11. Propagation of Electromagnetic Waves

PRINCIPLES

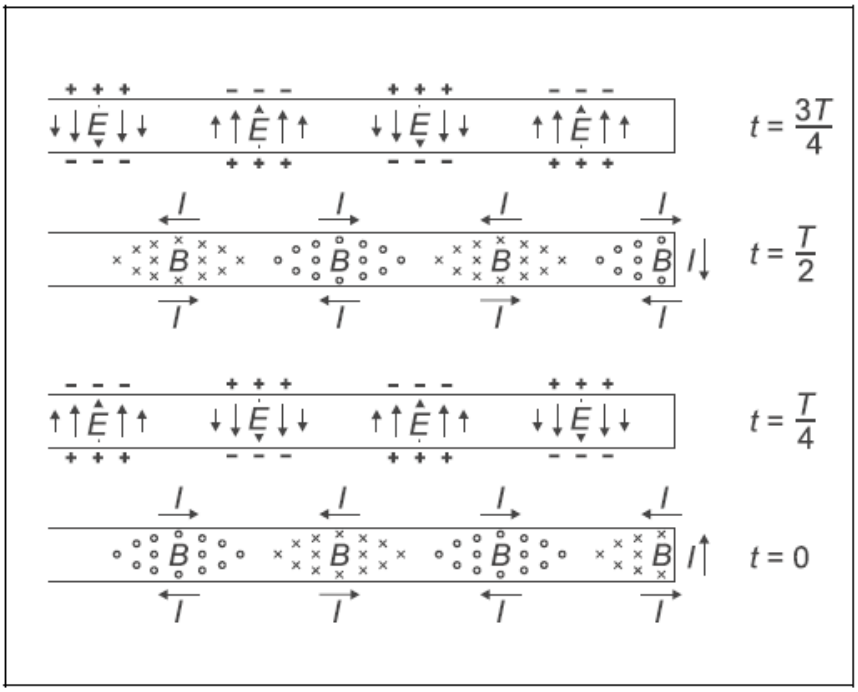
In 1890, *E. Lecher* proposed an arrangement of two parallel wires with a circular cross-section to study the propagation of electromagnetic waves. When a high-frequency electromagnetic field is transmitted onto such a *Lecher* line, a voltage wave

$$U = U_0 \sin(\omega t - kx), \tag{1}$$

with $\omega = 2\pi\nu$, $k = 2\pi/\lambda$ propagates in the direction x of the wires. The frequency ν and the wavelength λ of this wave agree with those of the transmitted field.

I. *Lecher* line with short-circuited end

Standing electromagnetic waves on a Lecher line and the corresponding currents *I* and charges (+,-) on the wires.



If the wires of the *Lecher* line are short-circuited at the end, then the voltage U is zero. A reflected wave arises with a phase shift of 180° with respect to the incoming wave. For example, a voltage wave $U_1 = U_0 \sin(\omega t - kx)$ coming in from the left together with a jumper at $x = 0$ gives rise to the reflected wave $U_2 = -U_0 \sin(\omega t + kx)$.
Both waves interfere to form the standing wave

$$U = U_1 + U_2 = -2U_0 \sin kx \cos \omega t. \tag{2}$$

The voltage between the wires is associated with a charge distribution along the wires. The displacement of these charges leads to a current I in the wires which propagates as a wave. There must be a permanent current at the jumper. The incoming current wave $I_1 = I_0 \sin(\omega t - kx)$ is, therefore, reflected without a change in phase; that is, the reflected current wave has the form $I_2 = I_0 \sin(\omega t + kx)$. I_1 and I_2 interfere to form the standing wave

$$I = I_1 + I_2 = 2I_0 \cos kx \sin \omega t. \tag{3}$$

Eqs. (2) and (3) show that the nodes of the voltage wave just correspond to the antinodes of the current wave and the antinodes of the voltage wave to the nodes of the current wave. The positions of the voltage nodes are

$$x = 0, -\frac{\lambda}{2}, -\lambda, -\frac{3\lambda}{2}, \cdots \tag{4}$$

that is, their distances from the end of the wires are multiples of $\lambda/2$.

II. Open ended *Lecher* line

The situation changes, when the end of the *Lecher* line is left open. Now there is a permanent voltage at the end; that is, the incoming voltage wave is reflected without a change in phase, whereas the current at the open end is always zero, the incoming current wave being reflected with a phase shift of 180^o. For the arising standing waves, the equations

$$U = U_1 + U_2 = 2U_0 \cos kx \sin \omega t \tag{5}$$

and

$$I = I_1 + I_2 = -2I_0 \sin kx \cos \omega t \tag{6}$$

follow. They can be obtained from *Eqs.* (2) and (3) by mutual exchange of U and I.

III. *Lecher* line terminated with the characteristic wave impedance

Standing waves do not arise if the ends of the *Lecher* line are connected by an ohmic resistance which is equal to the characteristic wave impedance of the *Lecher* line. In this case, incoming current and voltage waves are not reflected at the end of the line.

IV. Detection of standing waves

In the experiment, the propagation of decimeter waves (ν = 433.92 MHz) along a *Lecher* line is studied. The standing voltage wave is detected by means of a probe consisting of a lamp that connects two conducting pins. These pins are slid along the *Lecher* line at a fixed distance. At the voltage antinodes, the voltage between the two conducting pins has its maximum value, and the lamp lights up brightly. The standing current wave is detected by means of an induction loop connected to a lamp. At the current antinodes, the lamp lights up brightly because the magnetic field generated between the wires of the *Lecher* line oscillates at maximum amplitude.

SETUP

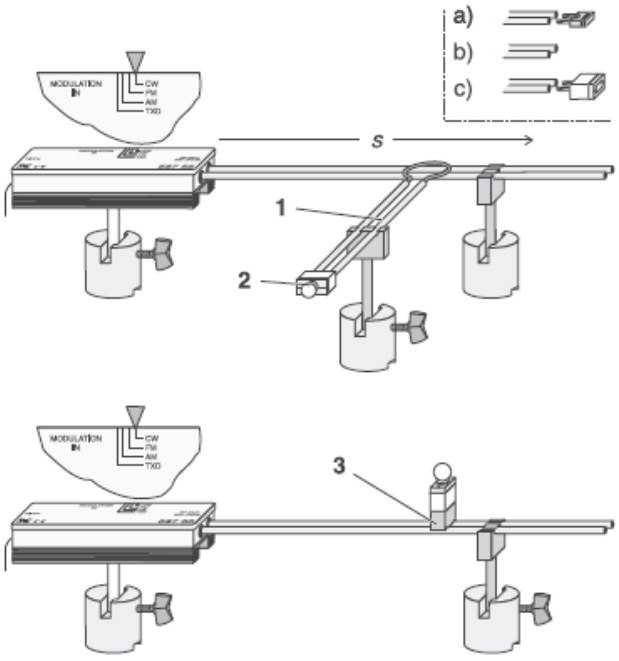


Fig. 1. Experimental setup for the detection of the current maxima and minima(above), and for the detection of the voltage maxima and minima(below).

1. Clamp the UHF transmitter in the saddle base and choose operating mode CW.

2. Plug the sections of the *Lecher* line together, slide on a holder with a rod from one end and clamp it in a base.

3. Plug the 4-mm plugs of the *Lecher* line into the antenna output of the UHF transmitter.

4. Align the UHF transmitter and the Lecher line in height so that the *Lecher* line is horizontal.

5. Slide a holder with a rod on the coupling loop from one end and clamp it in a saddle base.

6. Make an induction loop by putting the lamp socket E10 together with the lamp (2) on the coupling loop (1).

7. Align the induction loop so that the curved end is somewhat higher than the *Lecher* line.

CARRYING OUT THE EXPERIMENT

I. *Lecher* line with short-circuited end

1. Switch on the UHF transmitter by plugging in the plug-in unit.

2. Plug the bridging plug into the open end.

3. Slide the induction loop along the *Lecher* line and find a position where the lamp lights up as brightly as possible.

4. Optimize the brightness by shifting the induction loop perpendicularly to the *Lecher* line, and, if necessary, by carefully reducing its distance from the *Lecher* line without touching the *Lecher* line.

5. Slide the induction loop along the *Lecher* line, first “from the left to the right,” then “from the right to the left.” Make marks on the *Lecher* line at all points (current nodes) where the lamp just goes out. The current nodes are each in the middle of a “left” and “right” mark.

6. Assemble the plastic adapter (3) and the lamp socket E10 with the lamp (2) and place it on the *Lecher* line as a probe.

7. Slide the probe along the *Lecher* line, first “from the left to the right,” then “from the right to the left.” Make marks on the *Lecher* line at all points (voltage nodes) where the lamp just goes out. The voltage nodes are each in the middle of a “left” and “right” mark.

8. Measure the positions *s* of the current and voltage nodes on the *Lecher* line with a

steel tape measure starting from the output of the UHF transmitter and record them.

9. Use the probe to detect the voltage antinodes at the positions of the current nodes.

10. Use the induction loop to detect the current antinodes at the positions of the voltage nodes.

II. Open ended *Lecher* line

1. Use the probe to find the voltage nodes on the *Lecher* line and mark them.

2. Use the induction loop to find the current nodes on the *Lecher* line and mark them.

3. Measure the positions *s* of the current and voltage nodes on the *Lecher* line with the steel tape measure starting from the output of the UHF transmitter and record them.

4. Use the probe to detect the voltage antinodes at the positions of the current nodes.

5. Use the induction loop to detect the current antinodes at the positions of the voltage nodes.

III. *Lecher* line terminated with the characteristic wave impedance

※※ CAUTION ※※

1. The sustained load capacity of the 200 V terminator is only 2 W !!

2. Do not leave the 200 V terminator attached for more than 5 minutes !!

1. Place the 200 V onto the open end.

2. Look for the brightness maxima and minima of the lamp with the induction loop and the probe.