HOCHSCHULE RHEINMAIN

PHYSICS LAB 3

Experiment P3-2
Signal Propagation in Coaxial Cables

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1 Introduction

1.1 Terms and Definitions

Transmission Line

In there most simple form cables are made out of a conducting material to transport electrical energy or signals from point A to point B. The higher the frequency of the signal to transmit, the less the wave nature of can be neglected.

Characteristic Impedance, Velocity Factor and Propagation Speed

Characteristic impedance: The impedance, when connected to a transmission line, suppresses any reflections and standing waves [1].
Velocity factor: Relative signal propagation speed inside a transmission line expressed as percent of speed of light.
Propagation speed: The absolute speed at which a signal propagates through a medium.

Time Domain Reflectometry

A method to inspect properties of a transmission line i.e. length, characteristic impedance and velocity factor as well as the presence, nature and location of defects.

Avalanche Pulse Generator

A circuit to generate ultra short pulses on a scale of picoseconds. Its main working principle abuses the avalanche breakdown of a transistor across the collector-emitter line. The breakdown voltage is usually much higher than the voltages during normal operation.

Boost Converter

A circuit capable of *boosting* a constant current input voltage to a much higher output voltage by repeatedly switching an inductor on and off. The fly back voltage induced by the break down of the magnetic field gets stored in a capacitance and forms the voltage at the output terminals.

Pulse Width Modulation

A constant current switched on and off at a fixed frequency. The time the signal is considered high relatively to the period time is called the duty cycle.

Amplitude, Rise Time, Fall Time, Pulse Width

Amplitude: In a wider sense a term used to characterize repeating phenomena. It is defined as a signals maximum deviation from its arithmetic mean value.
Rise time: a technical term defined as the time it takes for a system to transition its output from 10% to 90% of an infinitesimal steep input signal.
Fall time: definition of rise time applies but with reversed transition. Pulse width: the time a signal dwells between its rising and its falling edge. Either edge is considered as

Bandwidth and Rise Time of an Oscilloscope

An oscilloscope can be considered as an low-pass filter. The bandwidth is the cut-off frequency at which the manufacturer guarantees a dampening of the input signal of $< 3\,\mathrm{dB}$.
Using the definitions above the maximum rise time the scope can reliably display calculates by

$$t_{rise} = t_{90\%} - t_{10\%} = \frac{1}{-2\pi B} \ln\left(\frac{1-0.9}{1-0.1}\right) \approx \frac{0.35}{B} \tag{1.1}$$

.

1.2 Preparation

Reflection on a Transmission Line

!!! Insert Diagram Here !!!

SPICE-Simulation of a Boost Converter

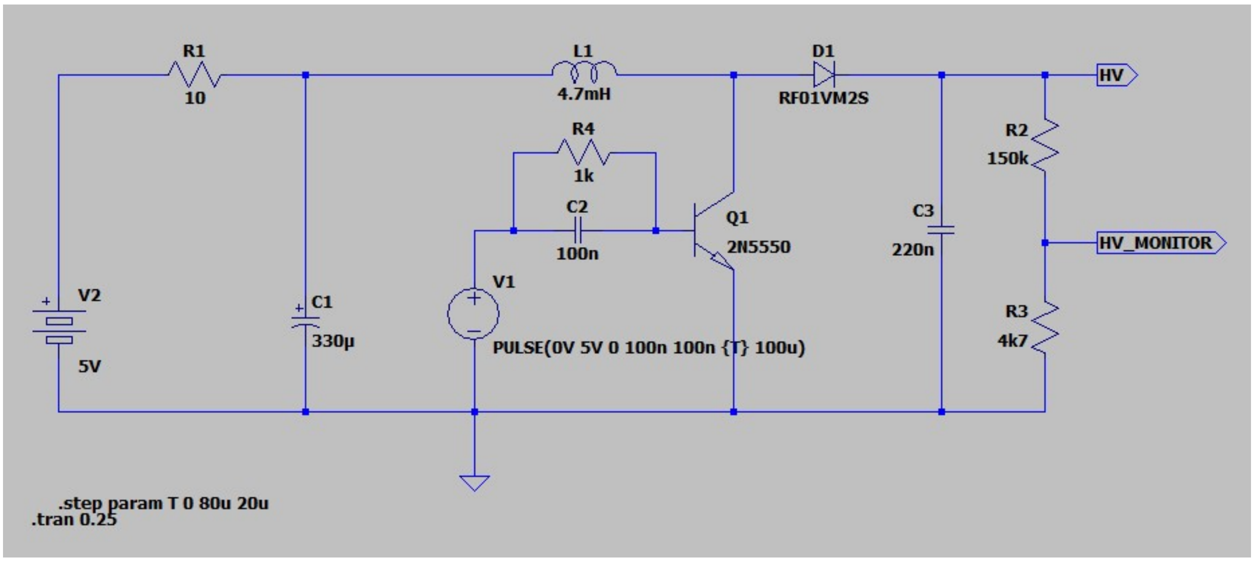

Figure 1.1: Simulated circuit of a boost converter using LTSPICE.

Charge/Discharge Time of a Capacitor

Charging:

$$U_{Br} = U_+ \left(1 - e^{-\frac{t_{charge}}{R_6 C_5}}\right)$$
$$\Leftrightarrow$$
$$t_{charge} = -\ln\left(1 - \frac{U_{Br}}{U_+}\right) \cdot R_6 C_5 \tag{1.2}$$

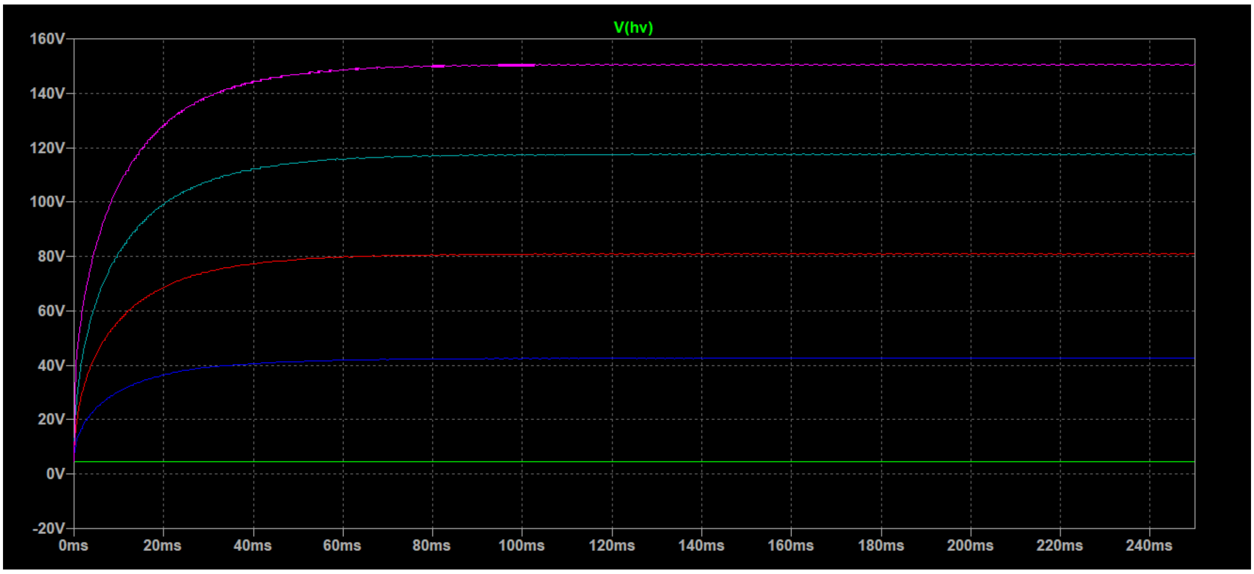

Figure 1.2: Plot of the output voltage at *HV*. The voltage is subsequently progressing towards a peak voltage of $\hat{U}_{HV} \approx 150\,\mathrm{V}$ with rising PWM duty cycle.

Discharging:

$$U_{C_5} = U_{Br}\left(e^{-\frac{t_{discharge}}{R_7 C_5}}\right)$$
$$\Leftrightarrow$$
$$t_{discharge} = -\ln\left(\frac{U_{C_5}}{U_{Br}}\right) \cdot R_7 C_5 \tag{1.3}$$

plugging in the values for $U_{Br} = 65\,\mathrm{V}, U_+ = 75\,\mathrm{V}, U_{C_5} = 5\,\mathrm{V}, C_5 = 2.2\,\mathrm{pF}, R_6 = 1\,\mathrm{M\Omega}$ and $R_7 = 51\,\Omega$ equates to the following charging/discharging times t_{charge} and $t_{discharge}$:

$$\begin{aligned} t_{charge} &= -\ln\left(1 - \frac{65\,\mathrm{V}}{75\,\mathrm{V}}\right) \cdot 10^6\,\Omega \cdot 2.2 \cdot 10^{-12}\,\mathrm{F} \\ &\approx 4.43 \cdot 10^{-6}\,\mathrm{s} \end{aligned} \tag{1.4}$$

$$\begin{aligned} t_{discharge} &= -\ln\left(\frac{5\,\mathrm{V}}{65\,\mathrm{V}}\right) \cdot 51\,\Omega \cdot 2.2 \cdot 10^{-12}\,\mathrm{F} \\ &\approx 2.88 \cdot 10^{-10}\,\mathrm{s} \end{aligned} \tag{1.5}$$

With these numbers, the minimum time per charge/discharge cycle would be the sum of both times. Thus, the maximum number of repetitions per second f_{Rep} is

$$f_{Rep} = (t_{charge} + t_{discharge})^{-1} \approx 225.7\,\mathrm{kHz} \tag{1.6}$$

Cable Characteristics of RG-58/U Coaxial Cable

Nominal characteristic impedance: $53\,\Omega$
Nominal velocity of propagation: 69.5%
Nominal delay (translates to the inverse of the absolute speed of propagation): $4.85588\,{}^{ns}/_{\mathrm{m}}$
The values above are taken from the technical data sheet [2].

Determining the Suitability of the Oscilloscope

The oscilloscope at hand is labeled with a bandwidth of $B = 200\,\mathrm{MHz}$. Following eq. (1.1) edges faster than

$$t_{rise_{min}} \approx \frac{0.35}{200\,\mathrm{MHz}} \approx 1.75\,\mathrm{ns} \tag{1.7}$$

Sampling Rate

2 Set-Up of Experiment

To perform the experiment the elements shown in fig. 2.1 are needed. They are listed below.

!!! Insert Figure Here !!!

Figure 2.1: Components needed for the experiment.

1. Oscilloscope
2. Coaxial cables in three lengths
3. Coaxial cables with unknown length and internal fault
4. Circuit board
5. Multimeter
6. T-piece
7. $50\,\Omega$ termination resistor
8. Termination box
9. Tape measure

A better overview of the circuit board will give the following fig. 2.2. Again, the components are listed below.

!!! Insert Figure Here !!!

Figure 2.2: Detailed view on the circuit board.

1. Pulse generator
2. Potentiometer
3. LCD
4. Boost converter
5. Arduino Nano Microcontroller board

The individual settings are explained in the execution chapter.

3 Execution

3.1 Boost converter

To examine the characteristics of the pulse generator, the potentiometer on the circuit board is first set completlly counterclockwise. The power supply is turned on, so that the duty cycle (in %) and the output voltage can be taken from the LCD. The two values are noted and the potentiometer is turned up until the value for duty cycle has increased by 10 %. Again the values are noted. This process is repeated until the potentiometer is turned completely clockwise.

3.2 Avalanche pulse generator

The potentiometer is set back to the fully counterclockwise position. Now the oscilloscope is needed and therefore switched on. The output of the pulse generator gets connected with the Oscilloscope via a short coaxial cable. The potentiometer is slowly turned up until a pulse appears on the oscilloscope. The display is adjusted so that the signal can be read easily. A photograph is taken for documentation purposes and the voltage shown on the LCD is noted. After that, the voltage is set to $U = 75\,\mathrm{V}$ and a second photograph is taken from the screen.

3.3 Signal propagation

3.3.1 Propagation time

For this experiment a T-piece is inserted between the oscilloscope and the pulse generator. Therefore, the T-piece is connected to channel 1 of the oscilloscope and the short coaxial cable from the pulse generator is plugged into the T-piece. A second T-piece is connected to channel 2 of the oscilloscope. One end of the T-piece in channel 2 is terminated with the $50\ \Omega$ terminal resistor, mentioned in the set-up chapter. There is one open end left on each T-piece. The three different coaxial cables get connected one after another to these ends. For each cable, there are two pulses shown on the oscilloscope. With the cursor function of the oscilloscope, the time delay between the pulses are measured and noted.

3.3.2 Cable characteristics

To investigate the cable characteristics, the length of the three cables given is measured with the tape measure. Afterwards they are connected one after another with the T-piece at channel 1. Channel 2 is not needed during this measurement. For each cable two photographs are taken from the oscilloscopes screen. The first photograph with an open end, the second with a short-circuited end. To short-circuit the end of the coaxial cable, a screwdriver is used. With the cursor function, the propagation time τ_0 (for open end) and τ_s (for short-circuited end) are read from the screen and noted.

Now, the termination box is connected to the open end of the cable. The potentiometer on the termination box is rotated while looking at the oscilloscopes screen. Once the oscilloscope shows a minimum amplitude of the reflected pulse, the setting of the potentiometer is not changed anymore. The termination box is removed and then connected to the multimeter. The multimeter is set so that the resistance of the termination box can be read from it. This procedure is repeated for the other remaining cables.

3.4 Time Domain Reflectometry

The cable with unknown length and an internal fault is now connected to the T-piece at channel 1. The first cursor of the oscilloscope is set to the origin pulse. The second cursor is first set to the pulse of the reflection of the internal fault. The time delay is noted. Then the second cursor is set to the pulse of the reflection of the cables end. The time delay is noted again.

4 Evaluation

4.1 Boost Converter

The characteristic curve of the boost converter is examined. In fig. 4.1 the output voltage is plotted against the duty cycle. SCIDAVIS returns the linear fit of the measuring points as

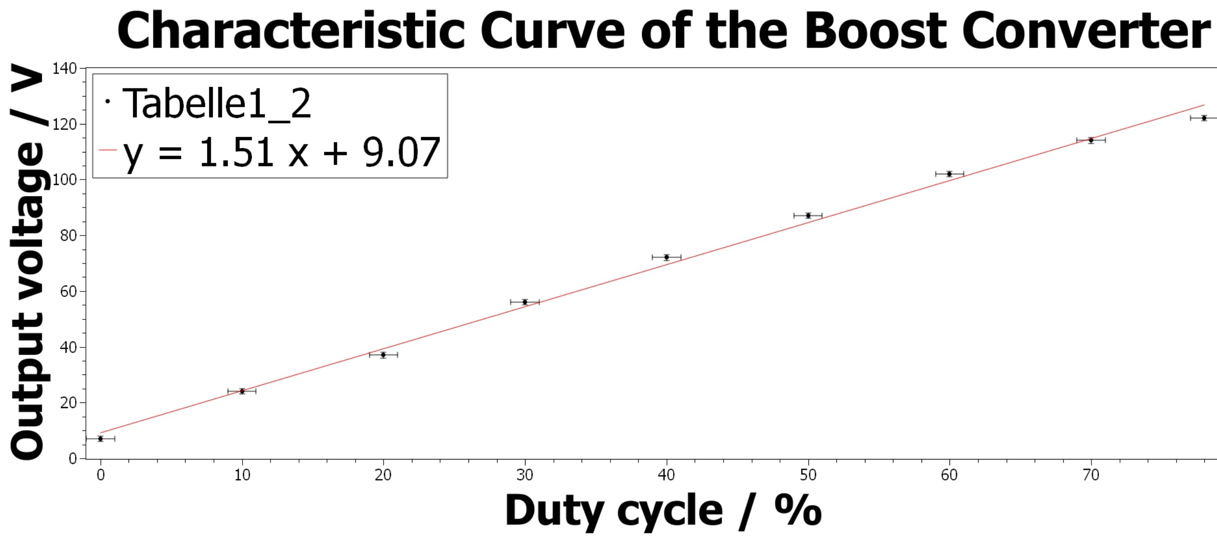

Figure 4.1: Characteristic curve of the boost converter.

$$U_{out}(dc) = 1.51\,\frac{\mathrm{V}}{\%} \cdot dc + 9.07\,\mathrm{V} \tag{4.1}$$

If the output voltages are compared with the simulated ones, there is observed a deviation of nearly $10\,\mathrm{V}$ in the higher voltage area. The lower voltages, however, are similar.

4.2 Avalanche Pulse Generator

The signal in fig. 4.2 is the first that appears after increasing the voltage to the minimum voltage $U_{min} = 70\,\mathrm{V}$. The repetition frequency of the avalanche pulse generator has been investigated and recorded as shown in fig. 4.3. In section 1.2 the theoretical value for the repetition frequency at $U = 75\,\mathrm{V}$ was calculated as $f_{Rep} = 225.7\,\mathrm{kHz}$. In the diagram in fig. 4.3 the value is around $90\,\mathrm{kHz}$. So there must be some deviations.

Next the characteristics of the pulse at a voltage of $U = 75\,\mathrm{V}$ are examined. Fig. fig. 4.4 gives the following:

$$\text{Amplitude:} \quad \hat{U} = 7.12\,\mathrm{V} \tag{4.2}$$

$$\text{Rise time:} \quad t_r = 2.33\,\mathrm{s} \tag{4.3}$$

$$\text{Fall time:} \quad t_f = 7.08\,\mathrm{s} \tag{4.4}$$

$$\text{Pulse width:} \quad t_w = 6.26\,\mathrm{s} \tag{4.5}$$

In comparison to a $500\,\mathrm{MHz}$ oscilloscope signal, it can be seen that the secondary pulsations are drawn more accurate in the $500\,\mathrm{MHz}$ oscilloscope. Rise and fall time and the pulse width is much shorter. Even the amplitude seems to be larger. Reason for this could be the higher capacity due to the higher bandwidth for more precise and better approximations.

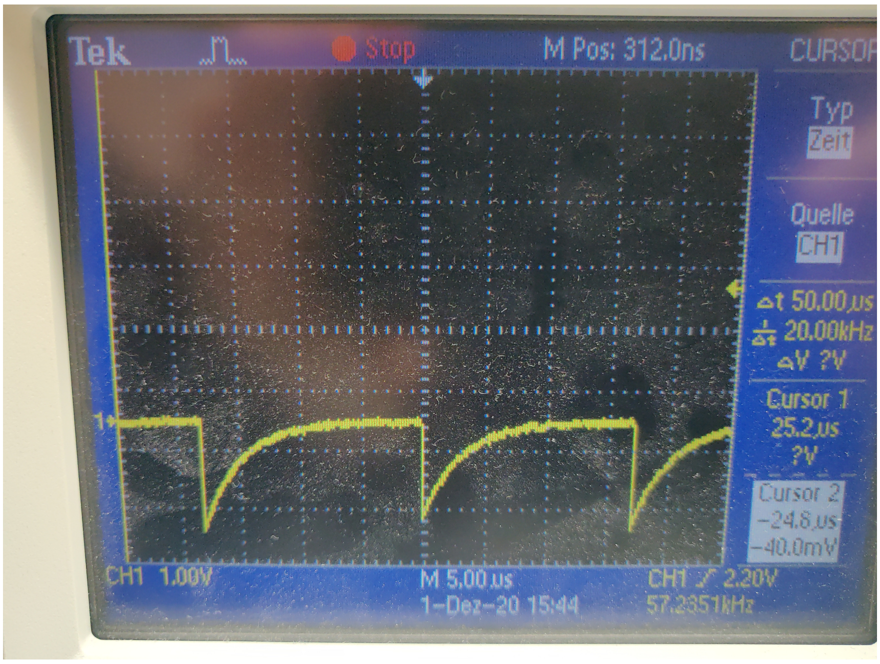

Figure 4.2: Avalanche pulse signal at U_{min}.

4.3 Signal Propagation

4.3.1 Propagation Time

The propagation speed can be determined by means of:

$$c_P = \frac{l}{t} \tag{4.6}$$

The measured propagation times and the calculated propagation speeds are summarized in the following table: The deviation of the propagation speed can be determined as follows:

Table 4.1: Delayed signal

Cable no.	$l \pm \Delta l$ / m	$t \pm \Delta t$ / ns	$c_P \pm \Delta c_P$ / $\frac{\mathrm{m}}{\mathrm{s}}$
1	4.95 ± 0.05	22.6 ± 1	$(2.19 \pm 0.12) \cdot 10^8$
2	10.04 ± 0.05	44.8 ± 1	$(2.24 \pm 0.06) \cdot 10^8$
3	0.77 ± 0.01	4.6 ± 1	$(1.67 \pm 0.39) \cdot 10^8$

$$\Delta c_P = \left|\frac{\partial c_P}{\partial l}\right| \cdot \Delta l + \left|\frac{\partial c_P}{\partial t}\right| \cdot \Delta t \tag{4.7}$$

$$= \frac{1}{t} \cdot \Delta l + \frac{l}{t^2} \cdot \Delta t \tag{4.8}$$

For cable no. 1 in table 4.1 e.g.:

$$\begin{aligned}\Delta c_{P,1} &= \frac{1}{22.6 \cdot 10^{-9}\mathrm{s}} \cdot 0.05\,\mathrm{m} + \frac{4.95\,\mathrm{m}}{(22.6 \cdot 10^{-9}\mathrm{s})^2} \cdot 1 \cdot 10^{-9}\mathrm{s} \\ &= 0.02 \cdot 10^8 \frac{\mathrm{m}}{\mathrm{s}} + 0.10 \cdot 10^8 \frac{\mathrm{m}}{\mathrm{s}} \\ &= 0.12 \cdot 10^8 \frac{\mathrm{m}}{\mathrm{s}}\end{aligned} \tag{4.9}$$

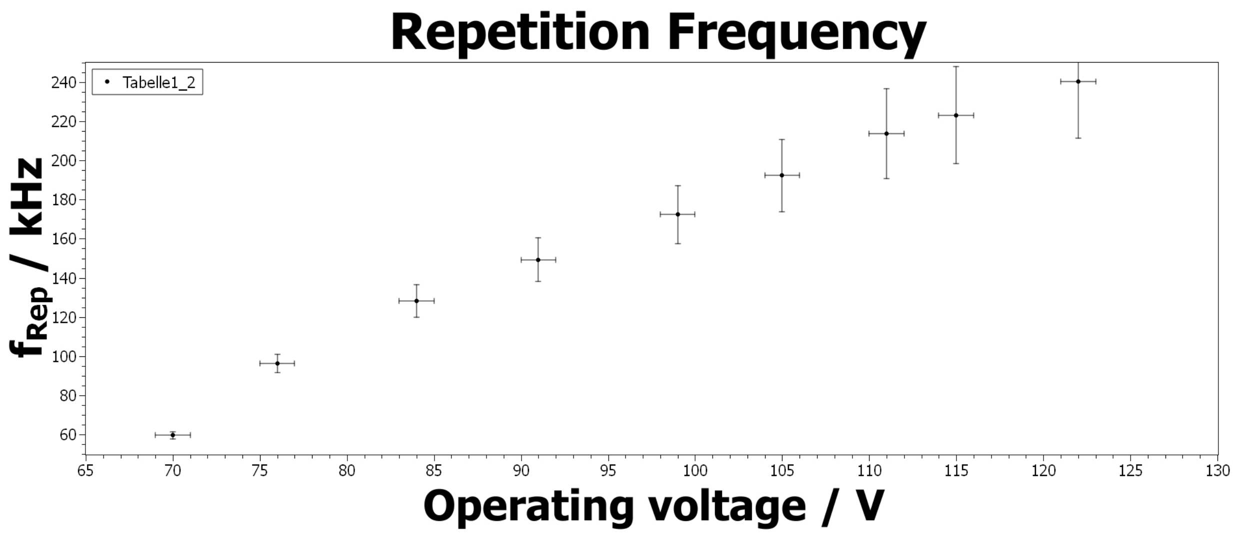

Figure 4.3: Repetition frequency

4.3.2 Cable Characteristics

fig. 4.5 shows the reflected pulse signal and fig. 4.6 the shorted and reflected pulse signal. The propagation speed can be calculated with eq.(6), the velocity factor with eq.(7) and the relative dielectric constant with eq.(9) of the instructions. At the minimum amplitude of the reflected pulse, the resistance R_{Term} equals Z_0. The determined and calculated characteristic values are summarized in the following table: The deviation

Table 4.2: Reflected signal

Cable no.	l / m	τ_0 / ns	τ_s / ns	c_P / $\frac{\mathrm{m}}{\mathrm{s}}$	VF / %	Z_0 / Ω	ε_R
1	4.95 ± 0.05	44.8 ± 1	44.8 ± 1	$(2.21 \pm 0.07) \cdot 10^8$	73.7 ± 2.3	80.2	1.84 ± 0.11
2	10.04 ± 0.05	89.6 ± 1	90.4 ± 1	$(2.24 \pm 0.04) \cdot 10^8$	74.7 ± 1.3	56.0	1.79 ± 0.06
3	0.77 ± 0.01	8.4 ± 1	10.8 ± 1	$(1.83 \pm 0.34) \cdot 10^8$	61.0 ± 11.3	56.4	2.69 ± 1.00

of c_P can be determined similar to eq. (4.8), but with a factor of 2. The one of VF as follows:

$$\Delta VF = \left|\frac{\partial VF}{\partial c_P}\right| \cdot \Delta c_P$$
$$= \frac{1}{c_0} \cdot \Delta c_P \qquad (4.10)$$

For cable no. 1 in table 4.2 e.g.:

$$\Delta VF_1 = \frac{1}{3 \cdot 10^8 \frac{\mathrm{m}}{\mathrm{s}}} \cdot 0.07 \frac{\mathrm{m}}{\mathrm{s}} = 2.3\%$$

And for ε_R:

$$\Delta\varepsilon_R = \left|\frac{\partial \varepsilon_R}{\partial VF}\right| \cdot \Delta VF \qquad (4.11)$$
$$= \frac{2}{VF^3} \cdot \Delta VF \qquad (4.12)$$

So for the first cable in table 4.2:

$$\Delta\varepsilon_{R,1} = \frac{2}{0.737^3} \cdot 0.023 = 0.11$$

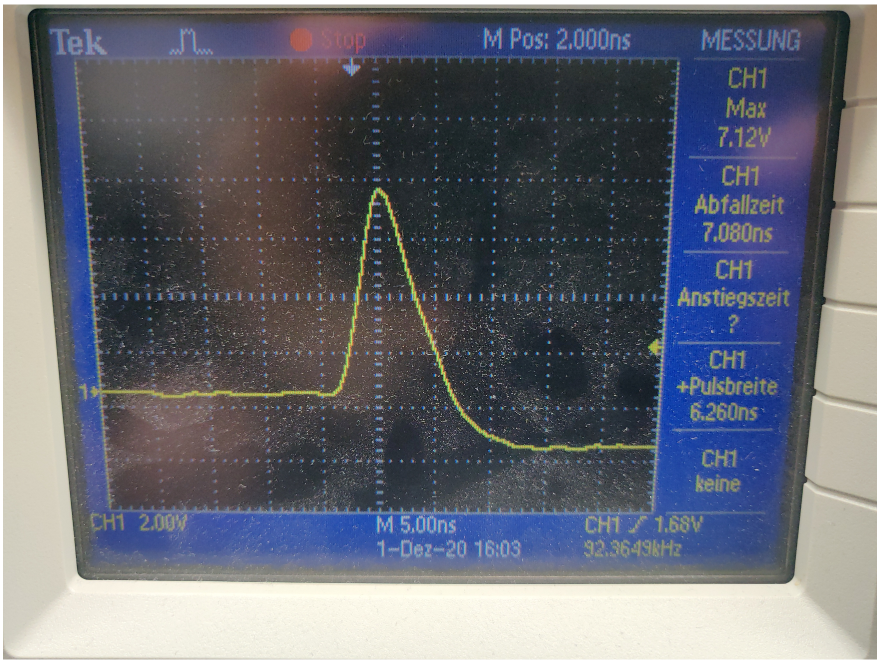

Figure 4.4: Pulse characteristics.

If the values are compared with the data sheet from the manufacturer, there can be seen some similarities and differences. The determined velocity factor of cable no. 1 and 2 is very close to the stated one (69.5%). The third cable is slightly different.

On the other hand, the impedance is given as $53\,\Omega$, with the second and third cable having a similar value, whereas the first cable differs somewhat.

4.3.3 Time Domain Reflectometry

For determining the unknown length and the position of the fault of the cable, the equation for the propagation speed has to be transformed to the length as

$$l = \frac{1}{2} \cdot c_P \cdot \tau \tag{4.13}$$

τ_{total} has been measured as $276\,\mathrm{ns}$ and τ_{fault} as $256\,\mathrm{ns}$. For the propagation speed the mean value $\bar{c_P} = 2.09 \cdot 10^8\,\frac{\mathrm{m}}{\mathrm{s}}$ is used. The values inserted in eq. (4.13) results:

$$l_{total} = \frac{1}{2} \cdot 2.09 \cdot 10^8 \frac{\mathrm{m}}{\mathrm{s}} \cdot 276 \cdot 10^{-9}\mathrm{s} = 28.84\,\mathrm{m}$$
$$l_{fault} = \frac{1}{2} \cdot 2.09 \cdot 10^8 \frac{\mathrm{m}}{\mathrm{s}} \cdot 256 \cdot 10^{-9}\mathrm{s} = 26.75\,\mathrm{m}$$

The deviation is determined with the following equation:

$$\Delta l = \left|\frac{\partial l}{\partial c_P}\right| \cdot \Delta c_P + \left|\frac{\partial l}{\partial \tau}\right| \cdot \Delta\tau \tag{4.14}$$
$$= \frac{1}{2} \cdot \tau \cdot \Delta c_P + \frac{1}{2} \cdot c_P \cdot \Delta\tau \tag{4.15}$$

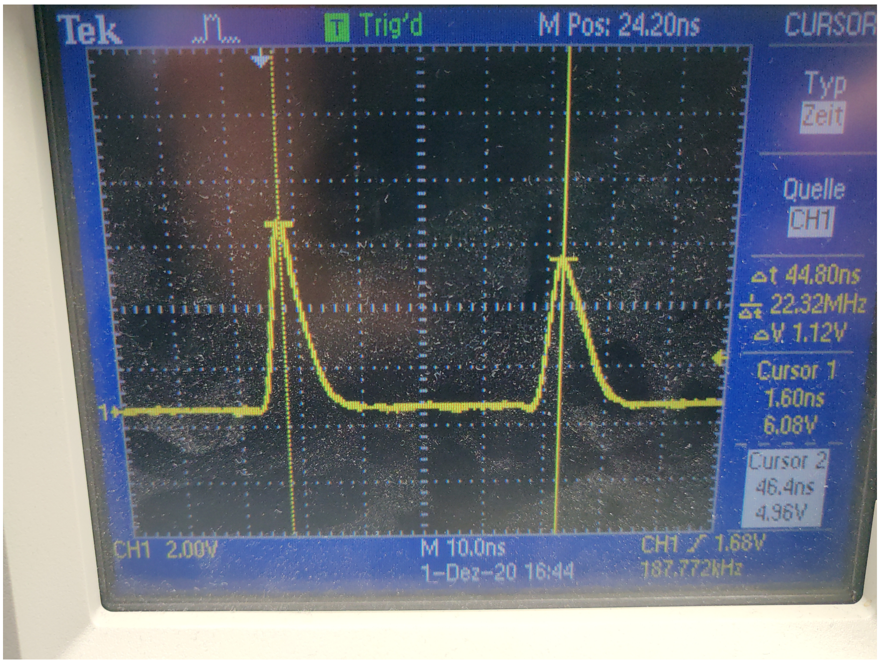

Figure 4.5: Reflected pulse signal

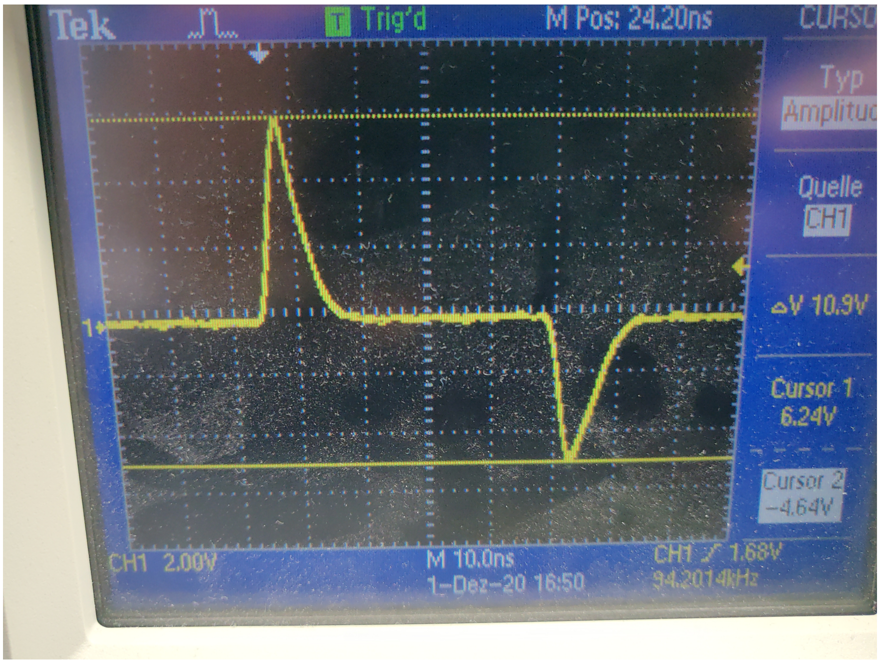

Figure 4.6: Shorted pulse signal

For the total length and the position of the defect:

$$\begin{aligned}\Delta l_{total} &= \frac{1}{2} \cdot 276 \cdot 10^{-9}\mathrm{s} \cdot 0.15 \cdot 10^{8}\frac{\mathrm{m}}{\mathrm{s}} + \frac{1}{2} \cdot 2.09 \cdot 10^{8}\frac{\mathrm{m}}{\mathrm{s}} \cdot 1 \cdot 10^{-9}\mathrm{s} \\ &= 2.07\,\mathrm{m} + 0.10\,\mathrm{m} \\ &= 2.17\,\mathrm{m}\end{aligned}$$

$$\Delta l_{fault} = 2.02\,\mathrm{m}$$

Summarized the total length is

$$l_{total} = 28.8\,\mathrm{m} \pm 2.2\,\mathrm{m} \tag{4.16}$$

and the position of the fault is at

$$l_{fault} = 26.8\,\mathrm{m} \pm 2.0\,\mathrm{m} \tag{4.17}$$

5 Conclusion

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A Distinct event

A Appendix

Figure A.1: During the course of the experiment captured oscillograms.

Table A.1: Handwritten notes corresponding each measurement.

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Bibliography

[1] ATIS. *ATIS Telecom Glossary. American National Standard T1.523-2001*. ATIS.

[2] Belden. *82240 Coax - RG-58/U Type technical Datasheet*. URL: https://catalog.belden.com/techdatam/82240.pdf (visited on 10/12/2020).