Synthesis of Extracted Pole Filters with Transmission Zeros in Both Stopbands and Non-Resonant Nodes of the Same Nature

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***Abstract*—Extracted pole filters alternating transmission zeros above and below the passband are intrinsically related to the use of non-resonant nodes of different nature (inductive and capacitive). This work demonstrates that it is possible to synthesize an extracted pole filter showing transmission zeros in both sides of the passband but implementing all non-resonant nodes of the same reactive nature, overcoming the limitations imposed by some technologies. The proposed feature is achieved by a special consideration of the input reflection phase of the generalized Chebyshev filter function, affecting input and output resonators and placing at most 2 zeros at the opposite band. A third order all-capacitive prototype filter has been synthesized and fabricated to validate the proposed statement. The concept allows to achieve all-capacitive or all-inductive filters.**

***Index Terms*—extracted pole, filter synthesis, non-resonant nodes.**

I. Introduction

THE possibility to design filters with arbitrarily placed transmission zeros (TZs) that are implemented by independent sections of the structure is the main advantage of the extracted pole technique. The contributions in [1], [2] presented the synthesis method to implement this technique exploiting the concept of the non-resonant node (NRN), that can be generalized to any technology [3]. An extracted pole section is made up of an NRN coupled to a dangling resonant node (RN) resonating at the frequency of the TZ, as in Fig. 1. The modularity provided by this technique is fantastic and offers also better sensitivity than more complex structures including cross-couplings.

One interesting topic concerning extracted pole sections is the sign of the frequency-invariant reactances (FIRs) that model NRNs in the lowpass domain. It is commonly accepted that an NRN-RN pair placing a TZ above the passband requires a negative NRN while a TZ below the passband requires a positive one. This influences how these nodes are implemented, either as capacitive or inductive reactances in the bandpass domain. This might not be an issue in some technologies such as coaxial cavity where NRNs can be detuned cavities or common microstrip inline where they might be stubs [4], [5]. However, there are some examples of technologies where only one nature of NRNs can be easily implemented. [6], [7] propose miniaturized extracted pole filter implementations using asymmetric coupled line structures. This configuration can only implement NRNs of inductive nature since the asymmetric coupled line sections are the result of the connection of a short-circuited stub (implementing a negative susceptance), a main line admittance inverter and the following short-circuited stub. The authors claim that the technology can only implement transmission zeros in the upper stopband because of that limitation.

Similarly, the E-Plane waveguide technology used in [8] is limited in that same way. The NRN is formed between septa

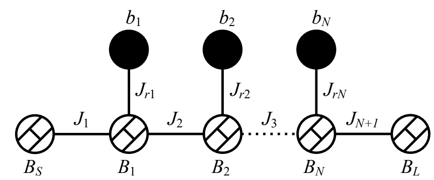

Fig. 1. General lowpass nodal scheme of an extracted pole filter. White dashed nodes are NRNs represented as frequency invariant susceptances B_i, black nodes are RNs made of a unit capacitor in parallel to a frequency invariant susceptance of value b_i and black lines are couplings in the form of admittance inverters.

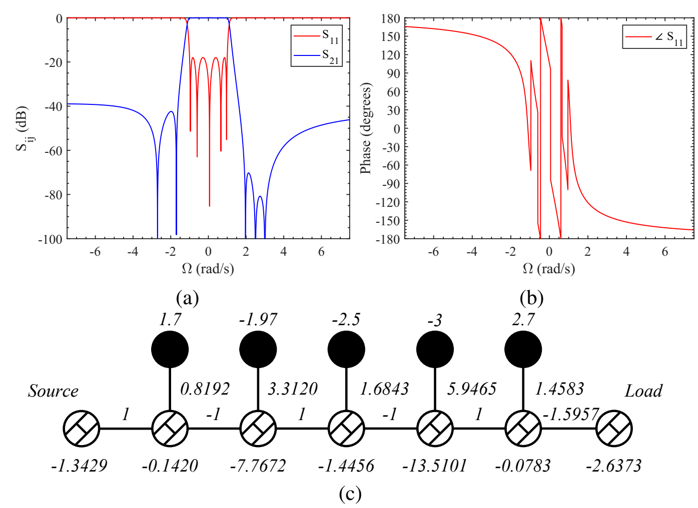

Fig. 2. 5th order filter example with 2 TZs at the lower stopband and all negative NRNs (all-inductive). (a) Lowpass magnitude response. (b) Lowpass reflection phase response. (c) Nodal lowpass network following the scheme in Fig. 1.

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and has an inductive behaviour. Therefore, apparently only TZs at the upper stopband can be implemented. Moreover, the same authors developed a more complex way to locate TZs at the lower stopband in [9] using a longer NRN with the so-called dual-mode extracted pole section that locates two poles and a single TZ. However, this approach is more complex and looses part of the modularity inherent to pure extracted pole.

In this paper we propose how to synthesize filters that locate TZs in both stopbands but keeping all NRNs of the same nature, that is, having the same sign. This is shown in the example in Fig. 2 where a 5th order filter with TZs at $-1.7,\ 1.97,\ 2.5,\ 3$ and -2.7 has been synthesized and all NRNs are negative. That is, all of inductive nature when implemented in the bandpass domain.

II. NRNs and Reflection Phase

Achieving filters with single-nature NRNs entails a careful consideration of the reflection phase of the filter function. As introduced in [10], the S-parameters of a generalized Chebyshev function are expressed as a function of the characteristic polynomials $P(s)$, $F(s)$ and $E(s)$.

$$\begin{bmatrix} S_{11}(s) & S_{12}(s) \\ S_{21}(s) & S_{22}(s) \end{bmatrix} = \frac{1}{E(s)} \begin{bmatrix} F(s)/\varepsilon_r & P(s)/\varepsilon \\ P(s)/\varepsilon & (-1)^N F(s)^*/\varepsilon_r \end{bmatrix} \quad (1)$$

The input reflection phase can be tailored if $F(s)$ is shifted by an exponential term of phase θ_{add}.

$$F'(s) = F(s)e^{j\theta_{add}} \quad (2)$$

Since during the extraction procedure in [1], [2] NRNs are computed as phase matching elements to the next extracted pole section, modifying the phase has an effect on their value. Let us discuss it with a simple example of order $N = 3$. Consider the TZ set of $\Omega = [\ 2.6, -2.2,\ 2.6]$ and return loss RL = 18 dB. In regular conditions we would expect the first and last FIR elements, let them be B_1 and B_3 as in Fig. 1, to be negative since they are related to a TZ above the passband. The internal FIR B_2 should then be positive. Fig. 3 shows the value of the three FIR elements with respect to the additional phase term θ_{add}. It is clearly seen that B_1 and B_3 transition from negative to positive value for extreme values of the reflection phase while B_2 stays inside the positive region. At $\theta_{add} = 180°$, both B_1 and B_3 exhibit the same sign as B_2. Each element has a wider range of phases for which its sign is inverted, however, they are positive at the same time only in the close vicinity of 180°. More in detail, the sign transition of B_1 happens when $\theta_{add} = 180 - \angle S_{11}(j\Omega_1)$ and the transition of B_3 is when $\theta_{add} = -180 + \angle S_{22}(j\Omega_3)$, where $S_{11}(s)$ and $S_{22}(s)$ are the original S-parameters of the unmodified Chebyshev function.

Clearly, this behaviour can be exploited to design filters that feature zeros in both stopbands only implementing NRNs of a single nature. To do so, some conditions must be met:

- θ_{add} must be fixed to 180°.
- The order of the filter must be at least 3 ($N \geq 3$)
- Internal TZs ($\Omega_k,\ k \in \{2, N-2\}$) must all have the same sign.

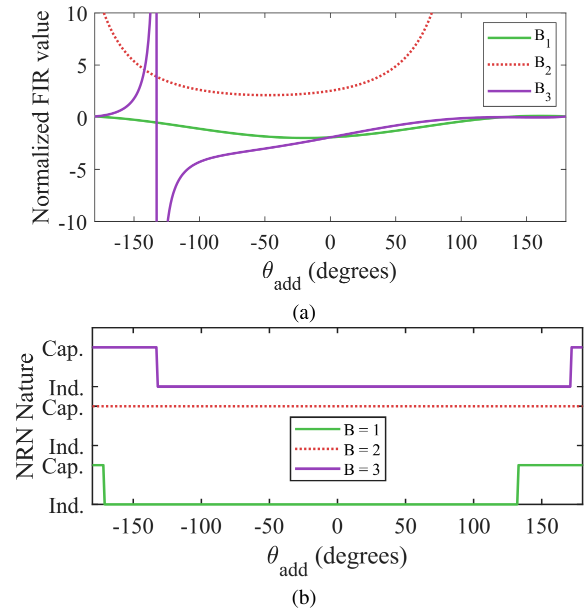


Fig. 3. Sweep on θ_{add} on the third order filter example. (a) Evolution of FIR values, (b) Nature of the synthesized NRN in the bandpass domain. *Ind.* stands for inductive, *Cap.* stands for capacitive.

- Ω_1 and Ω_N must be of opposite sign to internal TZs.

The internal TZs will define the nature of all NRNs since the FIR of their associated NRN-RN pair will maintain its sign for any value of θ_{add}. Thus, the first and last TZs must be the ones of opposite sign (i.e. allocated in the contrary stopband). In this case, up to two TZs can be allocated in the contrary band. In general terms, for a filter of order N, there will be 2 TZs in one stopband and N-2 in the other. This situation is found in the initial example in Fig. 2.

Notice that due to the input phase modification, the filter network requires the input and output NRNs, B_S and B_L that appear whenever you do not meet the phase condition for removing them, that is set in [1]. For example, since the filter in [5] is not limited to NRNs of a single nature, elements B_S and B_L can be set to zero. At the same time, [11], [12] show that sometimes the input and output NRNs are necessary, in this case directly connected to a dangling resonator due to the triple-mode structure employed.

Finally, it is worth mentioning that a result similar to the one we propose can be achieved using the technique in [13] where phase shifters are extracted instead of unitary inverters. In that case, elements B_1 and B_3 can be set to zero along with B_S and B_L at expense of implementing phase shifters of an exact value between all extracted pole sections, being B_2 the only remaining NRN.

III. Experimental Validation

To demonstrate the validity of our proposal, the third order filter of the example in section II has been manufactured. Since the internal TZ is negative, the sign of all FIRs will be positive what means that all of them will be implemented as capacitive reactances.

Let us start by synthesizing the filter setting $\theta_{add} = 180°$. The obtained lowpass values are shown on the nodal scheme

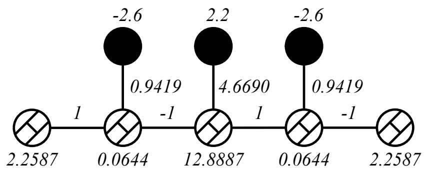
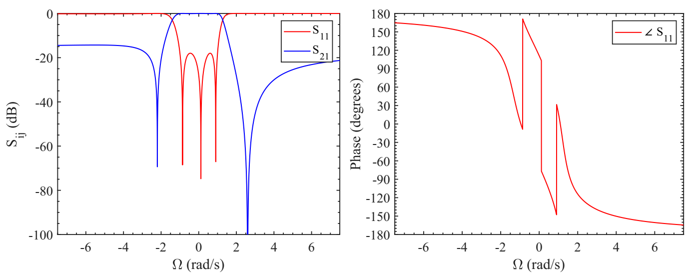


Fig. 4. Lowpass nodal scheme of the N = 3 example filter synthesized with $\theta_{add} = 180°$.



(a) (b)

Fig. 5. Lowpass response of the third order filter example with all-positive FIRs. (a) Magnitude, (b) Input reflection phase.

in Fig. 4, and Fig. 5 shows the lowpass magnitude and phase response of the synthesized filter.

For fast prototyping, the filter is implemented in microstrip technology, using quarter-wave lines at f_0 for the mainline couplings and open-circuited quarter-wave resonators at f_{TZ} (the position of TZs) in parallel with a lumped capacitor to ground for the NRN-RN pairs, similar to the case in [4].

The band specifications are central frequency $f_0 = 1480$ MHz and a bandwidth of 100 MHz. The chosen substrate is RO4003C with 508 μm thickness. In order to adapt the design to easily implementable transmission lines, the coupling matrix elements have been scaled so that the quarter-wave resonators have a characteristic impedance of $Z_r = 100\ \Omega$. After scaling, the resulting characteristic impedance of the main line quarter-wave lines $Z_{ml} = [15.59,\ 24.08,\ 24.08,\ 15.59]\ \Omega$. The lengths of the quarter-wave resonators are 29 mm for the first and third and 34.8 mm for the second. The length of the main line admittance inverters is 29.3 mm for the first and fourth, and 30 mm for the second and third. The NRNs are implemented with 0603 SMD lumped capacitors by Johanson Technology. The ideal values of the capacitive reactances after bandpass transformation are $C_{in/out} = 5$ pF for the input and output elements, $C_{1,3} = 1.469$ pF for the first and last NRNs and $C_2 = 11.94$ pF for the internal NRN.

Fig. 6 shows the fabricated filter. The comparison between measurement and full-wave simulation with ADS Momentum are depicted in Fig. 7 showing a good agreement. The fabricated filter shows an RL = 15.6 dB. As expected, it implements TZs at both sides of the passband. As known, mainline quarter-wave microstrip inverters introduce spurious responses close to the band affecting the out-of-band isolation as seen in Fig. 7 but do not affect our validation purpose.

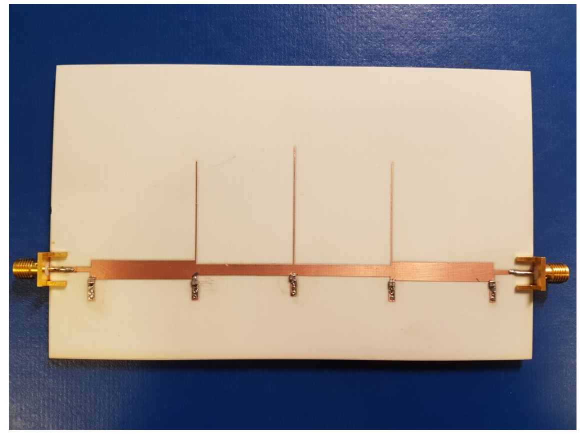


Fig. 6. Picture of the manufactured all-capacitive third order filter at $f_0 =$ 1480 MHz. 50 Ω access lines of 15 mm have been added at input and output to attach SMA ports.

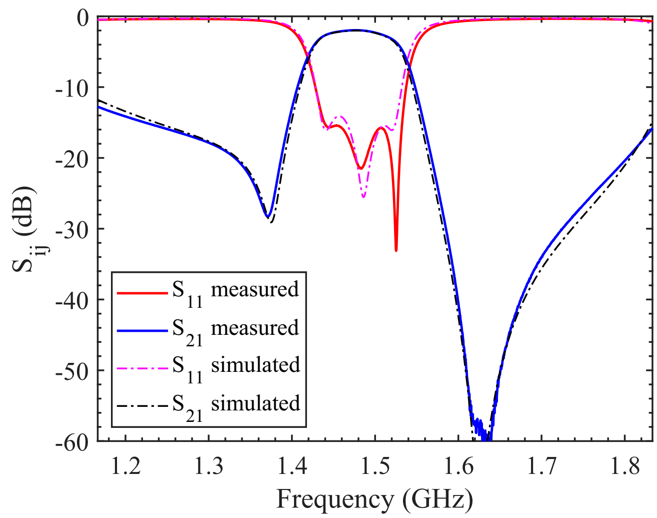


Fig. 7. Magnitude response of the manufactured third order filter and ADS-Momentum simulation.

IV. Conclusion

This work has covered the synthesis of extracted pole filters that feature transmission zeros in both stopbands implementing all NRNs with the same reactive nature. This is achieved thanks to modification of the input reflection phase of the filtering function adding a phase shift of 180° that is effective to modify the nature of first and last NRN. This approach is specially useful for technologies where only one nature of the NRNs is easily implementable. Using the reflection phase at convenience during the synthesis allows to improve the performance of the technology, allowing to implement more selective responses. The concept has been demonstrated in a simple all-capacitive third order microstrip filter.

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