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Milling Machine Validation through Microstrip Filter Manufacturing

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Abstract

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The milling machine at the Myyrmäki campus at Metropolia is used on a number of Engineering courses. Since there is no certainty about the precision of the aforementioned milling machine, it is unclear how much the production might affect the quality of the resulting printing circuit boards. Purpose of this project was to test the milling machine to get an estimation of how precise milling it is capable of.
The objective of this thesis project was to print the designed printed circuit boards using the milling machine at the Myyrmäki campus and then compare them to the printed circuit boards produced elsewhere. As a first step of the project, a printed circuit board concept was chosen to be a band-pass microstrip line filter. Next, mathematical calculations were performed to determine the dimensions of the filter, which were then confirmed by software simulations. Finally, the printed circuit boards were produced at Metropolia, as well as two electronics companies abroad, and the circuit boards were compared to each other and tested.
As a result of the project work, it was established that the Metropolia's milling machine was not able to fulfill the set requirements. A conclusion was made that using that milling machine for such precise production is not recommended, and alternative options were suggested.

Keywords: filter, microstrip line, transmission line, milling, printed circuit board, filter design, milling machine, PCB

Contents

List of Abbreviations

PCB: Printed circuit board. A sandwich structure of conductive and insulating layers.

NA: Network analyzer. A device that measures network parameters of electrical networks, e.g. transmission or reflection.

dB: A unit that expresses the ratio of two values of power.

MS: Microstrip. A type of electrical transmission line where a conductor is separated from a ground plane by a dielectric layer.

SM: The filter produced by Metropolia, having the dimensions of 119.5mm * 19.5mm. It was milled based on the design of filter 2.

SC: The filter produced by Aisler in China, having the same dimensions as SM. It was milled based on the design of filter 2.

SC2: The filter produced by PCBWay in China, having the same dimensions as SM. It was milled based on the design of filter 2.

BM: The filter produced by Metropolia, having the dimensions of 118.7mm * 24.3mm. It was milled based on the design of filter 1.

BC: The filter produced by Aisler in China, having the same dimensions as BM. It was milled based on the design of filter 1.

BC2: The filter produced by PCBWay in China, having the same dimensions as BM. It was milled based on the design of filter 1.

1 Introduction

The PCB milling machine at Metropolia Myyrmäki campus has been used for many lab assignments and other projects. The purpose of those assignments have been to give students an idea of work practices at a professional workspace, producing the required printed circuit boards. For this reason, it was important to have an idea how reliable the milling machine is, meaning its precision, consistency, and faultlessness. Picture of the milling machine can be seen in figure 1. Out of two milling machines at the electronics lab the machine marked as number 2 was chosen for this project, as the other device was not available.

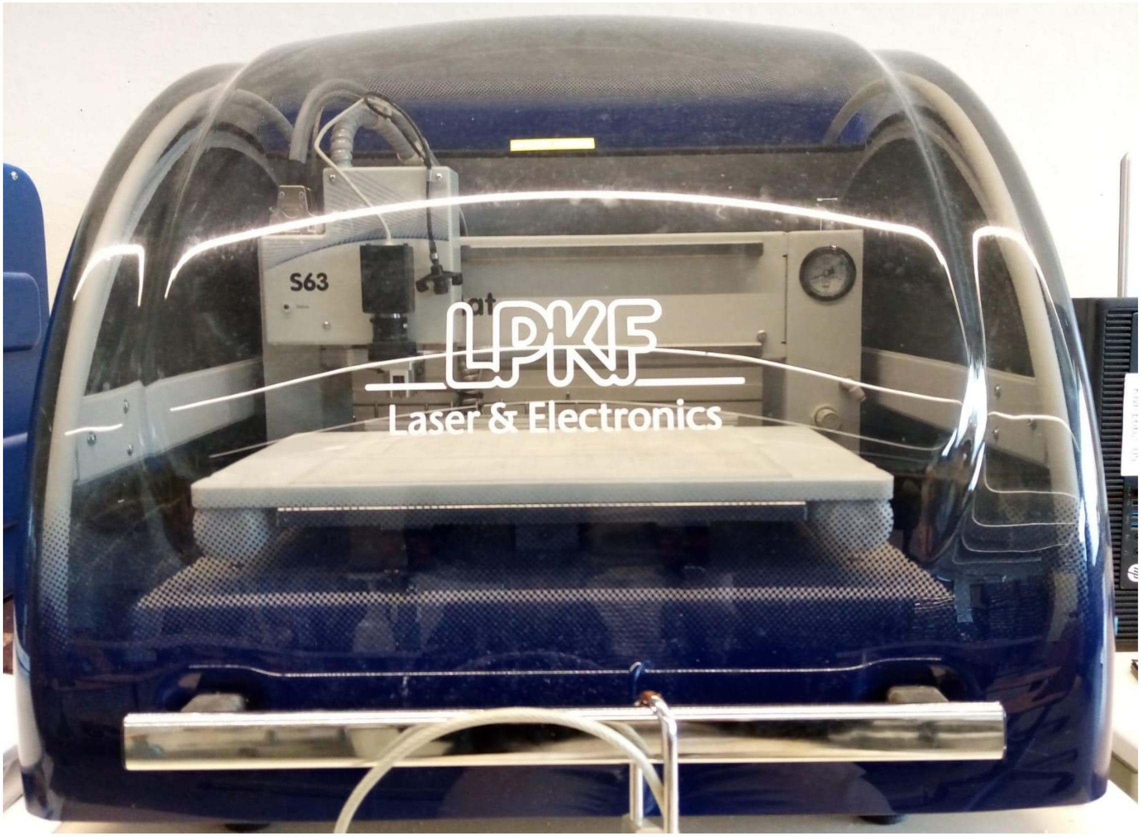

Figure 1. Milling machine 2 at the electronics laboratory

Idea of this thesis project was that the estimation of the machine functionality would be achieved by printing a designed PCB and comparing it with outsourced printed circuit boards of the same design. The PCB to be printed was decided to be a filter with low dimensions – to create challenges for the machine.

The plan was to first design and mill a filter at the university and analyze the PCB. Then, the next step would be to order the same filter from a number of companies and verify if those PCBs would show better performance. Based on the findings, it would be possible to assess how much error the milling machine at school might have produced compared to professional milling devices. That will allow the students who use the milling machine in the future to have more precise expectations regarding the resulting PCBs.

2 Theoretical Background

It was decided to print PCBs of microstrip coupled-line bandpass filters. Those filters do not include any components apart from coupled microstrip lines, which made production of them convenient. Also, at high frequencies the filter dimensions become very low, which was believed to cause a discrepancy between the filters produced at the university and abroad. The section below describes filters in detail, and the following section explains the characteristics of a microstrip line filter.

2.1 Filters and Filter Types

Filter is an electronic device that removes unwanted components from the input signal. Low-pass filters remove the signal higher than the certain frequency, and high-pass filters remove the signal below the desired frequency. Function of a band-stop filter is to cut out the signal at a certain frequency interval, while a band-pass filter only allows through the certain interval of frequencies. Band-pass filter is described in more detail in the next paragraph.

Bandpass filter is a type of a device that only allows through the signal at a certain frequency interval, greatly attenuating the signals at other frequencies.

The interval at which the signal is allowed though is called a passband, and the edge frequencies of it are called cut-off frequencies. Figure 2 shows an attenuation versus frequency graph of a bandpass filter. Passband region of a filter is determined at the interval, at which the attenuation is higher than -3 dB [1]. f_L and f_H in the figure are the low and high cut-off frequencies.

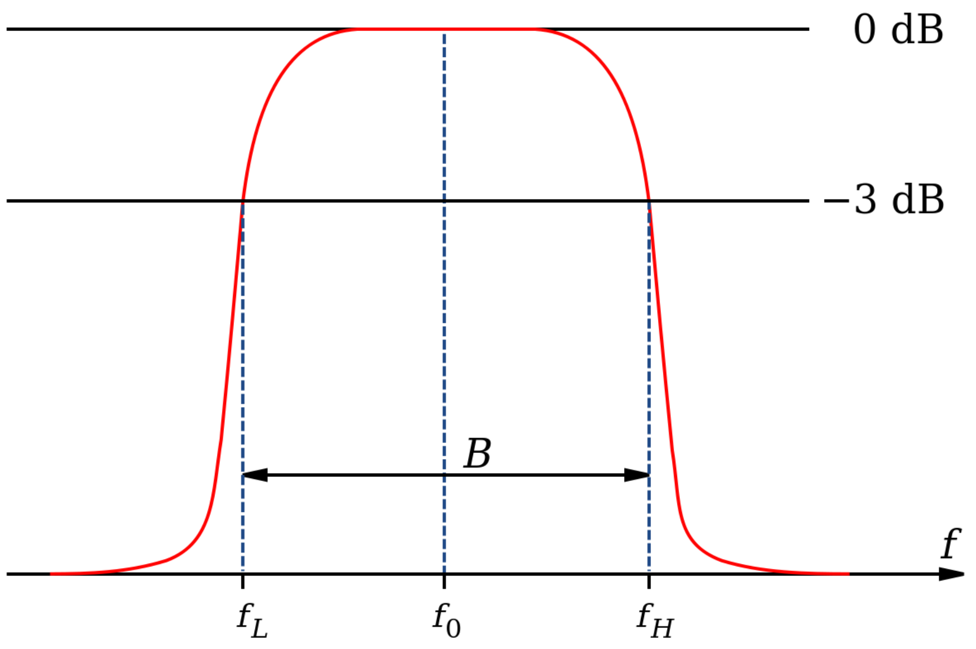

Figure 2. Bandpass filter graph, attenuation in dB versus frequency [1]

Decibels, dB is a way of measuring signal power attenuation or amplification. If there is a circuit component that causes the power of the signal going through to be changed from P_1 to P_2, then the ratio of power of the signal is

$$A_{P(ratio)} = \frac{P_1}{P_2} \tag{1}$$

Ratio of power in decibels is

$$A_{P(dB)} = 10 * \log\left(A_{P(ratio)}\right) \tag{2}$$

The ratio of power in dB is used when the ratio of the powers is very large, since the logarithmic scale offers more convenience when handling substantial numbers.

2.2 Microstrip Line Filter

As previously mentioned, microstrip line filters only consist of microstrip lines. Microstrip line is a type of a transmission line, which is a cable designed to conduct electromagnetic waves. The main feature of transmission lines is that they interact with other through electromagnetic fields. An example of a transmission line is displayed in figure 3 below.

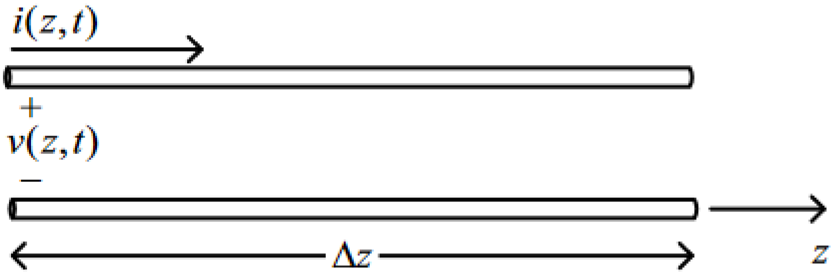

Figure 3. Transmission line configuration [2, 3]

As can be noticed in the figure 3 above, the voltage is applied between the two transmission lines, thus the bottom line can be referred to as a ground line. $V(z,t)$ is the value of the voltage applied between the transmission lines, $i(z,t)$ is the resulting current, and Δz is the length of the transmission line under examination, out of the total length z. Figure 4 below shows the effect of transmission lines interaction, displaying an equivalent circuit.

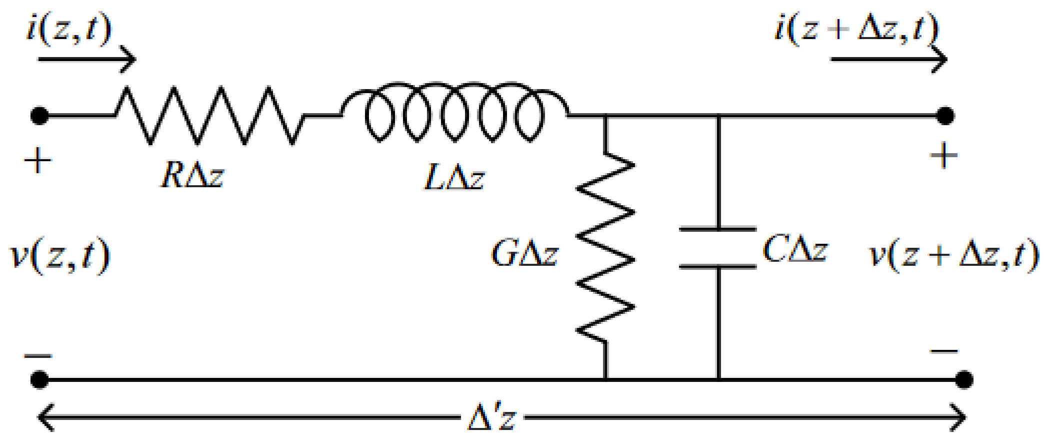

Figure 4. Transmission equivalent circuit [2, 3]

Figure 4 displays the electric values created in transmission lines. R is series resistance, L - series inductance, G is shunt conductance, and C is shunt capacitance. These values are presented as per unit length, which is why in figure 4 they are multiplied by Δz – length of the transmission line section.

Microstrip line filters utilize the aforementioned characteristic of transmission lines, using only those components as substitutes for resistors, capacitors, and inductors in filters. The microstrip lines located at the top layer of a PCB interact with the copper plane on the second layer of the board, acting as the required electronic components.

An example layout of a coupled-line microstrip filter is presented in figure 5 below. In the center are the microstrip lines on the circuit board, and to the sides the soldered connectors.

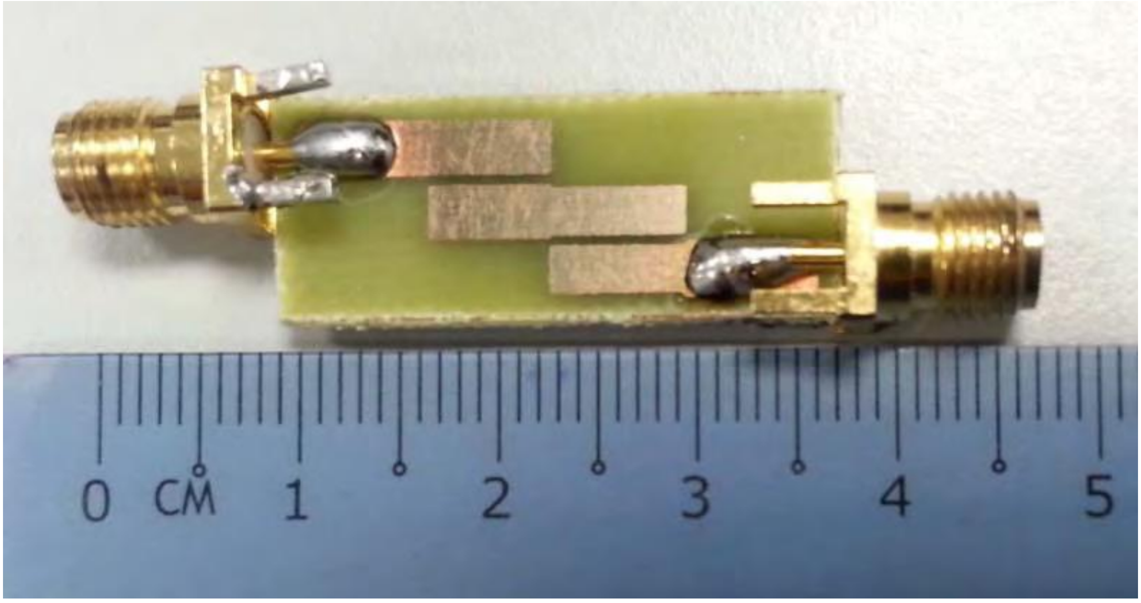

Figure 5. Example picture of a first order microstrip line filter [3, 2]

2.3 Filter Measurements

Standard filter measurements consist of transmission and reflection measurements. Purpose of those is to determine the characteristics of the filter, including its cut-off frequencies and bandwidth. Different types of measurements are described in this paragraph. Transmission power measurement presents a graph of amplification versus the chosen frequency range. Amplification is usually displayed in decibels, and the graph shows how much the chosen frequencies are attenuated by the filter. Transmission phase measurement displays a graph of phase change versus the frequency range. It compares the phase of the signal going into the filter to the phase of the signal escaping it. Filters cause different phase delays over different frequencies, and purpose of this measurement is to graphically present those delays. Reflection power measurement delivers a graph of reflected power versus frequency. This measurement shows how much of a signal given to the input of the filter is returned through the input, instead of being outputted through the output. Since signals that are supposed to be attenuated by the filter are not transmitted at their full power level, the most part of their power is reflected back through the input. Reflection phase measurement shows a graph of signal’s phase versus the frequency. It displays the phase delay of reflected signals over the chosen frequency range.

Smith chart is a plot of complex reflection coefficient in a polar form. It displays the values of real and imaginary components of the reflection coefficient in polar format. Examples of values on a Smith chart can be seen in figure 6 below.

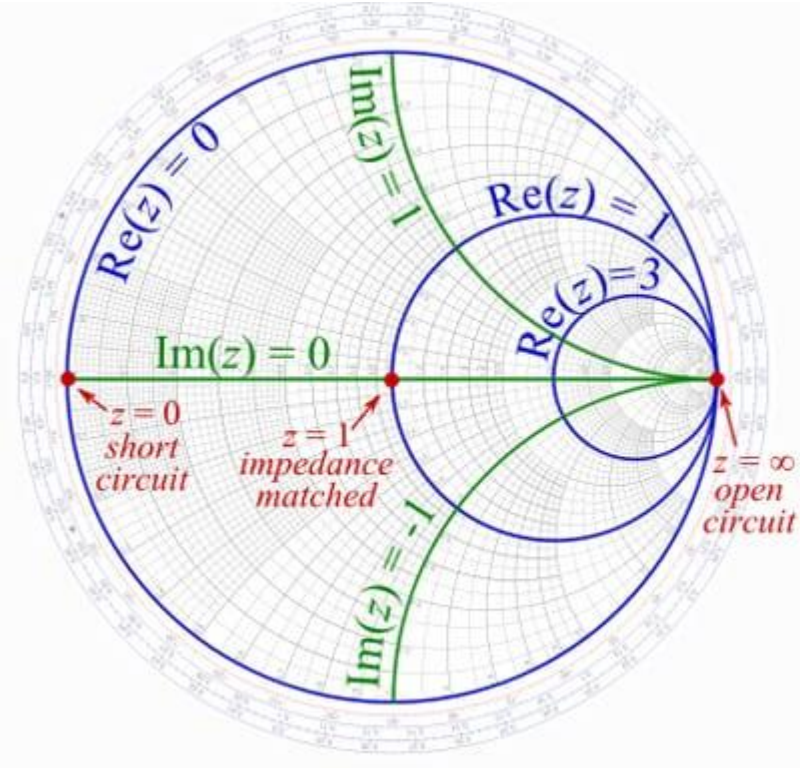

Figure 6. Smith chart scales [4]

Values on smith chart are normalized by a factor of output impedance, which is usually 50 Ohms. Smith chart allows to see how well the impedances of two components are matched, with the ideal case being in the center of the chart. In the center, as seen in the figure 6 above, the real part of the complex reflection coefficient $Re(z)$ is equal to one, while the complex part $Im(z)$ is zero.

3 Microstrip Line Filter Design

As discussed in the previous section, a band-pass microstrip line filter was chosen for production. Design of this filter included the tasks of determining the filter characteristics, then conducting calculations to determine physical dimensions of the filter and finally carrying out simulations to verify the calculation results.

3.1 Microstrip Line Filter Characteristics

First step in design of a microstrip line filter was to determine the desired characteristics of it. Since the network analysed used to measure the filters was able to make measurements of up to 3 GHz, it was decided to choose the filter frequencies on the interval 2 GHz – 3GHz. Filter input and output impedances were chosen as 50-ohm, to suit the network analyser, which also had 50-ohm port impedances. The filter characteristics are displayed in table 1 below.

Table 1. Desired filter characteristics

Filter #	Center frequency, f	Lower cut-off frequency, f_1	Higher cut-off frequency, f_2
1	2.5 GHz	2.25 GHz	2.75 GHz
2	2.5 GHz	2.1 GHz	2.9 GHz

Also, the calculations required prototype filter values, denoted as g_i for the filter's element number i. Those were taken from figure 7 below [5], being the Butterworth low-pass filter prototype values.

	Capacitor Input, R_S=R_L=1 Ω, f=1 rad/sec									
Order	C1	L2	C3	L4	C5	L6	C7	L8	C9	L10
1	2.000									
2	1.41421	1.41421								
3	1.00000	2.00000	1.00000							
4	0.76537	1.84776	1.84776	0.76537						

Figure 7. Butterworth prototype filter values [5]

The order of the filter was chosen to be four, which required the four prototype values: $g_1 = g_4 = 0.77, g_2 = g_3 = 1.85$. Also, g_0 and g_5 were given the value of 1 to provide the filter with 50-ohm input and output impedances. Notably, values of g were centrally symmetric, meaning $g_i = g_{5-i} \ for \ i\epsilon\{0, 1, 2\}$, which meant that the derived filter was to be symmetrical, accordingly.

After the desired filter characteristics had been decided upon, calculations were conducted to determine the physical dimensions of the filter. Those geometric proportions included the amount of microstrip lines, their sizes, and intervals between them.

3.2 Mathematical Calculations

Mathematical calculations used to determine the filter dimensions are listed below [6, 149].

First, the functional bandwidth was calculated, denoted as FBW:

$$FBW = \frac{f_2 - f_1}{\sqrt{f_2 * f_1}} \tag{3}$$

Next, values of $\frac{J_{0,1}}{Y_0}$ and $\frac{J_{j,j+1}}{Y_0}$ were discovered for i from 1 to 2:

$$\frac{J_{0,1}}{Y_0} = \sqrt{\frac{\pi * FBW}{2 * g_0 g_1}} \tag{4}$$

$$\frac{J_{j,j+1}}{Y_0} = \frac{\pi * FBW}{2} \sqrt{\frac{1}{g_j g_{j+1}}} \tag{5}$$

After that, even- and odd- mode impedances of every consecutive pair of microstrip lines were calculated. They were denoted as $Z_{oe_{j,j+1}}$ and $Z_{oo_{j,j+1}}$, consecutively:

$$Z_{oe_{j,j+1}} = \frac{1}{Y_0} * \left(1 + \frac{J_{j,j+1}}{Y_0} + (\frac{J_{j,j+1}}{Y_0})^2\right) \tag{6}$$

$$Z_{oo_{j,j+1}} = \frac{1}{Y_0} * (1 + \frac{J_{j,j+1}}{Y_0} - (\frac{J_{j,j+1}}{Y_0})^2) \tag{7}$$

Lastly, the even- and odd- mode impedance values were given pair by pair as an input to the coupled microstrip line calculator [7]. The input data also included the specifications of the material, from which the PCB was printed – it was FR-4, having values shown in the table 2 below.

Table 2. FR-4 material specifications

Metal thickness	Substrate thickness	Substrate loss tangent	Substrate rel. dielectric constant
0.05 mm	1.5mm	0.01mm	4.7

The calculator gave out the width and length of every pair of lines, as well as the space between them.

Tables 3 and 4 below display the calculated design values for the coupled microstrip line filters 1 and 2, respectively. Each filter consisted of 6 lines; however, the filters were symmetrical, and values of the first line were the same as values of the sixth line, etc. For that reason, only the values of the first three lines were calculated.

Table 3. Filter 1’s calculated dimensions

	Line 1	Line 2	Line 3
Width, w	1.26 mm	2.35 mm	2.54 mm
Distance, s	0.13 mm	0.57 mm	1.08 mm
Length, l	16.7 mm	16.2 mm	16.1 mm

Table 4. Filter 2’s calculated dimensions

	Line 1	Line 2	Line 3
Width, w	0.87 mm	1.84 mm	2.3 mm
Distance, s	0.13 mm	0.25 mm	0.54 mm
Length, l	16.9 mm	16.5 mm	16.2 mm

Figure 8 below shows the dimensions of a microstrip line filter. Width, length and spacing of microstrip lines previously listed in tables 3 and 4 correspond to the values l, w, s in figure 8, accordingly.

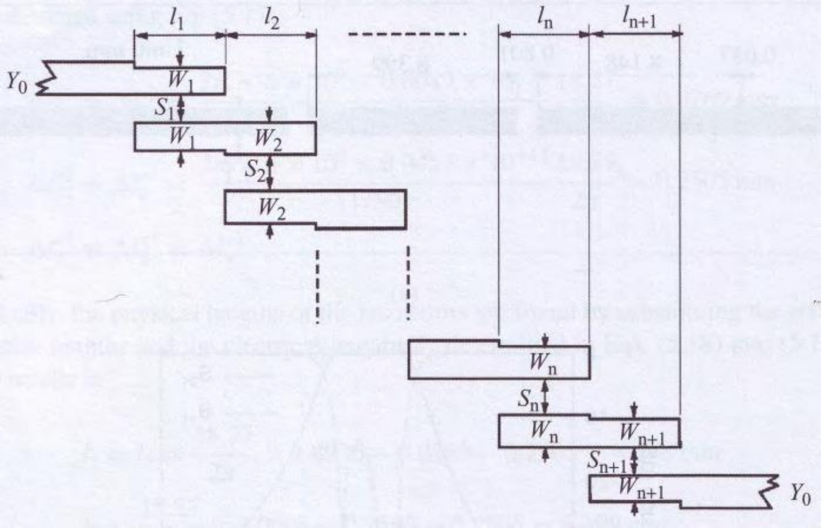

Figure 8. General structure of a microstrip line filter [8, 3]

In this case, the number of lines n was 6, and as previously noted, filters are centrally symmetric, meaning that values of line number n+1 were the same as line 1, number n – the same as number 2, and so on.

3.3 Microstrip Line Filter Simulation

Filter simulation was carried out in AWR MWO design environment. Goal of the simulation was to verify that filters operated correctly, fix any layout issues, and export Gerber files that were to be used for PCB printing.

Simulated values were S_{11} and S_{21} – input reflection and transmission coefficients of the filters, correspondingly. Scale for x-axis was chosen as megahertz – from 2 to 3 MHz, and for the vertical axis, signal power in decibels, dB.

Input transmission and reflection coefficients of the filter 1 (designed to have 2.25 GHz-2.75 GHz bandwidth) are shown in figures 9 and 10, accordingly.

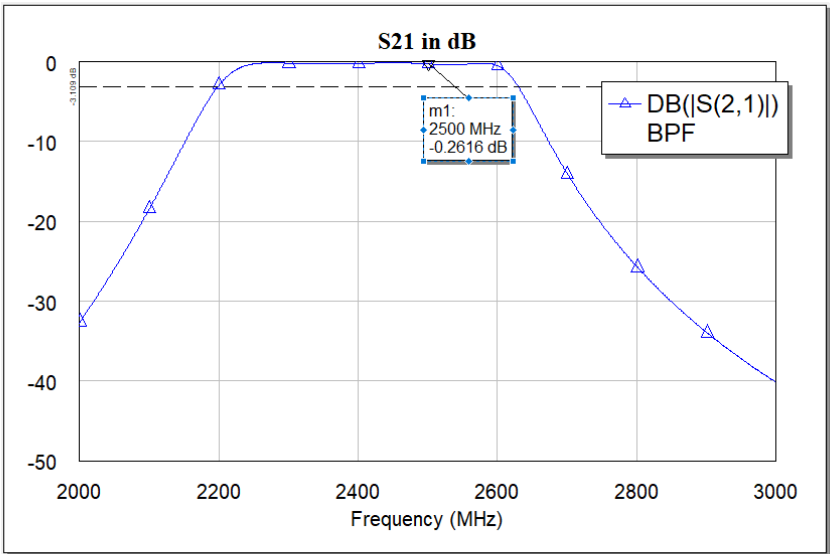

Figure 9. Filter 1 transmission coefficient in dB versus frequency

Figure 9 shows the transmission coefficient of the filter – which describes how much of the signal is transmitted through the filter. Near-0dB value at frequencies 2250-2600 GHz shows that the signal power at that interval was almost fully transmitted. From that figure, the passband bandwidth of the filter can be determined. The dashed line in the figure marks the -3dB limit, which indicates the passband to be 2.2 Mhz-2.63Mhz. Expected bandpass was 2.25 MHz – 2.75 MHz, which shows a notable difference, presumably caused by roughness of calculations.

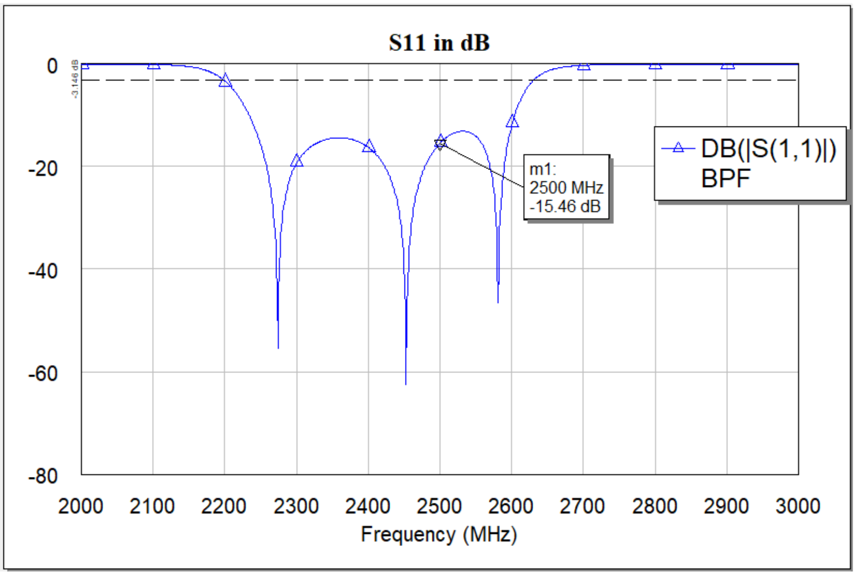

Figure 10. Filter 1 input reflection coefficient in dB versus frequency

As seen in figure 10 above, input reflection coefficient is almost 0 at frequencies of 2 MHz - 2.1 MHz and 2.7 MHz - 3 Mhz. Since 0dB is equal to one, almost all the signal at those frequencies was reflected at the input of the filter. At frequencies 2250-2600 GHz the reflection coefficient is quite low, under -20dB, which is 0.01, meaning that less than 1% of the signal was reflected at the input, hence more that 99% of it went through the input port.

The reflection coefficient was also measured on a Smith chart, presented in figure 11 below. The marker in the center indicates that the matching frequency of the filter was 2580 MHz.

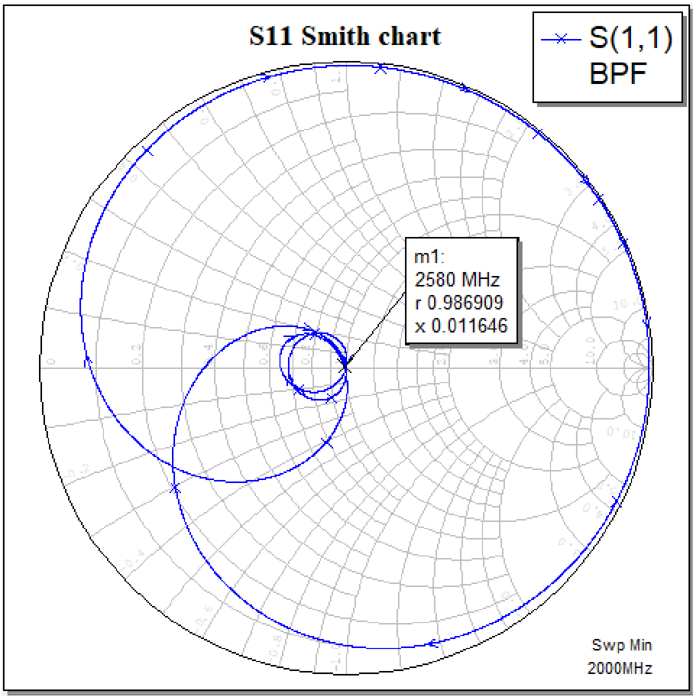

Figure 11. Smith chart of the filter 1

Next, the filter 2's transmission and reflection were simulated with the results shown in figures 12, 13 and 14. Filter 2 was designed to have the bandwidth of 2.1 GHz-2.9 GHZ.

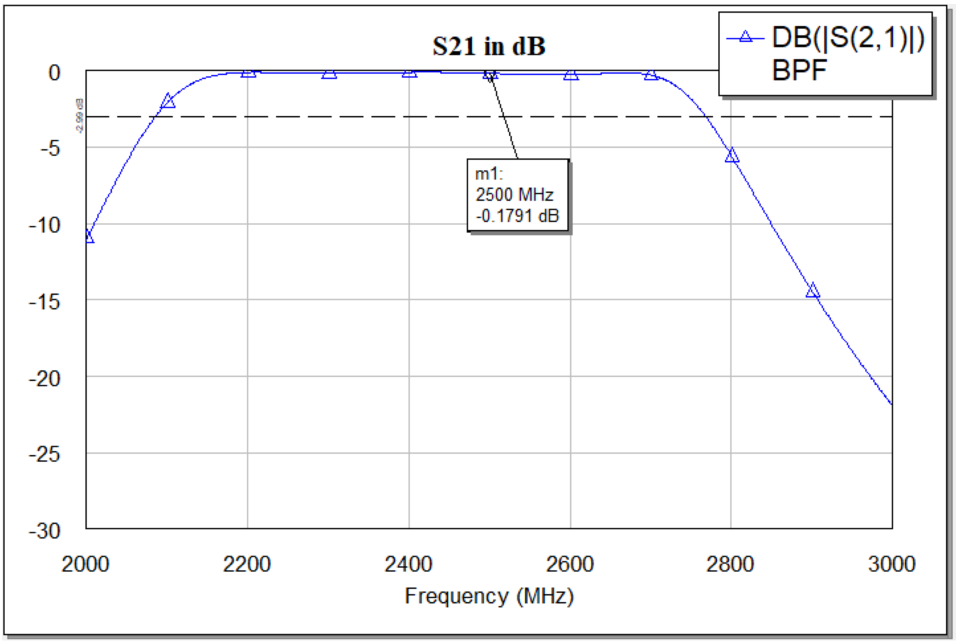

Figure 12. Filter 2 transmission coefficient in dB versus frequency

Transmission coefficient of the filter 2 showed the amplification of roughly -0.18 dB on the passband. Next, the reflection values were simulated, displayed in figures 13 and 14.

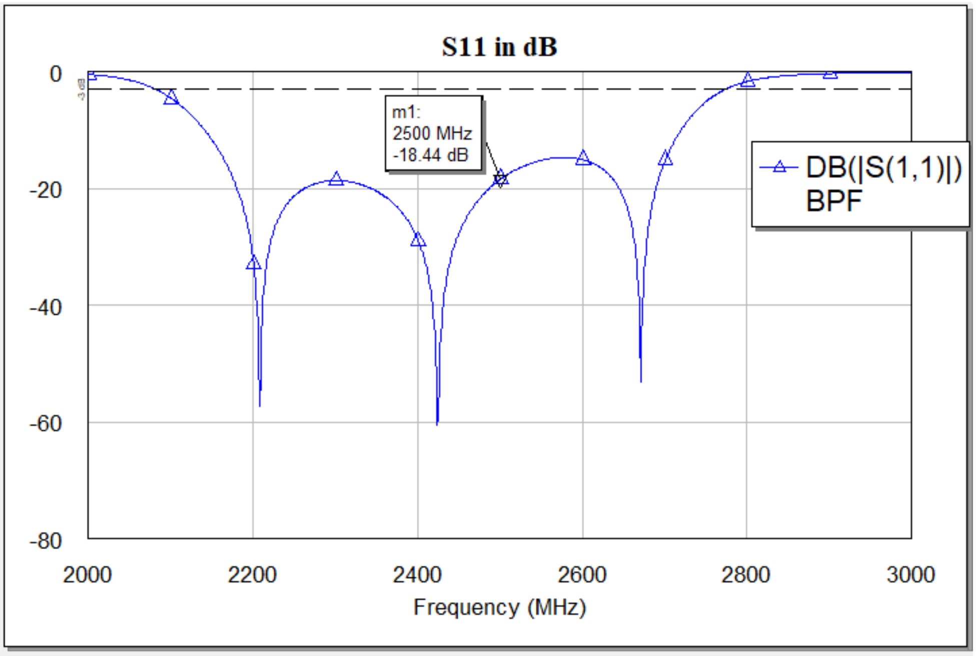

Figure 13. Filter 2 input reflection coefficient in dB versus frequency

Using the dashed -3dB limit line in figure 13, it can be determined that the passband of the filter 2 was 2.09 MHz – 2.77 Mhz. The cut-off values set during the calculations slightly differed, being 2.1 MHz and 2.9 MHz. After that, the reflection values were displayed on a Smith chart in figure 14.

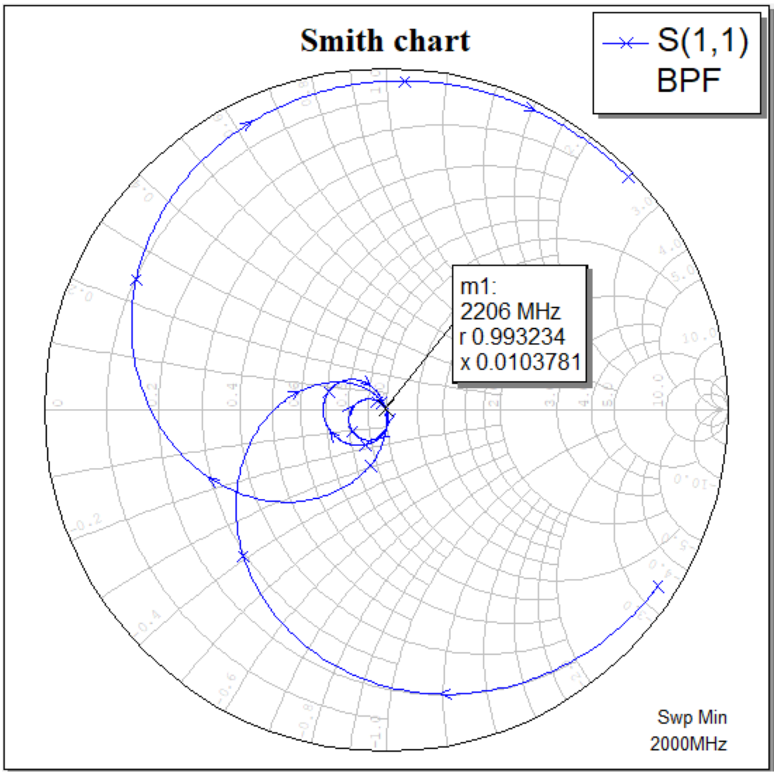

Figure 14. Smith chart of filter 2

As seen in figure 14, the frequency of matching was roughly 2200 MHz. The real part of the reflection coefficient was approximately 0.99, while the imaginary part was equal to 0.01.

After the filter simulation had been drawn, their layouts were set up, presented in figures 15 and 16. Filter 1's length was 118.7 mm and width - 24.3 mm. Length of filter 2 was 119.5 mm, and its width was 19.5 mm.

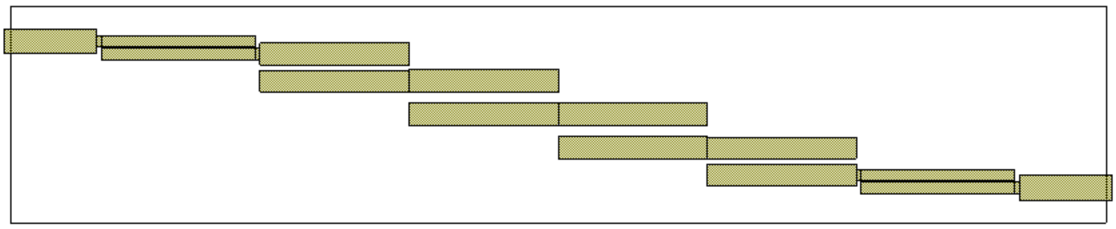

Figure 15. Layout of filter 1

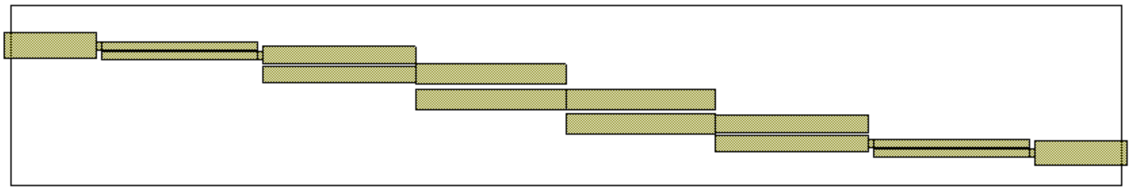

Figure 16. Layout of filter 2

Next stage of the project was the production of the designed and simulated filters.

4 Filter Milling and Outsourcing

It was decided to produce the pair of filters filter1 and 2 at Metropolia and order those filters from two companies in China. The companies were Aisler and PCBWay. Ordering was done by submitting the PCB Gerber files and defining the substrate specifications earlier presented in table 2: copper and board thicknesses.

The circuit boards received from Aisler were missing the second layer copper plane, which changed the board’s performance drastically. Measurements showed that the band-pass filters behaved unpredictably, and the results shown on the network analyser depended significantly on the present noise and interferences. For this reason, it was decided to attach the ground plane to the PCB by cutting out a plane circuit board and pressing it against the bottom of the PCB with screws. Additionally, the ground nodes of the connectors were connected with a stripped wire placed between the circuit boards, which ensured their connection to the ground plane. The resulting PCBs can be seen in figure 17. These PCBs produced by Aisler will be referred to as BC and SC in tables and figures. SC is the thinner filter with dimensions of 24.3 x 118.7 mm, and BC is 19.5 x 119.5 mm.

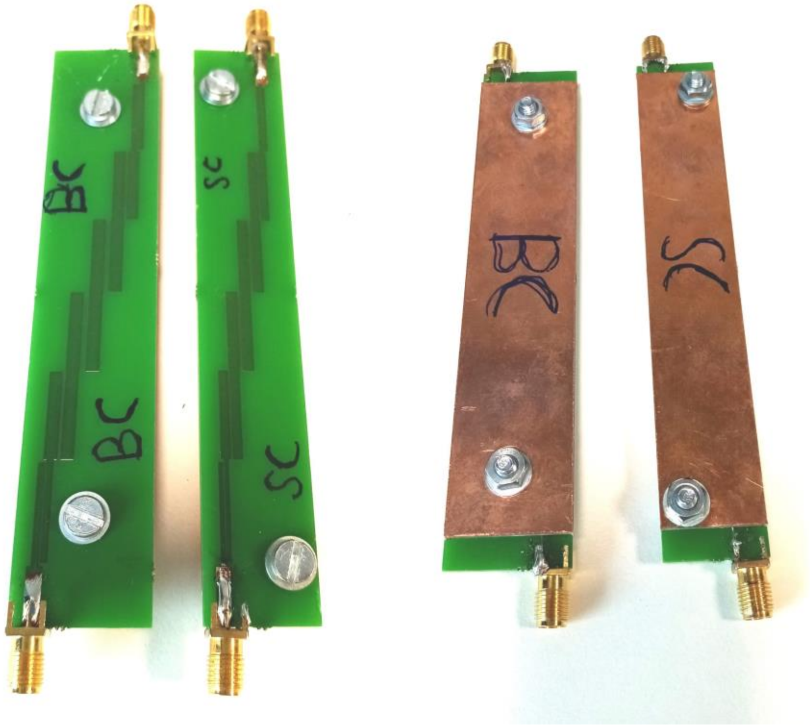

Figure 17. Modified PCBs from Aisler (left side – top view, right side– bottom view)

The circuit boards acquired from PCBway had the ground plane intact, as can be seen on the right side of figure 18. It was only required to solder the connectors to them. These PCBs are referred to as BC2 and SC2 in figures and tables. SC2 is the thinner filter with dimensions of 24.3 x 118.7 mm, and BC2 is 19.5 x 119.5 mm.

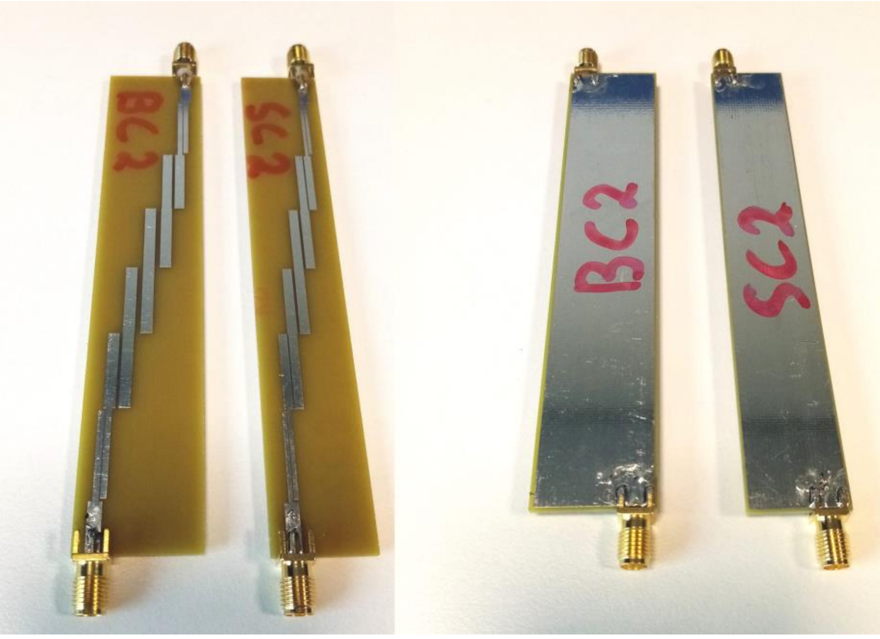

Figure 18. PCBs produced by PCBWay

PCBs milled at Metropolia also did not require an additional ground plane, since they were milled out of a two-sided circuit board sheet. It was only required to solder the connectors onto it, the resulting PCBs are displayed in figure 19 below.

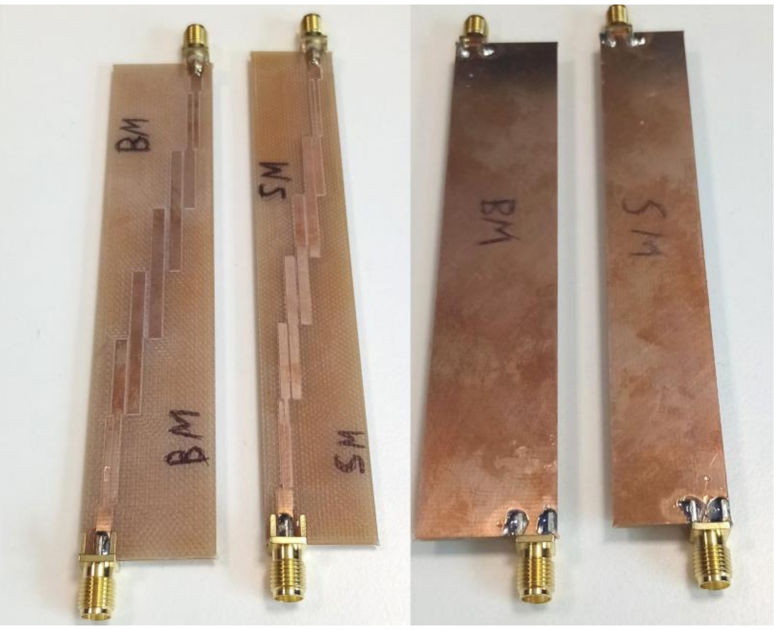

Figure 19. PCBs milled at Metropolia

In the previous chapter, the two designed filters are referred to as filter 1 and filter 2, where filter 1’s thickness was 24.3 mm, and filter 2’s – 19.5 mm. In this and following chapters the produced filters are referred to as B-filters and S-filters, “B” – for “Big”, thicker filter, and “S” – for smaller, thinner PCB. Denotation of BM implies “Big Metropolia”, BC – “Big China”, BC2 – “Big China 2”, etc.

5 Filter Measurement Setup

The network analyser used was a Hewlett Packard 8417ET analyser (later referred to as NA in the text) with measurement bandwidth of 0-3GHz. Picture of the NA is shown in figure 20 below.

Figure 20. 8417ET network analyzer

Transmission measurement required one input of the filter to be connected to the reflection input, and the other – to the transmission input of the NA, as shown in figure 21 below.

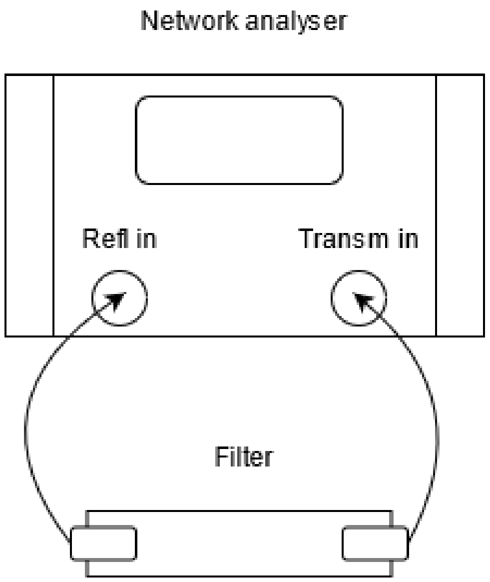

Figure 21. Transmission measurement block diagram

The reflection measurement is performed as shown in figure 22 below, by connecting one input of the filter to the reflection input of the NA. The second input of the filter, as well as the transmission input of the NA are left unconnected. Also, the wires that connect the filter to the network analyser are imperfect and have their own impedance, which is accounted for during the calibration process.

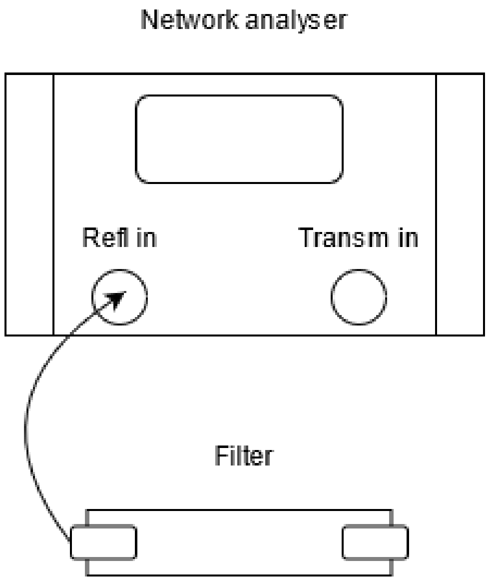

Figure 22. Reflection measurement block diagram

For the reflection measurement it was also required to connect the other filter connector (figure 22) to a 50-ohm standard. However, this detail was neglected during the measurements in this project.

6 Filter Measurements

The conducted measurements were magnitude and phase of the PCBs' transmission and reflection, and Smith's chart of their reflection coefficients.

6.1 Filter Transmission Measurements

First, the network analyser was set to frequency range of 2GHz-3GHz, and to the measurement of transmission. Next, it was calibrated, which required to connect the open, short circuit, and load standards to the reflection input, as well as a through-cable, connecting the inputs. Calibration was performed with the cables already connected to the network analyser's input ports to account for their impedances. Transmission measurement results of SM, SC and SC2 are displayed in figure 23 below.

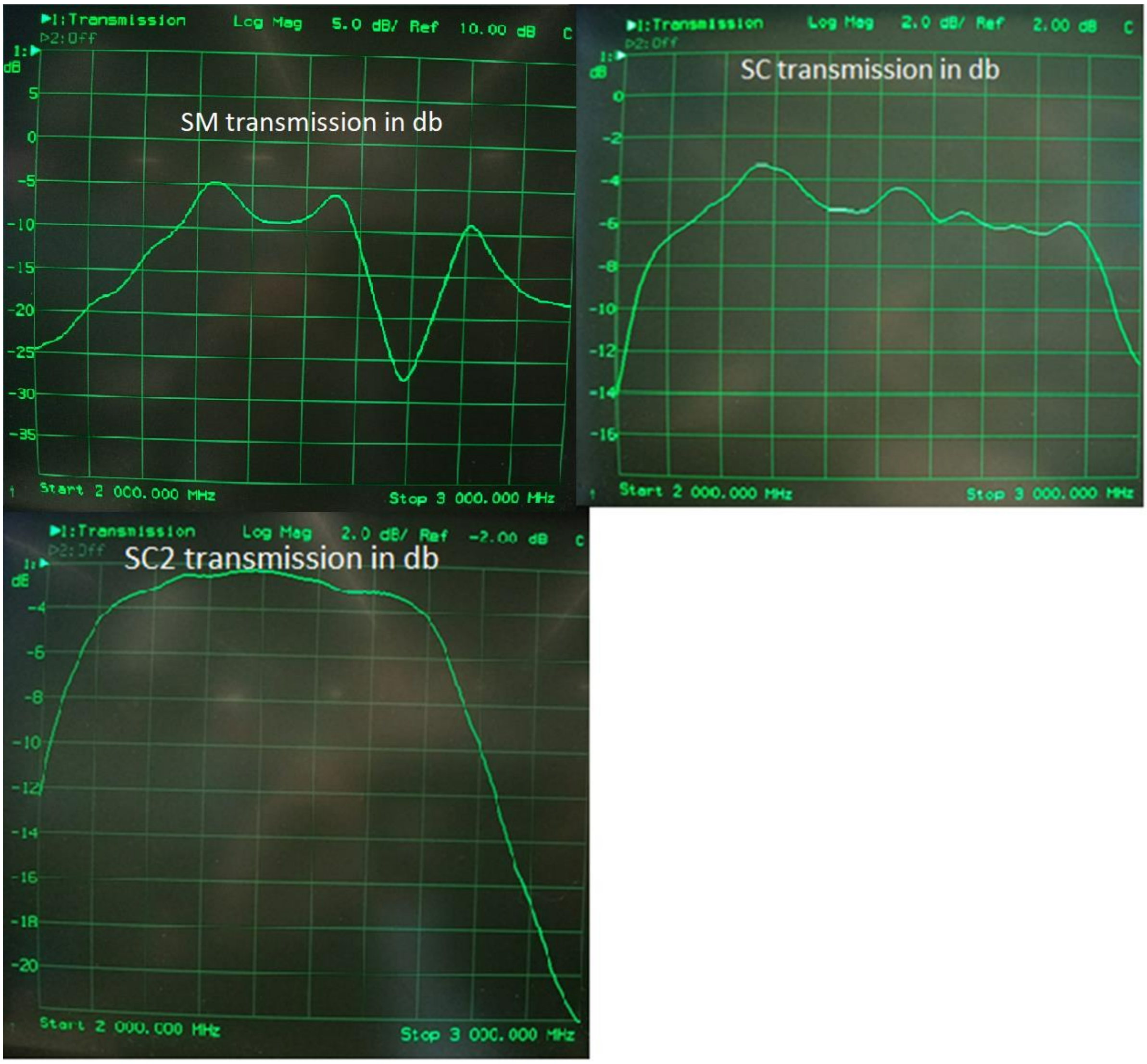

Figure 23. S-filters' transmission in dB

After the measurement of S-filters was finished, the B-filters were connected one by one and measured (figure 24). No recalibration was necessary, since the measurement settings were the same, the frequency range 2 GHz-3 GHz and the transmission measurement type.

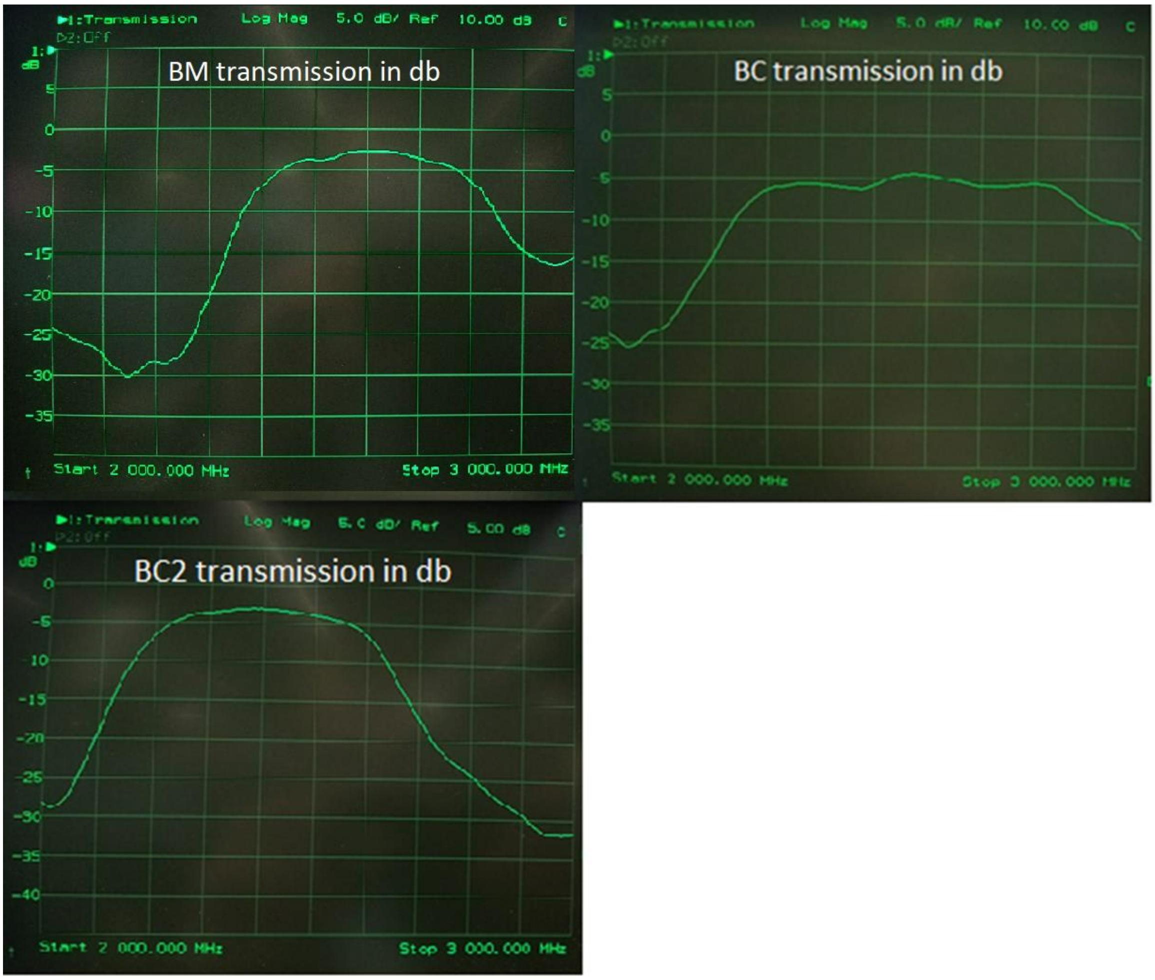

Figure 24. B-filters' transmission in dB

6.2 Filter Reflection Measurements

Firstly, the measurement parameters were set: the measurement of reflection, and frequency 2GHz-3GHz. Then, the network analyser was re-calibrated, which required to connect the open, short circuit, and load standards to the reflection input of the NA. Calibration was performed with the cable already connected to the network analyser’s reflection port to account for its impedance.

First, the measurements were taken on a logarithmic scale. S-filters were measured first, with the result displayed in figure 25.

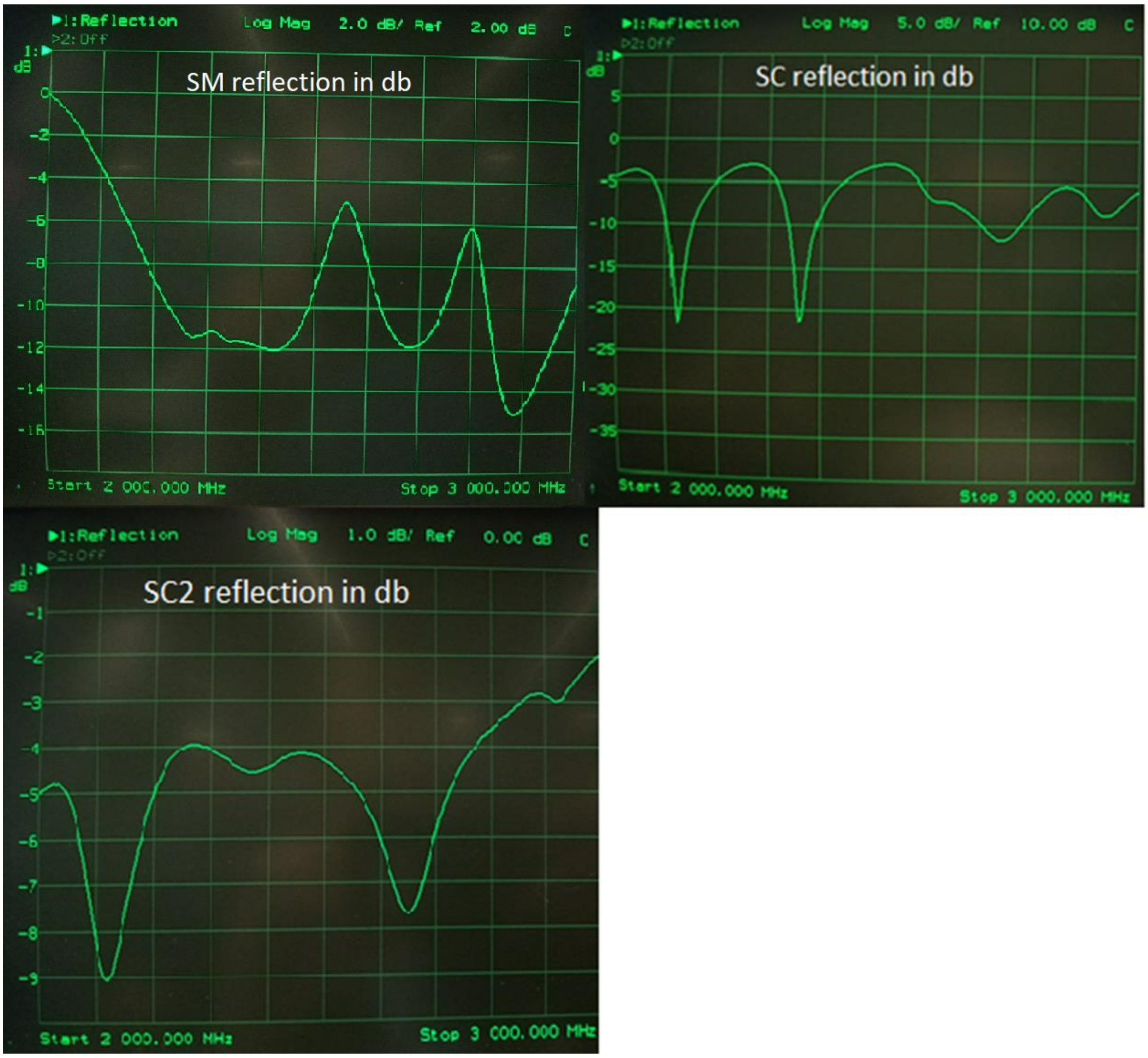

Figure 25. S-filters' reflection in dB

Then, the reflection of B-filters was measured in dB (figure 26).

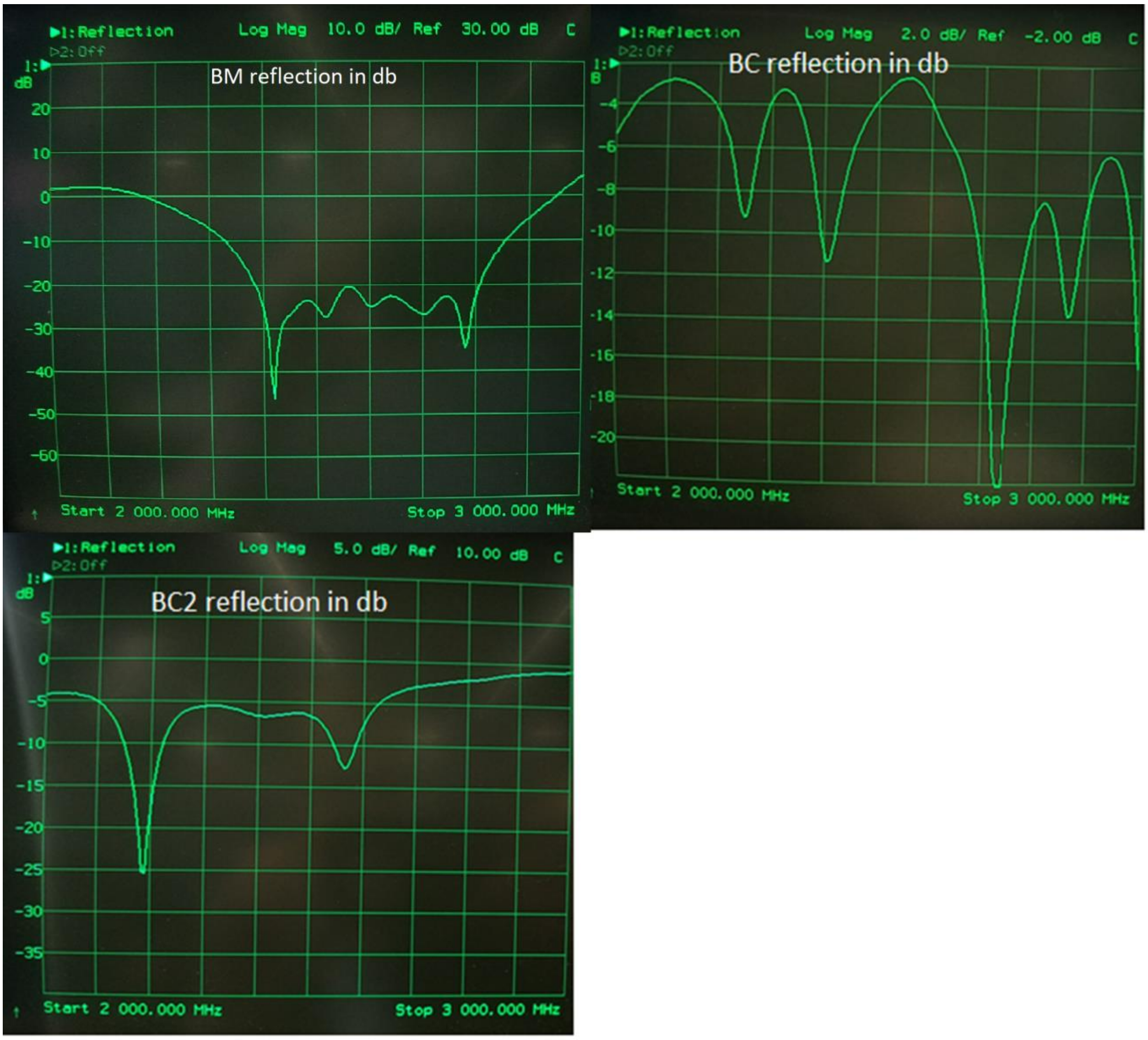

Figure 26. B-filters' reflection in dB

Next, the format of the display was set to Smith chart, and the reflection measurements were taken again. No recalibration was necessary since the measurement settings were not changed.

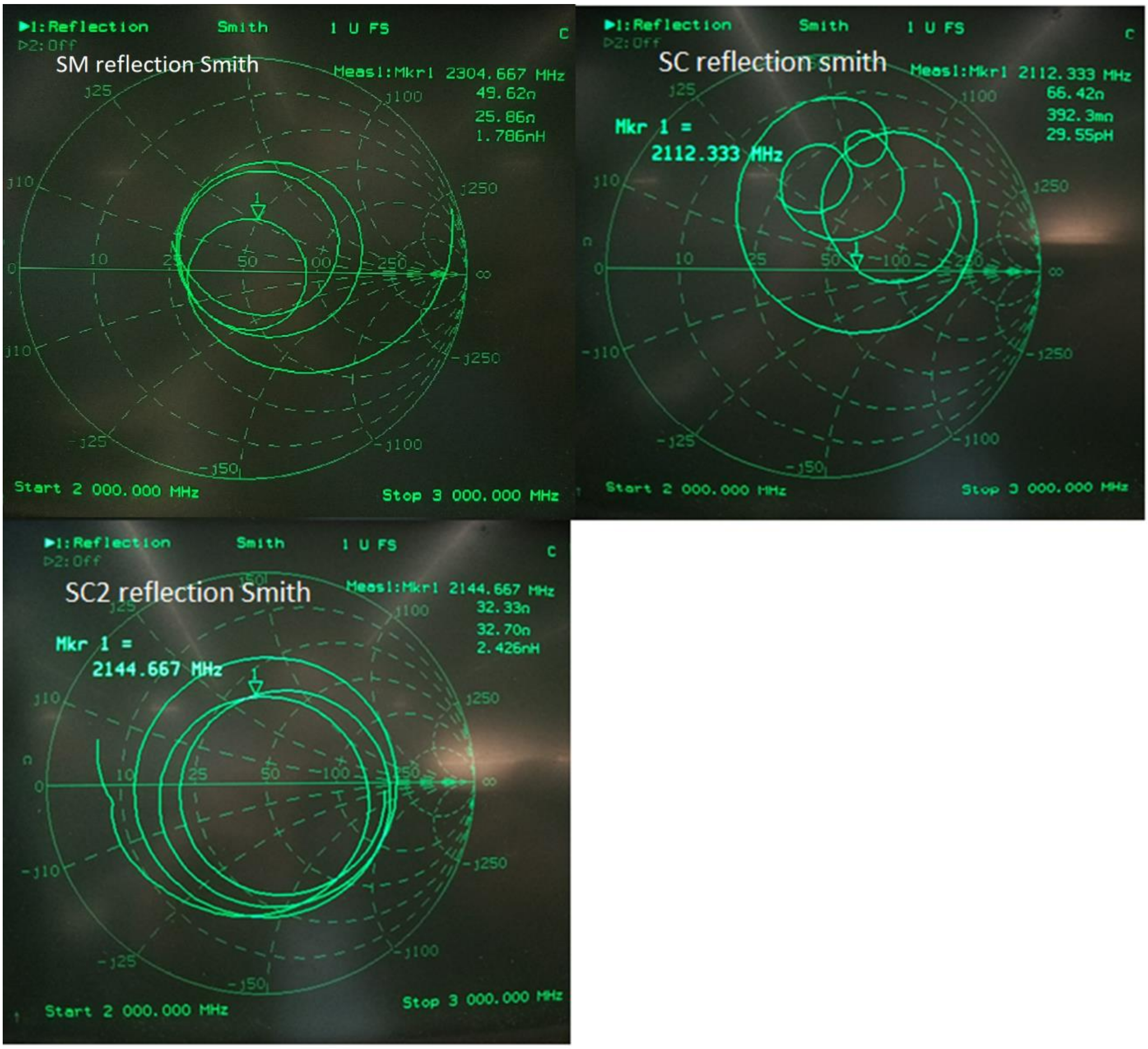

Figure 27. S-filters' Smith charts of reflection

Smith charts of S-filters’ reflection can be seen in figure 27 above, and of B-filters – in figure 28 below.

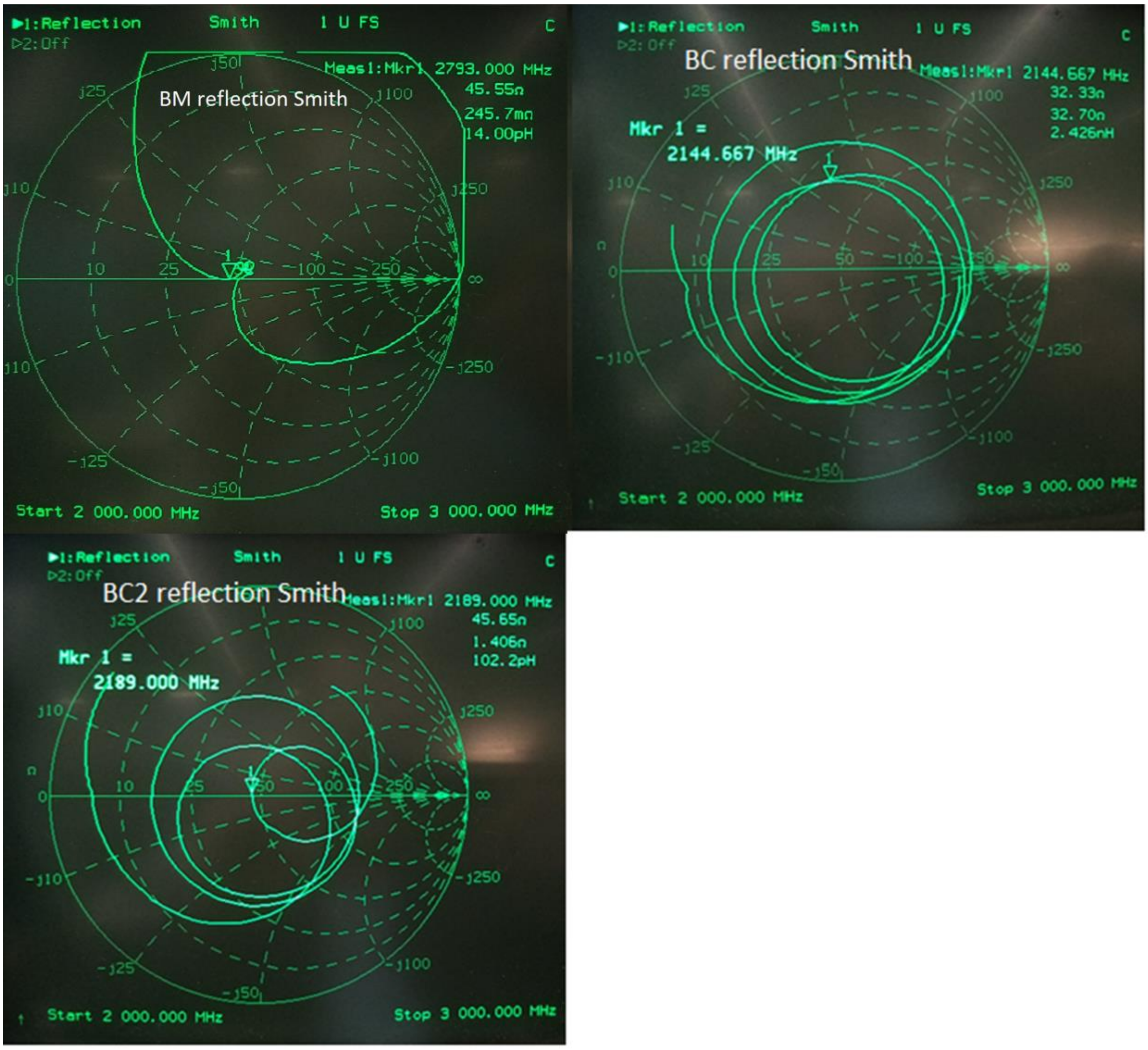

Figure 28. B-filters' Smith chart of reflection

As seen in figures 27 and 28 above, a marker was used during the Smith chart measurements to determine the coordinates of the point closest to the matching point.

7 Results

7.1 Transmission Simulation and Measurement Results

Transmission power measurements are compared by their bandwidth, attenuation at the bandwidth, and attenuations at the ends of the measurement spectrum. Table 5 below shows the expected and acquired transmission values of filter2.

Table 5. Comparison of expected and simulated transmission power of S- and B-filters

Filter	Bandwidth [GHz]	Bandwidth atten. [dB]	2GHz atten. [dB]	3GHz atten. [dB]
Expected, filter2	2.1-2.9	0	-	-
Simulated, filter2	2.1-2.77	-0.2	-11	-22
Measured, SM	2.3-2.8	-5 to -25	-25	-18
Measured, SC	2.15-2.7	-3	-14	-13
Measured, SC2	2.1-2.75	-2	-12	-22
Expected, filter1	2.25-2.75	0	-	-
Simulated, filter1	2.2-2.63	-0.3	-33	-40
Measured, BM	2.4-2.8	-3	-25	-15
Measured, BC	2.25-2.85	-5	-24	-12
Measured, BC2	2.2-2.7	-4	-29	-32

Expected values of attenuation at the ends of the spectrum at 2GHz and 3GHz were not set during the calculations, for this reason the corresponding fields are left blank in table 5.

7.2 Reflection Simulation and Measurement Results

Expected value of attenuation at the 2.5GHz was not set during the calculations, for this reason the corresponding fields are empty in table 6, which compares the simulated and measured reflection power.

Table 6. Comparison of expected and simulated reflection power of B- and S-filters

Filter	Bandwidth [GHz]	2GHz atten. [dB]	2.5GHz atten. [dB]	3GHz atten. [dB]
Expected, filter2	2.1-2.9	0	-	-
Simulated, filter2	2.1-2.77	0	-18.4	0
Measured, SM	2.1-3	0	-9	-16
Measured, SC	2.1-2.95	-5	-3	-5
Measured, SC2	2-2.7	-5	-4.3	-2
Expected, filter1	2.25-2.75	0	-	0
Simulated, filter1	2.2-2.63	-0.1	-15.5	-0.1
Measured, BM	2.25-2.9	2	-25	4
Measured, BC	2.25-2.7	-6	-4	-16
Measured, BC2	2.15-2.6	-5	-6	0

Table 7 below displays the results of Smith chart simulations and measurements. Since some of the filters did not reach the ideal matching point, values for the “matching point” columns were chosen from the nearest point to the center of the Smith chart.

Table 7. Matching values of S- and B- filters

Filter	Matching frequency [MHz]	Matching real value, normalized	Matching im. value, normalized
Simulated, filter2	2206	0.99	0.01
Measured, SM	2304	0.99	0.52
Measured, SC	2112	1.32	0.008
Measured, SC2	2145	0.64	0.64
Simulated, filter1	2580	0.97	0.01
Measured, BM	2793	0.91	0.01
Measured, BC	2145	0.64	0.64
Measured, BC2	2189	0.9	0.03

8 Discussion

First, comparing the expected and simulated transmission values of filters 1 and 2, it can be noticed, that the differences are minor. The bandwidth divergence is of maximum 0.13 GHz, and the bandwidth attenuation differed from the expected by maximum 0.3 dB, as seen in table 5. The measurements of SM filter show that it does not operate as required, since its attenuation at the bandwidth varies drastically. That implies that the filter does not provide stable attenuation over the bandwidth. Filters SC and BC, as well as SC2 and BC2 and also BM display the required filtering behaviour, attenuating the signals outside the bandwidth more, than signals in the bandwidth range. All the filters from China have bandwidth like the simulated, however SC2 and BC2 have closed attenuation values to the simulated, compared to SC and BC.

Analysis of reflected power results of table 6 shows that the attenuation of filters SC and SC2 is similar at frequencies of 2 GHz, 2.5 GHz and 3GHz, varying by maximum of 2.3 dB. Also, filters BC and BC2 have similar attenuations at 2 GHz and 2.5 GHz, diverging by maximum 2 dB. Attenuation values of filters BM and BC are the closest to the simulated values, although still varying by at most 6.4 dB. Since the reflected power graphs have a few drops, the numerical data is not conclusive, and the graphical measurements must be considered as well. Comparison of graphs in figures 13 and 25 shows that the waveform of SC and SM filters is distinctly dissimilar from the simulated filter 2, and that the filter SC2 displays more resemblance to the simulation. However, while for the most part of the bandwidth attenuation of the simulated filter is roughly -20dB, SC2 filter has the attenuations of -2 dB. Collation of measured B-filters to the simulation in figures 10 and 26 allows to notice that only the BM-waveform resembles the simulated waveform.

Comparison of the filters described numerically in table 7 allows to note that the filters SM, SC, and BC2 have the closest normalised matching values to the simulation. The matching frequencies of filters SC2 and BM are the closest to the simulated, however their imaginary normalized values show a difference of 0.64 from the simulation results.

Additionally, Appendix 1 contains measurements of transmission and reflection phases of filters. The transmission measurement shows that SC and SC2, as well as BC and BC2 have a stable phase response to the frequency. However, only SC2 and BC2 have a stable waveform of the reflection measurement.

The results of measurement comparison of the previous paragraphs indicate that filters BM and BC2 have the values closest to the simulated. BC2 performs better than BM according to the transmission power measurements, however, surprisingly, reflection power measurements show that BM outperforms the simulation, as well as the BC2.

The filters 1 and 2 required a precision of 0.13mm during the milling, since it was the smallest gap between the microstrip lines. The milling machine at Metropolia utilized the 0.2mm drilling tool to create those gaps, which played a critical role on the performance of the filters SM and BM. Additionally, the reason why filters SC and BC showed undesired results was the ground plane that was attached manually to the PCB. Since there was a small gap left between the plane and the PCB, it increased the distance between the microstrip lines, causing the filters' function to be altered.

9 Conclusion

Discussion of the measurement results allowed for an interpretation that the filters produced in Metropolia showed inconclusive results, since the filter BM fulfilled the set requirements, while the SM did not. Presumably, that was due to the imprecision of the milling, which caused the microstrip lines on the PCBs to have wider gaps than required. The first pair of filters produced in China also displayed undesirable results, supposedly due to the additional improvements that were performed to boost its functionality. Lastly, the second pair of filters ordered from China showed satisfactory outcomes in most of the measurements, and the most appropriate functionality for a bandpass filter.

Since this project showed that the milling machine at Metropolia does not perform well with the precision of 0.13 mm, more research is required to find out the exact precision of its production. For the time being, it is recommended to use other milling machines available at the university or to outsource the PCBs that require the precision over 0.2 mm.

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Appendix 1. Transmission and Reflection Phase Measurements

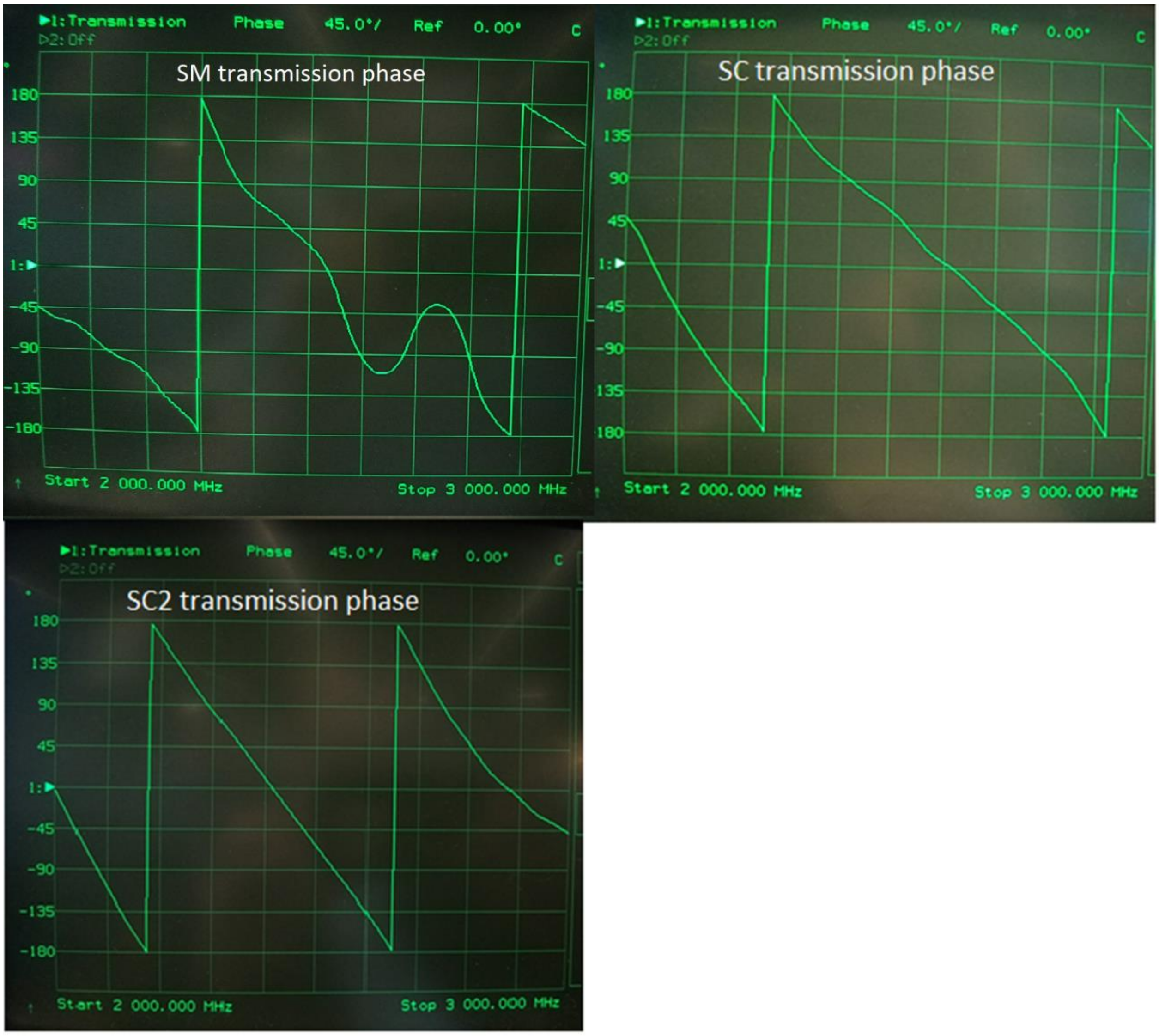

Figure 29. S-filters' transmission phase measurements

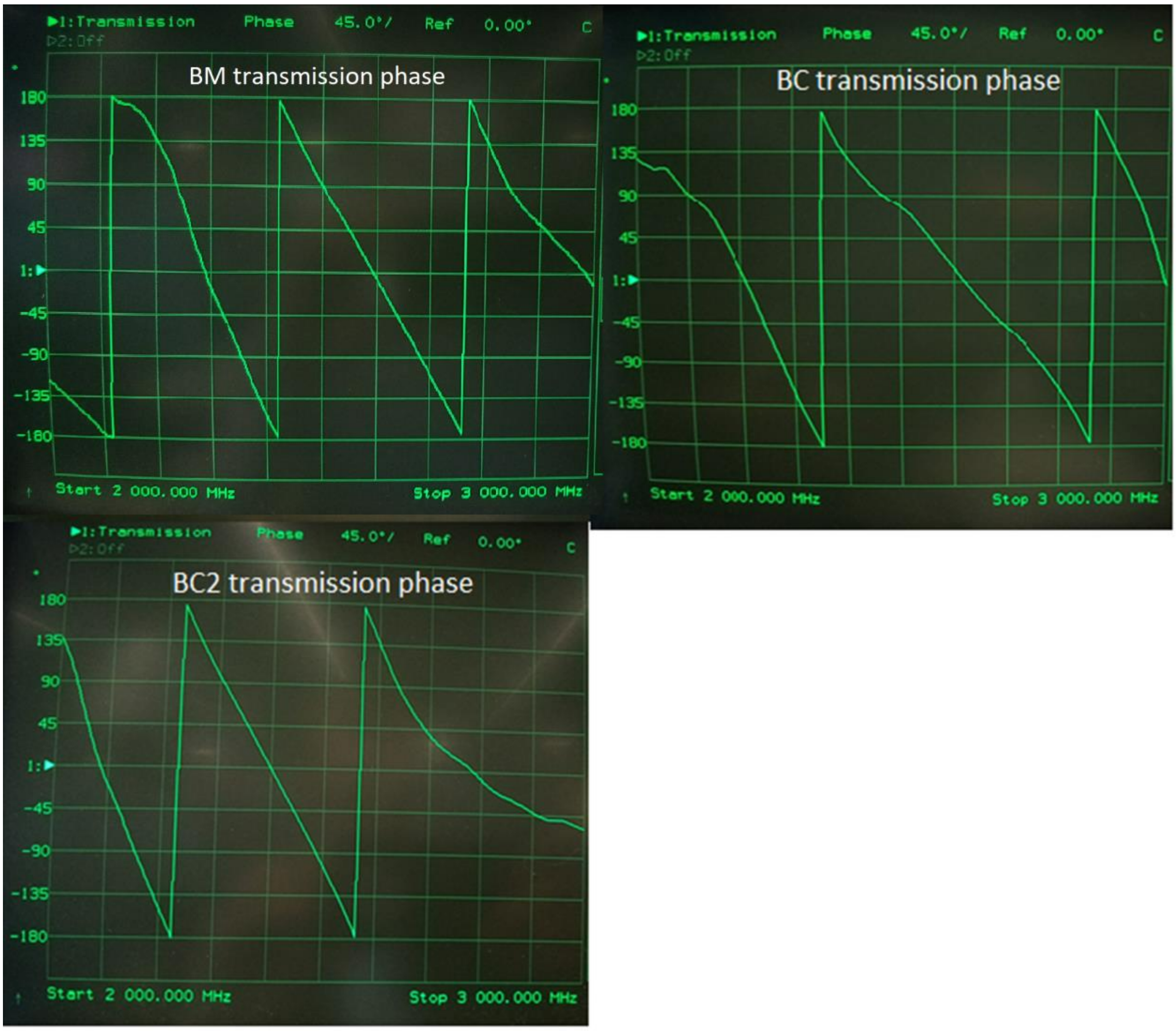

Figure 30. B-filters' transmission phase measurements

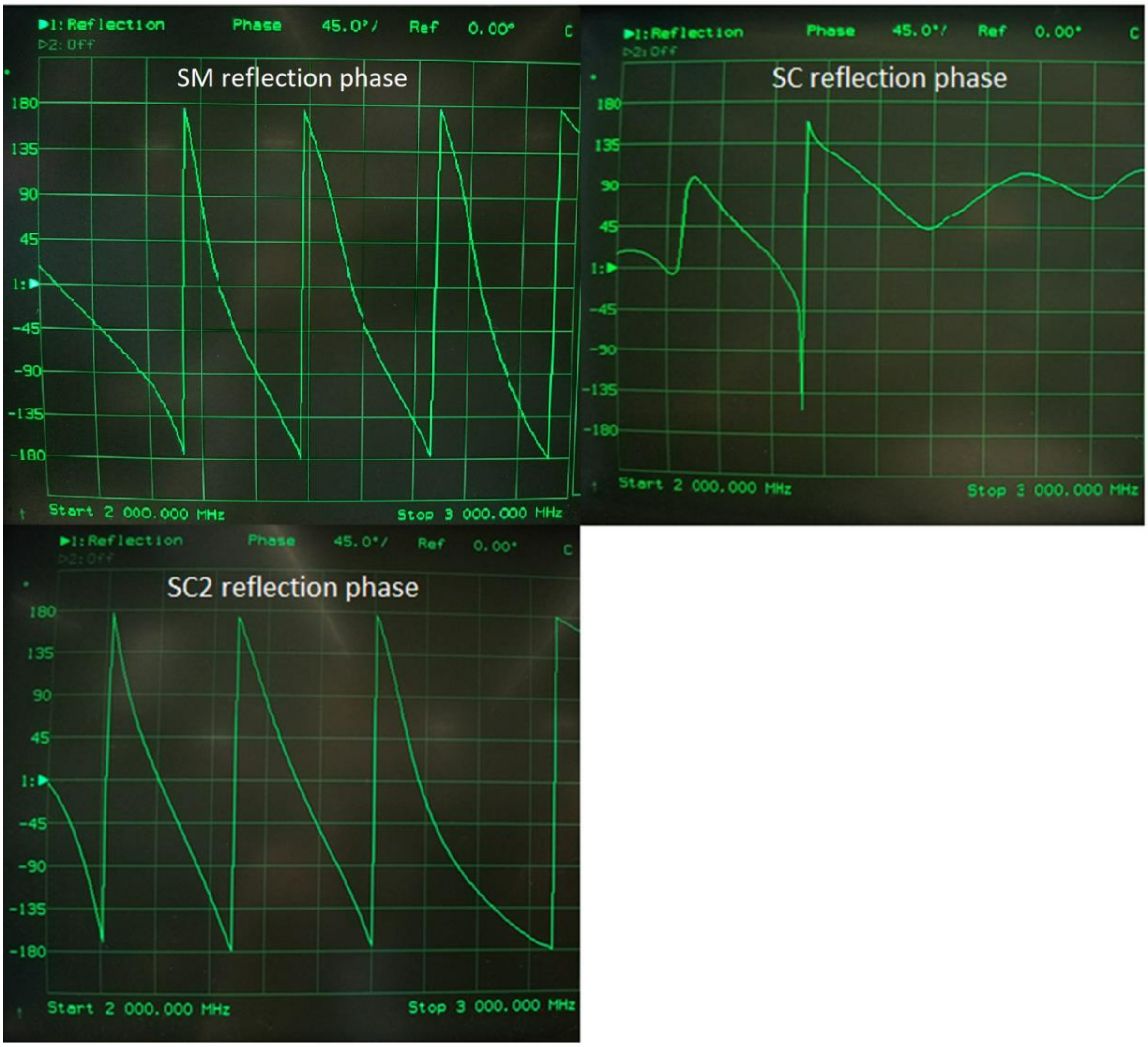

Figure 31. S-filters' reflection phase measurements

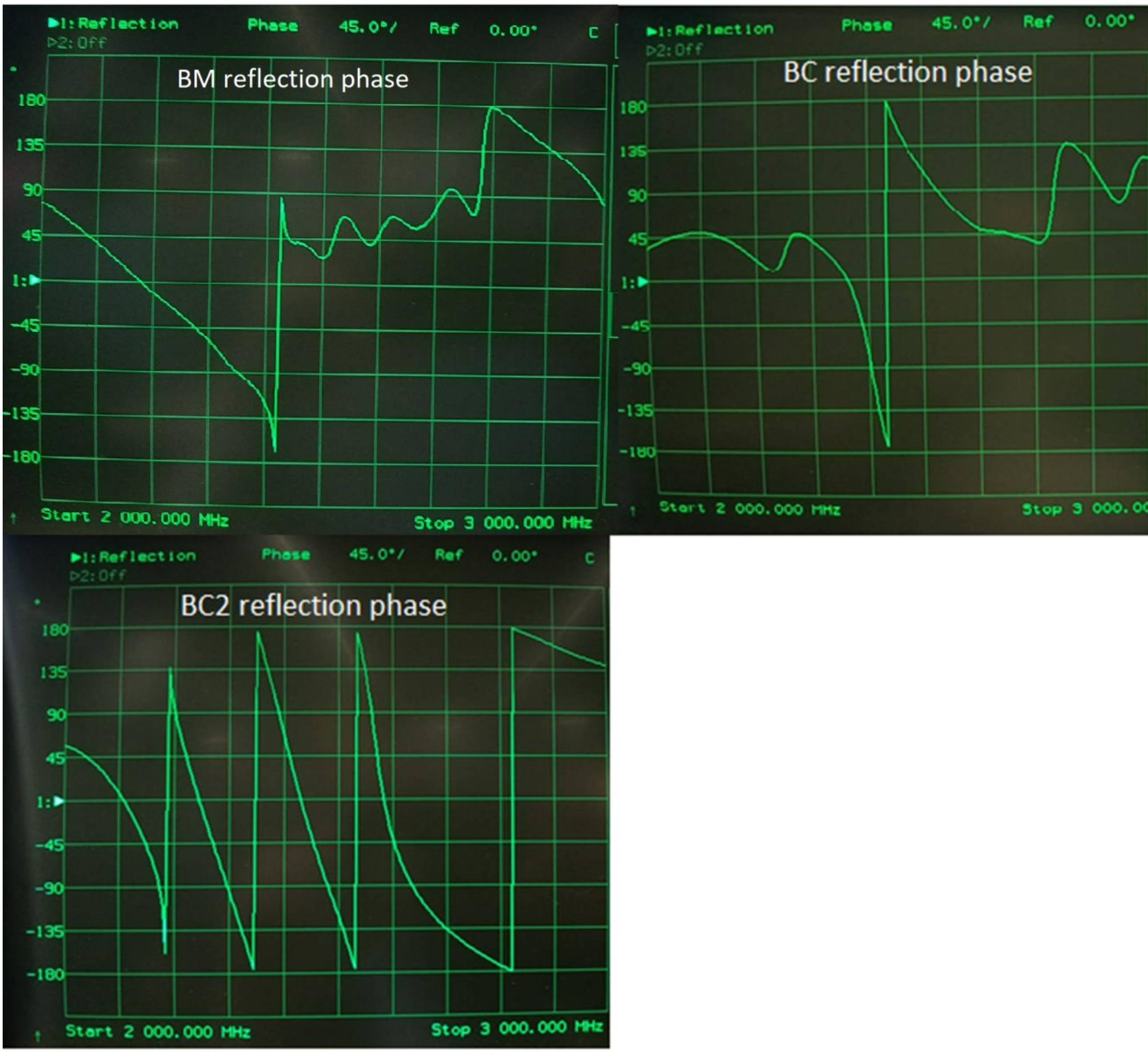

Figure 32. B-filters' reflection phase measurements