Exhaustive Synthesis and Realization of Extended-Box Topologies With Dispersive Couplings

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***Abstract*—In this paper, an exhaustive general synthesis method is proposed for the extended-box topologies with dispersive couplings, which is very suitable for the realization of the monoblock dielectric resonator filters. The difficulty of introducing the diagonal cross coupling calls for the extended-box topology. When properly utilizing the inevitable dispersion effect of the negative coupling introduced by a metalized blind hole, an extra transmission zero generates. Multiple solutions can be observed by solving the polynomial equation system established based on the congruent transformation, from which the solution most suitable for realization can be selected and realized. A six-pole filter in extended-box topology with a dispersive coupling is synthesized and EM designed for validation.**

***Index Terms*—Coupling matrix, Dispersive couplings, Filter synthesis, Monoblock dielectric resonator filters, Transmission zeros**

I. Introduction

To satisfy the stringent out-of-band specifications, transmission zero (TZ) is an essential element in the response of microwave filters. For the realization with coaxial resonators that are mostly used for base station application, cross coupling is the most popular way to introduce TZs since the resonators non-adjacent in the topology can be flexibly arranged to be physically adjacent. For waveguide filters, non-resonant nodes [1] are mostly used to introduce TZs due to the inconvenience of realizing cross couplings, the size is increased at the expense of the simple in-line layout. Besides cross coupling and non-resonant node, dispersive coupling is the third way to generate TZs in filters. It has been utilized in waveguide filters to generate TZs simply in the in-line topology and with no volume increase [2], [3].

However, when generating TZs close to the passband simply with a dispersive duplet, the required dispersive coupling can be very strong. Then the spurious mode generated by the dispersive coupling structure comes close to the passband and deteriorates the rejection. Therefore, the cascaded topologies with both dispersive couplings and cross couplings provide a compromised solution [4]. Dispersive couplings help to simplify the layout of the filter while cross couplings appearing within triplets or quadruplets are used to realize Tzs close the passband.

In the fifth generation (5G) communication system, the miniaturization of filters becomes necessary with the application of the Multiple Input Multiple Output (MIMO) system. Monoblock dielectric resonator (MDR) filters have regained their popularity with the merit of volume reduction. Different from the traditional type of MDR filters which are built in the comb-line structure propagating TEM mode [5], a new type of MDR filter propagating quasi-TEM mode is presented in [6] very recently. A rather high Q factor is obtained in such kind of MDR, which is comparable to that of the cavity coaxial resonators currently used in the base station. The features of small size and high Q factor make MDR filters become the new trend in the 5G and future communication system.

With the metalized cylindrical ridge on top of the dielectric resonator providing a size reduction and frequency control, MDR filters have higher flexibility in the layout than a pure waveguide filter yet lower than a coaxial resonator filter. Only cross couplings between two physically adjacent resonators can be conveniently introduced, the diagonal cross couplings in a cascaded quadruplet are much harder to realize. This feature calls for the extended box topology [7]. Extended box topologies are rarely used in the coaxial realization mainly due to the multiple solution issue [8] that brings difficulties to post-fabrication tuning. However, these topologies have much potential in MDR filters since the fabrication can be quite accurate and merely some fine-tuning is required. Therefore, the tuning can hardly be affected by other solutions.

Besides the difficulty in the layout, the negative coupling, realized by a metalized blind hole [6], demonstrates an inevitable dispersion effect that further affects the locations of the TZs. According to the shortest path rule for dispersively coupled resonator filters [4], the natural dispersion characteristic of the negative coupling in the extended box topology can be utilized to generate an extra TZ. In this paper, an exhaustive synthesis method for extended box topologies with dispersive couplings will be introduced and verified by a 6-pole MDR filter with 3 TZs.

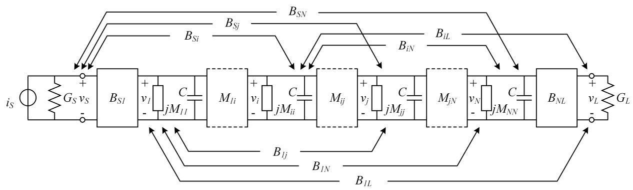

Fig. 1. Low pass equivalent circuit

II. Dispersively Coupled Resonator Network

We now consider the low-pass circuit represented in Fig.1, where the couplings $M_{i,j}$ between circuits can be either frequency-independent or linearly frequency-dependent. The input and output couplings $B_{S,k}$ and $B_{k,L}$ are supposed to be frequency-independent. Kirchhoff's law yields the following state space equations in descriptor form for this kind of low-pass circuits,

$$\begin{cases} \mathbf{Md}\dot{x} = -j\mathbf{Mo}x + \mathbf{B}v \\ i = \mathbf{B}^t x \end{cases} \tag{1}$$

where the state vector x is defined as $x = jU$ with $U(k)$ being the voltage in resonator k. The slope matrix $\mathbf{Md}$ is an $n \times n$ positive definite matrix with all the diagonal elements normalized to unity, representing the resonators in the lowpass domain, and the other nonzero terms representing the slope coefficients of the dispersive couplings. The constant coupling matrix $\mathbf{Mo}$ is a matrix of the same size as $\mathbf{Md}$ representing the constant part of the coupling coefficients between resonators and the diagonal terms representing the frequency offset of each resonator from the center frequency. Matrix $\mathbf{B}$ is $n \times 2$, consisting of the couplings between input/output and resonators. The 2×1 voltage vector v and current vector i represent the voltages and currents respectively at both ports of the circuit.

We will call circuital realisation the triplet $(\mathbf{Md}, \mathbf{Mo}, \mathbf{B})$ corresponding to system (1). Let P be a non-singular matrix, we set $w = P^{-1}x$ to be the new state space variable and obtain:

$$\begin{cases} \mathbf{Md}\, P\dot{w} = -j\mathbf{Mo}\, P\, w + \mathbf{B}v \\ i = \mathbf{B}^t\, Pw \end{cases}$$

and eventually,

$$\begin{cases} (P^t\, \mathbf{Md}\, P)\dot{w} = -j(P^t\mathbf{Mo}P)w + (P^t\mathbf{B})v \\ i = (P^t\mathbf{B})^t w \end{cases}$$

This shows the $(P^t\mathbf{Md}P, P^t\mathbf{Mo}P, P^t\mathbf{B})$ is a circuit realisation with same transfert function, here admittance matrix, as $(\mathbf{Md}, \mathbf{Mo}, \mathbf{B})$. In this context P is therfore called a congruent transformation.

III. Exhaustive Synthesis

Suppose that we have a target topology $(\mathbf{Md}^g, \mathbf{Mo}^g, \mathbf{B}^g)$ in mind characterised by three sets of indices (T_1, T_2, T_3) defined as,

$$\forall (i,j) \in T_1\ \mathbf{Md}^g_{i,j} = 0$$
$$\forall (i,j) \in T_2\ \mathbf{Mo}^g_{i,j} = 0$$
$$\forall (i,j) \in T_3\ \mathbf{B}^g_{i,j} = 0$$

Let S be a scattering matrix, compatible with our target topology, for which we have computed a canonical non-dispersive realization of the form $(\mathbf{Id}, \mathbf{M}', \mathbf{B}')$. Following [8] and preceding section, the algebraic set of equation characterising all congruent transformations passing from former circuital realisation to our target topology is the following:

$$\begin{cases} (P^tP)_{i,j} = 0,\ \forall (i,j) \in T_1 \\ (P^tP)_{i,i} = 1,\ \forall i \\ (P^t\mathbf{M}'P)_{i,j} = 0,\ \forall (i,j) \in T_2 \\ (P^t\mathbf{B}')_{i,j} = 0,\ \forall (i,j) \in T_3 \\ t \cdot Det(P) - 1 = 0 \end{cases} \tag{2}$$

where t is an additional help variable, used to impose the non-singularity of the congruent transformation.

Solving this polynomial equation system exhaustively yields all the solutions to the coupling matrix synthesis problem associated to our target topology. Among all observed circuital realisation the most suitable ones for realization can be chosen. This procedure can help us to identify the potential of unconventional topologies with dispersive couplings that might be suitable for some specific implementations like MDR filters where diagonal cross couplings are inconvenient to be introduced and the negative couplings are naturally dispersive.

IV. A Six-Three Filter Example

The filter to be designed is with the following specifications:

- 21 dB return loss in passband: 3.5 GHz - 3.7 GHz
- Tzs: 3.39 GHz, 3.72 GHz, 3.81 GHz

The topology of the filter is as shown in Fig. 2. Due to the symmetry that the overall topology keeps unchanged if we exchange the input and output port, only half of the real solutions are listed here for simplicity. The input and output coupling are both 1.017 in the two solutions so we only show **Mo** and **Md** here. The first solution is

$$\mathbf{Mo}^{(1)} = \begin{pmatrix} 0.022 & 0.821 & 0 & -0.153 & 0 & 0 \\ 0.821 & -0.17 & 0.366 & 0 & 0 & 0 \\ 0 & 0.366 & -0.648 & -0.783 & 0 & 0.200 \\ -0.153 & 0 & -0.783 & -0.865 & 0.453 & 0 \\ 0 & 0 & 0 & 0.453 & 0.367 & 0.800 \\ 0 & 0 & 0.200 & 0 & 0.800 & 0.022 \end{pmatrix}$$

with $Md^{(1)}(3,4) = 0.726$. The other solution is

$$\mathbf{Mo}^{(2)} = \begin{pmatrix} 0.022 & 0.554 & 0 & 0.643 & 0 & 0 \\ 0.554 & 0.753 & 0.37 & 0 & 0 & 0 \\ 0 & 0.37 & 0.084 & -0.441 & 0 & 0.799 \\ 0.643 & 0 & -0.441 & -0.529 & 0.122 & 0 \\ 0 & 0 & 0 & 0.122 & -0.982 & 0.284 \\ 0 & 0 & 0.799 & 0 & 0.284 & 0.022 \end{pmatrix}$$

with $Md^{(2)}(3,4) = 0.090$.

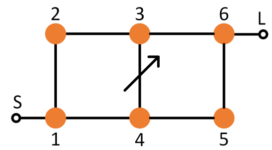

Fig. 2. Topology of the filter with coupling (3-4) being dispersive.

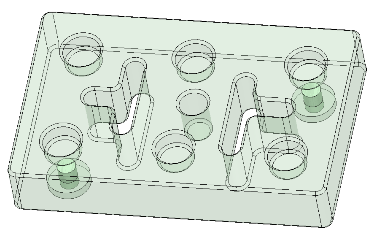

Fig. 3. EM model of the MDR filter.

For MDR filters, the dispersion effect is introduced by the negative coupling and the slope of which should be moderate to avoid the influence of the spurious mode. Therefore, the second solution is selected for realization since it satisfies both of the requirements.

The EM model of the filter is shown in Fig. 3, corresponding to the topology in Fig. 2. All the positive couplings are realized by partial-width walls and the only negative dispersive coupling is realized by the blind hole, by controlling the offset and depth of which we obtain the desired $Mo(3,4)$ and $Md(3,4)$. As seen such MDR filters based on dispersive extended box topologies are very compact and fabrication friendly when compared to the introduction of a diagonal cross coupling. The EM simulated response is superposed on the synthesized response in Fig. 4, demonstrating a very good agreement with the circuital model.

V. Conclusion

In this paper, an exhaustive synthesis method for extended box topologies with dispersive couplings is proposed. By analytically solving the polynomial equation system verified by the congruent transformation, multiple solutions for the desired topology are found: this provides us with different choices to pick out from. A 6-pole MDR filter is realized to validate the method. The topology not only avoids diagonal cross couplings that are fabrication-inconvenient but also utilizes the inevitable dispersion effect of the negative coupling.

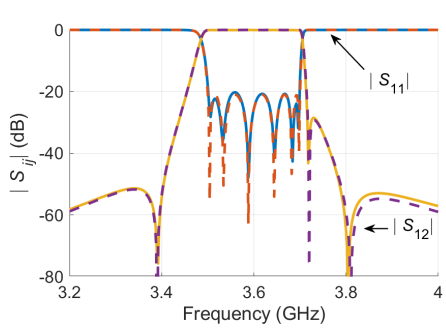

Fig. 4. The simulated response (solid lines) and the synthesized response (dashed lines).

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