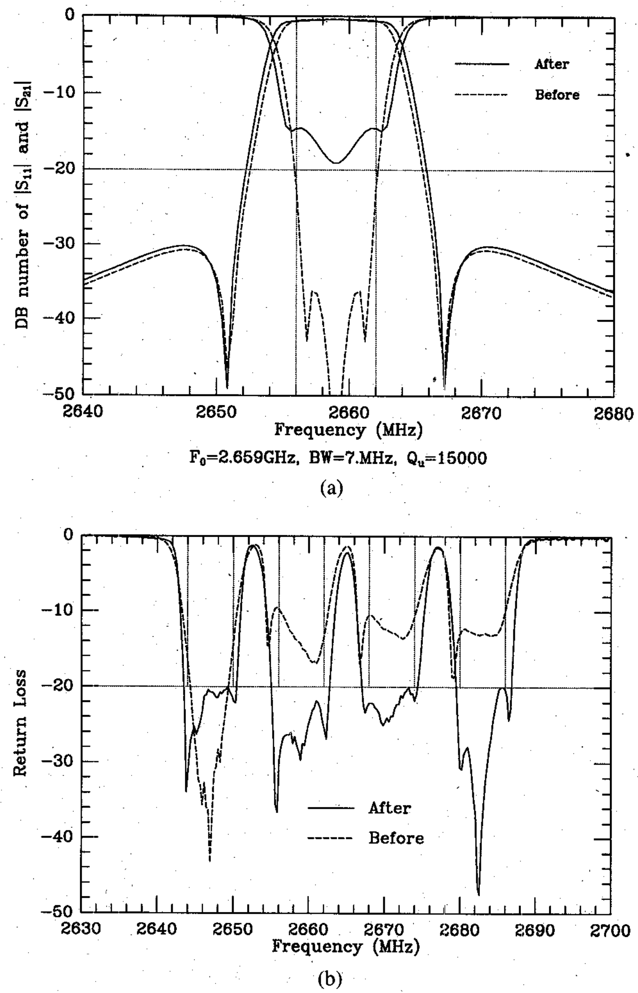

Fig. 3. (a) Single filter responses before and after optimization. (b) 4-channel multiplexer responses before/after optimization, with $d_1 = 2.0/1.980''$, $d_2 = 2.0/2.360''$, $d_3 = 2.0/1.440''$, $d_4 = 2.0/2.525''$, $l_1 = 2.0/1.695''$, $l_2 = 2.0/2.720''$, $l_3 = 2.0/1.650''$, $l_4 = 2.0/2.945''$.

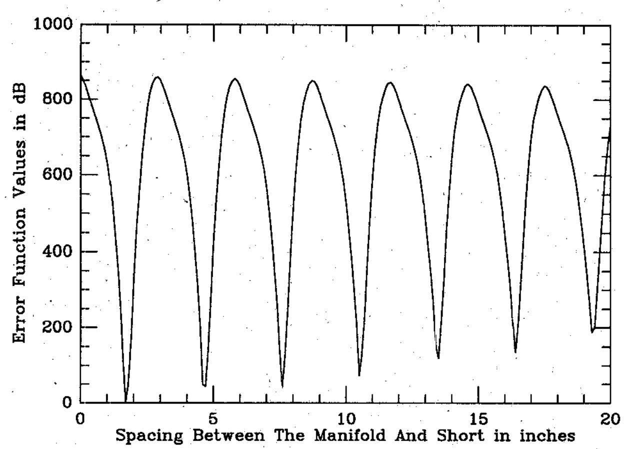

Fig. 4. Error function variation with the short circuit spacing.

III. Multiplexer Channel Expansion

Manifold multiplexer channel expansion can be done by adding more channels to the common port of the original multiplexer. The restriction is that the extra channel frequency bands have to be out of the original multiplexer frequency band (lower or higher). Optimization is carried out on the spacings, stubs and the filter parameters of the new added channels only, including the spacing from the common port of the original multiplexer to the first new added T-junction.

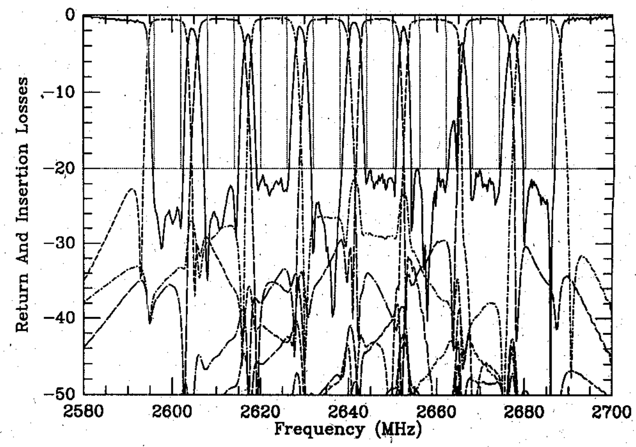

Fig. 5. Four more channel expansion on an existing 4-channel multiplexer under the channel order from short: $f_1 < \cdots < f_4 < f_5 < \cdots < f_8$.

Computer simulation has been done and shows satisfactory results. In Fig. 5, four channels are added to a previously designed 4-channel multiplexer in the way described above with the channel frequency order of $f_1 < \cdots < f_4 < f_5 < \cdots < f_8$. Similar results were obtained when one, two or three channels are added to the original multiplexer.

Referring to Fig. 2, the channel filters are placed on the manifold such that the order of their frequencies can be either $f_1 < f_2 < \cdots < f_n$ or $f_1 > f_2 > \cdots > f_n$. In both cases, the optimization can be accomplished and the error functions can be minimized to zero. When adding more channels to a well designed multiplexer, the only restriction on the additional channel frequencies is to be out of the original multiplexer frequency band. Assume the channel order of the well designed n-channel multiplexer is $f_1 > f_2 > \cdots > f_n$, two of the possible ways to add k more channels are: (A) $f_n > f_{n+1} > \cdots > f_{n+k}$, (B) $f_{n+1} > f_{n+2} > \cdots > f_{n+k} > f_1$. Fig. 6 shows the response of adding 4 more channels to an original 4-channel multiplexer in the order of (B), and similar results can be obtained in the order of (A).

IV. Tolerance Analysis

A method to simulate the sensitivity of an optimized manifold multiplexer for a given fabrication tolerances has been developed. The method can be described as follows:

1) Set a tolerance for all the manifold dimensions.
2) Randomly select a set of values for the dimensions within the tolerance.
3) Run simulation program to compute the multiplexer response.
4) Repeat procedures 2) and 3) several times (e.g. 10 times) to obtain the worst response.
5) If the worst response given at procedure 4) is better than the acceptable specifications, set a new looser tolerance and repeat procedures 2), 3) and 4). On the other hand, if the worst response given at procedure 4) does not satisfy the specifications, set a new tighter tolerance and repeat procedure 2), 3) and 4).
6) The tolerance to be used for manufacturing is that giving the worst response that satisfies the required multiplexer specifications.

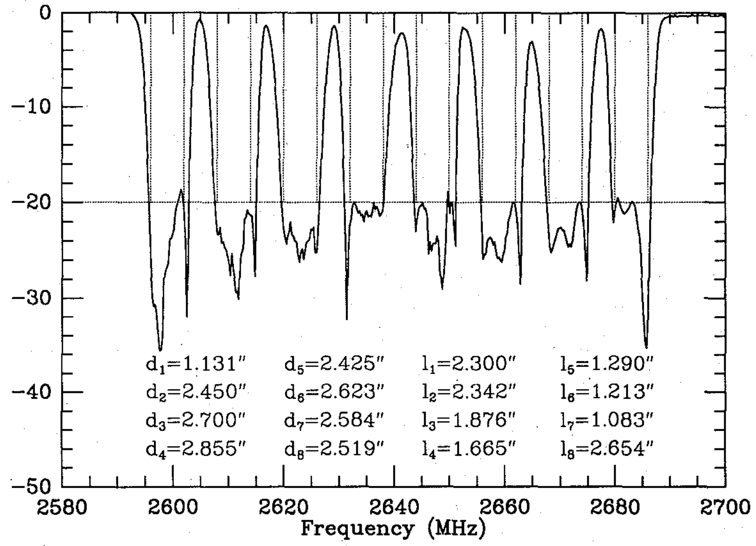

Fig. 6. Four more channel expansion on an existing 4-channel multiplexer under the channel order from short: $f_5 > \cdots > f_8 > f_1 > \cdots > f_4$.

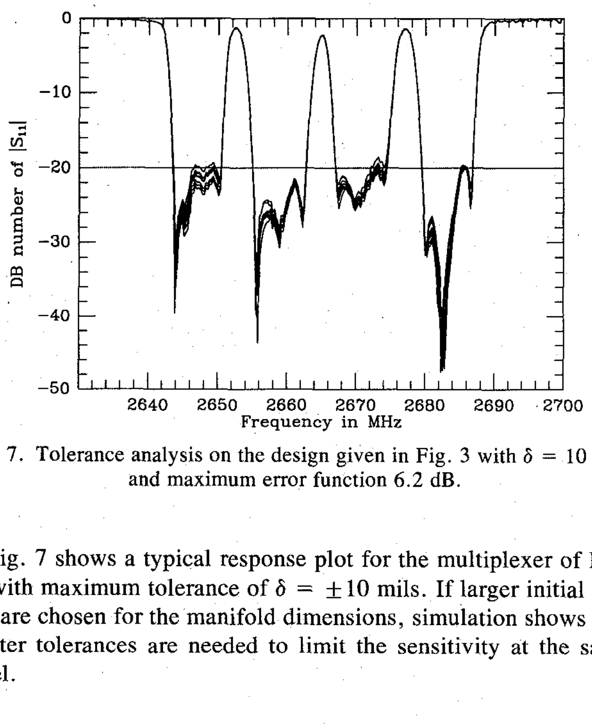

Fig. 7. Tolerance analysis on the design given in Fig. 3 with $\delta = 10$ mils and maximum error function 6.2 dB.

Fig. 7 shows a typical response plot for the multiplexer of Fig. 3, with maximum tolerance of $\delta = \pm 10$ mils. If larger initial values are chosen for the manifold dimensions, simulation shows that tighter tolerances are needed to limit the sensitivity at the same level.

Conclusion

The CAD method proposed for adding channels to an already existing manifold multiplexer, with no modifications to the existing channels, provides operational flexibility which was not achievable before. This process can make the manifold multiplexer quite desirable in many applications, such as satellite ground stations and instructional television (ITV) distribution systems, where only channel dropping directional filters are predominantly used. The manifold multiplexer offers several advantages such as lower loss, better selectivity and in band flatness and smaller size. It also offers economic advantages since it requires less than half the number of components (i.e. filters), than the corresponding channel dropping approach.

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