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Application of the *N* + 2 Transversal Network Method to the Study of a Coupled Resonator Filter

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Abstract

This paper presents a new approach to synthesize admittance function polynomials and coupling matrices for coupled resonator filters. The *N* + 2 transversal network method is applied to study a coupled resonator filter. This method allowed us to determine the polynomials of the reflection and transmission coefficients. A study is made for a 4 poles filter with 2 transmission zeros between the *N* + 2 transversal network method and the one found in the literature. A MATLAB code was designed for the numerical simulation of these coefficients for the 6, 8, and 10 pole filter with 4 transmission zeros.

Keywords

Resonator Filter, Coupling Matrix, Transmission Zero, Transversal Network Method

1. Introduction

Terrestrial and space communications have undergone significant development in recent years thanks to the use of increasingly sophisticated equipment, among which are prominently those that provide signal processing such as filters [1] [2]. The integration of wireless transmission systems in the radiofrequency and microwave domains requires the reduction of the dimensions of each elementary function of the transmission-reception chain [3] [4]. The ever-increasing number of users of the frequency spectrum in these areas has created new constraints on the end elements of telecommunication systems [5]. Electrical performance, increased selectivity and miniaturization to be improved are the main constraints.

The problems of increasing selectivity have led in recent years to the development of an original topology aimed at improving electrical responses both in the bandpass and in the attenuated band.

It is with this in mind that many techniques and electromagnetic modeling methods have been developed in recent decades, with the aim of designing small-sized elements while increasing their performance and minimizing their cost.

The study of coupled resonator filters has been the subject of much work in recent years [6] [7]. Researchers have developed numerical methods to solve various complex problems. But the determination of poles, transmission zeros and the important rejection level for a limited filter order and consequently, a reduced loss level are still a major challenge. The objective of this work is to apply the $N + 2$ transversal network method to coupled resonator filters prior to their design and realisation for use in the millimetre band.

In this frequency band, we are faced with technological difficulties. Indeed, given the wavelengths involved, the technological dispersion must be as low as possible to ensure that the device operates correctly. Furthermore, for similar reasons, the use of such components requires an in-depth study of these resonator filters before they can be produced. Specialised methods must therefore be applied to improve the electromagnetic characteristics of the filters.

2. Theory

The starting point for the synthesis of the circuit coupling matrix is the determination of the transfer and reflection polynomials which can be written in the general form [8]:

$$S_{11}(s) = \frac{P(s)}{\varepsilon_r E(s)} \tag{1}$$

And

$$S_{21}(s) = \frac{F(s)}{\varepsilon E(s)} \tag{2}$$

The functions $P(s)$, $F(s)$ and $E(s)$ are polynomials depending on the complex frequency s. For the filter to be stable $E(s)$ must be a Hurwitz polynomial [9].

The polynomials $E(s)$ and $F(s)$ are of degree N while $P(s)$ is of degree N_{fz}. N being the order of the filter and N_{fz} the number of transmission zeros if $N_{fz} < N$ and $\varepsilon_r = 1$.

The filter is said to be canonical if $N_{fz} = N$ and $\varepsilon_r \neq 1$. For the purpose of this synthesis, we will restrict ourselves to the case of the circuit consisting of an array of N coupled lossless resonators.

Let's consider a network of coupled resonators whose equivalent circuit is made of N loops. It has two accesses (**Figure 1**), at the input we have an impedance R_1 and at the output the load R_N. These accesses can be normalized to 1 by inserting transformers at the input and output, filter synthesis based on such a network was first introduced by [10].

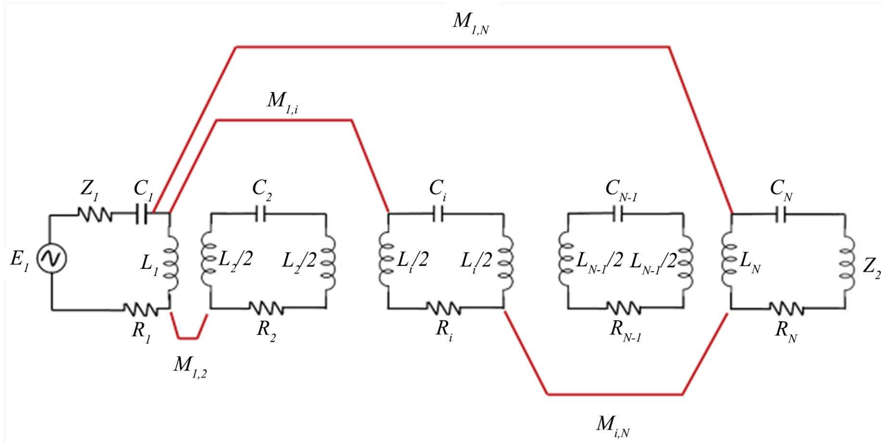

Figure 1. Equivalent circuit of a filter with N coupled resonators.

By applying the law of meshes to each resonator to the internal circuit of **Figure 1**, we have the following relations:

$$[V]=[Z][i] \tag{3}$$

$$\begin{bmatrix} V_1 \\ 0 \\ \vdots \\ 0 \end{bmatrix} = [R+SI+jM] = \begin{bmatrix} i_1 \\ i_2 \\ \vdots \\ i_n \end{bmatrix} \tag{4}$$

$$R=\begin{bmatrix} R_1 & 0 & \cdots & 0 \\ 0 & 0 & \cdots & 0 \\ \vdots & \vdots & \ddots & \vdots \\ 0 & 0 & \cdots & R_n \end{bmatrix}$$

$$M=\begin{bmatrix} M_{11} & M_{12} & \cdots & M_{1n} \\ M_{12} & M_{22} & \cdots & M_{2n} \\ \vdots & \vdots & \ddots & \vdots \\ M_{1n} & M_{2n} & \cdots & M_{nn} \end{bmatrix}$$

$$SI=\begin{bmatrix} S & 0 & \cdots & 0 \\ 0 & S & \cdots & 0 \\ \vdots & \vdots & \ddots & \vdots \\ 0 & 0 & \cdots & S \end{bmatrix}$$

where $[R]$ is the resistance matrix, $[M]$ is the mutual coupling matrix of order N between resonators of elements M_{ij} designating the coupling between resonators i and j, assumed independent.

$[I]$ is the identity matrix and $S=\frac{j}{\omega}\left(\frac{\omega}{\omega_o}-\frac{\omega_o}{\omega}\right)$ is the common resonance pulsation of the synchronized resonators. To obtain an operation of the network of coupled resonators in short-circuit, it is enough to pose, $R_1 = R_N = 0$ (*i.e.* $R = 0$) in Equation (4). Under these conditions the current $[I]$ is given by:

$$[I]^t=[jM+SI][V] \tag{5}$$

2.1. Determination of the Matrix $[Y_N]$ from the Transmission and Reflection Coefficients $S_{21}(s)$ and $S_{11}(s)$

The considered network being symmetrical and reciprocal, we can put the admittance matrix $[Y_N]$ of the whole network in the form (**Figure 2**) [10].

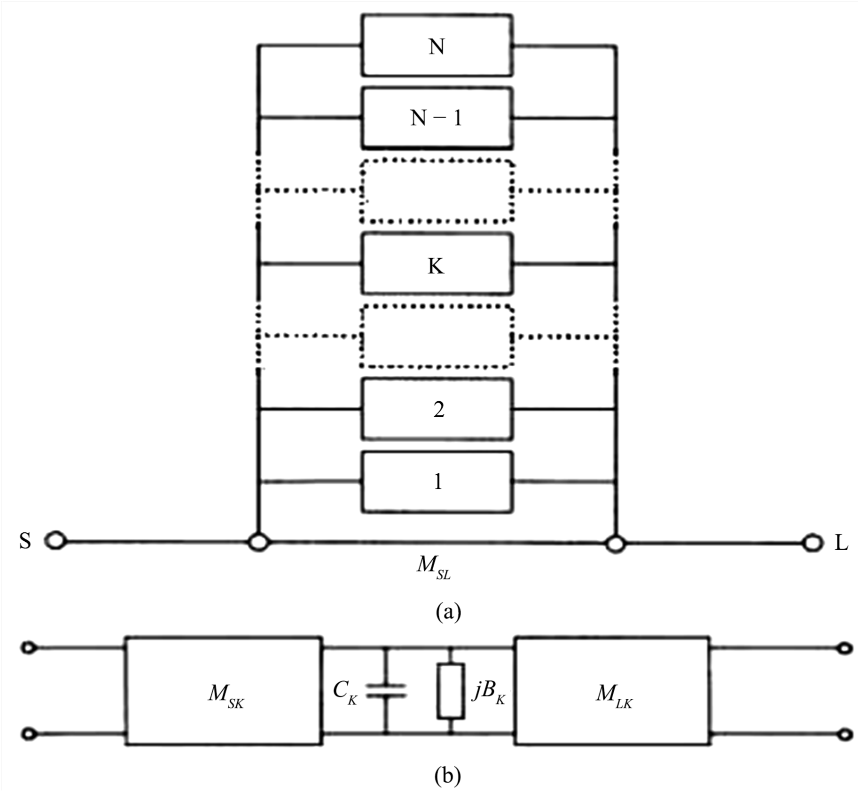

Figure 2. Canonical transverse array, (a) transverse array matrix *N*; (b) equivalent circuit of the K^{th}.

$$[Y_N]=\begin{bmatrix} Y_{11}(s) & Y_{12}(s) \\ Y_{21}(s) & Y_{22}(s) \end{bmatrix}=j\begin{bmatrix} 0 & K_\infty \\ K_\infty & 0 \end{bmatrix}+\sum_{k=1}^{n}\frac{1}{s-j\lambda_k} \quad (6)$$

With

$$Y_{21}(s)=\sum_{k=1}^{n}\frac{r_{21k}}{s-j\lambda_k}$$

$$Y_{22}(s)=\sum_{k=1}^{n}\frac{r_{22k}}{s-j\lambda_k}$$

The real constant $K_\infty=0$ was introduced here to account for the number of transmission zeros $K_\infty=0$, the fully canonical case where the number of finite transmission zeros (N_{fz}) is equal to the filter degree *N*. In this case, the degree of the numerator of $Y_{21}(s)$ is equal to that of its denominator. We calculate the coefficient K_∞ such that:

$$K_\infty=\frac{\varepsilon_r}{\varepsilon}\left(\frac{1}{\varepsilon_r+1}\right) \quad (7)$$

2.2. Synthesis of the *N* + 2 Transversal Matrix

The elements of the coupling matrix are given by the relation (7).

$$\begin{cases} M_{sL} = K_{\infty} \\ \dfrac{r_{21k}}{s - j\lambda_k} = \dfrac{M_{Sk}}{M_{Lk}} \\ \dfrac{r_{22k}}{s - j\lambda_k} = \dfrac{M_{Lk}^2}{sC_k + jB_k} \end{cases} \quad (7)$$

The residues r_{21k} and r_{22k} and the eigen values λ_k are determined from the polynomials of the transmission coefficients $S_{21}(s)$ and reflection coefficients $S_{11}(s)$ of the filter and thus, by equating the real and imaginary parts, it is possible to obtain the coupling coefficients M_{ij} between the different resonators [11].

$$\begin{cases} C_k = 1,\ B_k\left(\equiv M_{kk}\right) = -\lambda_k;\ M_{Sk}M_{Lk} = r_{21k} \\ M_{Lk} = \sqrt{r_{22k}}\ \text{ et }\ M_{Sk} = \dfrac{r_{21k}}{\sqrt{r_{22k}}} \quad k = 1, 2, \cdots, N \end{cases} \quad (8)$$

2.3. Similarity Transformation and Annihilation of Matrix Elements

In a similarity (rotation) transformation on an N + 2 coupling matrix, M_1 is performed by pre- and post-multiplying the original matrix M_0 by an N + 2 rotation matrix, R and its transpose R^t [12].

$$M_1 = R_1 M_0 R_1^t \quad (8)$$

where M_0 is the original matrix, M_1 is the matrix after the transformation operation and R is the rotation matrix defined as shown by the matrix in **Figure 3**.

	1	2	3	4	5	6	7
1	1						
2		1					
3			Cr	-Sr			
4				1			
5			Sr		Cr		
6						1	
7							1

Figure 3. 7th degree rotation matrix Rr pivot.

3. Results and Discussion

3.1. Application of the *N* + 2 Transversal Network Method

In order to master the filter synthesis process, using the N + 2 transversal network method, we will first validate this method by an application on the filter proposed by R. Cameron [10]. Finally, we will synthesize and analyze a filter of order 6 and order 8.

Filter Proposed by R. Cameron

In this section we will make a comparative study of resonator filters using the $N + 2$ transversal network method and the one proposed by R. Cameron. We consider the following specifications:

- The order of filter is 4 and has 2 transmission zeros: +j1, 3217 and +j1, 8082;
- The reflection corresponds to 22 dB in the passband. By following the different steps previously mentioned to determine the coupling matrix with the $N + 2$ transversal array method, we obtained the following coupling matrix:

$$[M_0] = \begin{bmatrix} 0.000 & -0.6037 & 0.3048 & -0.4860 & 0.7130 & 0.000 \\ -0.6037 & 1.5535 & 0.000 & 0.000 & 0.000 & 0.6037 \\ 0.3048 & 0.000 & -1.1981 & 0.000 & 0.000 & 0.3028 \\ -0.4860 & 0.000 & 0.000 & -1.0883 & 0.000 & 0.4860 \\ 0.7130 & 0.000 & 0.000 & 0.000 & -0.0263 & 0.7130 \\ 0.000 & 0.6037 & 0.3028 & 0.4860 & 0.7130 & 0.000 \end{bmatrix} \quad (9)$$

$[M_0]$ is a 4-pole coupling matrix of the R. Cameron resonator filter [10]. The first row and the first column correspond to the numbering of the poles and the input/output ports [13].

This matrix is symmetrical with respect to its transpose. The coupling matrix (4) is selected according to the homogeneity of its coupling values. Indeed, the couplings for this matrix are between 0.6037 and 0.3048 while they are between 0.4860 and 0.7130 for the second solution. There is a coupling matrix topology that characterizes the filter architecture. A rotation sequence is applied to this matrix to change its topology and therefore adapt the filter architecture to the implementation technology. We proceeded to 4 rotations of the matrix $[M_0]$ to obtain the following coupling matrix $[M_1]$ which will allow us to realize the filter with the desired configuration as shown in **Figure 4**.

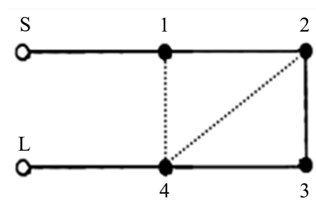

Figure 4. Coupling diagram (4-2).

$$[M_1] = \begin{bmatrix} 0.000 & -1.0963 & 0.000 & 0.000 & 0.000 & 0.000 \\ -1.0963 & 0.1535 & 0.9604 & 0.000 & 0.3604 & 0.000 \\ 0.000 & 0.9604 & -0.1432 & -0.2863 & 0.7740 & 0.000 \\ 0.000 & 0.000 & -0.2863 & -0.9243 & -0.5678 & 0.000 \\ 0.000 & 0.3604 & 0.7740 & -0.5678 & 0.1549 & 1.0958 \\ 0.000 & 0.000 & 0.000 & 0.000 & 1.0958 & 0.000 \end{bmatrix} \quad (10)$$

Knowing the polynomials $S_{11}(s)$ and $S_{21}(s)$ of the reflection and transfer functions, we will plot in **Figure 5** and **Figure 6** the filter responses given by [10] and our simulations.

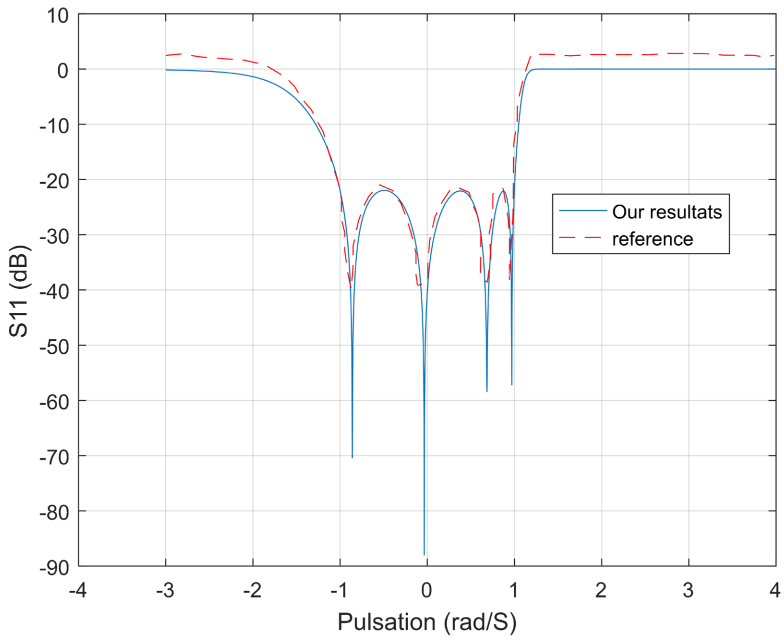

Figure 5. Reflection frequency response of the 4-pole filter.

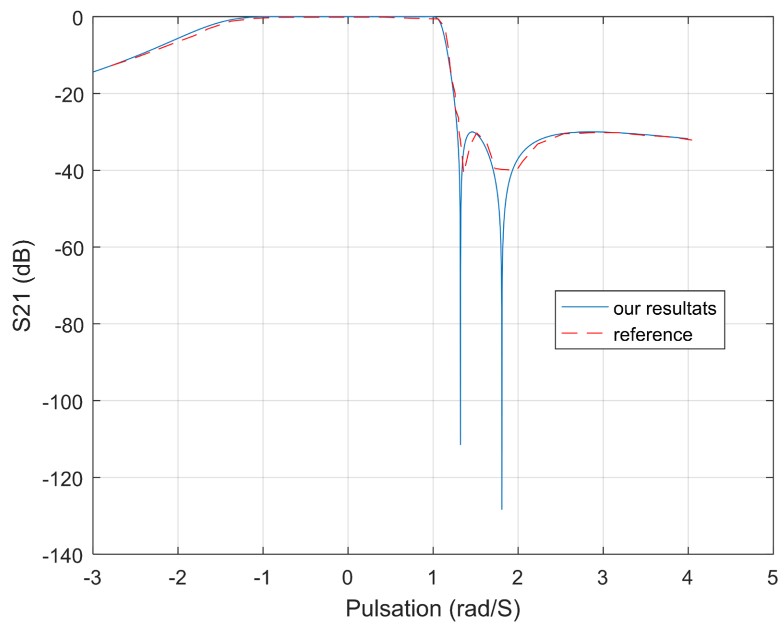

Figure 6. Transmission frequency response of the 2-zero filter.

Figure 5 and **Figure 6** show a good agreement between our results and those proposed by R. Cameron [10]. This shows a good control of the method used. In the following we propose to analyze the synthesis of the 6th and 8th order filters.

3.2. 6-Pole Bandpass Filter with 4 Transmission Zeros

After studying the R. Cameron filter of order 2, we propose to analyze a band-pass filter with coupled resonators, in order to obtain the transfer and reflection polynomials with the bandpass filter using the six-pole coupling matrix whose characteristics are as follows:

- It is of order 6 and has 4 transmission zeros: −j3.0431; −j1.8082; j1.3217 and j5.1910;
- The reflection losses correspond to 20 dB; contains two transmission zeros on each side of the bandwidth. Using the same procedure we obtain the following matrix.

$$[M_0]=\begin{bmatrix} 0.000 & 0.3168 & 0.2935 & 0.4403 & 0.4538 & 0.4935 & 0.4934 & 0.000 \\ 0.3168 & 1.2104 & 0.000 & 0.000 & 0.000 & 0.000 & 0.000 & -0.3143 \\ 0.2935 & 0.000 & -1.1791 & 0.000 & 0.000 & 0.000 & 0.000 & 0.2989 \\ 0.4403 & 0.000 & 0.000 & -1.0804 & 0.000 & 0.000 & 0.000 & -0.4409 \\ 0.4538 & 0.000 & 0.000 & 0.000 & 1.0417 & 0.000 & 0.000 & 0.4534 \\ 0.4935 & 0.000 & 0.000 & 0.000 & 0.000 & 0.4639 & 0.000 & 0.4936 \\ 0.4934 & 0.000 & 0.000 & 0.000 & 0.000 & 0.000 & 0.3873 & -0.4933 \\ 0.000 & -0.3143 & 0.2989 & -0.4409 & 0.4534 & 0.4936 & -0.4933 & 0.000 \end{bmatrix} \quad (11)$$

This matrix is not unfeasible in practice, so we will use the configuration shown in Figure 7.

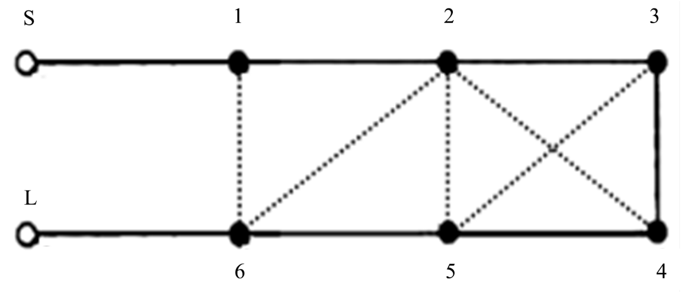

Figure 7. Coupling diagram (6-4).

After all the rotations we have obtained the following matrix.

$$[M_1]=\begin{bmatrix} 0.000 & 1.0360 & 0.000 & 0.000 & 0.000 & 0.000 & 0.000 & 0.000 \\ 1.0360 & 0.0059 & -0.8663 & 0.000 & 0.000 & 0.000 & 0.0066 & 0.000 \\ 0.000 & -0.8663 & 0.0066 & 0.5912 & 0.000 & -0.1605 & -0.0120 & 0.000 \\ 0.000 & 0.000 & 0.5912 & 0.0623 & -0.7036 & 0.0889 & 0.000 & 0.000 \\ 0.000 & 0.000 & 0.000 & -0.7036 & -0.1706 & -0.5829 & 0.000 & 0.000 \\ 0.000 & 0.000 & -0.1605 & 0.0889 & -0.5829 & 0.0122 & -0.8667 & 0.000 \\ 0.000 & 0.0066 & -0.0120 & 0.000 & 0.000 & -0.8667 & -0.0003 & -1.0369 \\ 0.000 & 0.000 & 0.000 & 0.000 & 0.000 & 0.000 & -1.0369 & 0.000 \end{bmatrix} \quad (12)$$

After determining the coupling matrix we have represented the frequency response of the filter shown in Figure 8.

The analysis of these simulation results from Figure 8 presents 4 transmission zeros on both sides of the bandwidth as planned by the specifications, the reflection losses are estimated at 20 dB, the losses are 60 dB at the lower lobe and 30 dB at the upper lobe.

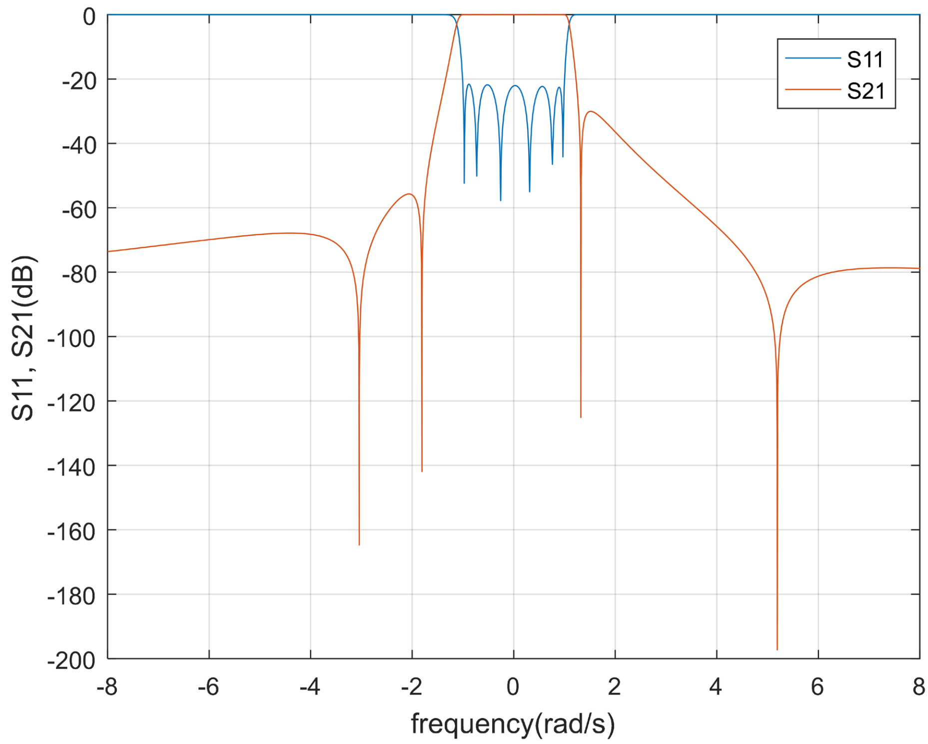

Figure 8. Frequency response of 6 poles to 4 zeros.

3.3. Analysis of an 8-Pole Filter with 4 Transmission Zeros

This section presents the analysis of the filter using the same load book with the 6 order filter. The transfer function meeting the electrical specifications has the following indications: 8 poles and 4 transmission zeros whose original matrix is as follows.

$$[M_0]=\begin{bmatrix} 0.00 & 0.299 & 0.292 & 0.375 & 0.384 & 0.360 & 0.366 & 0.402 & 0.402 & 0.00 \\ 0.299 & 1.159 & 0.00 & 0.00 & 0.00 & 0.00 & 0.00 & 0.00 & 0.00 & -0.298 \\ 0.292 & 0.00 & -1.141 & 0.00 & 0.00 & 0.00 & 0.00 & 0.00 & 0.00 & 0.307 \\ 0.375 & 0.00 & 0.00 & -1.102 & 0.00 & 0.00 & 0.00 & 0.00 & 0.00 & -0.379 \\ 0.384 & 0.00 & 0.00 & 0.00 & 1.091 & 0.00 & 0.00 & 0.00 & 0.00 & 0.382 \\ 0.360 & 0.00 & 0.00 & 0.00 & 0.00 & -0.781 & 0.00 & 0.00 & 0.00 & 0.360 \\ 0.366 & 0.00 & 0.00 & 0.00 & 0.00 & 0.00 & 0.742 & 0.00 & 0.00 & -0.366 \\ 0.402 & 0.00 & 0.00 & 0.00 & 0.00 & 0.00 & 0.00 & -0.302 & 0.00 & -0.402 \\ 0.402 & 0.00 & 0.00 & 0.00 & 0.00 & 0.00 & 0.00 & 0.00 & 0.254 & 0.402 \\ 0.00 & -0.298 & 0.307 & -0.379 & 0.382 & 0.360 & -0.366 & -0.402 & 0.402 & 0.00 \end{bmatrix} \quad (13)$$

From the original matrix $[M_0]$ we proceeded to a technique which consists in making 8 rotations to obtain couplings. The equivalent circuit consists of rectangular half-wave resonators illustrated in **Figure 9**.

The topology compatible with a filter realization presented in **Figure 9**, shows a bulky device and following the same procedure of the previous sections, we obtained the following rotation matrix.

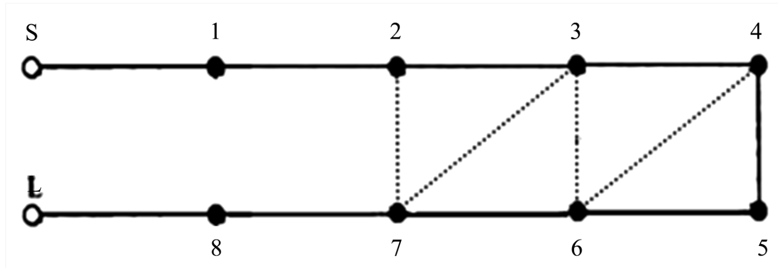

Figure 9. Coupling diagram (8-4).

$$[M_1]=\begin{bmatrix} 0.000 & 1.025 & 0.000 & 0.000 & 0.000 & 0.000 & 0.000 & 0.000 & 0.000 & 0.000 \\ 1.025 & 0.002 & -0.849 & 0.000 & 0.000 & 0.000 & 0.000 & 0.000 & 0.000 & 0.000 \\ 0.000 & -0.849 & 0.002 & 0.597 & 0.000 & 0.000 & 0.000 & -0.002 & 0.000 & 0.000 \\ 0.000 & 0.000 & 0.597 & 0.000 & -0.541 & 0.000 & -0.118 & -0.006 & 0.000 & 0.000 \\ 0.000 & 0.000 & 0.000 & -0.541 & 0.036 & -0.649 & -0.066 & 0.000 & 0.000 & 0.000 \\ 0.000 & 0.000 & 0.000 & 0.000 & -0.649 & -0.134 & 0.535 & 0.000 & 0.000 & 0.000 \\ 0.000 & 0.000 & 0.000 & -0.118 & -0.066 & 0.535 & 0.010 & -0.595 & 0.000 & 0.000 \\ 0.000 & 0.000 & -0.002 & -0.006 & 0.000 & 0.000 & -0.595 & 0.006 & -0.852 & 0.000 \\ 0.000 & 0.000 & 0.000 & 0.000 & 0.000 & 0.000 & 0.000 & -0.852 & -0.012 & 1.030 \\ 0.000 & 0.000 & 0.000 & 0.000 & 0.000 & 0.000 & 0.000 & 0.000 & 1.030 & 0.000 \end{bmatrix} \quad (14)$$

This step of the synthesis allows us to find the dimensions between resonators that allow us to realize the different couplings M_{ij} of the coupling matrix $[M_1]$. Indeed, for a given dimension between resonators, the shape of the frequency response of the coupled resonators is given in **Figure 10**.

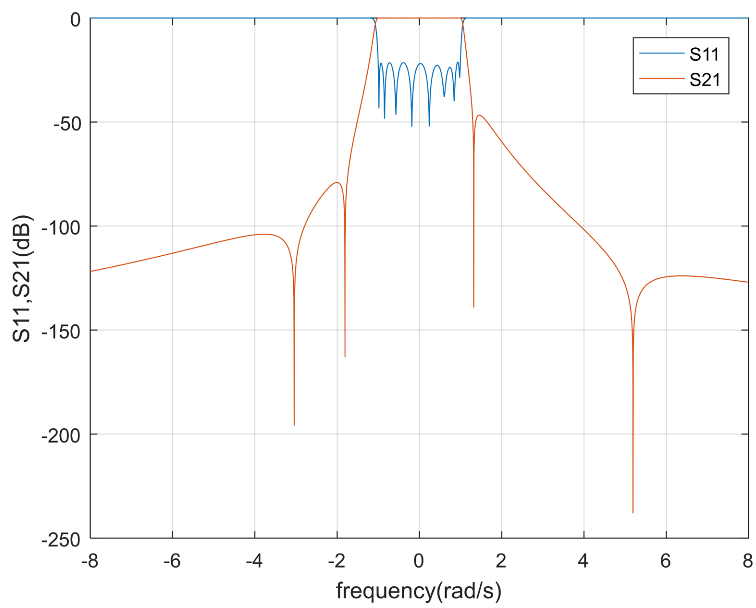

Figure 10. Frequency response of 8 poles to 4 zeros.

Therefore the frequency response corresponds to the coupling diagram (8-4) which has four transmission zeros on each side of the passband. The reflection losses are estimated at 20 dB and the insertion losses are 80 dB at the lower lobe and 50 dB at the upper lobe.

3.4. Comparison of Frequency Responses

Figure 11 shows a comparative study of the transmission responses for different values of N with 4 transmission zeros.

Table 1 shows a comparative study of 6, 8 and 10 order filters with 4 transmission zeros. We see that the order of the filter influences the lobe levels and the bandwidth. The insertion loss increases as N increases.

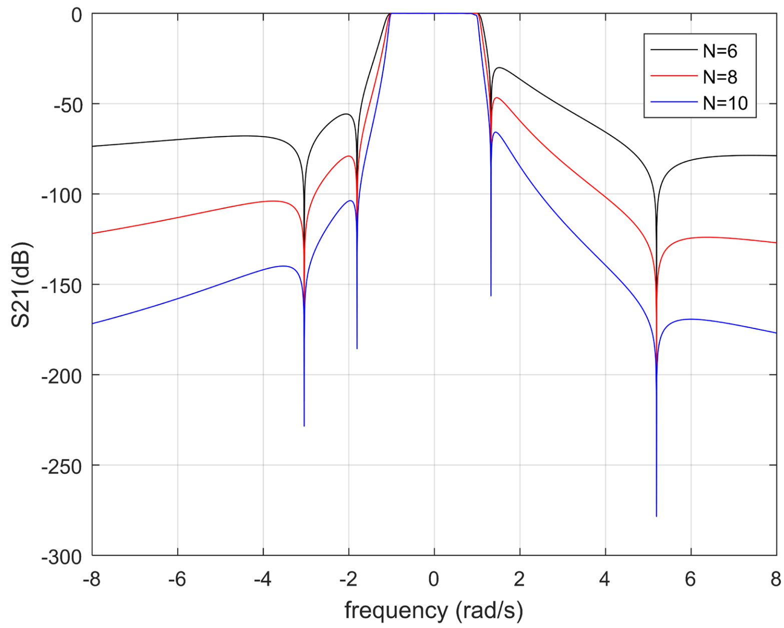

Figure 11. Comparison of 6, 8 and 10 order filters.

Table 1. Comparative table of filters.

Order of the N filter	Insertion losses in the passband (dB)	Lower lobe	Upper lobe	Bandwidth
6	0.02625	55.73	30.16	2.2160
8	0.02825	79.18	47.09	2.1270
10	0.05723	104.1	65.78	2.0490

4. Conclusion

The work undertaken in this article is part of the analysis of microwave filters using the $N + 2$ transversal network method. First, we have validated this method by an application on the filter proposed by R. Cameron. A good control of the synthesis process has been observed. The filters of orders 6, 8 and 10 with 4 transmission zeros have been studied. We found that the order of the filter influences the width of the bandwidth and the level of insertion losses. There are many prospects for this work. The filters studied in this article will be designed and produced. Applying Gram Smith's method to couple resonator filters; make a comparative study of resonator filters with 4, 6, 8 and 10 poles using the $N+2$ transversal network method in order to draw a conclusion on the bandwidth.

Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

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