FILTER CONSTRUCTION TECHNIQUES

Introduction

The passive LC Chebyshev lowpass and highpass filters are widely used in EMI/RFI testing to provide the many types of frequency selectivity that are required. For example, the 5- or 7-element Chebyshev high and lowpass filters are frequently placed in front of a spectrum analyzer for signal pre-selection. Another application of a lowpass filter is to reduce the harmonic levels of clock oscillators. Many articles have already been published on the simplified design of these filters (see References 1 through 9), but there has been little information published on the specialized construction techniques that are necessary if these filters are to have maximum effectiveness. This article will explain these specialized techniques so that the average technician or engineer will be able to construct a filter with the assurance that it will function as intended.

Effective Filter Performance Becomes More Difficult To Achieve Above 50 MHz

For both the low and highpass filters, proper performance becomes more difficult to achieve as the frequency increases above 50 MHz. This is because strays of the filter components, such as inductor inter-winding capacity and capacitor lead inductance, begin to become significant and more difficult to control at frequencies above 50 MHz. In comparison, as the frequency decreases the strays of the filter components become less significant than before, and at very low frequencies, the components approach that of a lumped element with predictable parameters.

For the lowpass filter, the most difficult frequency spectrum to control is the filter stopband above 50 MHz, whereas for the highpass filter, it is the passband above 50 MHz that becomes touchy. Because of these basic differences in the lowpass and highpass filter responses, two different construction techniques must be used to obtain satisfactory operation above 50 MHz.

Lowpass Filter Construction

Satisfactory lowpass filter performance is indicated by a passband insertion loss of less than 1 dB below the cutoff frequency, a gradually increasing insertion loss between about 0.8 and 1.2 times the cutoff frequency, and a stopband insertion loss of greater than 80 dB at two or three octaves above the cutoff frequency. For example, at two octaves above the cutoff frequency, a 7-element Chebyshev lowpass filter has an insertion loss in excess of 80 dB, and this level of loss should extend up to 1 GHz and above if proper components and construction techniques are used.

The inductors and capacitors used in high-frequency filters must have a self-resonant frequency (SRF) as high as possible, and certainly at least one decade above the filter cutoff frequency. Although the powdered-iron core toroidal inductor is frequently used at high frequencies because of its high Q and self-shielding characteristic, this inductor type must be used with discretion because it has a relatively high interwinding capacity which results in a lower SRF as compared to the solenoid-wound inductor type. At frequencies above 100 MHz, the solenoid-wound inductor (either iron or air-core) becomes more feasible because of its high SRF. For example, the CAMBION* type 551-5172 molded r-f chokes have inductance values ranging from 0.022 to 0.082 uH with published SRF values from 1245 to 750 MHz, respectively. These inductors are unshielded (for maximum SRF), and care must be used to minimize coupling between inductors, either by separation or orientation of the winding axes at right angles for a multi-inductor filter.

The most suitable capacitor type for lowpass filtering is the ERIE Button® mica capacitor because of its minimum series inductance (a consequence of its physical configuration) and its bulkhead mounting installation; however, this capacitor type is not as conveniently available from electronic distributors as it has been in the past. An almost equally effective capacitor for lowpass filter construction is the ERIE monolithic Red Cap with an NPO (Ultra-stable) high-Q dielectric material. This type is widely available from distributors and it is much easier to obtain and less expensive than the Button mica type. Although the Red Cap can be manufactured with a 500-volt rating, only the 100-volt rating is normally stocked by distributors. The monolithic construction of the capacitor produces a very high SRF, and even though the capacitor does not have a feed-through configuration, it is possible to obtain satisfactory stopband performance in a lowpass filter if the capacitor is mounted with minimum lead length on the filter partitions. A Teflon feed-through connector can be used to connect one filter section to the next.

Lowpass filter construction techniques using the Button mica capacitor were discussed in the 1979 issue of ITEM, and the reader is referred to page 122, Figure 4 of that issue for an example of suitable lowpass filter construction. Figures 5 and 6 on page 124 of the same issue show the effects of the absence and presence of bulkhead partitions on the filter stopband response.

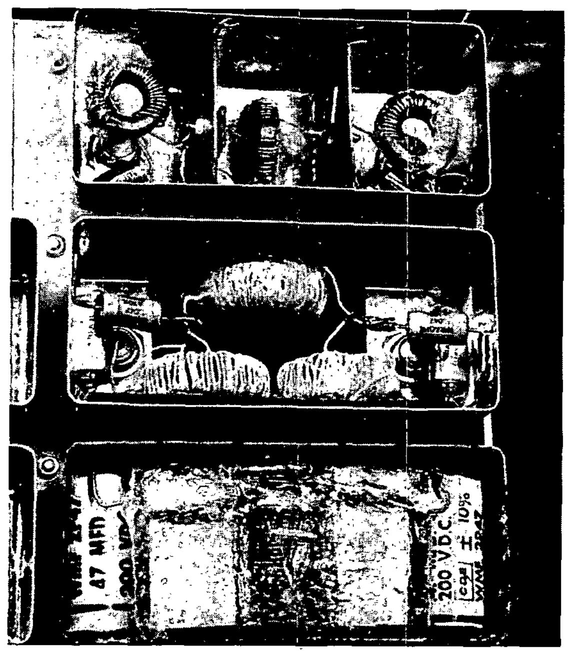

Figure 1. Examples of Lowpass Filter Construction for Cutoff Frequencies of 1 MHz, 100 kHz and 10 kHz. The 1 MHz filter is at the top of the photograph. Note how the Teflon feed-throughs and the ERIE Red Caps are mounted on the metal partitions of the 1 MHz filter.

*CAMBION Catalog 800, p. 226

Figure 1 shows an example of suitable lowpass filter construction techniques for cutoff frequencies of 10k, 100k and 1MHz. In the 1-MHz filter, partitions with Teflon feed-throughs and ERIE Red Caps are used to obtain satisfactory stopband attenuation to 1 GHz. Partitions were not required for the other two filters. Figure 2 shows the filter schematic diagram.

Highpass Filter Construction

As with the lowpass filter, special care is required to obtain satisfactory highpass filter performance at frequencies well above the cutoff frequency, except the filter *passband* is now in the difficult frequency range. This means the filter insertion loss must remain low (preferably less than 1 dB) up to as high a frequency as possible. With proper components and construction, the passband of a highpass filter can be made to extend to two or more decades above the cutoff frequency. The secret in accomplishing this is to minimize r-f signal reflections by mounting the filter components on a microstrip transmission line which is used to join the filter to the input and output connectors of the metal case containing the filter components.

A microstrip transmission line is comprised of a printed circuit board which has a ground plane on one side and a single track on the other side with a width of proper dimension to give the proper r-f impedance. The function of the microstrip track is to provide a matched impedance line to the r-f signals being passed by the filter at frequencies well above the cutoff frequency. At these relatively high frequencies, the capacitors appear to be transparent to the signal, and the inductors appear to be open circuits. Thus, as far as the passband signal is concerned, the filter components are not present. The only "component" that the passband signal sees is that of the microstrip transmission line, and if the line is correctly dimensioned, the signal will pass with little reflective loss. Of course, the effectiveness of the transmission line is dependent on the SRF of the filter components which surround it. Losses will be introduced when the inductors start becoming capacitive, and when the capacitors start becoming inductive. But, if proper high-frequency components are used, the degradation of the microstrip line will occur only above the maximum frequency of the filter passband.

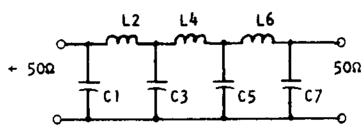

Figure 2. Schematic diagram of the 7-element lowpass filter shown in Figure 1.

To demonstrate the effectiveness and importance of using a microstrip line in the construction of highpass filters, two highpass circuits were assembled in a metal case 3-½″ long by 1-½″ wide and 1-½″ deep. BNC connectors were installed on each end of the case, and the center pins were interconnected with a p-c track about 0.14 inches wide. No ground plane was used on the other side of the p-c board. The insertion loss response of this circuit was plotted to 1.5 GHz, and it is shown in Figure 3.

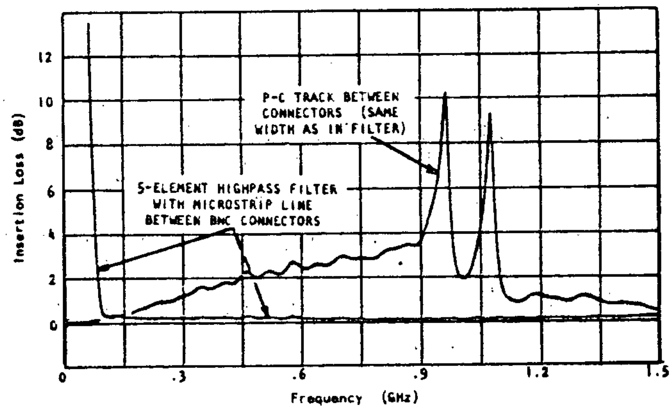

Figure 3. Insertion Loss Responses of a Highpass Filter with a Microstrip Line and a P-C Track Without a Ground Plane. The response of the filter demonstrates the importance of using a microstrip line to obtain a satisfactory passband response to 1.5 GHz.

Between 300 and 900 MHz, the insertion loss increased from about 1 dB to more than 3 dB. Between 900 and 1200 MHz, two insertion loss peaks up to 10 dB were noted. These losses are attributed to signal reflections due to the gross mismatch occurring between the 50-ohm impedance of the test system and the p-c track. Of course, this amount of insertion loss is unacceptable in the passband of a highpass filter.

The second circuit tested was a 5-element 100 MHz highpass filter which had its components placed on the same width p-c track previously used, and a ground plane under the track was connected to the shells of the BNC connectors. The Teflon extrusion around the center pins of the BNC connectors was cut off with an X-ACTO knife so the connector could butt directly against the p-c board, thus effectively simulating an end-launch connector. The board thickness and dielectric constant were such that the impedance of the p-c trace was 50 ohms. The response of the highpass filter circuit is also shown in Figure 3, and the improvement in the passband response (as compared to the p-c track without ground plane) is obvious. The highpass filter with microstrip line has less than 0.5 dB of insertion loss up to 1.5 GHz. This is what should be expected in a properly designed and constructed highpass filter. Note that the filter insertion loss increases abruptly (as it should) around 100 MHz.

BASIC Computer Program for Calculating a Microstrip Transmission Line.

Because of the importance of using a properly dimensioned microstrip line in highpass filter construction, a simple BASIC computer program is presented in Appendix A. If the user inputs the requested data (dielectric constant, dielectric thickness, and an initial track width), a listing of microstrip impedances versus track width will be printed. The width having an impedance closest to the desired impedance (50 ohms in this case) should be used. For the p-c board material used in this example (Teflon fiberglass), the track width to give approximately a 50 ohm impedance was 0.145 inches.

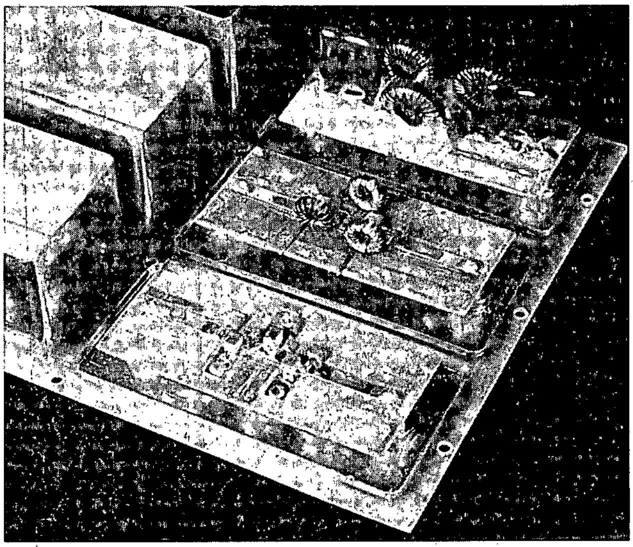

Figure 4. Three examples of highpass filter construction. The upper filter (with the largest component size) has a cutoff of 1 MHz, the middle filter cuts off at 10 MHz, and the lower filter cuts off at 100 MHz. All filters use microstrip transmission lines for extended high frequency performance.

Examples of Highpass Filter Construction

Figure 4 shows three highpass filters with cutoff frequencies of 1, 10 and 100 MHz. The schematic diagram of these filters is shown in Figure 5. As shown in the photograph, the ERIE Red Cap capacitors are mounted on the microstrip track across breaks in the track. The shunt inductors connect from the track through eyelets to the ground plane under the p-c board. Iron-powder toroidal cores were used in the 1-MHz and 10-MHz highpass filter construction. The CAMBION fixed-monolithic micro inductor, type 555-1083 was used in the 100-MHz filter. Although the 10-MHz and 100-MHz passband responses are satisfactory for the intended application (a decade filter box where the passband response was required to extend only one decade above the cutoff frequency), the filter passband could be further extended at lower cost by using different inductors.

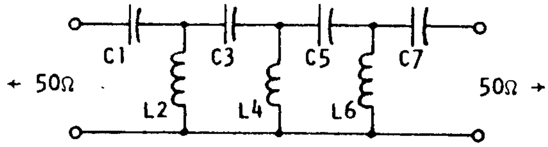

Figure 5. Schematic diagram of the 7-element highpass filters shown in Figure 4.

In the 10-MHz filter, the toroidal inductors should be replaced by the CAMBION molded r-f choke, type 550-3399 (0.1 - 100 uH) because it has a higher SRF than the toroidal inductors. In the 100-MHz filter, the monolithic inductors, although they perform satisfactorily, should be replaced with the previously discussed molded choke, CAMBION type 551-5172, because this choke is about 1/5 the cost of the monolithic inductor, and because it has a much higher SRF. For example, in the 0.047 uH value, the molded choke has an SRF of 1060 MHz as compared to 660 MHz for the monolithic inductor. Actually, the monolithic inductor is designed for application in complex printed circuits requiring a compact inductor form with solder pads for p-c track mounting. Consequently, the cost of this more complex inductor type is higher than the simpler molded choke type. For typical non-stringent filter construction such as shown in Figure 4, the molded r-f choke is a better choice than the monolithic type.

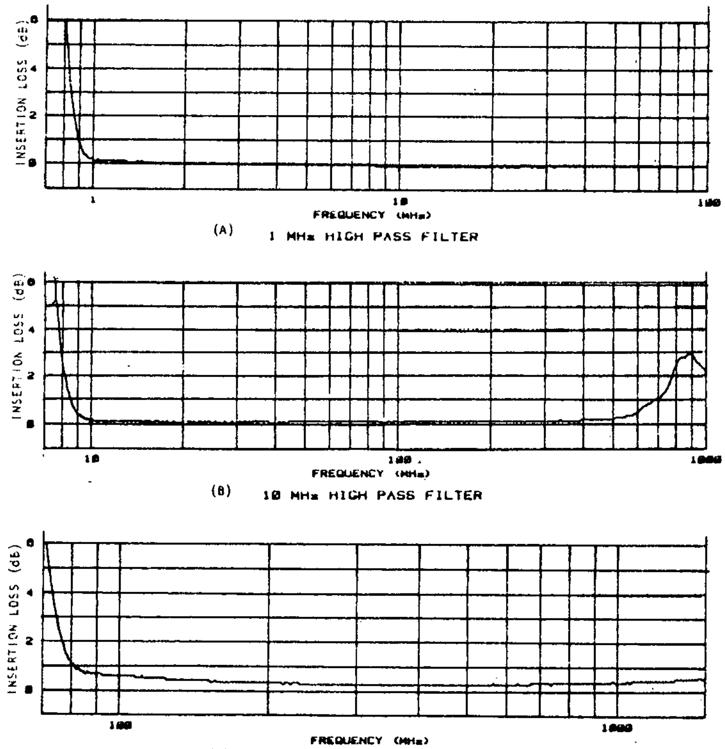

Figure 6. Passband Insertion Loss Responses for the three highpass filters shown in Figure 4.

Figure 6 (A, B and C) shows the respective passband responses of the 1-, 10- and 100-MHz filters shown in Figure 4. The 1-MHz filter passband insertion loss [Figure 6(A)] is less than 0.2 dB two decades above the cutoff frequency, and this is to be expected from a properly designed and constructed highpass filter. The 10-MHz filter response exceeds 0.5 dB above 600 MHz, and this undesired performance is attributed to the low SRF of the toroidal inductors that were used in the filter construction. If the recommended inductors had been used instead, it is anticipated that the passband response of the 10-MHz filter would have extended to 1000 MHz. The 100-MHz filter passband response extends to 1.5 GHz, but the insertion loss is a little higher than it should be. The 0.5 dB loss over the passband probably could be reduced by half if the recommended molded choke had been used instead of the monolithic inductors. [The slight wiggles in the response curves are a consequence of the digital spectrum analyzer plotting routine, and they are not to be associated with the actual filter response.]

A Simpler Method of Microstrip Mounting

In the microstrip mounting used in the filter assembly shown in Figure 4, the soldering of the ground plane is difficult. But this is the only suitable filter assembly method in which the two BNC connectors can be mounted on the front panel of a filter box similar to that shown in Figure 7. If a simpler assembly is desired for a single filter box, the manner of construction shown in Figure 8 is much easier to implement. Here, the BNC connectors are mounted on the ends of a metal box, and a microstrip line is placed between the connectors with the center pins being soldered to the microstrip track. The Teflon extrusions around the connector pins are cut to provide a butt fit to simulate an end-launch effect for minimizing reflective losses. The p-c board is rotated (the nuts on the BNC connectors are still loose to allow rotation of the microstrip assembly) to bring the underside of the board into view. The ground plane is then soldered to the BNC threads. The board is again rotated to bring the p-c track into view, and then the p-c track is cut and the capacitors and inductors are installed. After all components are soldered in place, the connector nuts are tightened. This completes the assembly of the highpass filter in an arrangement that is much easier to realize for single filter applications.

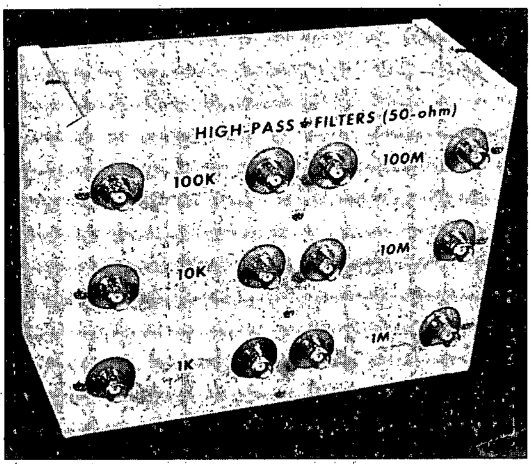

Figure 7. Six highpass filters are conveniently mounted in one metal box. All filters are mounted on an insulated board to provide desired isolation between the filter grounds. For this type of filter mounting, it is necessary that the microstrip mounting arrangement shown in Figure 4 be used.

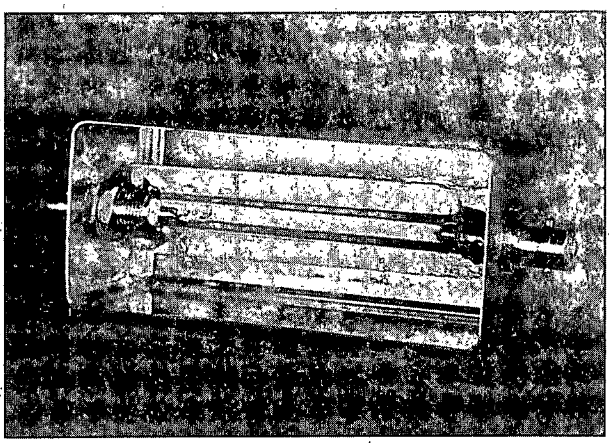

Figure 8. For the single filter assembly, this method of microstrip mounting is easier to implement than that shown in Figure 4.

Summary

Success in high-frequency filter construction depends on using r-f rated components in a configuration that is best suited for the particular filter type being constructed. This means using capacitors and inductors having the highest possible self-resonant frequency (SRF).

For the lowpass filter, the Button mica is optimum, but he ERIE Red Cap is a satisfactory alternate if the Button type is not available. The CAMBION molded r-f chokes have high SRF and can be used if care is taken to prevent coupling between inductors in a multi-inductor filter.

For best lowpass filter stopband performance (in excess of 80 dB), partitions should be used for cutoff frequencies above 10 MHz. For highpass filters having a requirement that the passband extend to 1 GHz, the use of microstrip line is mandatory.

The construction techniques discussed in this article are suitable for the many non-stringent filtering requirements frequently encountered by the average technician or engineer.

APPENDIX A

```
10 REM   FILE 1-18. PROGRAM FOR CALCULAT-
         ING MICRO-STRIP IMPEDANCE VS.
         WIDTH.
20 REM   THICKNESS=.0015 IN. FOR 1-OZ. COP-
         PER, 0.003 INCH FOR 2-OZ. COPPER.
30 PRINT
40 DISP "SPECIFY DIELECTRIC CONSTANT";
50 INPUT E
60 DISP "DIELECTRIC THICKNESS IN INCHES";
70 INPUT H
80 DISP "INITIAL TRACK WIDTH IN INCHES";
90 INPUT W
100 REM  T-VALUE IN LN. 110 FOR 1-OZ. COPPER
         THICKNESS.
110 T=0.0015
120 PRINT "DIELECTRIC CONSTANT ="E
130 PRINT "DIELECTRIC THICKNESS (INCHES)="H
140 WRITE (15,150) "TRACK THICKNESS
    (INCHES)="T
150 FORMAT F7.4
160 PRINT
170 PRINT "Z                    TRACK WIDTH"
180 PRINT "(OHMS) (INCHES)"
200 X=87/SQR(E+1.41)
210 Y=LOG((5.98*H)/(0.8*W+T))
220 Z=X*Y
230 IF Z>60 THEN 290
240 IF Z<40 THEN 290
250 WRITE (15,260)Z,W
260 FORMAT 2X,F7.1,3X,F7.3
270 W=W-0.005
280 GOTO 200
290 PRINT
300 PRINT "END OF WIDTH RANGE FOR Z SPECI-
    FIED IN PROGRAM LN 230,240."
310 PRINT
320 END
```

PROGRAM RUN

DIELECTRIC CONSTANT = 2.7
DIELECTRIC THICKNESS(INCHES)=0.0625
TRACK THICKNESS(INCHES)=0.0015

Z (OHMS)	TRACK WIDTH (INCHES)
42.9	0.170
44.2	0.165
45.5	0.160
46.8	0.155
48.2	0.150
49.7	0.145
51.1	0.140
52.7	0.135
54.3	0.130
55.9	0.125
57.7	0.120
59.5	0.115

END OF WIDTH RANGE FOR Z SPECIFIED IN PROGRAM LN 230,240.

References

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FILTERING FOR SWITCHING POWER SUPPLIES

General

In order to supply electronic equipment with energy from the line supply, components are needed which transform the AC current into various DC voltages. In most cases when transforming and rectifying a voltage, stabilization and a galvanic separation is required.

Conventional equipment fulfills this task with a power line transformer, a rectifier and a regulated adjustable element. The transformer converts the voltage and separates galvanically the secondary voltage from the line. The rectifier delivers a DC voltage, which is stabilized by the adjustable element (generally a series transistor) independently from the load conditions.

Using this principle, neither the volume nor the weight can be reduced in the manner required with modern construction techniques for miniaturization of equipment. Particular disadvantages are the large and heavy line transformer and the lossy voltage stabilizer. The high losses produce heat which again must be conducted away via large heat sinks or blowers.

These disadvantages can be removed by increasing the operating frequency and substituting the series transistor with a regulated switch. The principle of switching power supplies is based on these two measures.

Switching power supplies have a higher efficiency, lower weight, and lower volume than conventional line components. These advantages are based mainly on the fact that switched operations of the adjustable element lead to lower losses and smaller heat sink volume and weight, and a higher operating frequency enables the transformer and the secondary side filter elements to be easily miniaturized.

These great advantages have to be seen in the light of a disadvantage which cannot be ignored. In order to obtain a high efficiency, the operating frequency must be high and the switching time of the adjustable element must be chosen as short as possible. Due to the high frequency, a wide interference spectrum is produced in the frequency domain with high amplitude values, which is caused by the fast switching flank of the adjustable element. To better understand the interference voltages produced, we will investigate the causes of this phenomenon more closely.

Cause of the Interference Voltage

In a line switching regulator, the rectified line voltage is converted into a rectangular square wave with a pair of transistors (half bridge forward converter) or two pairs of transistors (full bridge forward converter). The transistors are driven so that positive and negative voltages are alternately applied across the primary winding of the transformer. Due to the transistor switch, this voltage change cannot suddenly occur, but is time-delayed by the rise time ($T_f \sim 500$ns)of fall time ($T_r \sim 1000$ns). As a consequence, a trapezoidal wave is applied to the transformer.

Due to the periodical amplitude changes in the time domain, discrete frequencies are produced in the frequency domain. This occurrence can be deduced with the help of the Fourier analysis. To simplify, we assume identical rise