High Frequency Communications

Design and Simulation of Frequency-Specific High-Pass Filter: Analyzing Ideal and Real-World Component Performance in the 900MHz Band

by

Adam Szajgin

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Syddansk Universitet

Contents

1. Introduction

This report presents the design and simulation of a high-pass filter, targeted at the 900 MHz frequency band. The 900 MHz band is widely used in 2G, 3G, and 4G telecommunications in Denmark, making it a relevant choice for filter design in modern wireless communication systems. The filter is designed to meet specific performance requirements, including a maximum of 0.5dB attenuation in the passband (from 900MHz) and a minimum of 30 dB attenuation in the stopband (I assumed this frequency to be up to 700MHz).

The choice of 700MHz is to account for the other popular frequency used in Denmark at 700MHz. However its important to note here that, those choices are freely done, and they're not the primary purpose of the project, which is to determine how much do parasitic components influence the filter performance.

The design process begins with simulations using ideal components, followed by more realistic simulations incorporating parasitic elements such as resistance and inductance in capacitors and inductors. The results of these simulations are compared and analyzed to assess the performance of the designed filters and analyze **how much parasitic elements influence filter performance**.

2. Design Process

To design the filter, I used an online calculator Marki Microwave to get a grasp of the filter parameters I needed to design my filter with (meaning the filter type (Chebyshev, Bessel, etc), and order of the filter).

Then, in a simulation environment called "Qucs", I designed the filter by using "Tools" - "Filter Synthesis". The best type for this filter requirements was Chebyshev and of 9'th order (I elaborate on the order of the filter more later).

For the filter design, I used a set of standardized components from the E24 series, which is widely popular and used within the electronic industry.

3. Designed filter schematics

The resulting high-pass filter circuit is presented below:

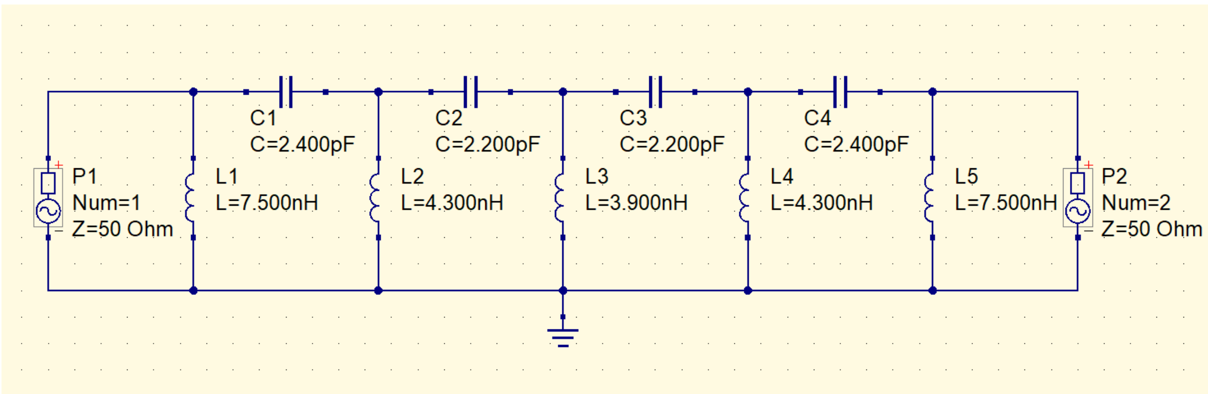

Fig. 1. Designed high-pass filter

4. Simulation with ideal components

For the designed circuit, I have determined the transmission and reflection characteristics:

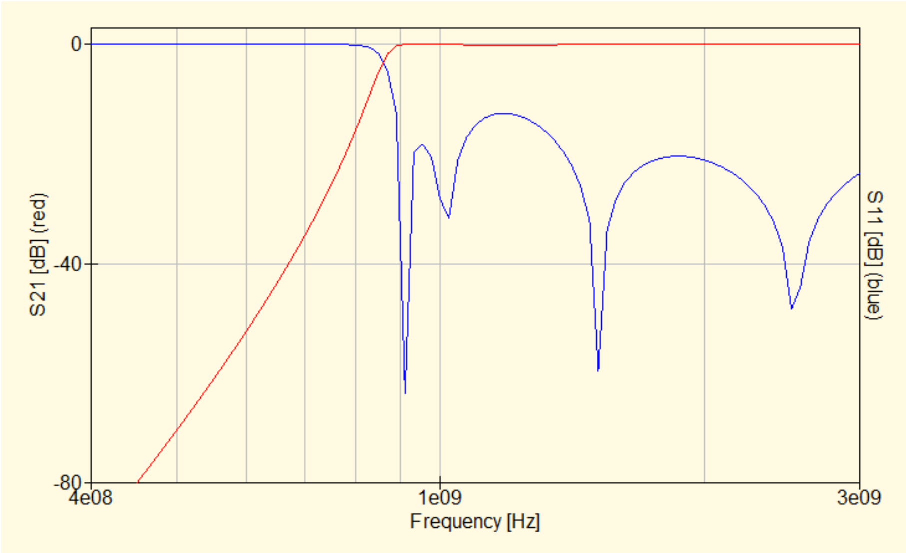

Fig. 2. Characteristics; transmission (S21 - red) and reflection (S11 - blue) for the designed filter with ideal components

And I have determined the following filter parameters:

— **Worst attenuation in the passband:**

This occurs at a frequency of f = 1170 MHz, with a value of around -0.25 dB.

— **Matching in the passband:**

Best matching occurs at a frequency of f = 911 MHz, with a value of around -64 dB. The worst matching is at f = 1170 MHz, with a value of -13 dB (This result is due to the type of filter designed, comment on that later)

— **Worst attenuation in the stopband:**

For this type of filter, the worst attenuation occurs at the highest stopband frequency. Assuming the stopband is defined up to 700 MHz, the worst attenuation at 700 MHz is around -35 dB.

This filter represents the theoretical optimum of what such a design can achieve. It was later used as a benchmark to compare the performance of the filter incorporating parasitic elements. The results demonstrate that this filter performs exceptionally well, and I am highly satisfied with its design and effectiveness, as it meets all of the assumed requirements.

5. Non-Ideal Behavior of Filter Elements and Their Realization, account for ESR

In this section, I discuss the non-ideal aspects of the inductors and capacitors used in the filter, particularly focusing on their series resistance (ESR). The ESR is an important parameter as it affects the overall performance of the filter, especially in high-frequency applications.

To account for the non-idealities of the components, I calculated the ESR values for a Quality Factor (Q) of 20 and a frequency (f) of 900 MHz (it was the target frequency). The following formulas were used to calculate the ESR:

$$Q_L = \frac{\omega_0 L}{ESR} \Rightarrow ESR = \frac{2\pi f L}{Q_L}$$
$$Q_C = \frac{1}{\omega_0 C ESR} \Rightarrow ESR = \frac{1}{2\pi f C Q_C}$$

The calculations for the ESR's of the used Inductors and Capacitors are presented below:

1. For $L_1, L_5 = 7.5\,nH$:

$$ESR = \frac{2\pi f L}{Q} = \frac{2\pi(900 \times 10^6)(7.5 \times 10^{-9})}{20} \approx 2.1$$

2. For $L_2, L_4 = 4.3\,nH$:

$$ESR = \frac{2\pi f L}{Q} = \frac{2\pi(900 \times 10^6)(4.3 \times 10^{-9})}{20} \approx 1.2$$

3. For $L_3 = 3.9\,nH$:

$$ESR = \frac{2\pi f L}{Q} = \frac{2\pi(900 \times 10^6)(3.9 \times 10^{-9})}{20} \approx 1.1$$

4. For $C_1, C_4 = 2.4\,pF$:

$$ESR = \frac{1}{2\pi f C Q} = \frac{1}{2\pi(900 \times 10^6)(2.4 \times 10^{-12})(20)} \approx 3.7$$

5. For $C_2, C_3 = 2.2\,pF$:

$$ESR = \frac{1}{2\pi f C Q} = \frac{1}{2\pi(900 \times 10^6)(2.2 \times 10^{-12})(20)} \approx 4.0$$

Therefore the schematic using components with ESR looked like so:

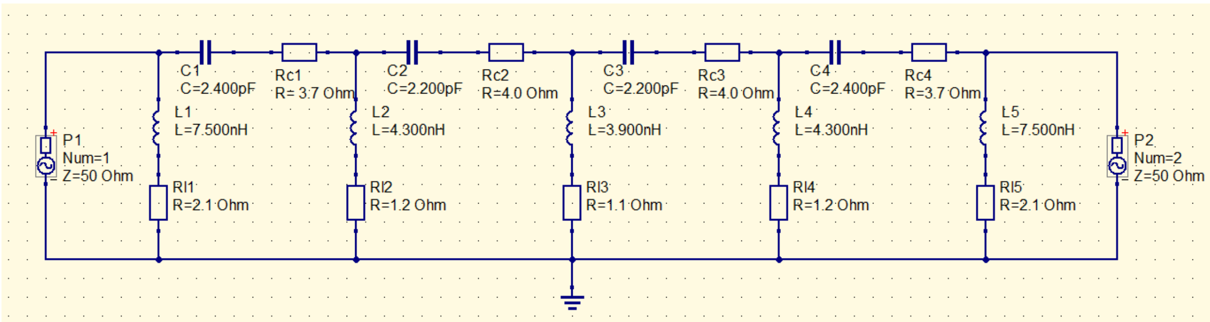

Fig. 3. Designed High-Pass filter with elements taken into account for ESR

As a result of the conducted simulation, I've plotted following characteristics:

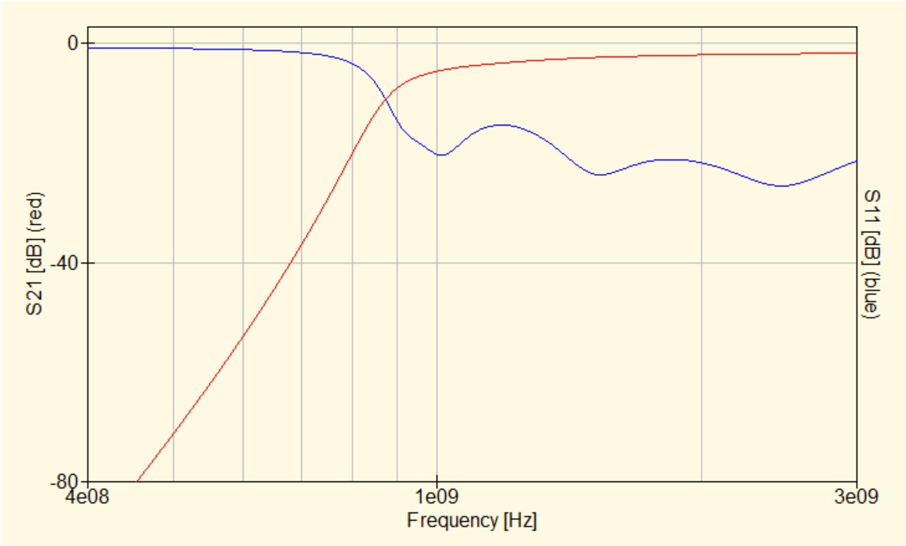

Fig. 4. Characteristics; transmission (S21 - red) and reflection (S11 - blue) for the designed filter with elements taken into account for ESR

And I have once again determined the following filter parameters:

— **Worst attenuation in the passband:**

This occurs at a frequency of f = 900 MHz, with a value of around -8 dB. At the point of the previous worst attenuation frequency (1170 MHz), the attenuation now is equal to -3.5 dB. The required 0.5 dB attenuation doesn't even appear at 8000 MHz (it goes up to -1.4 dB).

— **Matching in the passband:**

The best matching occurs at a frequency of f = 2450 MHz, with a value of around -26 dB. The worst matching is at f = 1170 MHz, with a value of -15 dB. Around 900 MHz, best matching was: -18 dB

— **Worst attenuation in the stopband:**
For this type of filter, the worst attenuation occurs at the highest stopband frequency. Assuming the stopband is defined up to 700 MHz, the worst attenuation at 700 MHz is around -37 dB. Previously, -35 dB.

Overall, this filter performed noticeably worse than the ideal one. The attenuation within the passband was significant, therefore potentially interfering with incoming signals at those frequencies. Additionally, the passband shifted toward higher frequencies, resulting in signal interference around 900 MHz (jamming the signal with it's 7dB attenuation). To address these issues, the filter would require redesigning to better align with the target frequency. This could involve increasing the filter's order and lowering the start frequency of the desired passband.

6. Non-Ideal Behavior of Filter Elements and Their Realization, account for ESL and parasitic Capacitance

In this section, I discuss the non-ideal aspects of the inductors and capacitors used in the filter, particularly focusing on their equivalent series inductance (ESL) and equivalent parasitic capacitance ($C_{parasitic}$).

The theory tells us that each component exhibits non-ideal behavior at higher frequencies due to parasitic effects. Inductors are characterized by their parasitic capacitance ($C_{parasitic}$), which arises from the inter-turn capacitance of the coil. Similarly, capacitors have an equivalent series inductance (ESL) primarily due to the leads and internal connections. These parasitics play a crucial role in the overall performance of the filter, especially at high frequencies.

The equivalent circuits of the inductors and capacitors are shown below:

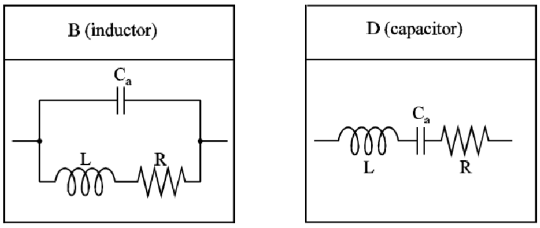

Fig. 5. Equivelent Circuit Model for an Inductor and a Capacitor

To calculate the parasitic Capacitance and the ESL of used components, I've used following formulas:

$$ESL = \frac{1}{(2\pi f)^2 C} \quad (capacitors)$$

$$C_{parasitic} = \frac{1}{(2\pi f)^2 L} \quad (inductors)$$

To determine these values, I first needed to identify the resonance frequencies of the components. To achieve this, I sourced real-world components from the TME store. The selected components were specifically designed for high-frequency applications:

— L1, L5 = 7.5 nH: CW0603 - 7.5 FERROCORE, f = 4.8 GHz
— L2, L4 = 4.3 nH: CW0603 - 4.3 FERROCORE, f = 5.9 GHz
— L3 = 3.9 nH: CW0603 - 3.9 FERROCORE, f = 6.9 GHz
— C1, C2, C3, C4: Murata GCQ Series, f = 5.9 GHz

The calculations for the parasitic elements of the inductors and capacitors used are presented below:

1. For $L_1, L_5 = 7.5\,nH$:

$$C_{parasitic} = \frac{1}{(2\pi \cdot 4.8 \times 10^9)^2 \cdot 7.5 \times 10^{-9}} \approx 146.7\,fF$$

2. For $L_2, L_4 = 4.3\,nH$:

$$C_{parasitic} = \frac{1}{(2\pi \cdot 5.9 \times 10^9)^2 \cdot 4.3 \times 10^{-9}} \approx 169.4\,fF$$

3. For $L_3 = 3.9\,nH$:

$$C_{parasitic} = \frac{1}{(2\pi \cdot 6.9 \times 10^9)^2 \cdot 3.9 \times 10^{-9}} \approx 136.6\,fF$$

1. For $C_1, C_4 = 2.4\,pF$:

$$ESL = \frac{1}{(2\pi \cdot 5.9 \times 10^9)^2 \cdot 2.4 \times 10^{-12}} \approx 331.1\,pH$$

2. For $C_2, C_3 = 2.2\,pF$:

$$ESL = \frac{1}{(2\pi \cdot 5.9 \times 10^9)^2 \cdot 2.2 \times 10^{-12}} \approx 303.5\,pH$$

Therefore the schematic using real components looked like so:

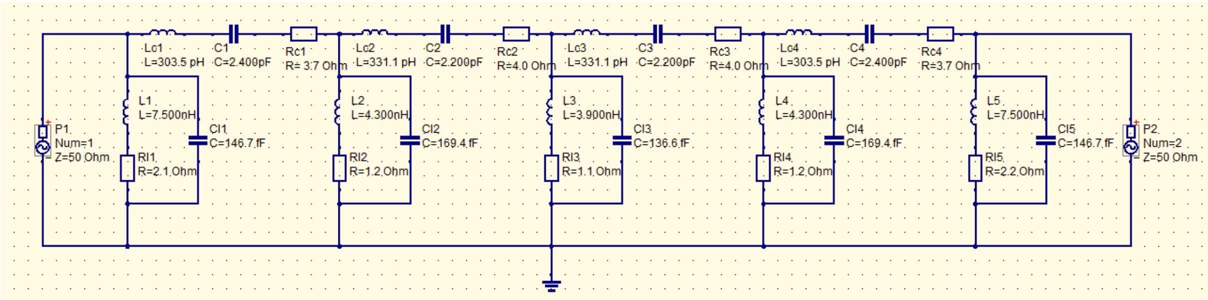

Fig. 6. Designed High-Pass filter with real elements

As a result of the conducted simulation, I've plotted following characteristics:

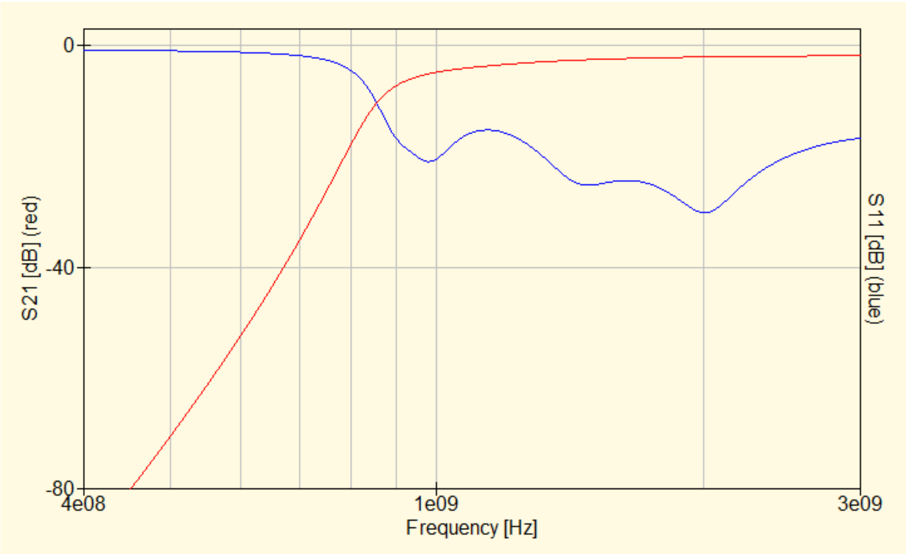

Fig. 7. Characteristics; transmission (S21 - red) and reflection (S11 - blue) for the designed filter with real world components

And for the last time, I determined the following filter parameters:

— **Worst attenuation in the passband:**

This occurs at a frequency of f = 900 MHz, with a value of around -7 dB. At the point of the previous worst attenuation frequency (1170 MHz), the attenuation now is equal to -3.6 dB. The required 0.5 dB attenuation doesn't even appear at 8000 MHz (it goes up to -1.4 dB).

— **Matching in the passband:**

The best matching occurs at a frequency of f = 1999 MHz, with a value of around -30 dB. The worst matching is at f = 1170 MHz, with a value of -15 dB. Around 900 MHz, best matching was: -21 dB

— **Worst attenuation in the stopband:**

For this type of filter, the worst attenuation occurs at the highest stopband frequency. Assuming the stopband is defined up to 700 MHz, the worst attenuation at 700 MHz is around -37 dB. Previously, -35 dB.

This filter performs very similarly to the previous one. The parasitic capacitances and inductances did not influence the performance of the filter by a lot (in comparison to the ESR only one) as they were very little (inductances of hundreds pH and capactiances of hundreds fF). This has to do with the fact that the components I used were designed for High Frequency applications - had very high resonance frequency.

7. Analysis and Comparison

The primary goal of this project was to design and analyze high-pass filters targeting the 900 MHz frequency band, **assessing the impact of non-idealities such as ESR and parasitic effects on performance**. Initially, the filters were designed under ideal conditions to achieve a passband attenuation of 0.5 dB at 900 MHz and a stopband attenuation of 30 dB at 700 MHz. These ideal filters served as benchmarks for evaluating real-world performance.

The degradation in performance across different implementations is summarized in the table below:

Parameter	**Ideal Filter (dB)**	**With ESR (dB)**	**With Parasitics (dB)**
Best S11 (Reflection) near 900 MHz	-64.0	-18.0	-21.0
Worst S21 (Attenuation) at 900 MHz	-0.5	-8.0	-7.0
Worst Attenuation (S21) at 700 MHz	-35.0	-37.0	-37.0

Table 1. Key Performance Metrics for Ideal, ESR, and Parasitic Filters

The graphs in the figure below further illustrate how S11 and S21 characteristics degrade with the introduction of ESR and parasitic effects:

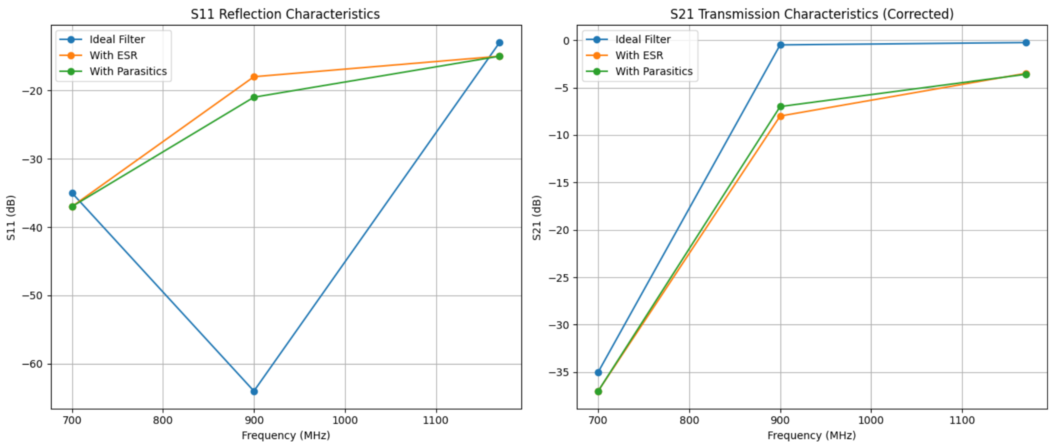

Fig. 8. Visualization of the performance of the filters

The filter order greatly influenced the reflection coefficient (S11). Higher-order filters, such as the 9th-order Chebyshev filter, provided sharper transitions between passband and stopband (for both S11 and S21) with improved impedance matching. Under ideal conditions, the S11 reflection parameter reached an exceptional -64 dB at 900 MHz, demonstrating minimal signal reflection and excellent matching.

However, introducing non-idealities led to significant degradation. With ESR, best matching dropped to -26 dB, and the inclusion of parasitic effects reduced it less to -30 dB. At the critical frequency of 900 MHz, matching worsened even further to -18 dB (ESR) and -21 dB (parasitics). Similarly, the S21 transmission parameter showed increased attenuation in the passband, with real-world filters reaching -8 dB (ESR) and -7 dB (parasitics) at 900 MHz, compared to the ideal -0.5 dB. Despite this, stopband attenuation remained consistent at 30 dB, meeting the design requirements.

Between S11 and S21, the reflection parameter experienced more severe degradation due to component imperfections, underscoring the sensitivity of impedance matching to practical limitations. This highlights the need for high-Q components to minimize performance losses.

8. Conclusion

In conclusion, the real-world filters failed to meet the project's initial assumptions of -0.5 dB attenuation in the passband and excellent matching at 900 MHz. However, the stopband attenuation criteria were successfully met, maintaining the required 30 dB attenuation at 700 MHz. The overall design provided valuable insights into the impact of component non-idealities on high-frequency filter performance.

The introduction of ESR had the most significant impact on the filter's performance, far outweighing the influence of parasitic capacitance or ESL. This underscores the importance of prioritizing ESR when selecting components. Ensuring a high-quality factor (Q) for inductors and capacitors should be a key focus, as it directly affects both the transmission and reflection characteristics of the filter.

For future designs, employing components with higher Q factors, exploring distributed element filters, or optimizing the PCB layout to further minimize parasitic effects could significantly enhance filter performance. This project highlights the necessity of iterative refinement and the incorporation of practical considerations to bridge the gap between theoretical predictions and real-world implementations in high-frequency filter design.