Optics

Velocity of light
Measuring with short light pulses

LD Physics Leaflets

P5.6.2.2

Determining the propagation velocity of voltage pulses in coaxial cables

Objects of the experiment

- Determining the propagation velocity of voltage pulses in coaxial cables from the time difference between the direct and reflected voltage pulse and the measuring distance.
- Investigating reflection at the end of the cable.

Principles

Coaxial cables are often used for transmitting electrical signals. Deploying and using them is easy and trouble free, as the inner conductor is screened by an outer conductor, and the external space thus remains field-free.

The propagation of voltage pulses in coaxial cables is calculated using the telegraph equation. This uses a finite velocity *v*; assuming negligible resistance losses in the cable, this is calculated as:

$$v = \frac{1}{\sqrt{L'C'}} \qquad \text{(I)}$$

(*L'*: inductance per unit of length,
C': capacitance per unit of length)

For high signal frequencies, this equation gives us:

$$v = \frac{c}{\sqrt{\varepsilon_r \mu_r}} \qquad \text{(II)}$$

(ε_r: relative permittivity,
μ_r: relative permeability of the insulator between the inner and outer conductor)

v is less than the velocity of light in a vacuum *c*, but is on the same order of magnitude.

If the cable end is open, i.e. the inner and outer conductors are not conductively connected, the voltage pulses are reflected at the cable end in their full amplitude. If the two conductors are shorted at the cable end, the voltage pulses are reflected with the reverse sign. Generally speaking, reflection attenuates the pulse by the factor

$$r = \frac{R - Z}{R + Z} \qquad \text{(III)}$$

where *R* is the pure resistive termination at the end of the cable. *Z* specifies the relationship between the voltage amplitude *U* between the inner and outer conductor and the current amplitude *I* in the direction of the conductor, and is termed the characteristic wave impedance:

$$U = Z \cdot I \qquad \text{(IV)}$$

For a loss-free line and high signal frequencies, this value is:

$$Z = \sqrt{\frac{L'}{C'}} \qquad \text{(V)}$$

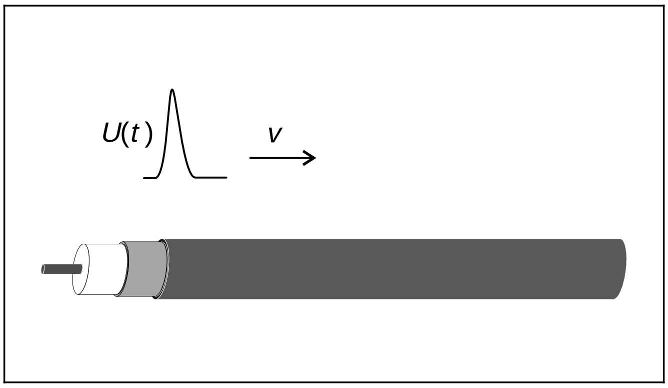
The reflection of the voltage pulses at the cable end can be used to measure the propagation velocity. Following the reflection, the pulses return to the oscilloscope, delayed by the transit time. The propagation velocity can be calculated from the double cable length and the time difference between the direct and the reflected voltage pulse as read from the oscilloscope.

The light velocity measuring instrument with the small triple mirror placed over the exit window is used to generate suitable voltage pulses. The voltage pulses are channeled to an oscilloscope and then via a T-adapter into a section of coaxial cable 10 m long, with a characteristic wave impedance of 50 Ω

The special design of the light velocity measuring instrument permits the use of a relatively simple oscilloscope (minimum scanning rate 20 MHz).

The voltage pulses are generated with a repetition frequency of 40 kHz. This ensures sufficient brightness of the signal on the oscilloscope screen, even when using the maximum sweep rate of the oscilloscope.

Just before the voltage pulse is emitted in the light velocity measuring instrument, a trigger signal is output. Therefore, when externally triggered, the complete voltage pulse always appears on the oscilloscope screen. It is thus not necessary to use an oscilloscope with built-in delay line.



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Apparatus

1 Light velocity measuring instrument	476 50
1 Plug-in unit 230 V/12 V AC	562 791
1 Two-channel oscilloscope 303	575 211
2 BNC cables, 1 m	501 02
1 BNC cable, 10 m	501 024
1 T-adapter	501 091
1 Straight BNC	501 10
1 BNC/4 mm adapter	575 35
1 STE regulation resistor 1 kΩ, 1 W	577 79
1 STE resistor 47 Ω, 2 W	577 28
1 Saddle base	300 11

Setup

Set up the experiment as shown in Fig. 1.

- Switch on the light velocity measuring instrument by plugging in the plug-in unit and place the small triple mirror on the top window.
- Attach the T-adapter to oscilloscope channel I, and use the short BNC cables to connect the “Pulses” output to the T-adapter and the “Trigger” output to the external trigger input on the oscilloscope.
- Using the oscilloscope settings form table 1, find a voltage pulse.

Table 1: Oscilloscope settings, e.g. for the two-channel oscilloscope 303 (Cat. No. 575 211).

Operating mode:	channel I only
Channel I:	DC, 5 - 100 mV/cm
Zero line:	middle of screen
Triggering:	external, AC, + (rising edge)
Trigger level:	automatic
Time-base sweep:	0.2 μs/cm, cal.
X-magnification:	1×
Intensity:	maximum

Carrying out the experiment

a) Measuring the propagation velocity:

- Connect the 10 m BNC cable to the T-adapter and observe the change in the voltage pulse.
- Switch the x-magnification of the oscilloscope to 10x.
- Shift the maximum of the voltage pulse to a vertical grid line on the left side of the oscilloscope screen by varying the x-position.
- Read off the time difference *t* between the direct and the reflected voltage pulse and write this value in your experiment log (see Fig. 2).

b) Investigating the reflection at the cable end:

- Set the STE regulation resistor to the maximum value (red mark facing up).
- Terminate the long BNC cable with the STE regulation resistor via the BNC straight and the BNC/4 mm adapter and observe the change in the voltage pulse.
- Set the STE regulation resistor to lower values and observe the change in the oscillogram.
- Replace the regulation resistor with the 47 Ω resistor.

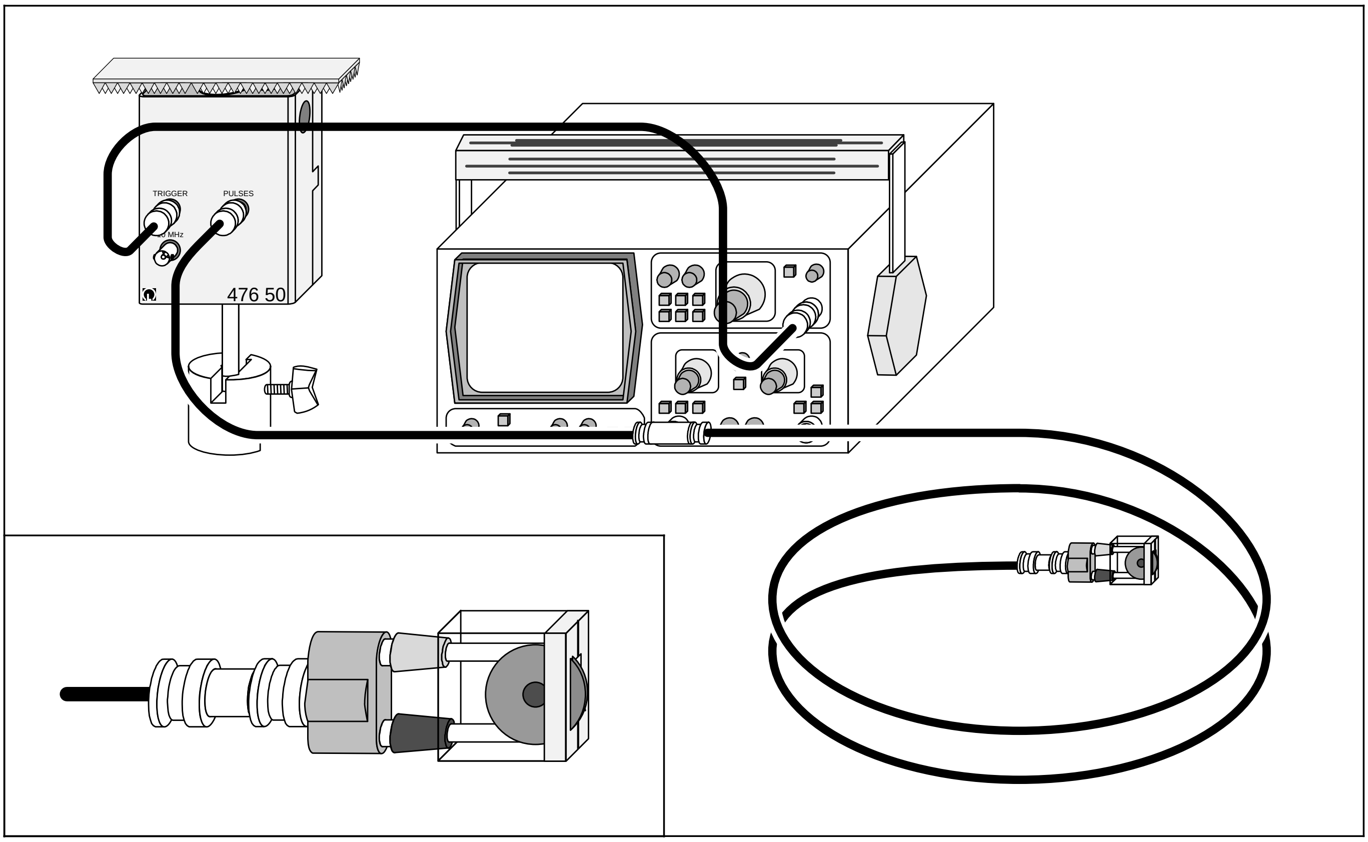


Fig. 1 Complete experiment setup
(Detail sketch: variable terminator at the cable end)

Measuring example and evaluation

a) Measuring the propagation velocity:

Interval between the direct and the reflected pulse: 5 cm,

time-base sweep: 0.2 $\frac{\mu s}{cm}$, x-magnification: 10×

We obtain

$$t = 5 \cdot \frac{1}{10} \cdot 0.2 \mu s = 0.1 \mu s$$

and from this

$$v = 2 \cdot \frac{10\,m}{t} = 2.0 \cdot 10^8 \, \frac{m}{s}$$

A comparison with the literature value for the velocity of light

($c = 3.0 \cdot 10^8 \, \frac{m}{s}$) gives us $v = \frac{2}{3} c$.

In equation (II), inserting the value $\mu_r = 1$ gives us a value for the relative permittivity of $\varepsilon_r = 2.25$, which is what we would expect for Teflon as a dielectric.

b) Investigating the reflection at the cable end:

At the open end of the cable (terminating resistance $R = \infty$), the voltage pulses are reflected and reach the oscilloscope input a second time with a time delay (see Fig. 2a).

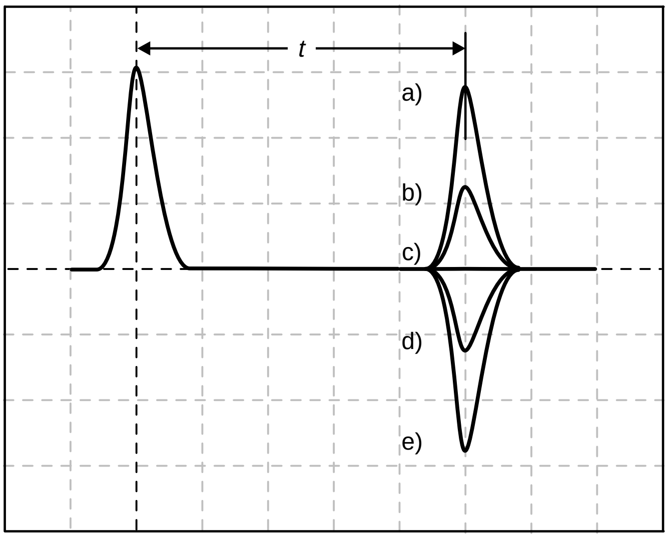
When the terminating resistor is reduced, the reflected voltage pulse is attenuated (see Fig. 2b).

When the terminating resistor at the cable end is identical to the characteristic wave impedance of the cable (R = 50 Ω), the voltage pulse at the cable end is completely absorbed (see Fig. 2c).

The polarity is inverted when the terminator is less than the characteristic wave impedance (see Fig. 2d).

When the inner and outer conductors are short-circuited ($R = 0$), the polarity of the reflected voltage pulses is inverted (see Fig. 2e).

Fig. 2 Direct voltage pulse and reflected voltage pulse, observed for different terminating resistances at cable end (see text)



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