Related Topics

Diffraction of water waves, interference of waves, Huygens' Principle, principle of "phased arrays antennas".

Principle

A set of circular water waves is generated simultaneously and the resulting interference is observed. By increasing the number of interfering circular waves, Huygens' Principle can be verified. With the aid of plane water waves, diffraction phenomena of waves at different obstacles (slit, edge, double-slit etc.) are investigated. In a further experiment, the principle of "phased array antennas" can be demonstrated. To do so, two circular waves are generated to interfere and the resulting interference pattern on varying the phase of one of the circular waves with respect to the other one is observed.

Note: All experiments should be started in permanent light mode. The use of the stroboscope light mode is only necessary when it is explicitly mentioned.

Equipment

1	Ripple Tank with LED-light source, complete	11260-88
	consisting of:	
	1 Basic unit	11260-02
	1 Power supply 12 V DC / 2 A	12151-99
	1 Accessory set	11260-12
	1 Drawing table	11260-13
	1 Wave tray	11260-14
1	Ext. vibration generator for ripple tank	11260-10
	including:	
	2 Connecting cord, 32 A, 500 mm, black	07361-05

Fig. 1: Overview

Tasks

1. Use the comb to generate two circular waves and observe the resulting interference. Increase the number of interfering circular waves up to ten by using all teeth of the comb to demonstrate Huygens' Principle.
2. Generate plane water waves and use a barrier to demonstrate diffraction at an edge. Then, form a slit and observe diffraction behind the slit. Repeat this experiment for a double-slit.
3. By using the integrated wave generator as well as the external wave generator, generate two circular waves and observe the interference. Vary the phase of the external wave generator and observe the resulting interference pattern to understand the principle of "phased array antennas".

Set-up and procedure

Task 1: Standing waves and Huygens' Principle

Mount two dippers at the end positions of the comb, fix it to the mounting rod and move the mounting rod to the centre of the wave tray (Fig. 2). Ensure that the dippers contact the water surface equally.
Observe the resulting wave image at different frequencies (between 15 Hz and 40 Hz) in permanent light mode. The settings are made using the keypad of the ripple tank device (Fig. 3).

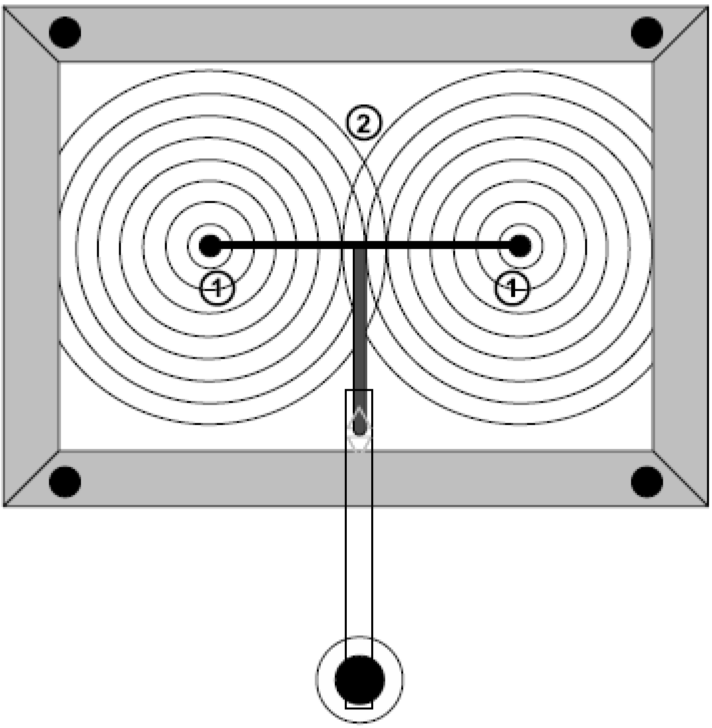

Fig. 2: Arrangement for interference of **two** circular wave fronts moving in opposite directions. The comb-shaped wave exciter is fitted with two dippers (1) to obtain a distinct interference pattern (2).

If necessary, adjust the exciter amplitude to each frequency so that clear wave patterns result. Compare the wavelength near the two dippers – where the waves progress in a clearly visible way – with the line spacing in the area between the dippers. It is advisable to do this by drawing several wave crests of the progressing wave area and several wave crests from the area between the dippers on the sheet of paper on the drawing table to enable easier comparison of the wavelengths.
Then, switch to stroboscopic light mode (button "LED") and select a frequency difference Δf between stroboscopic lighting and exciter frequency between −0.5 Hz and −1.5 Hz. Note your observations.
After that, switch back to permanent light mode. Fix each of the two dippers to the first comb tooth on both sides as seen from the centre of the comb. Move the mounting rod close to the edge of the wave tray as shown in Fig. 4.

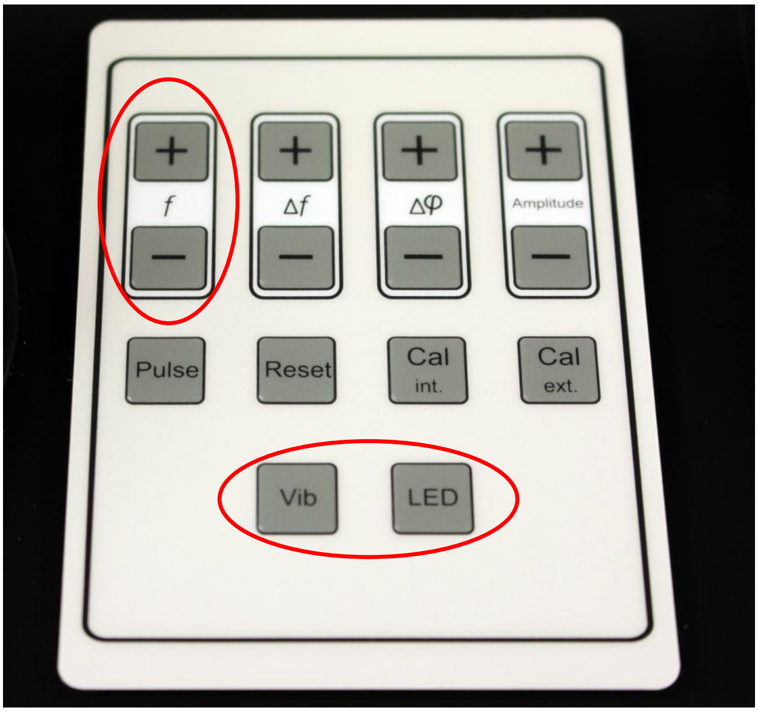

Fig. 3: Keypad of the ripple tank.

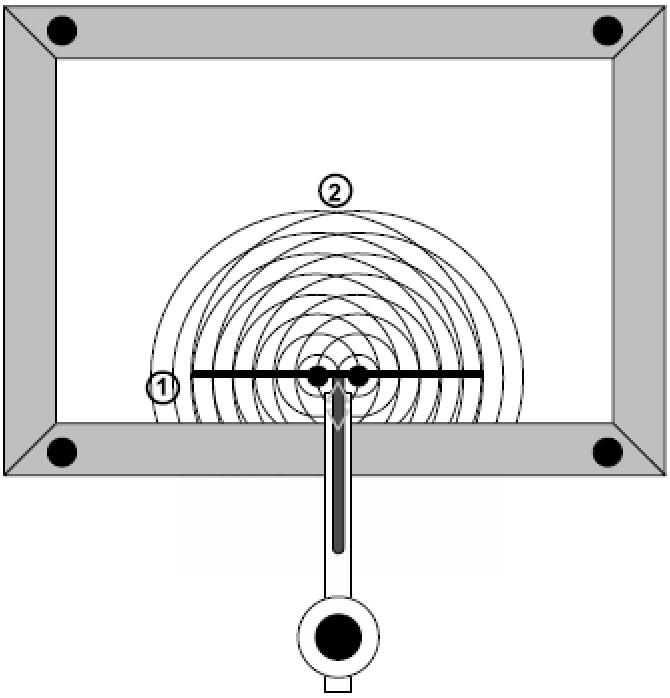

Fig. 4: Arrangement for demonstrating interference with two dippers. The two circular waves generated by the comb-shaped wave exciter (1) superimpose to form a characteristic interference pattern (2).

Select an exciter frequency between 20 Hz and 25 Hz at the ripple tank device and adjust the amplitude so that a clear wave pattern occurs.
Vary the exciter frequency and investigate the effect of the frequency shifts on the interference pattern. Note your observations.
Then, the effect of changes in the distance between the dippers on the interference pattern at a constant frequency (around 20 Hz to 30 Hz) is examined. Consecutively move each dipper to a further tooth in the

outer direction of the comb. It must be ensured that the two dippers are always at the same distance from the middle of the comb. Again, note your observations.

Finally, investigate Huygens’ Principle. To do this, attach each of the two dippers back to the first comb tooth on each side seen from the middle of the comb (see above). Attach a third dipper to the second tooth on one side as shown in Fig. 5.
Select an exciter frequency between 20 Hz and 25 Hz and the amplitude so that you can observe a clear wave pattern. Your chosen frequency remains the same for this task. Then, observe the interference for four, six, eight and ten dippers and compare the observed interferences with each other. It is important to ensure that the distance between the dippers remains constant.

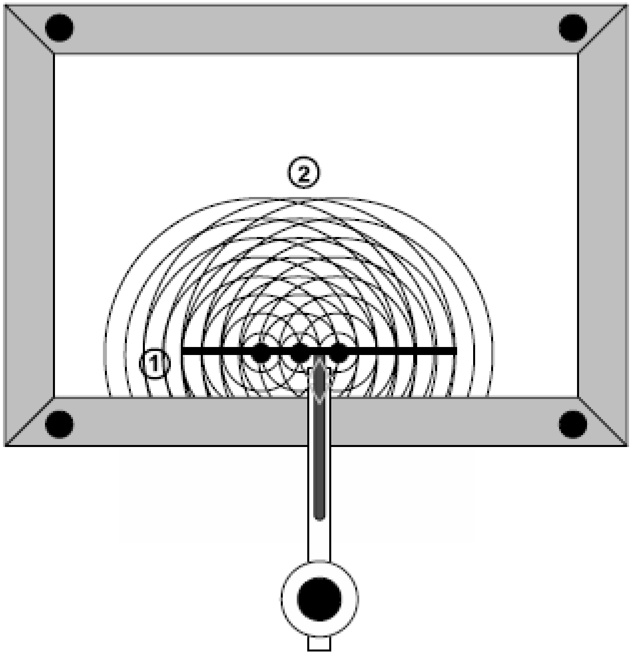

Fig. 5: Arrangement for interference formation with **three** generators. The three circular waves generated by the comb-shaped wave exciter (1) superimpose to form a characteristic interference pattern (2).

Task 2: Interference and diffraction at several objects

Replace the comb by the plane wave exciter. With the aid of the adjusting screws, adjust the wave tray horizontally to get the same water level all over the tray. Adjust the plane wave exciter in a way that it is exactly parallel to the water surface. This adjustment is important since otherwise no clear wave patterns of plane waves would be possible. Then, place a 71 mm barrier into the wave tray to set up the experiment as shown in Fig. 6. Select an exciter frequency between 18 Hz and 25 Hz and adjust the amplitude so that a distinct wave pattern results.
After observing the wave pattern, the experiment is repeated with single plane waves generated on pushing the button "Pulse" (see Fig. 3). Again, observe the resulting wave pattern. After investigating diffraction at an edge, diffraction at a wide slid is now examined. Place a second 71 mm barrier into the wave tray to form a 3 cm wide slit as shown in Fig. 7. Select an exciter frequency between 18 Hz and 25 Hz and an amplitude so that you can see a distinct wave pattern.

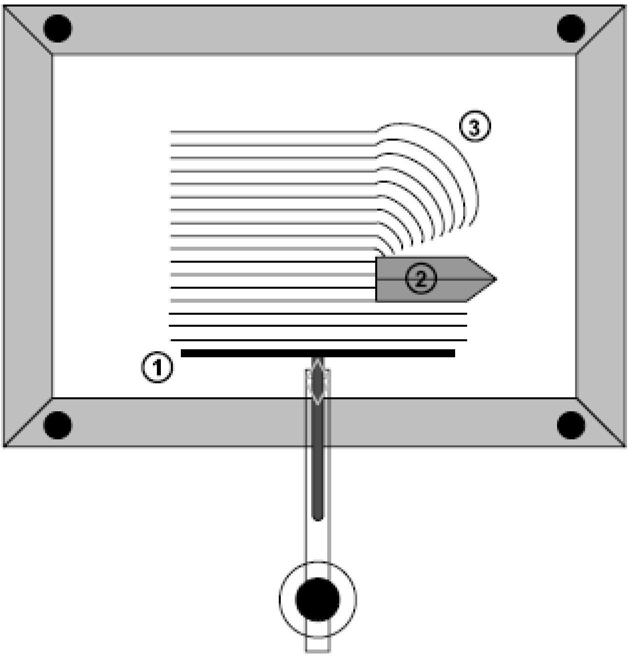

Fig. 6: Experiment arrangement for demonstration at an **edge**. The wave front (1) generated by the plane wave exciter reaches the 71 mm barrier (2), which acts as an edge in this case. Circular waves are emanated from it, which penetrate the geometric shadow area (3).

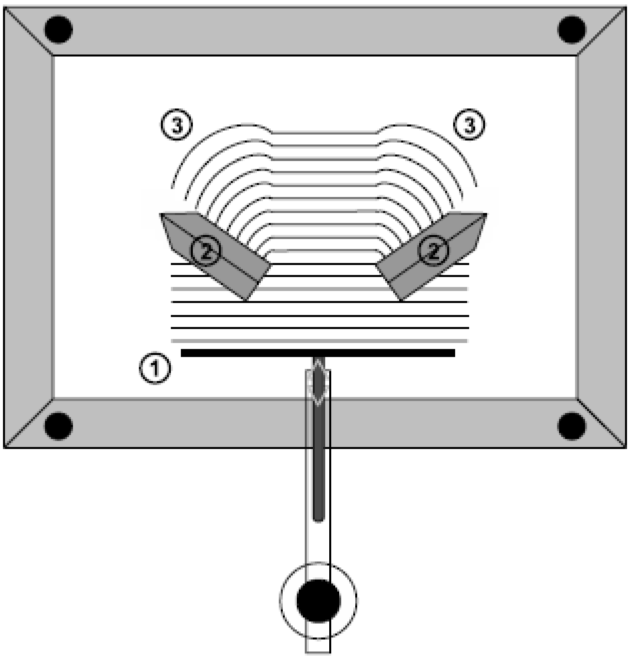

Fig. 7: Arrangement for demonstration at a **wide slit**. The wave front (1) generated by the plane wave exciter reaches the 3 cm wide slit formed by the two 71 mm barriers (2). The wave front is diffracted there: circular waves emanate from the barriers and propagate in the geometric shadow areas (3).

After that, form a narrow slit (about 1 cm) as shown in Fig. 8. Use the settings as before and observe the wave pattern. You should be able to observe a diffraction pattern as it can be seen in Fig. 8.

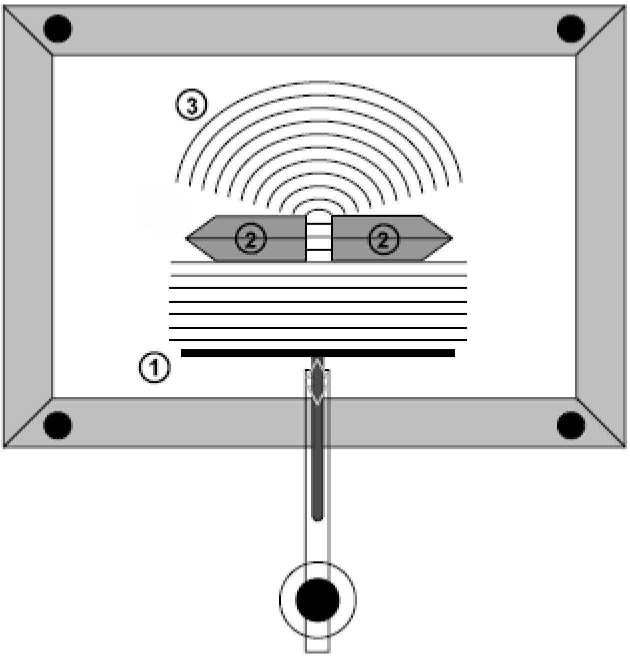

Fig. 8: Arrangement for demonstration at a **narrow slit**. The wave front (1) generated by the plane wave exciter reaches the 1 cm slit (2) formed by the two barriers. Circular waves emanate from this slit (3) and propagate in the geometric shadow area.

In the next experiment, interference and diffraction at a double slit are investigated. To do this, place the two 71 mm barriers and the 30 mm barrier into the wave tray to form a double-slit as shown in Fig. 9. The two slits should be the same width (about 1 cm).

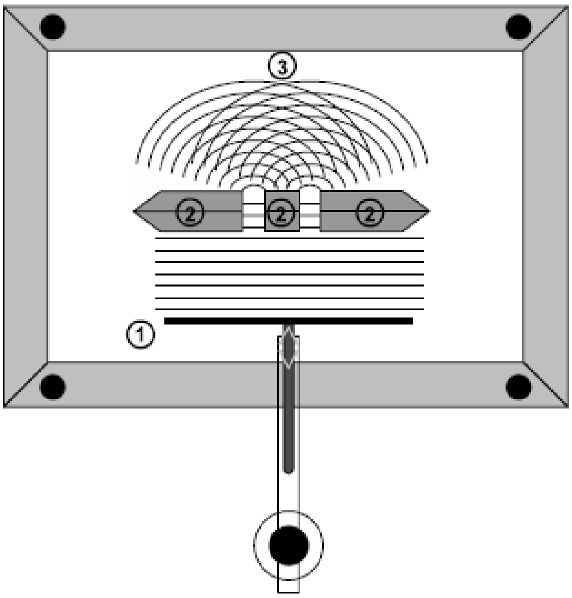

Fig. 9: Arrangement for demonstrating interference and diffraction at a **double slit**. The plane wave front that is generated by the plane wave exciter (1) reaches the double slit formed by the barriers (2). Circular waves emanate from both slits and interfere behind the double slit (3).

Select an exciter frequency between 15 Hz and 30 Hz and adjust the initial amplitude so, that the plane waves can be seen in front of the double slit. Subsequently, raise the amplitude until you can see the interference pattern behind the double-slit (Fig. 9). Observe this interference pattern.

At the same frequency, the distance between the two slits is then shortened. To do this, replace the 30 mm barrier by the 10 mm barrier. Then, move the two 71 mm barriers closer to the 10 mm barrier to form a double-slit, which has the same width as before (about 1 cm; see Fig. 10). Observe the resulting interference pattern and compare it with your observations at larger slit distance.
Finally, vary the exciter frequency and observe the interference and diffraction patterns to investigate the influence of the wavelength on the interference pattern.
When finished, remove the barriers from the wave tray.

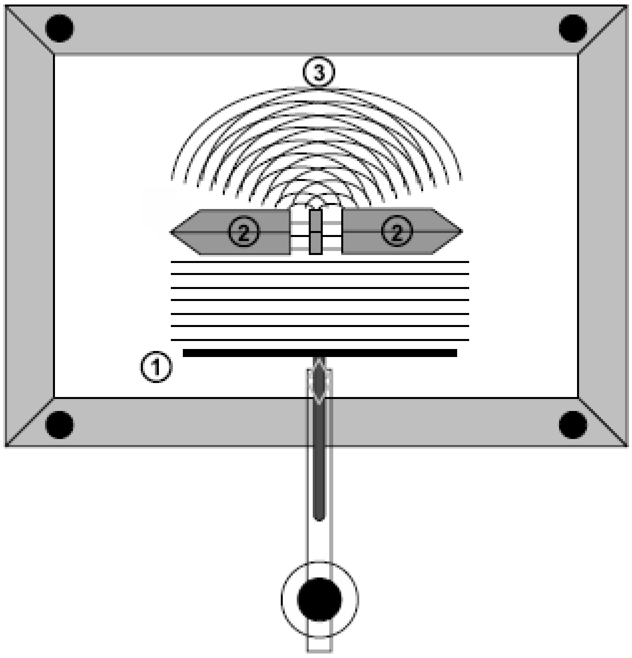

Fig. 10: Arrangement for demonstrating interference and diffraction at a **double slit** with **shortened slit distance**. The plane wave front generated by the plane wave exciter (1) reaches the double slit, which is formed by the three barriers (2). Circular waves emanate from both slits and interfere behind the double slit (3).

Task 3: Principle of phased array antennas

In this task, the principle of phased array antennas is investigated. Use the two connection cables to connect the external vibration generator to the ripple tank device. The integrated as well as the external vibration generator are then positioned relatively to the wave tray as shown in Fig. 11.
Select an exciter frequency between 20 Hz and 25 Hz and switch on the stroboscopic light mode. The amplitude should be chosen so that a clear interference pattern results (standing wave). At this moment, both exciters oscillate in phase ($\Delta\varphi = 0°$) at the same frequency.

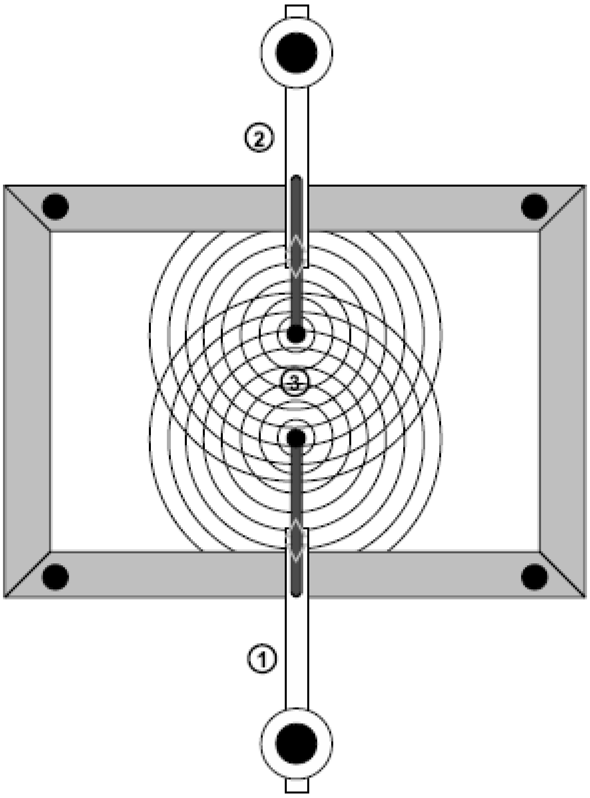

Fig. 11: Experiment for demonstrating the effect of a **phase difference** $\Delta\varphi$ of two circular waves on their interference pattern. The circular waves generated by the integrated (1) and by the external vibration generator (2) superimpose to form a standing wave between the two exciters (3) (Task 1).

Use a pencil to draw several antinodes (bright stripes) on a sheet of paper placed on the drawing table (Fig. 12). It can be helpful to fix the sheet of paper to the drawing-table using strips of adhesive tape or similar means.

Now, select a phase difference $\Delta\varphi$ (Fig. 3) of 45°, 90°, 135°, 180°, 225°, 270°, 315° and 360° = 0° one after the other and observe the interference pattern (standing wave) for each case. Here, compare the antinodes of the visible interference pattern with the antinodes drawn on the sheet of paper ($\Delta\varphi = 0°$). Note your observations.

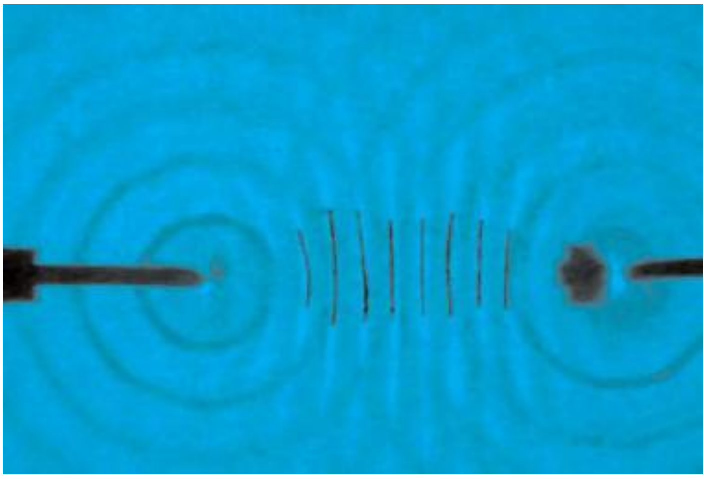

Fig. 12: Snapshot as shown in Fig. 11 at a phase difference of $\Delta\varphi = 0°$. The interference pattern (standing wave) as well as the drawn antinodes can be identified.

Theory and Evaluation

Task 1: Standing waves and Huygens' Principle

Standing waves

A standing wave pattern is formed between the wave generators (dippers). The distance between the bright and dark stripes along the connection line between the wave generators (standing wave) is half the size of the wavelength of the progressing waves visible near the two exciter centres (Fig. 13). The formation of a standing wave can also be seen in Fig. 14.

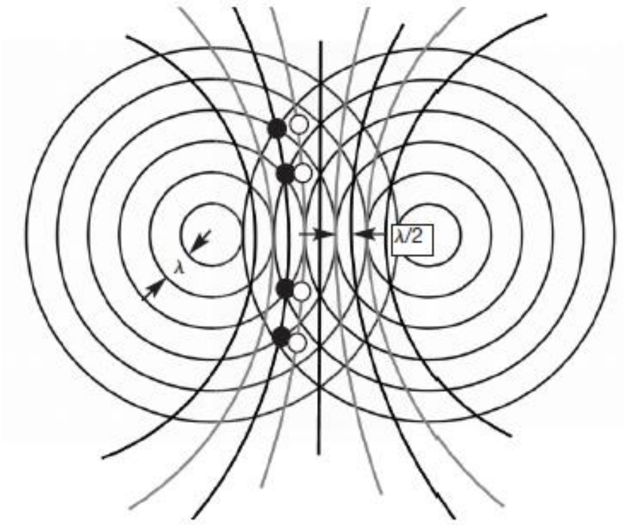

Fig. 13: Schematic illustration of the visible superimposition of the wave fields of two point generators with wavelength λ. Locations at which the wave trains constructively interfere (filled circles) lie on the black lines; those which destructively interfere (unfilled circles) lie on the grey lines. Together they form a standing wave pattern. The hyperbolae of constructive interference appear in the wave pattern as light-coloured stripes, the hyperbolae of destructive interference appear as dark stripes. Along the connection line between the exciters, the superimposed standing wave generated has a wavelength of $\lambda/2$.

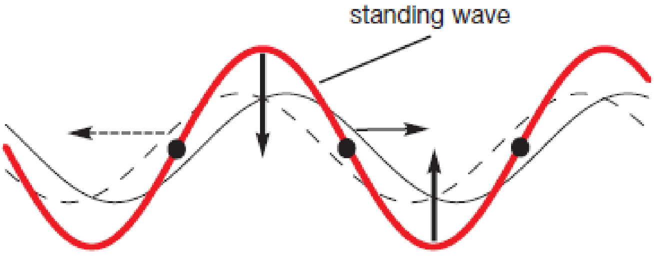

Fig. 14: Formation of standing wave. Two waves with same frequency and same amplitude propagate in opposite directions (- - - - and ——). Whenever these two waves interfere, a standing wave will be formed (thick red line) as a superposition of both waves. Nodes are points of no displacement where the resulting standing wave remains zero at all times (the two moving waves cancel out each other). The points between two nodes are called antinodes. These points are a result of constructive interference of the two moving waves.

In the subsequent stroboscopic light mode, where a frequency difference Δf between the stroboscope light and exciter frequency enables the propagation velocity of the waves to be substantially slowed down, the same wavelength is observed between the wave generators as in the outer area. A periodic change between wave crests and troughs can be seen. This periodic change is explained in Fig. 14.

As the two wave generators oscillate in phase, one expects constructive interference (maximum wave amplitude) at all locations for which the following relationship of the difference between their distances Δl from the two exciters is valid:

$$\Delta l = m\lambda \qquad (m = 0, \pm 1, \pm 2, ...)$$

At locations, whose path difference from the exciter centres is

$$\Delta l = \frac{2m+1}{2} \cdot \lambda \qquad (m = 0, \pm 1, \pm 2, ...),$$

the two waves mutually cancel out.

In the case of standing water waves, the nodes appear as lines with constant average brightness. The locations of the antinodes on the other hand, as soon as a wave crest exists, appear as intensive bright lines. At the time of a wave trough, the intensity is only negligibly lower than in the area of the nodes. As the eye cannot differentiate between the phases of the oscillations due to its limited time resolution capacity, it only differentiates the lighter antinodes from the darker nodes in the time average. The distance between adjacent nodes or antinodes is - as observed in the experiment – therefore $\lambda/2$.
In stroboscope light mode it is possible to see in the snapshot of the standing waves that their wavelength is identical to that of the progressing waves. If the stroboscope frequency ($\Delta f \neq 0$) is adjusted slightly the oscillations are slowed down for the eye to such an extent that the periodic change from wave crests to wave troughs can be recognised in the area of the antinodes of the standing waves.

Note:
Standing waves can also be produced by reflection. A convincing demonstration can be achieved with the help of a single wave exciter located in the centre of the circle of the concave reflector from the accessory set (11260-99) of the ripple tank. Standing waves near the reflector can be seen the best.

Huygens' Principle

Some of the wave patterns observed are shown in the following figures. With two point-like wave sources (Fig. 15) three wavebands of roughly the same width are identified. These wavebands can be observed with three wave generators in the same location; however, they are narrower and an additional, narrower waveband can be identified between these bands (Fig. 16). It is clearly separated from the main wavebands by two stripes.

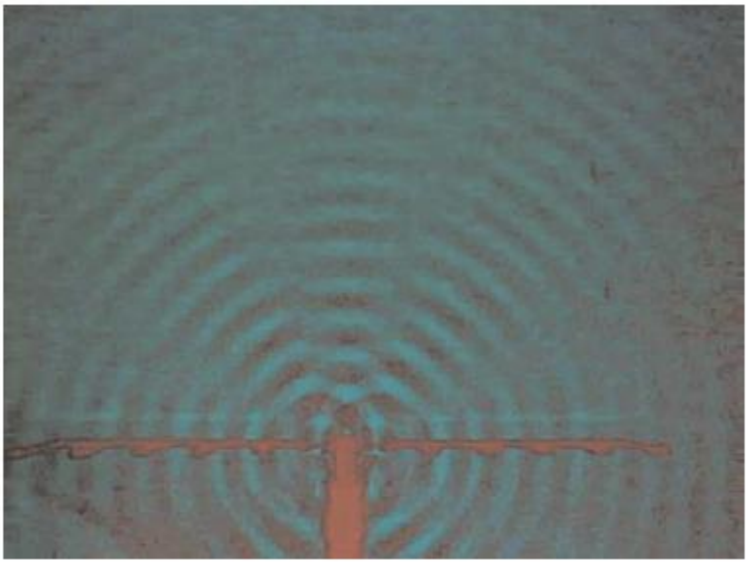

Fig. 15: **Two** dippers – snapshot as shown in Fig. 4. Three wavebands with roughly the same width can be observed, which are separated from each other by two stripes with negligible wave modulation.

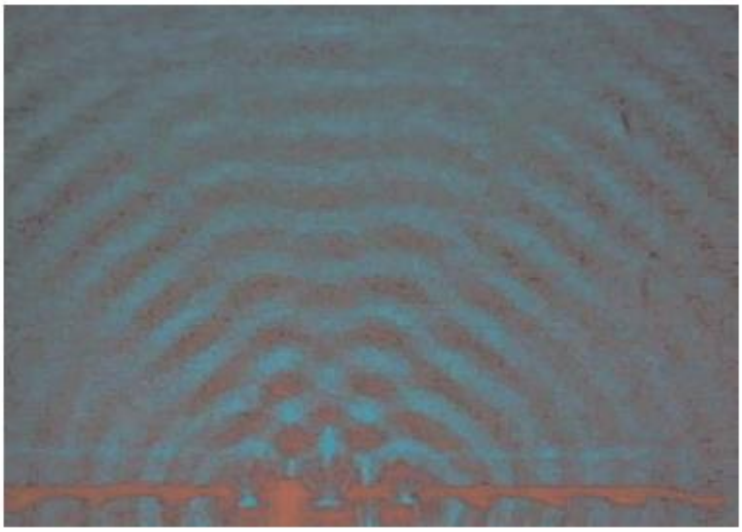

Fig. 16: **Three** dippers – snapshot as shown in Fig. 5. An additional waveband compared to Fig. 15 can be identified in the middle. Overall, the wavebands are narrower.

With four exciter centres (Fig. 17) two additional, narrow wavebands can be observed between each of the three main wavebands of Fig. 15. The main wavebands have become even narrower.

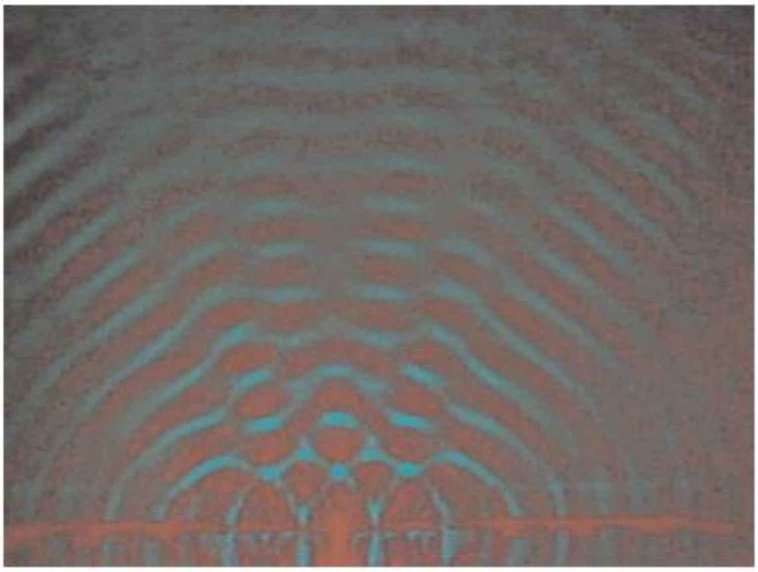

Fig. 17: **Four** dippers. The number of wavebands has increased and they are narrower than in the interference of two circular waves. The waves are no longer as circular as with two generators (Fig. 15).

On further increasing the number of dippers, the number of wavebands is further increased and they become even narrower. The interference pattern of ten dippers (Fig. 18) near the exciter centres is similar to the wave pattern of a plane wave (Fig. 19).

The three wavebands identifiable in Fig. 15 (two dippers) are the zeroth interference order and the two wavebands symmetrically following these are the first interference orders. For reasons of simplification we want to exclude the immediate surroundings to clarify the formation of additional interference bands between the zeroth and first order when the number of wave generators is increased. For locations whose distances from the exciters are large compared to the distance d between the generators, the following applies to two wave exciters (Fig. 20) for the path difference Δl between the two interfering waves:

$$\Delta l = d \sin \alpha.$$

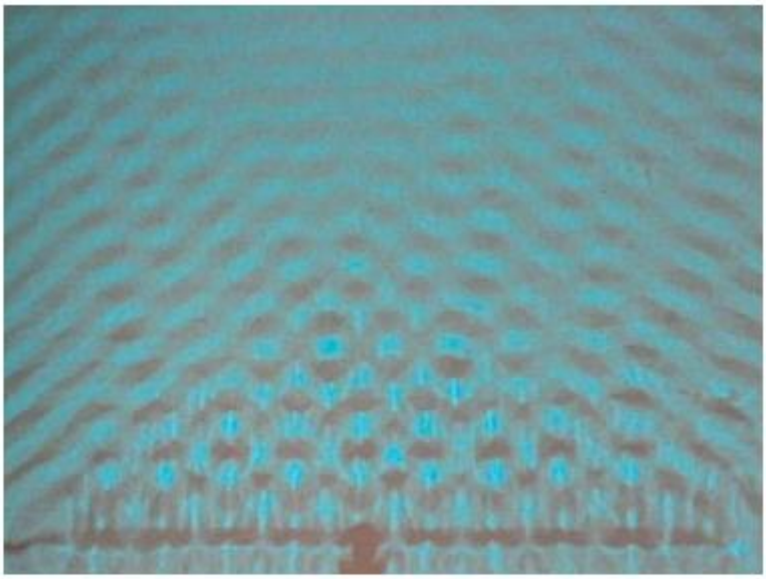

Fig. 18: **Ten** dippers. The interference pattern of the ten superimposed circular waves can be identified. The number of wavebands has again increased so that the interference pattern directly behind the wave generator is similar to the wave pattern of a plane wave (Fig. 19).

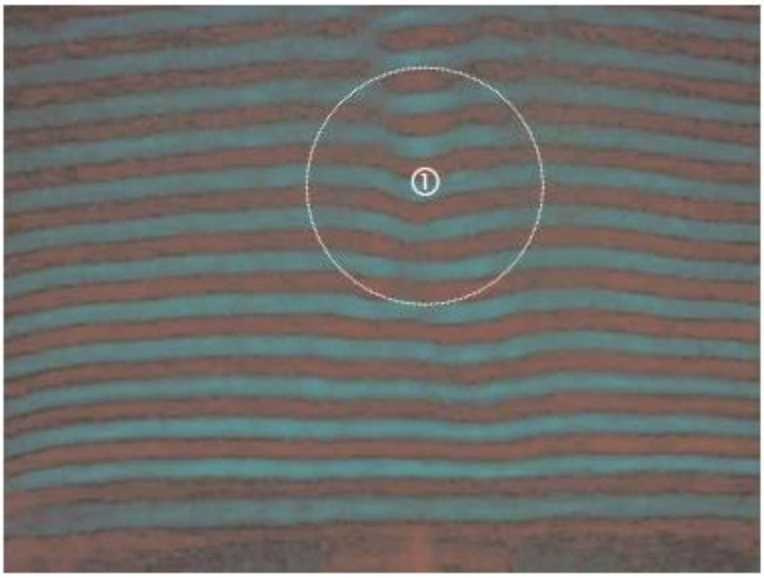

Fig. 19: Wave pattern of a plane wave. Area (1) is identified as an artefact.

For the first order maximum, $\Delta l = \lambda$ must be true so that (irrespective of the number of exciters!):

$$\sin\alpha = \frac{\lambda}{d}$$

is valid.

Accordingly, the angle between the zeroth and first order for which complete destruction (destructive interference / cancelling out of waves) results ($\Delta l = \lambda/2$) is:

$$\sin\alpha = \frac{1}{2} \cdot \frac{\lambda}{d}\,.$$

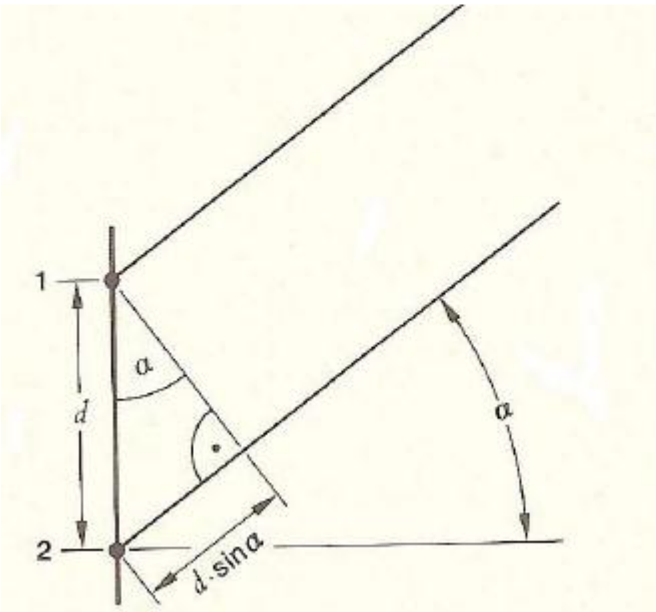

Fig. 20: Schematic diagram of the formation of maxima and minima with two wave generators.

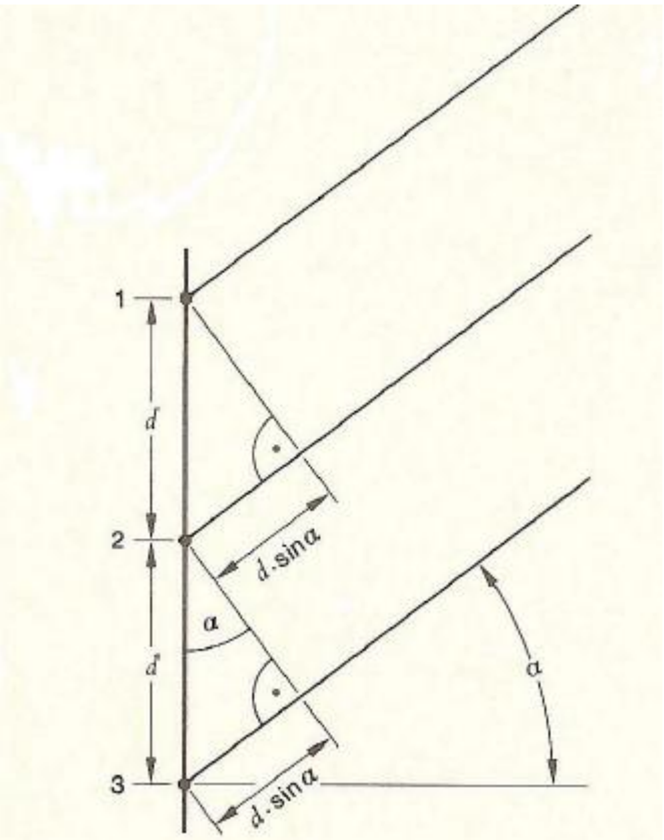

Fig. 21: Schematic diagram of the formation of maxima and minima with three wave generators.

From Fig. 21, it can be seen that complete destruction does not occur with three exciters at the same angle α. As a result, the complete destruction of the wave fronts emanating from exciters 1 and 2 leads to a fully undisturbed wave pattern of exciter 3. However, three sine waves completely cancel out each other if they are out of phase by either 1/3 or by 2/3 of a period. This can be clearly shown in a particularly graphic way in the vector (phasor) diagram.

Thus, two secondary minima result, as can be seen in Fig. 16:

1st Secondary minimum:

$$d \cdot \sin\alpha = \frac{1}{3}\lambda \Rightarrow \sin\alpha = \frac{1}{3}\,\frac{\lambda}{d}$$

2nd Secondary minimum:

$$d \cdot \sin\alpha = \frac{2}{3}\lambda \Rightarrow \sin\alpha \frac{2}{3}\,\frac{\lambda}{d}$$

The formation of three secondary minima with four wave exciters (Fig. 17) can be explained using Fig. 22. Cancellation occurs if the waves emanated from exciters 1 and 2 will compensate for each other like the waves emanated from exciters 3 and 4. On the other hand the waves emanated from exciters 1 and 3 and those from the exciters 2 and 4 can also cancel each other out.

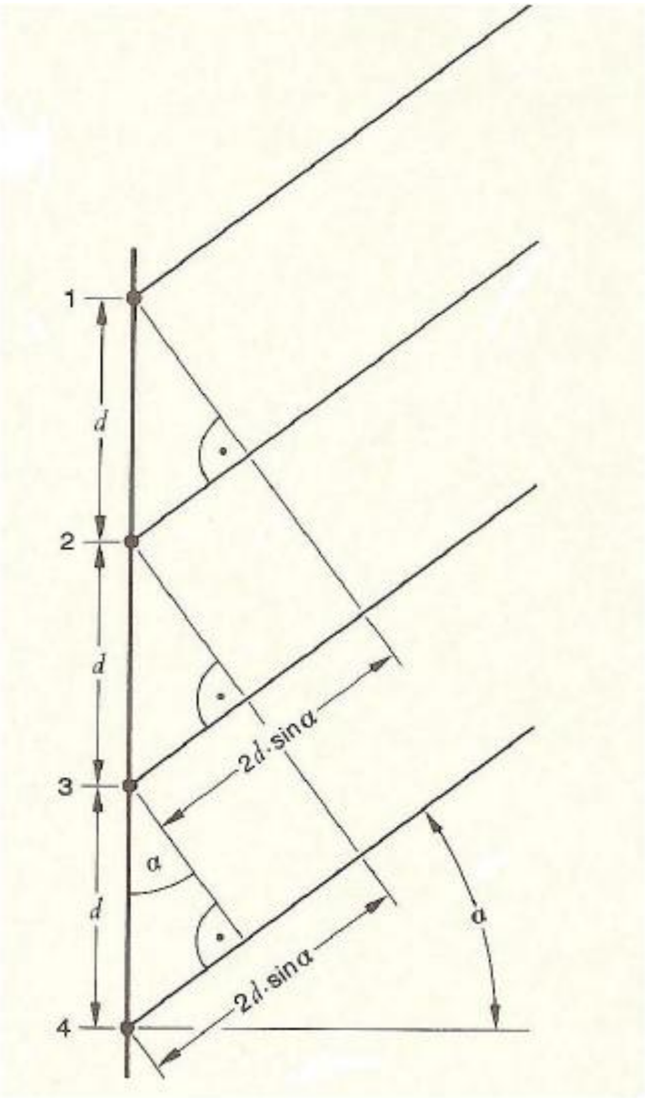

Fig. 22: Schematic diagram of the formation of maxima and minima with three wave generators.

Thus, starting from the zeroth order, the following secondary minima result:

1st secondary minimum:

$$2d \cdot \sin\alpha = \frac{1}{2}\lambda \Rightarrow \sin\alpha = \frac{1}{4}\frac{\lambda}{d}$$

2nd secondary minimum:

$$d \cdot \sin\alpha = \frac{1}{2}\lambda \Rightarrow \sin\alpha = \frac{1}{2}\frac{\lambda}{d}$$

3rd secondary minimum:

$$2d \cdot \sin\alpha = \frac{3}{2}\lambda \Rightarrow \sin\alpha = \frac{3}{4}\frac{\lambda}{d}$$

If the number of exciters is increased further, the circular waves are superimposed according to the principle described above. The larger the number of circular wave exciters the more the resulting interference pattern resembles that of the wave pattern of a plane wave.
In this experiment this phenomenon is indicated by the ten wave exciters (Fig. 18). Of course, this number is not sufficient to achieve a plane wave, but on the basis of Fig. 18 and Fig. 19 it is easy to extrapolate how the interference pattern would look if there was an even higher number of exciter centres. Then the resulting image is that of a plane wave (Fig. 19). Precisely this is stated by Huygens' Principle.

Task 2: Interference and diffraction at several objects

Edge and wide slit

The plane waves pass the barrier. A circular wave propagates from the edge of the barrier into its geometric shadow area (Fig. 23).

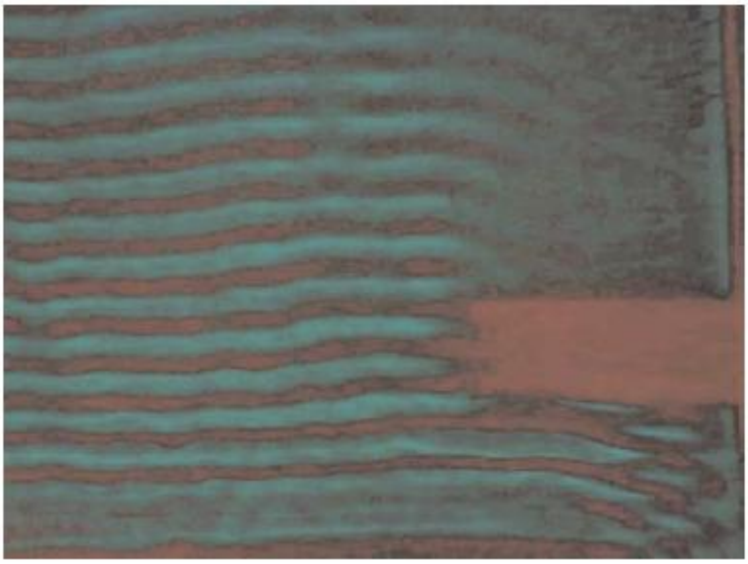

Fig. 23: Diffraction at an **edge**. The circular wave emanating from the barrier can be clearly recognised in the geometric shadow area of the barrier.

The part of the plane waves that hits the barrier is reflected so that a standing wave results in front of the barrier.
When working with short wave trains it can be seen that the circular wave emanating from the edge of the barrier propagates in all directions.

From the two barriers that form the 3 cm wide slit, circular waves emanate into the geometric shadow area (Fig. 24). In the middle behind the slit an interference pattern can be observed where the zeroth interference order is substantially wider than the higher orders.
The results of both experiments can be explained with the help of Huygens’ Principle. While an infinite number of elementary waves are superimposed in the undisturbed wave field to form a plane wave field, the elementary wave emanating from the edge into the shadow area of the barrier does not superimpose with other waves and can be directly observed there.
The slit opening can be considered to be a location with an infinite number of point generators. The elementary waves emanating from these generators interfere behind the slit to form a characteristic pattern.

Note:
The interference pattern of the wide single slit differs from that of a double slit in a characteristic way. At a large distance from the single slit the zeroth interference order is twice as wide as the higher orders. In the case of the double slit the same widths result there for all orders.

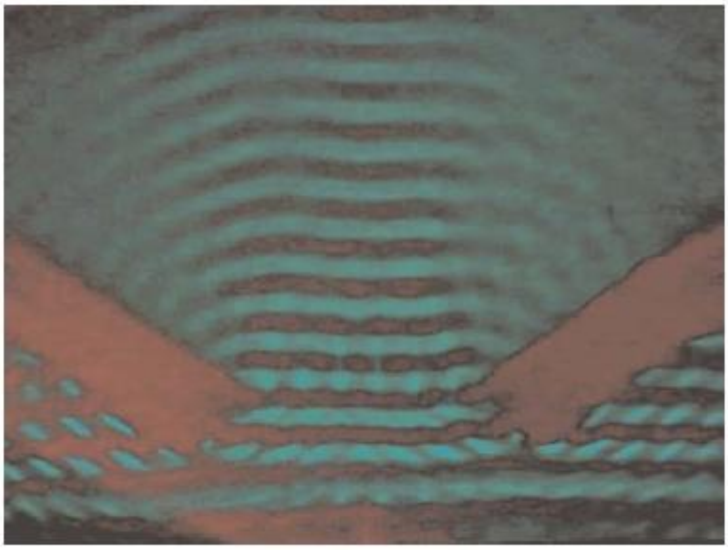

Fig. 24: Interference and diffraction at a **wide slit**. An interference pattern can be seen behind the slit whose zeroth interference order is substantially wider than the higher orders. Circular waves emanate from the two barriers into their geometric shadow area.

Narrow slit

Circular waves emanate from the slit and penetrate the geometrical shadow area (Fig. 25).
The slit, which is narrow in comparison to the wavelength, is the starting point for an elementary wave (Huygens’ Principle). The diffraction is observed in a pure form, i.e. without a superimposed interference pattern. When performing the analogous experiment with light waves a slit whose width is larger than the wavelength must be used in order to achieve adequate image brightness. In this case pure diffraction cannot be observed since always interferences occur (see above), that interrupt the diffraction pattern. Therefore, the observation of pure diffraction at a narrow slit is only possible with water waves.

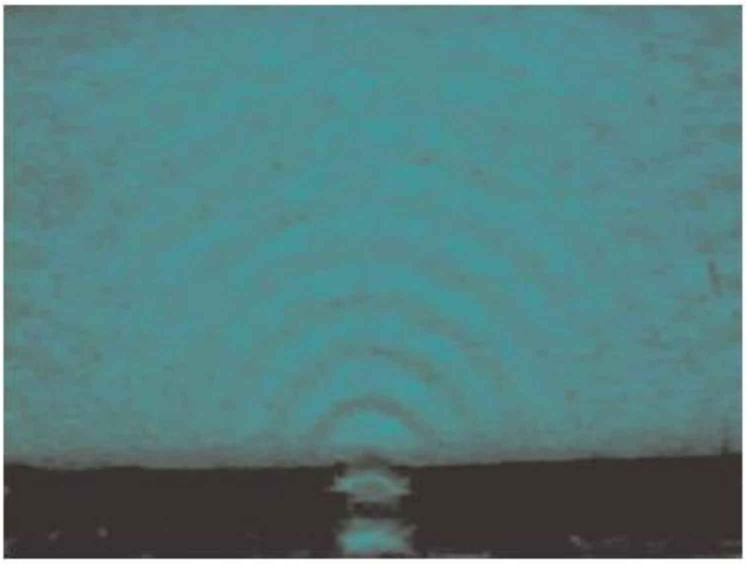

Fig. 25: Diffraction at a **narrow slit**. The circular waves emanating from the slit as well as their propagation into the barriers' geometric shadow area can be clearly recognized.

Double-slit

In the middle of the wave image one observes a waveband that is perpendicular to the connection line of the two slits. Symmetrically to this waveband, there alternate wavebands without wave generation and wavebands with wave generation to both sides (Fig. 26).

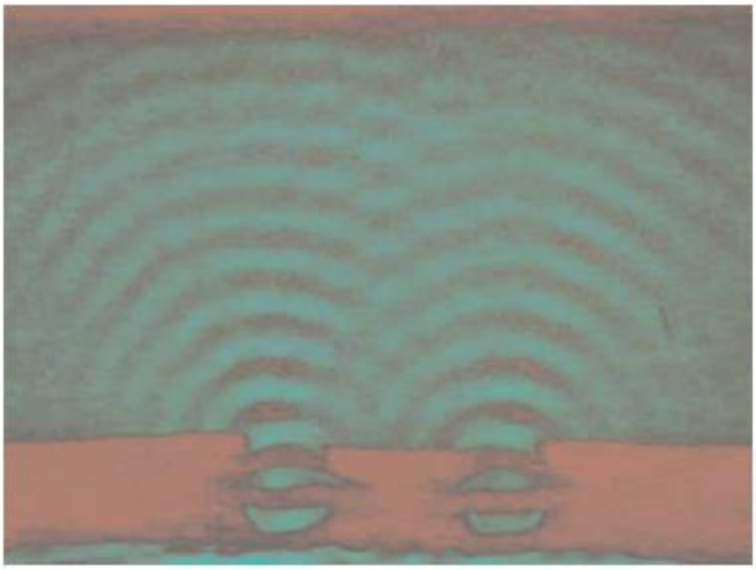

Fig. 26: Interference at a **double-slit**. Circular waves emanate from both slits and form a characteristic interference pattern behind the slit.

On shortening the distance between the two slits at constant wavelength, the distance between adjacent wavebands gets larger (Fig. 27). The same effect is achieved on increasing the wavelength at constant slit distance.

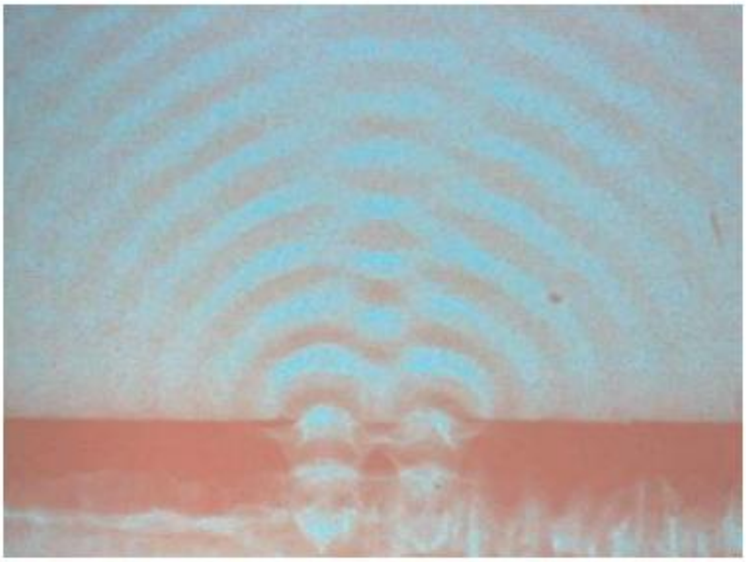

Fig. 27: Interference at a **double-slit** with **shortened slit distance**. In comparison to Fig. 26, the distance between adjacent wavebands is larger.

Both slits are centres of two circular waves according to Huygens' Principle. These circular waves interfere behind the double-slit in the same way as circular waves interfere generated by two point generators (Task 1).

Note:
When dealing with light waves the diffraction at a double-slit cannot be observed in such a pure form. For intensity reasons, one uses slit widths that are much larger than the wavelength. This is why diffraction phenomena with light waves are always accompanied with interference phenomena.

Task 3: Principle of phased array antennas

It can be seen that at a phase difference of $\Delta\varphi \neq 0°$ the antinodes drawn on the sheet of paper no longer match the antinodes of the visible interference pattern as they do for $\Delta\varphi = 0° = 360°$ (Fig. 28). Thus, the visible interference pattern is shifted compared to the drawn antinodes. This shift increases as the phase difference $\Delta\varphi$ increases.
When the phase difference is 180°, the antinodes of the interference pattern have reversed compared to the drawn antinodes (Fig. 30). A node in the interference pattern can now be observed at the point where an antinode was drawn on the sheet and vice versa.

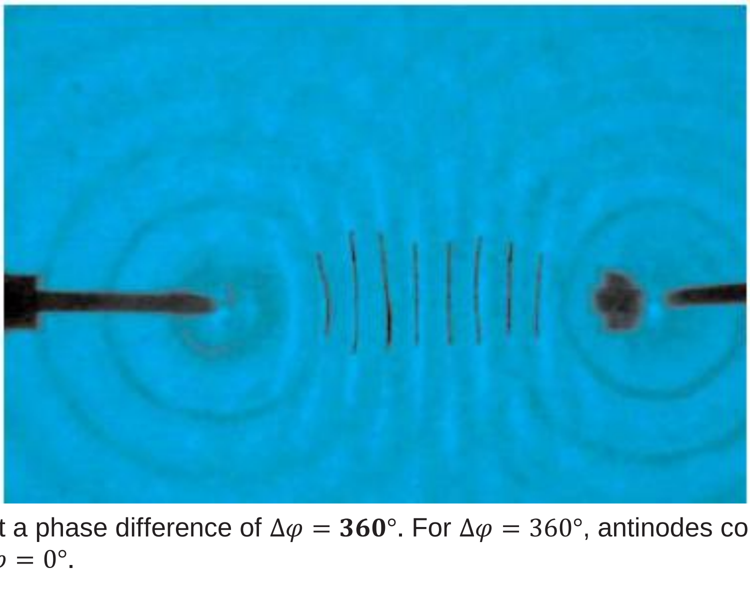

Fig. 28: Snapshot at a phase difference of $\Delta\varphi = \mathbf{360°}$. For $\Delta\varphi = 360°$, antinodes coincides with the antinodes of $\Delta\varphi = 0°$.

If the phase difference is further increased there is a further shift (Fig. 29 to Fig. 31) until, at a phase difference of $\Delta\varphi = 360° = 0°$, the drawn antinodes once again match the antinodes of the interference pattern (Fig. 28).
With increasing phase difference the waves of the two exciter centres are shifted relative to each other, whereby a phase difference of 180° corresponds to a half wavelength and a phase difference of 360° corresponds to a whole wavelength, which is shown by the results in Fig. 30 and Fig. 28.

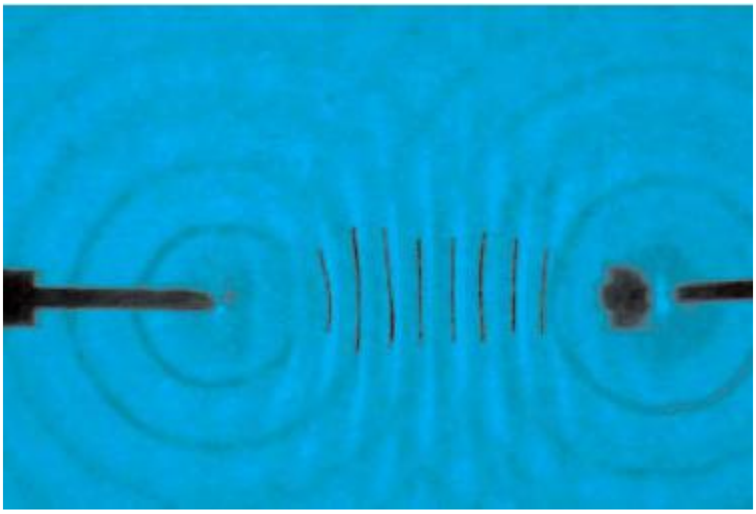

Fig. 29: Snapshot at a phase difference of $\Delta\varphi = \mathbf{90}°$. It can be seen that the interference pattern is shifted compared to the drawn antinodes.

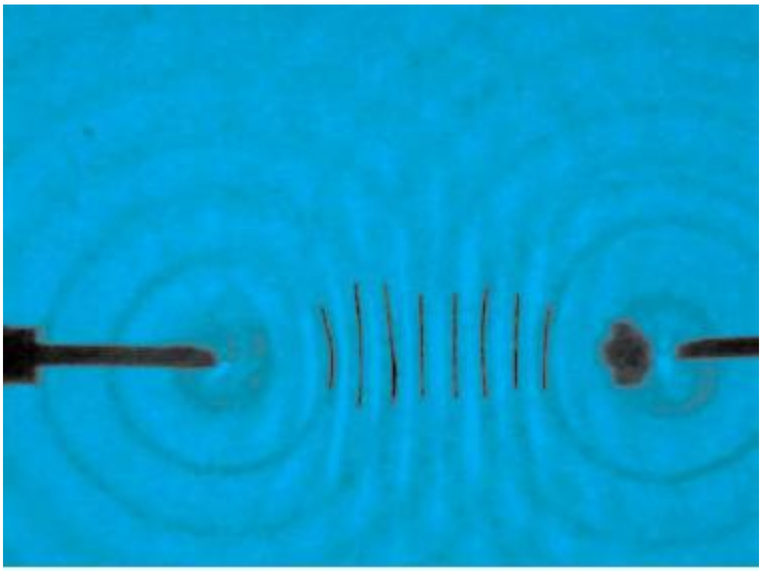

Fig. 30: Snapshot at a phase difference of $\Delta\varphi = \mathbf{180}°$. It can be seen that the nodes of the interference pattern are now at the positions of the drawn antinodes and vice versa.

When two in-phase circular waves are superimposed, a characteristic interference pattern – a standing wave – results, whereby there are areas of constructive and destructive interference. The locations of constructive interference lie on hyperbolae, which are at a distance of $\Delta l = \lambda \cdot m$ (m = 1, 2, 3, …) from the exciter centres; locations of destructive interference lie on hyperbolae at a distance of $|\Delta l| = \frac{1}{2} \cdot \lambda$, $\frac{3}{2} \cdot \lambda$, $\frac{5}{2} \cdot \lambda$, … from the exciter centres (Task 1).
If an area of constructive interference (antinodes) in an interference pattern of two circular waves that are in-phase is now compared with that of two circular waves with 180° phase shift, this phase shift causes the formation of antinodes at the positions where nodes can be seen with in-phase interference.

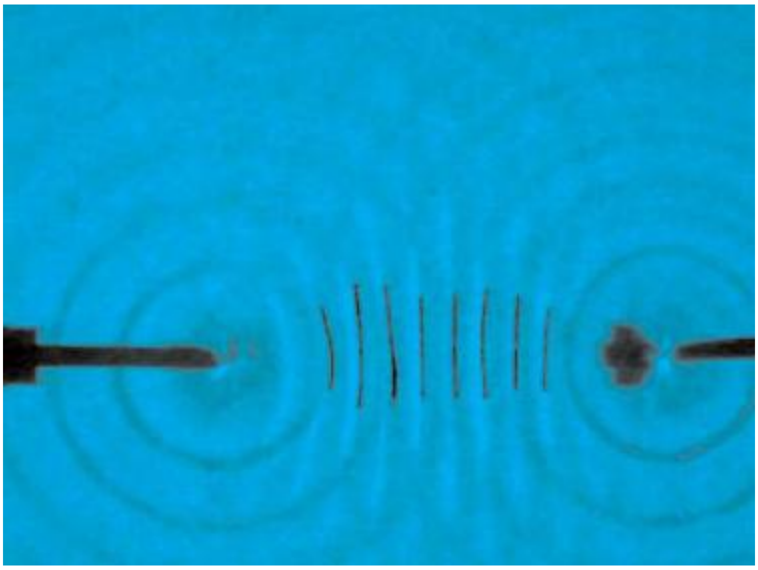

Fig. 31: Snapshot at a phase difference of $\Delta\varphi = \mathbf{270}°$. A further shift of the observed interference pattern is observed.

The same applies for the formation of the nodes. The phase shift thus causes a shift of the nodes and antinodes.

At a phase shift of 360° the shift is then advanced so far that the nodes and antinodes can once again be seen in precisely the same place as with in-phase interference.
The effect of controlling interference patterns is used to build so called “phased array antennas”. Those antennas consist of many single emitters, which are arranged in groups. On varying the phase of some of these groups one can strengthen the signal (constructive interference) in a desired direction and weaken the signal (destructive interference) in other directions.
Phased array antennas are used as radar antennas for example in anti-aircraft rockets systems, for weather research, in satellites etc.

As a conclusion, this experiment shows the possibilities of using water waves to depict diffraction and interference phenomena of waves. Water waves have many advantages compared to light waves when dealing with diffraction phenomena since pure diffraction cannot be observed with light waves. Moreover, a practical example (phased array antennas) of using interference phenomena of waves can be demonstrated and explained with water waves. Therefore, this experiment can help to get a better knowledge of diffraction and interference phenomena of waves and of their practical use.