Accurate Design of High-Performance Diplexers for Mobile Communication Base Stations Applications

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***Abstract*—This work describes a modified approach for extracting the equivalent circuit parameters, as there are the resonant frequency of each resonator, the coupling bandwidths and the external Qs from multi-port Y-matrix and group delay of the input reflection coefficients. The extractions of equivalent circuit parameters and the fine tuning for three-dimensional simulating models are achieved by utilizing the EM simulating software HFSS. Then, a novel method for designing microwave diplexers is proposed. Compared to the methods existed, all interacting effects are allowed taking into account. One circuit parameter can be related to one dominate geometrical variation in the three-dimensional model. The detailed design steps illustrating the design of a diplexer for mobile communication base stations applications are presented. The designed device with a novel tunable electrical coupling structure is then fabricated. The comparison between measurements and simulations has validated the new design method with high efficiency.**

Keywords—microwave diplexers; multi-port; Y-matrix; group delay; electrical coupling

I. INTRODUCTION

Microwave diplexers are widely employed in practically all communication systems. As the frequency spectrum becomes more crowded, the specifications for channel filters have tended to become much more severe. This is particularly true for the front-end transmit/receive (Tx/Rx) diplexers in the base stations of mobile communications systems. Better design methods are needed to realize diplexers with high performance. Therefore, the interest in the accurate design method of diplexers is greatly increased in these years.

With the rapid development of computer technology, computer-aided-design (CAD) approaches are playing more and more important roles in the design of microwave passive components, such as filters, diplexers and multiplexers. Generally speaking, the design steps are mainly consist of synthesis and tuning. Many significant works have illustrated how to approach the synthesis of a class of microwave filters, diplexers and multiplexers[1-4]. Nevertheless, only a few reports about accurate tuning methods of filters have been found [5-6]. In fact, the tuning procedure today is still based mainly on optimization. The optimization with the desired goal specified by S_{21} and S_{11} is not very promising. Besides, an S_{11}or S_{21} goal function cannot be directly related to dominant geometrical variations, so that all parameters must be optimized simultaneously causing an immense parameter space to deal with. It's hard to satisfy the requirements of solving complex engineering problems.

In this work, a modified method of extractions of equivalent circuit parameters is presented based on the theories of multi-port Y-matrix and group delay of the input reflection coefficients in [5] and [6]. The extraction procedure is realized in commercial software HFSS and an accurate design method which can be applied in a large class of practical diplexer implementations is then introduced. Here, the method proposed has been verified through the design and fabrication of a diplexer for GSM base stations applications.

II. THEORY

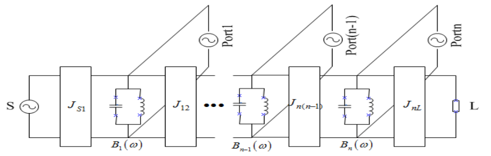


Fig. 1. Equivalent circuit model of an N pole bandpass filter with source (S) and load (L) and N additional internal ports 1 to n.

In Fig. 1 an equivalent circuit model of an N pole bandpass filter is shown. It basically contains resonant circuit $B_n(\omega)$ and admittance inverters $J_{n,n+1}$. $B_n(\omega)$ represents the resonator while $J_{n,n+1}$ means the coupling between adjacent resonators. For every resonator one additional internal port is defined. Therefore, the 2 port filter network turns to an N+2 port network and an (N+2)×(N+2) Y-matrix can be obtained. The matrix is shown below.

$$Y=\begin{bmatrix} y_{ss}\ y_{s1} & y_{s2} & \cdots & & \\ y_{1s}\ y_{11} & & & & \vdots \\ y_{2s} & \ddots & & y_{(n-1)n} & y_{(n-1)l} \\ \vdots & & y_{n(n-1)} & y_{nn} & y_{nl} \\ y_{ls} & \cdots & y_{l(n-1)} & y_{\mathrm{ln}} & y_{ll} \end{bmatrix} \quad (1)$$

The resonant frequency ω_n of the nth resonator can be calculated by using the following relation:

$$\operatorname{Im}\left\{y_{nn}\left(\omega_n\right)\right\}=0 \tag{2}$$

The Eigen-frequency of each resonator only depends on the diagonal elements of the Y-matrix. The imaginary part of diagonal elements will be 0 at resonant frequency.

The coupling bandwidth also can be extracted from the Y-matrix elements in a similar way with

$$kbw_{n(n+1)}=\frac{J_{n,n+1}}{\sqrt{b_n b_{n+1}}}=\frac{\operatorname{Im}\left\{y_{n(n+1)}\left(\omega_n\right)\right\}}{\sqrt{b_n b_{n+1}}} \tag{3}$$

Where

$$b_n=\frac{f_0}{2}\frac{\partial \operatorname{Im}\left\{y_{nn}\left(\omega\right)\right\}}{\partial\omega} \tag{4}$$

Both the diagonal and non-diagonal elements carry the coupling information. It should be noticed that coupling values between any resonators, including the cross couplings and parasitic couplings can be quantified through the relations (3) and (4). As is well known, cross couplings are often used to improve frequency selectivity by producing transmission zeros. On the contrary, parasitic couplings should be restricted because of the effects on frequency responses. Both of them are important to accurate design of diplexers.

The external Qs are computed by the group delay values with the relations proposed in [5].

$$Q_e=\frac{\Gamma_d\left(\omega_0\right)\cdot\omega_0}{4} \tag{5}$$

Group delay of the input reflection coefficients is defined as:

$$\Gamma_d\left(\omega\right)=-\frac{\partial\angle S_{11}}{\partial\omega} \tag{6}$$

where $\angle S_{11}$ = the phase of S_{11} and ω = angular frequency.

III. DESIGN PROCEDURE

A. *Synthesis*

The specifications refer to a diplexer used for GSM base stations applications. The following characteristics are assigned.

(1) Passband: 1850-1915 MHz (RX), 1930-1995 MHz (TX); (2) VSWR: 1.3; (3) Insert Loss: 3 dB; (4) Isolation: >70 dB @1930-1995 MHz (RX), >70 dB @1850-1915 MHz (TX).

With the specifications above, the number of two channel filters' poles and transmission zeros can be acquired by utilizing the synthesis method in [1]. Both of them have 9 poles and 2 transmission zeros. Then, the following results can be obtained with the same process presented in [3].

RX Filter:

resonant frequency $f_{0,i}$ (MHz):

[1856.6,1879,1880.8,1900.9,1880.4,1880.3,1899.4,1880.9, 1879.7];

main couplings $kbw_{i,i+1}$:

[54.52,40.95,32.58,32.04,37.51,33.99,38.56,66.25];

cross couplings kbw_{35},kbw_{68}: [20.56, 20.43];

external Qs Qe: [24.28,20.32]

TX Filter:

resonant frequency $f_{0,i}$ (MHz):

[1978.2,1965.1,1963.6,1946.6,1964.1,1965,1941.8,1964.4, 1965.8];

main couplings $kbw_{i,i+1}$:

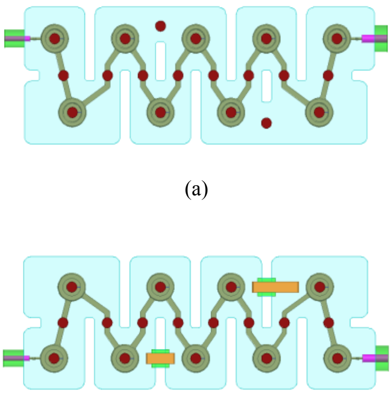
[53.12,40.38,30.3,33.72,38.22,31.76,36.66,67.825];

cross couplings kbw_{35},kbw_{68}: [-17.25, -24.7];

external Qs Qe: [26.27,20.97]

B. *Tuning and optimization*

The simulating models of RX and TX filter in HFSS are shown in Fig. 2 (a) and (b).



(a)

(b)

Fig. 2. Three-dimension simulating models of filters.(a) RX filter, (b) TX filter

In Fig. 3, a novel electrical coupling structure is designed in TX filter. It's realized by bending both ends of a piece of thin copper with a thickness of 0.4 mm and a width of 4 mm. The structure is fixed between two resonant rods by a Teflon support. The coupling values can be tuned by changing the distance between the structure and the rod. The proposed structure has better tunability than conventional electrical coupling structures. The positions of both ends can be easily moved as the copper is thin and soft after fabrication.

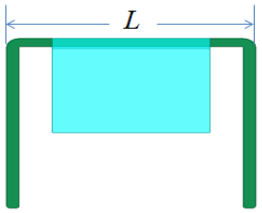
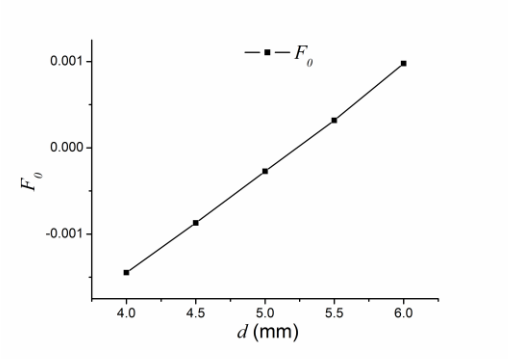
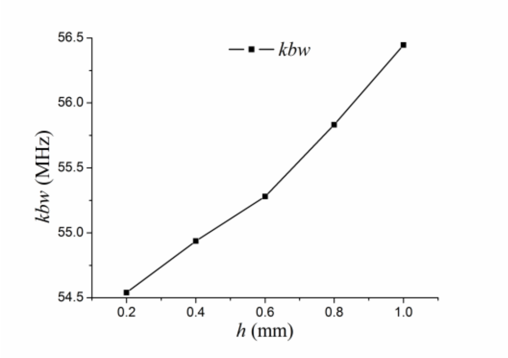


Fig. 3. Electrical coupling structure.

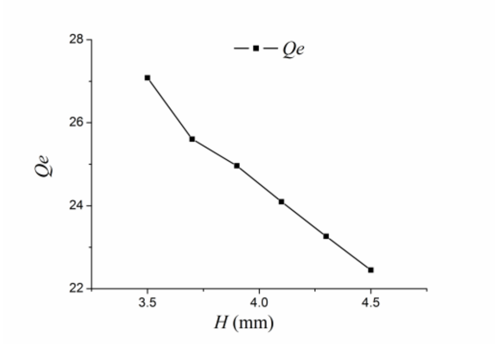
All dominate geometrical variations which are related to the corresponding equivalent circuit parameters need to be pointed out here. The depths of frequency tuning screw d, the heights of coupling structure h and the heights of the welding point H are related to resonant frequencies of each resonators, coupling bandwidths between adjacency resonators and external Qs, respectively. All of the values can be obtained by parameter sweeping with properly sweeping steps. The relations between geometrical variations and equivalent circuit parameters are reported in Fig. 4 (a), (b) and (c).



(a)



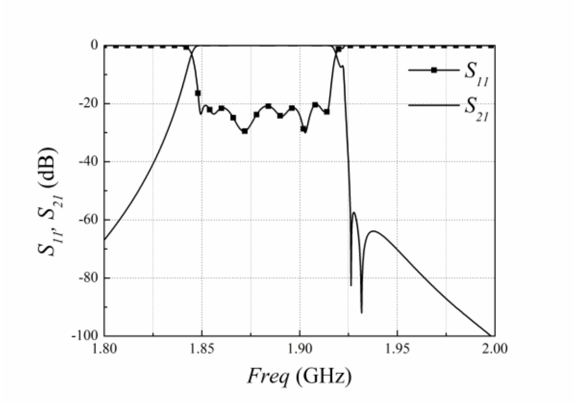
(b)



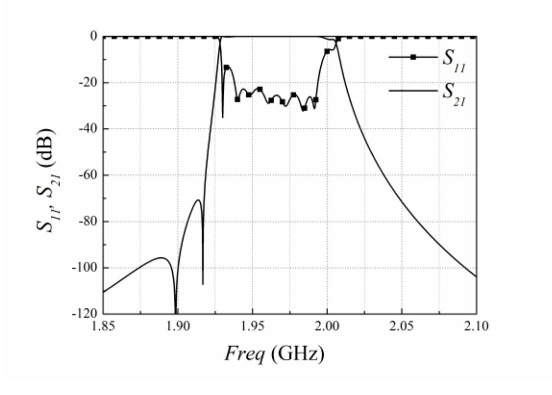
(c)

Fig. 4. Relations between geometrical variations and equivalent circuit parameters.(a) resonant frequencies of each resonators and the depths of frequency tuning screw, (b) coupling bandwidths between adjacency resonators and the heights of coupling structure, (c) external Qs and the heights of the welding point.

The frequency response of RX and TX filter is illustrated in Fig. 5 (a) and (b), respectively. It should be noted that both RX and TX filter have 2 transmission zeros which is in accordance with the synthesis results. Generally, it's difficult to realize transmission zeros in three-dimension simulating with conventional methods. Therefore, high precision of the proposed method are proved by the appearance of the transmission zeros.



(a)



(b)

Fig. 5. Frequency response of RX and TX filter.(a) RX filter, (b) TX filter.

C. Fabrication

Fig. 6 illustrates the fabricated diplexer (top view with the cover removed). Note, however, that tuning screws have been provided both for resonators and for coupling structures in order to relax the requested fabrication accuracy and to allow, at the same time, an accurate alignment of the diplexer.

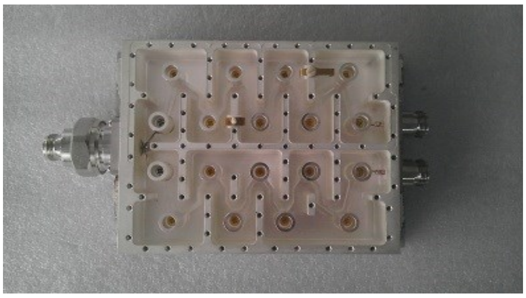


Fig. 6. Photograph of the manufactured diplexer (top cover removed).

In Fig. 7, the measured response of the fabricated diplexer (after a first alignment) is compared with the synthesized response. A satisfactory agreement between the curves can be observed. The deterioration of S_{11} after fabrication is predicted, so the return loss is assigned as -25 dB when synthesizing. The testing results meet the requirements perfectly.

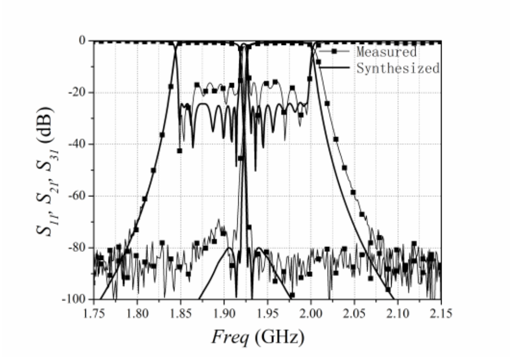


Fig. 7. Measured attenuation and return loss of the diplexer after a first alignment; synthesized response is reported for comparison.

IV. CONCLUSION

A modified parameters extraction approach based on multi-port Y-matrix and group delay of input reflection coefficients has been proposed. The extraction (or tuning) process has been realized in three-dimension models by utilizing HFSS. Then, an accurate design method of diplexers has been introduced. All interacting effects are considered and each filter parameter has a corresponding dominate geometrical variation. The proposed method has been verified by the design, fabrication and application of the proposed diplexer for mobile communication base stations applications.

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