Extended Path Filter Configurations

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***Abstract*—In this work we introduce a method for increasing the maximum number of transmission zeros in the response of path filters. This recently introduced inline filter configuration allows for up to four transmission zeros on the imaginary axis. The solution proposed in this work, while maintaining the inline configuration, increases the number of transmission zeros up to N-1 (with N order of the filter). The novel concept allowing the additional zeros introduction is verified by means of the design of a waveguide filter of order 8 with 6 transmission zeros.**

Keywords—inline filter, transmission zeros, synthesis

I. INTRODUCTION

Path filter configuration is an inline topology recently introduced [1] that allows up to 4 transmission zeros in the frequency response. The basic configuration, shown in Fig. 1, consists of three cascaded blocks of inline coupled resonators, each characterized by the assigned number of coupled resonators (n_S, n_D, n_L).

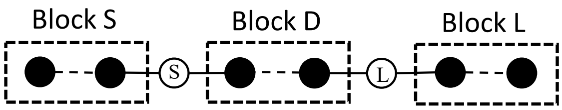

Fig. 1. Structure of Path Filters. The three inline blocks are composed of n_S, n_D, n_L coupled resonators respectively.

Source and Load termination are located between blocks (S-D) and (D-L) respectively. Blocks S and L, which are hanging from source and load, will be referred hereinafter as dangling blocks. The scattering parameters define the path filter response at source (port 1) and load (port2). Assuming lossless, lumped resonators and ideal (frequency-invariant) inverters, the *S* matrix in the normalized (lowpass) frequency domain *s* is defined by the characteristic polynomials *P(s), F(s), E(s)* [2]:

$$S_{11} = \frac{F(s)}{E(s)}, \quad S_{22} = \frac{(-1)^{np} F(s)^*}{E(s)}, \quad S_{21} = \frac{P(s)}{E(s)}$$

where $np=n_S+n_D+n_L$ is the overall order of the filter. It can be easily verified that the path filter topology allows up to n_S+n_L imaginary transmission zeros. It has been shown that, if a quasi-elliptic response is targeted, a maximum of two transmission zeros can be extracted by each dangling block. For this reason, it is assumed that path filters allow up to four imaginary transmission zeros in the response.

In [1] a method for evaluating the characteristic polynomials of path filters has been introduced under the assumption $S_{11}=S_{22}$. In fact, this condition requires that every transmission zero must also be a double eigenvalue of the synthesized network. Enforcing this condition, the polynomials can be evaluated once the filter order and the transmission zeros are assigned (assuming the Generalized Chebycheff characteristic [2]). However, the return loss cannot be arbitrarily chosen but depends on the assigned transmission zeros. In addition, the transmission zeros must be defined by a single parameter, so only the following four assignments are possible:

- One Transmission zero (or two coincident)
- Two symmetric transmission zeros
- Two coincident pairs of symmetric zeros (four TZs)

The obtained return loss value increases with the distance of the transmission zeros to the passband.

To increase the flexibility in assigning the electrical requirements of the path filters, additional transmission zeros could be introduced by exploiting the inner block D (Fig. 1). However, the introduction of these zeros must not alter the inline topology of the block in order to maintain the main feature of path filters. A suitable solution is the use of frequency-variant couplings (FVC), which allow the introduction of transmission zeros in inline topologies [3]-[5]. The evaluation of the path filter characteristic polynomials in the case that block D also introduces transmission zeros does not change with respect to the procedure presented in [1] (in case of symmetric zeros extracted by the dangling blocks, the additional transmission zeros must also exhibit the same symmetry for the procedure to work properly).

II. SYNTHESIS OF PATH FILTERS WITH ADDITIONAL ZEROS

Once the characteristic polynomials of the new configuration have been evaluated, blocks *S* and *D* can be extracted by means of classical extracted-pole techniques [6]. The inner block *D* is then defined by the remaining polynomials $P_D(s)$, $F_D(s)$, $E_D(s)$. Note that, in the considered case, $P_D(s)$ is not a constant as in the case of classical path filters (its roots represent the additional zeros introduced by the inner block). We can then synthesize the inner block with an inline FVC configuration, using recently published procedures [7,8]. The resulting coupling matrix, combined with the extracted parameters of the dangling blocks, represent the overall coupling matrix of the modified path filter configuration. Note that also a non-diagonal capacitance matrix results from the synthesis, whose off-diagonal elements represent the FVC couplings.

The last step of the synthesis consists in the de-normalization of coupling and capacitance matrices so as to obtain the universal parameters necessary for the dimensioning of the physical structure implementing the path filter.

As an example, let consider the following requirements:

$np=8$, $n_S=n_D=n_L=2$, $zS=zL=[1.1i, -1.1i]$, $zD=[1.45i, -1.45i]$

Note that four zeros (two coincident symmetric pairs) must be extracted by the dangling blocks and two symmetric zeros by the inner block *D*.

The characteristic polynomials obtained by using the procedure in [1] are:

P(s)=[0.1555i 0 0.7032i 0 1.0188i 0 0.4786i]

F(s)=[1 0 2.4918 0 2.0859 0 0.6352 0 0.04177]

E(s)=[1 2.0133 4.5185 5.6907 6.4512 5.1761 3.4056 1.4981 0.48047]

It can be observed that the additional zeros have not modified the resulting return loss (21.2 dB) with respect to the value obtained if only the zeros produced by the dangling blocks are present. As in classical path filters the zeros extracted by the dangling blocks should be the closest to the passband so as to ensure that resulting return loss value is not too large.

Extraction of dangling blocks produces the following result (the elements of the final coupling matrix are reported):

$M_{11}=M_{22}=0$, $M_{12}=1.1$, $M_{S1}=0.6132$

$M_{88}=M_{77}=0$, $M_{78}=1.1$, $M_{L8}=0.6132$

The polynomials of block *D* are:

P_D= [0.1555i 0 0.3269i], F_D=[1 0 0.6874 0 0.0285]

E_D=[1 1.2614 1.4829 0.9124 0.3282]

Using the procedure in [7], the coupling and capacitance matrices of block *D* with FVC inline topology is obtained (the frequency-variant couplings are in position 2 and 4 respectively):

$$M_D=\begin{bmatrix} 0 & 0.6696 & 0 & 0 & 0 & 0 \\ 0.6696 & -0.551 & 0.6862 & 0 & 0 & 0 \\ 0 & 0.6862 & -0.44 & 0.4272 & 0 & 0 \\ 0 & 0 & 0.4272 & 0.44 & 0.6862 & 0 \\ 0 & 0 & 0 & 0.6862 & 0.551 & 0.6696 \\ 0 & 0 & 0 & 0 & 0.6696 & 0 \end{bmatrix}$$

$$C_D=\begin{bmatrix} 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 1 & -0.473 & 0 & 0 & 0 \\ 0 & -0.473 & 1 & 0 & 0 & 0 \\ 0 & 0 & 0 & 1 & 0.473 & 0 \\ 0 & 0 & 0 & 0.473 & 1 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 \end{bmatrix}$$

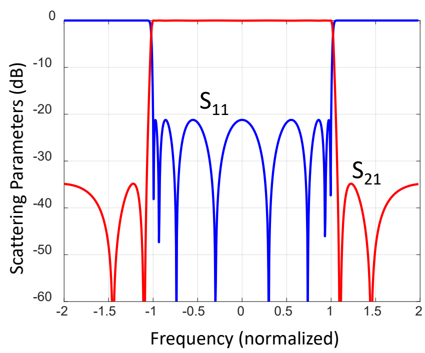

Fig. 2. S parameters of the synthesized novel path filter

From M_D and C_D we get the elements of the coupling (*M*) and capacitance (*C*) matrices of the novel path filter (those from the dangling blocks have been specified above):

$M_{33}=M_{66}=-0.5507$, $M_{44}=M_{55}=-0.4406$, $M_{S3}=M_{L7}=0.6996$, $M_{34}=M_{56}=0.6862$, $M_{45}=0.4272$, $C_{34}=-0.473$, $C_{56}=0.473$

The filter response as computed from *M* and *C* matrices is shown in Fig. 2.

III. De-Normalization and Waveguide Implementation

Assume that the novel path filter synthesized in the previous Section is de-normalized with f_0=5 GHz and B=100 MHz (B_n=0.02). The de-normalized network is characterized by the resonating frequencies and the coupling coefficients determined from the coupling and capacitance matrices by means of the following formulas:

$$f_{0,k}=f_0\left(\frac{B_nM_{k,k}}{2}+\sqrt{\left(\frac{B_nM_{k,k}}{2}\right)^2+1}\right),$$

$$k_{i,j}=B_nM_{i,j},\quad kv_{i,j}=C_{i,j}$$

$$Q_{S,i}=\frac{1}{B_nM_{S,i}^2},\quad Q_{L,np}=\frac{1}{B_nM_{L,np}^2}$$

The resulting de-normalized filter is described by the routing scheme in Fig. 3 where the computed de-normalized parameters are also reported.

Fig. 3. Routing scheme of the de-normalized filter. Numbers above black circles are the resonating frequencies of the resonators; numbers below the lines are the coupling coefficients (or the external Q for those connected to source or load). For FVCs also the *kv* parameter is reported.

To implement the considered filter in waveguide technology (assumed waveguide cross section: 45 x 22.5 mm) the equivalent circuit in Fig. 4 is derived from the de-normalized parameters (the procedure proposed in [9] has been used to this purpose).

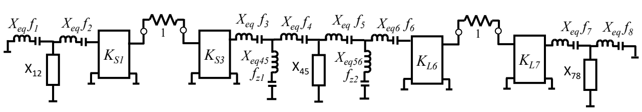

Fig. 4. Equivalent circuit of the de-normalized filter suitable for waveguide implementation

The elements of the circuit in Fig. 4 are then be replaced with physical waveguide components. The first elements to replace are the horizontal series resonators which are implemented by cavities operating on TE_{101} mode. Then, a suitable coupling structure must be devised to realize the two inverters connected to the input/output ports. The found solution is constituted by a T-Junction on the waveguide E-plane connected to two shunt reactances by means of waveguide sections of suitable length. The resulting circuit, reported in Fig. 5a, must then be adjusted by optimization for compensating the frequency dispersion of the physical components (the optimization is however very fast because it is carried out at circuit level). The S parameters obtained after the optimization are shown in Fig. 5b.

The following step of the dimensioning is the replacement of the shunt reactances in Fig. 5a with physical structures. We have used inductive irises for implementing the frequency-invariant reactances and partial height posts with square cross section for the series resonators [9]. The irises are defined by thickness (*tw*) and aperture (*W*) whereas the posts dimensions are the thickness (*t*), the offset with respect the waveguide center (*off*) and the penetration into the waveguide (*h*).

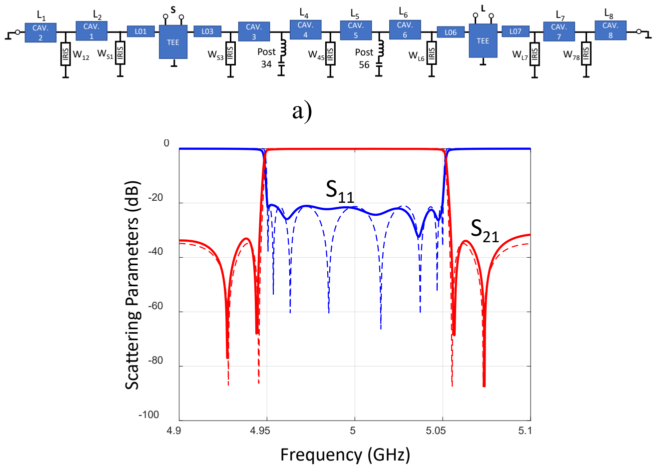

Fig. 5. a) Schematic path filter configuration after replacing the elements of the equivalent circuit in Fig. 4 with waveguide components. b) Response of the circuit after optimization (solid lines). The ideal response (Fig. 2) is also reported for comparison.

The dimensioning of irises and posts is carried out by imposing the computed *S* parameters (obtained through full-wave simulations) as close as possible to those of the ideal elements shown in Fig. 5a (the loading effect produced by the physical components is taken into account by properly correcting the lengths of the adjacent cavities). Fig. 6 shows the drawing of the finally dimensioned structure (all the geometrical parameters are reported on the figure).

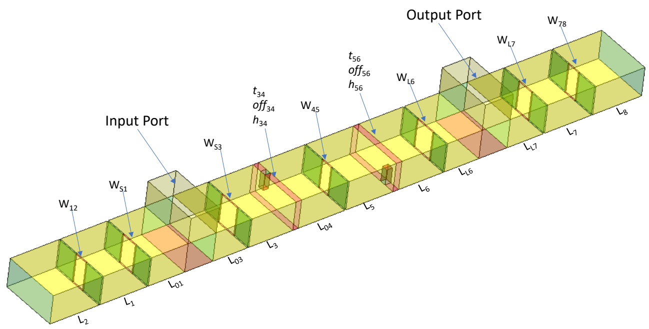

Fig. 6. Drawing of the novel path filter with the relevant dimensions (all irises have the same thickness *tw*=1mm).

The assigned dimensions are those obtained from the circuit optimization and are reported below (all dimensions are in mm; the irises thickness is *tw*=1mm).

L_1=37.51, L_2=39.18, L_{S1}=28.35, L_{S3}=28.64, L_3=35.56, L_4=37.7, L_5=37.11, L_6=35.34, L_{L6}=27.71, L_{L7}=29.67, L_7= L_1, L_8=L_2, W_{12}=10.75, W_{S1}=13.44, W_{S3}=16.43, W_{45}=9.55, W_{L6}=16.4, W_{L7}= W_{S1}, W_{78}= W_{12}, t_{34}=4.56, off_{34}=12.1, h_{34}=11.85, t_{56}=4.4, off_{56}=12.33, h_{56}=12.39.

The response of the filter in Fig. 6 has been computed with a full wave simulator (μWave Wizard from Mician) and the result is reported in Fig. 7. For comparison, also the optimized circuit response is reported on the same figure. The good agreement between the two responses validates the design procedure for the novel path filters here proposed. Note the excellent accuracy of this procedure, despite no full wave optimization of the overall physical structure has been used.

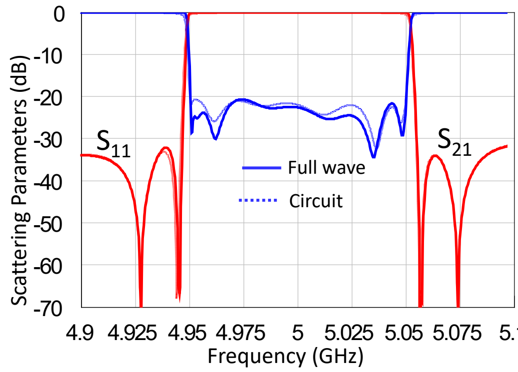

Fig. 7. Response of the dimensioned path filter with full wave analysis (solid lines). For comparison, the response of the equivalent circuit with ideal couplings (Fig. 5a) is also reported (dashed lines).

IV. Conclusion

In this work we have extended the basic configuration of path filters [1] to allow the introduction of additional transmission zeros in the response. The additional zeros are generated in the inner part of the path filter by means of frequency-dependent couplings (FVCs), so as to comply with the intended inline topology. A design procedure for the novel type of path filters has then been presented, suitable for rectangular waveguide implementation. A test filter operating at 5 GHz with 2% normalized bandwidth and 6 transmission zeros (two generated by FVCs) has been designed for validating the novel design procedure. The full wave simulation of the designed structure is in excellent agreement with the expectations.

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