

## “Fréedericksz transition on air” - Supplementary information

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### I. Construction of the nematic cell

**Attention: Wear latex or nitrile protective gloves! Protect your eyes with safety goggles and work under a fume hood during the cleaning and etching processes!**

#### 1.1. Preparation before the etching of ITO electrodes.

- The large slides, 75mm x 25mm x 1.1mm from Aldrich-Sigma, coated with indium tin oxide (ITO) electrodes, are easier to use than the small ones 25mmx25mmx1.1mm.

- Before etching, clean slides, coated with ITO electrodes, using a soap and hot water. Rinse them with demineralized water and dry with a clean air (or Nitrogen) stream.

- Identify sides of the glass slides coated with ITO electrodes using an ohmmeter. Typically, the resistance measured between two points, at a few mm distance, is of the order of 20-100 Ohm. It is quite difficult to identify ITO coatings visually!

- Apply an electrical (or other) adhesive tape to areas on the ITO coatings that you want to protect during the etching. In the example shown in Fig.1a, the ITO electrodes on both glass slides are partially covered with an electrical adhesive tape. If you want to display, for example, the letter M, incise with a scalpel, on one of the slides, contours of the letter M (see Fig.1b). Finally, using tweezers, remove the adhesive tape from the M-shaped area (see Fig.1c).

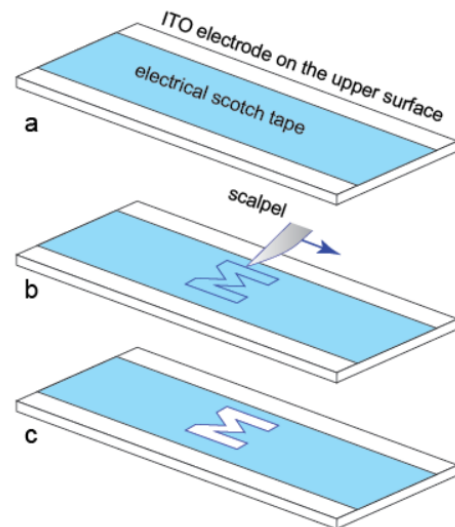


Fig.1: Preparation of glass slides for etching.

#### 1.2. Etching of the ITO electrodes

- Prepare about 100ml of a 10% solution of HCl in water (such weak solutions are commercially available).

- Prepare a few grams of a zinc (Zn) powder (swarfs) by filing or grating a sheet of zinc with a file or a grater.

- Put the glass slides partially covered with the adhesive tape at the bottom of a shallow glass beaker. The ITO coatings must be situated on upper sides of slides. Cover entirely glass slides with the HCl solution (see Fig.2).

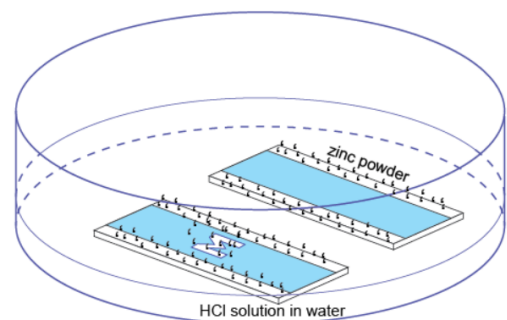


Fig.2.The etching process.

- Sprinkle the unprotected areas of the ITO coatings with the zinc powder (see Fig.2). Reaction of HCl with Zn delivers hydrogen *in statu nascendi*, visible as gas bubbles, which removes the ITO coating from unprotected areas. If necessary, add more zinc powder to areas poor in hydrogen bubbles.

- After 5 minutes of the etching process, remove glass slides from the beaker with tweezers and rinse with a tap water. Check with the ohmmeter the efficiency of the etching. If necessary, resume the etching process.

### 1.3. Coating of the ITO electrodes with PVA solution

- Prepare about 100ml of a 1% solution of poly-vinyl alcohol (PVA) in hot demineralized water.

- Remove the adhesive tapes and clean the glass slides with soap and hot water. If necessary, use ethanol to remove residues of the adhesive polymer. Rinse with demineralized water and dry with a clean air stream.

- Rinse glass slides with acetone (**work under a hood in a chemistry lab!**) and dry them again with clean air stream.

- Identify once more with the ohmmeter the glass sides coated with ITO electrodes! It is very disappointing to coat the wrong side of the slide.

- Using a plastic pipette, wet the ITO electrode of **one of the glass slides** with the PVA solution (see Fig.3a). Do not wet 5 mm wide stripes on extremities of the glass slide that must remain free of PVA, for electrical connections (see Fig.3).

- Place the wet glass slide almost vertically on a blotting paper, as shown in Fig.3b, in a dust-free environment. Let it dry (without blowing) for one hour. Faint yellowish or orange interference colors indicate the presence of the PVA coating. Usually, after the drying, the thickness of the PVA coating increases from the top to the bottom. This is not important. However, if dust particles, surrounded by well visible PVA mounds are present, clean the slide again (hot water, acetone) and repeat the PVA coating procedure.

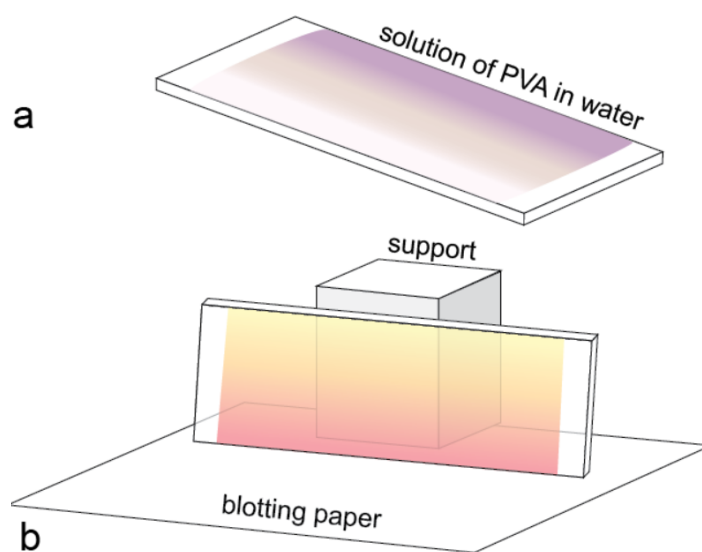


Fig.3. Coating of an ITO electrode with PVA. a) Slide partially wet with PVA solution. b) Vertical position of the slide during drying.

- Let dry the glass slide with the PVA coating for one hour, at 120°C, in an oven.

- Coat with PVA the second glass slide using the same method.

#### 1.4. Buffing of the PVA coating

- In this and next operations, wear latex gloves. Surfaces of the PVA coatings should stay clean!

- Using a double-sided adhesive tape, fix a 7cm x 9cm band of a velvet fabric on a polystyrene box ( $\approx 9\text{cm} \times 7\text{cm}$ ). (See Fig. 4 and 6).

- For a better contact of this velvet band with the PVA coating it is useful to make it "bumpy". For this purpose, insert a second, 3cm x 7cm band of the velvet fabric between the first band and the box surface (see the dotted rectangle in Fig. 4 and the band of the double-sided adhesive tape in Fig. 6).

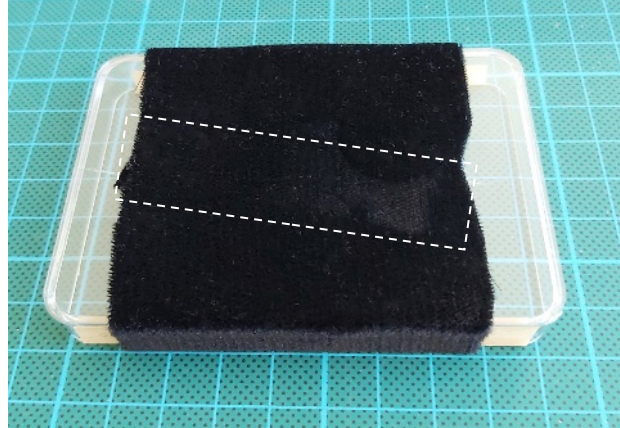


Fig.4.The buffing tool.

- On a large flat surface, surround one of the PVA coated glass slides by four other ordinary glass slides (of the same thickness 1.1 mm but without the expensive ITO coating) and fix this assembly with a adhesive tape (see Fig.5). The purpose of this operation is to prevent motions of the PVA coated glass slide during buffing.

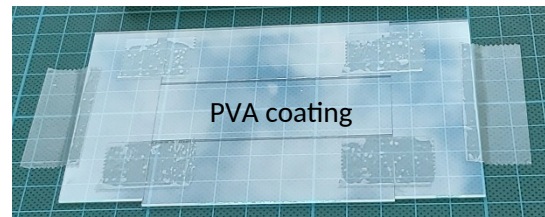


Fig.5. Assembly of glass slides used during the buffing process. It prevents motions of the PVA coated glass slide.

- During the buffing, the polystyrene box carrying the velvet fabric must be guided. For this purpose, using a double-sided adhesive tape, fix two long and rigid metallic or plastic pieces acting as guides (see Fig.6.)

- Place gently the buffing box with the velvet fabric on the PVA coated glass slide. Move the buffing box, back and forth, about twenty times on a distance of 4 cm (see Fig.6). Do not press too much the buffing box against the slide.

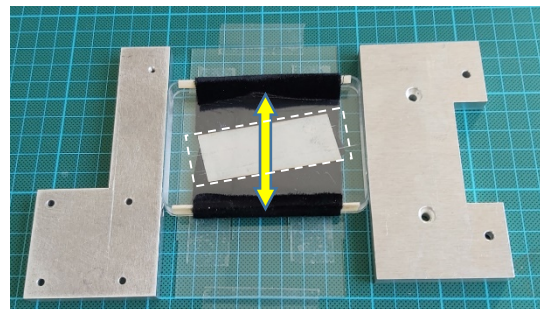


Fig.6. Buffing of the PVA coating. The buffing tool is guided by two metallic

- After the buffing, using tweezers, remove the glass slide from its "flat cage". Remove dust particles (if any) from the buffed glass slide with a stream of Nitrogen (or clean air).

- Repeat the same operations with the second glass slide.

### 1.5. Assembling an empty cell

- Cut two 3mm wide and about 25mm long stripes from a Mylar sheet (or from any other plastic flat sheet that does not dissolve in 5CB). They will be used as spacers. The thickness  $d$  of spacers should range between 40 and 110  $\mu\text{m}$  (or a little more).

- Identify for the last time, with the ohmmeter, sides of the glass slides coated with the ITO electrodes.

- Put the etched slide, with the ITO electrode oriented upward, on a flat surface (see Fig.7a).

- Put the two Mylar spacers on the slide as shown in Fig.7a.

- Put the second glass slide, with the ITO electrode oriented downward, on the Mylar spacers. If the Mylar spacers moved during this operation restore their positions using tweezers (see Fig.7b).

- Put a heavy object in the center of the cross-shaped assembly of slides. It should fit inside the 25mmx25mm square (Fig.7b).

- Prepare the epoxy glue (for example, Araldite) by mixing its two components. Using a matchstick or a plastic pipette spread the epoxy glue along the edges, parallel to the spacers, of the upper glass slide (see Fig.7c).

- Let the epoxy glue polymerize overnight.

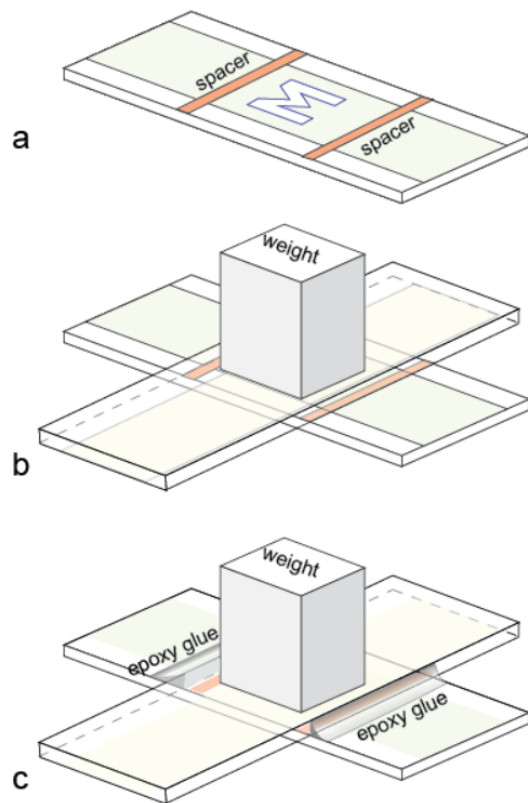


Fig.7. Assembling the cell.

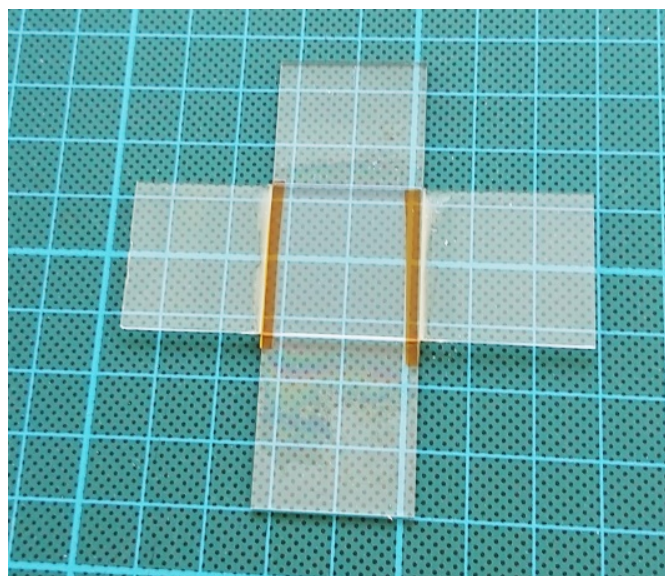


Fig.8. View of the assembled cell, filled with 5CB, ready for experiments.

### 1.6. Filling the assembled cell with 5CB

- Put the assembled cell on a flat surface in such a manner that the free edges of the gap between the glass slides are accessible. Using a micropipette, fill the cell, drop after drop (see Fig.8), with 4-Cyano-4'-pentylbiphenyl (5CB).

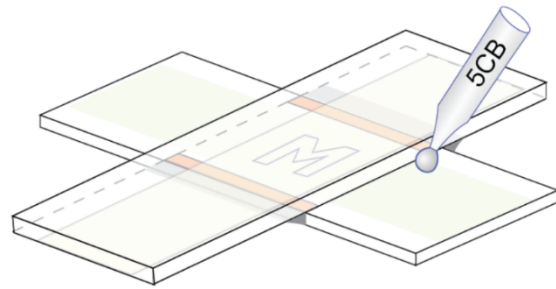


Fig.9. Filling the cell with 5CB.

- It is interesting to observe progression of 5CB inside the gap with the USB camera equipped with an adequate lens as shown in Fig.13. Work in transmitted light mode.

- During and after the filling, a tangle of black lines is present in the cell. Note that the name “nematics”, coined by George Friedel in 1922, stems from the Greek word “νημα” = “thread”. These are disclinations discussed shortly in the article (see also Fig.19 in section IV below).

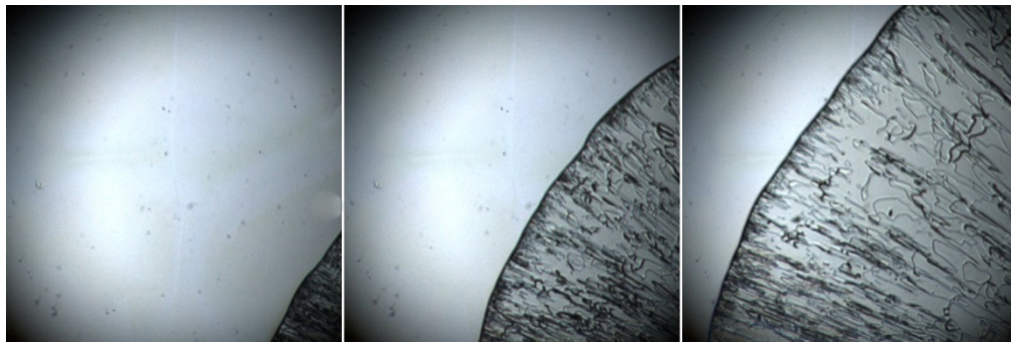


Fig.10. Presence of disclinations – black lines – during the filling of the cell with 5CB.

Observe evolution of these lines in time. They form slowly shrinking loops that collapse, one after another. After about one hour, the cell is free of disclinations and can be used for the detection of the Fréedericksz transition.

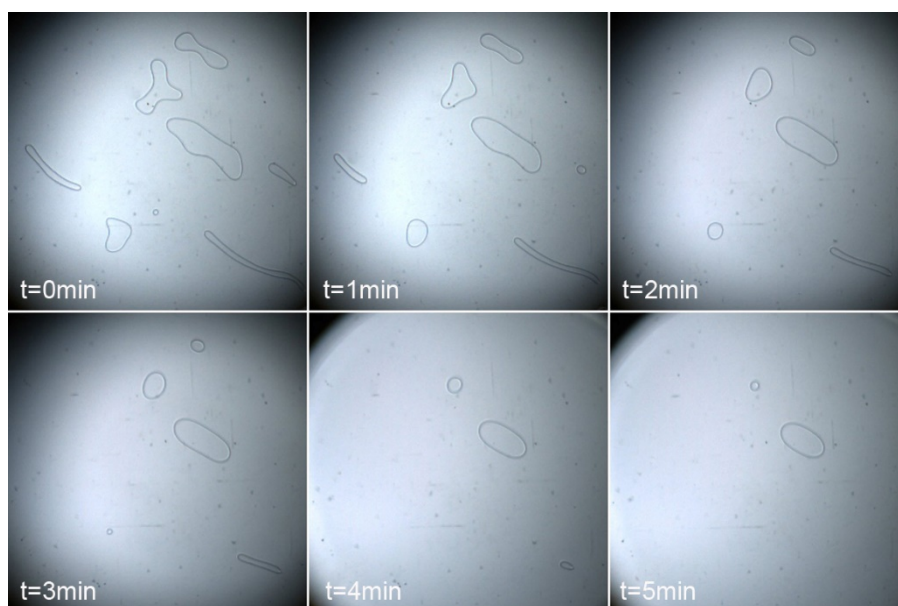


Fig.11. Collapse of disclinations loops.

## II. Setup

### II.1. General view

Figures 12 and 13 below show general views of the setup.

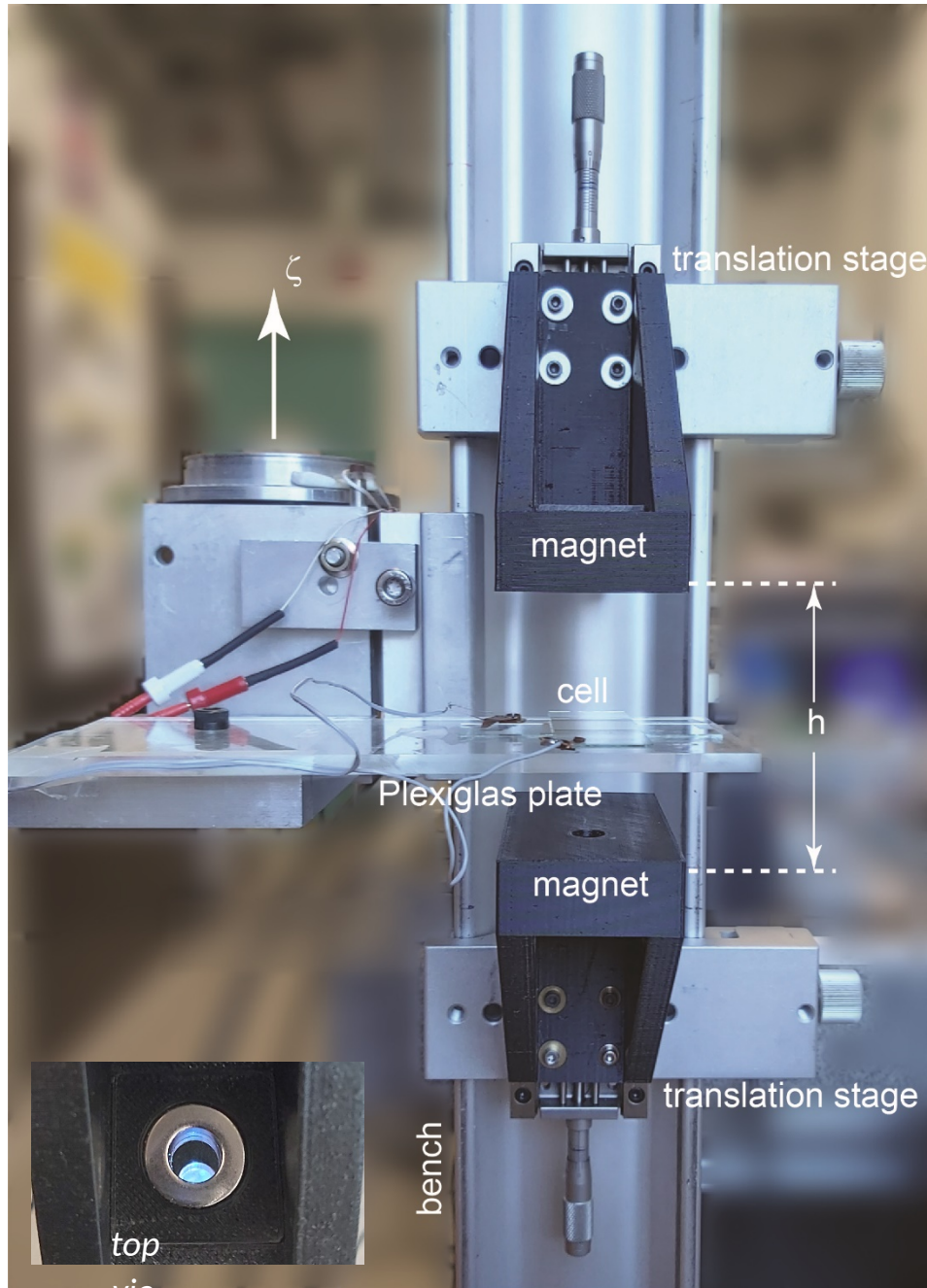


Fig.12. View of the vertical optical bench with two the microtranslation stages carrying supports of the two stacks of annular magnets. The nematic cell is fixed on the horizontal Plexiglas plate that can rotate around the  $\zeta$  axis parallel to the bench. The insert shows a detailed top view of the upper stack of three cylindrical magnets lodged in its support made with a 3D printer.



II.3  
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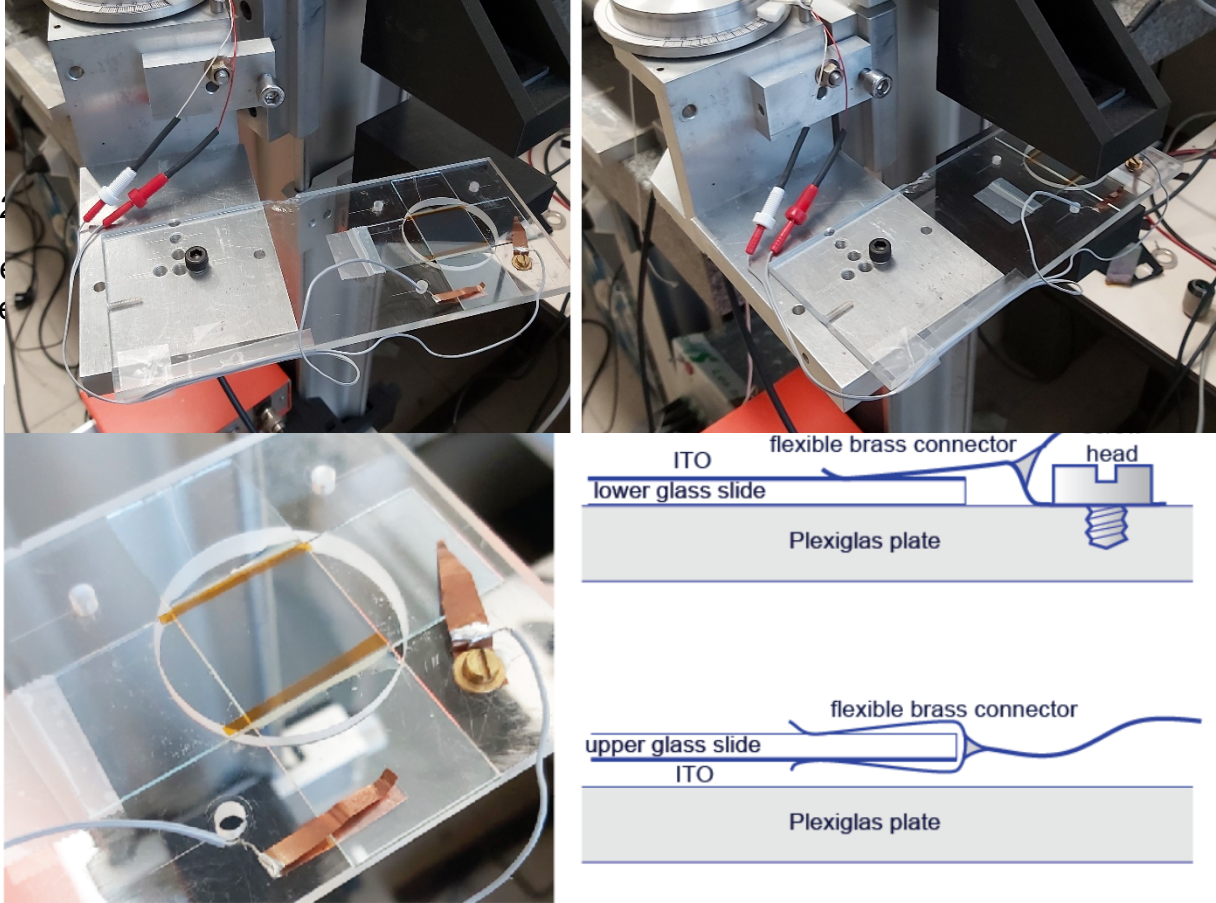


Fig.14. Electrical connections with the ITO electrodes. They are made by means of flexibles brass connectors.

### II.3. Optical system

In Fig.15 we show the whole setup with the optical system tailored for observations of the Fréedericksz transition.

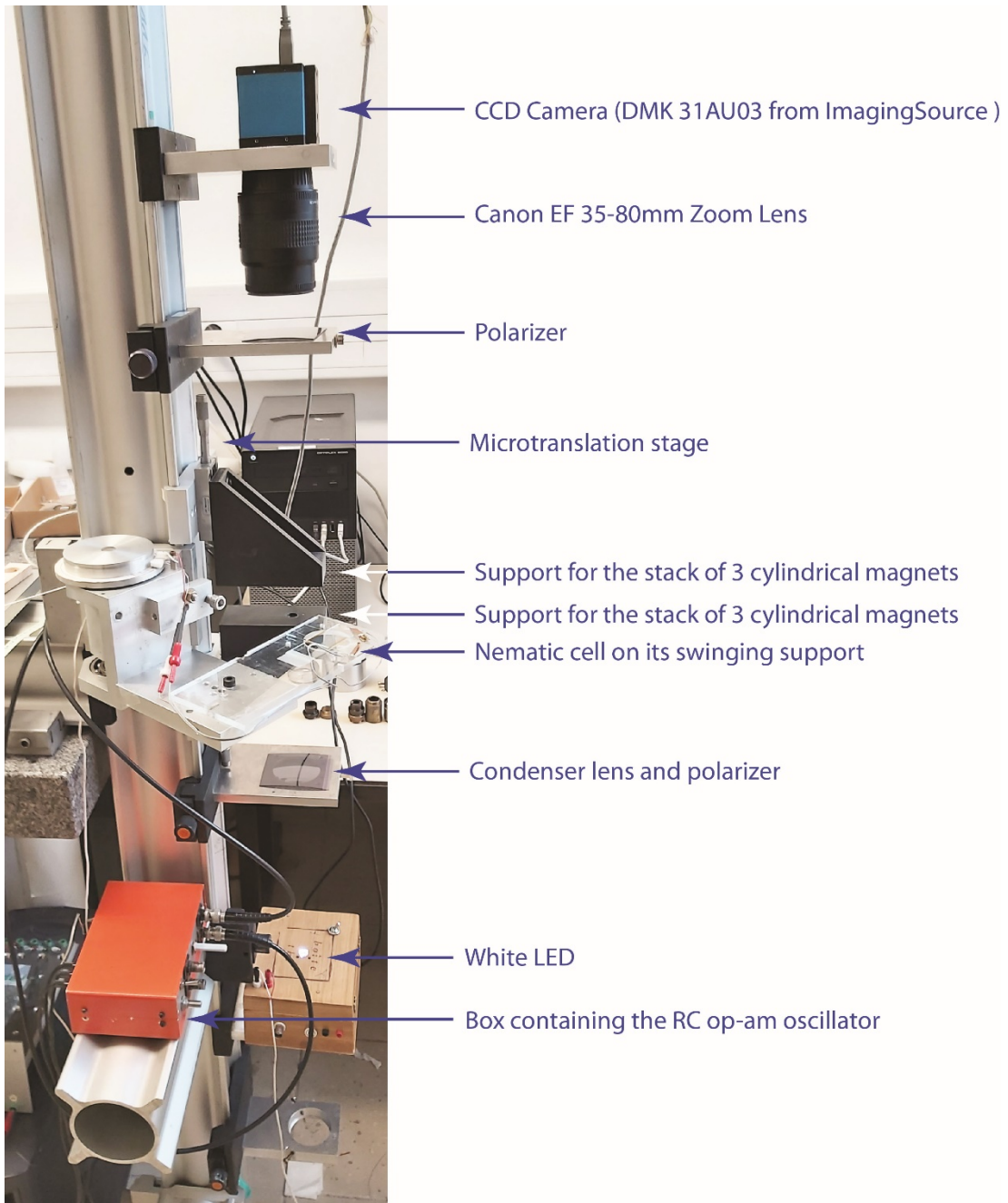


Fig.15. View of the whole setup. The optical system is tailored for observations of the Fréedericksz transition by means of a CCD camera coupled to a popular Canon zoom lens EF35-80. For a better readability of this picture, the nematic cell is in its out-of-field position.



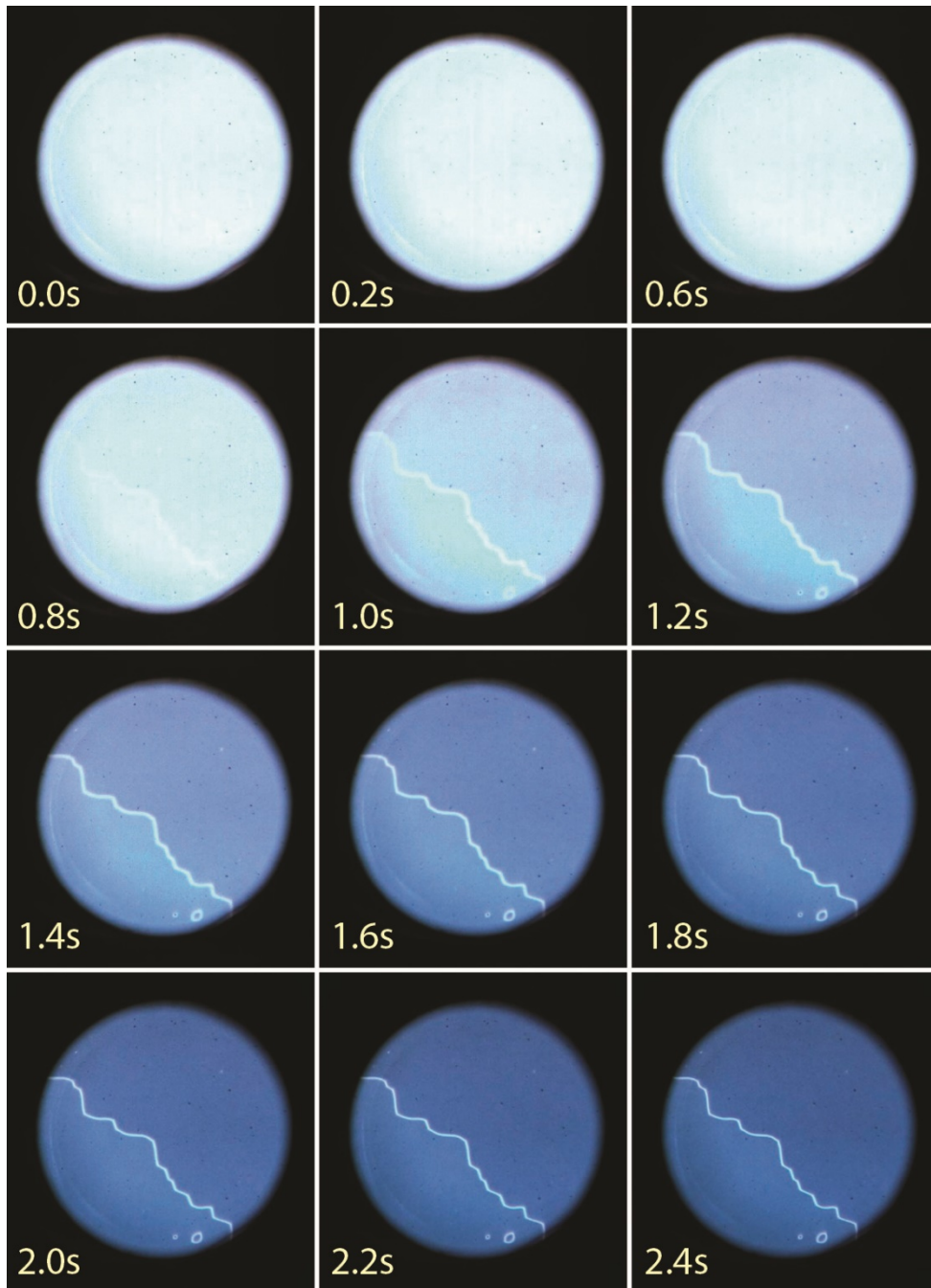


Fig.16. Pictures of the electric field-induced Fréedericksz transition taken with the optical system represented in Fig.13. The oblique white line is a wall separating areas with positive and negative tilt angles defined in Fig.10c of the article. Pictures were taken with slightly decrossed polarizers.

### II.3. Calibration of the op-amp oscillator, measure of the dielectric permittivity

For  $R=100\text{k}\Omega$  and a fixed ratio  $R_2/(R_1+R_2)$  (see Eq.1 of the paper), the period  $T$  of oscillations of the RC op-amp oscillator depends on the capacitance  $C$  ( $C_1$ ,  $C_1+C_2$ ,  $C_1+C_c$  or  $C_1+C_c+C_s$ ). With the samples' cable disconnected, the minimal value of  $C$  is  $C_1=470\text{pF}$ .

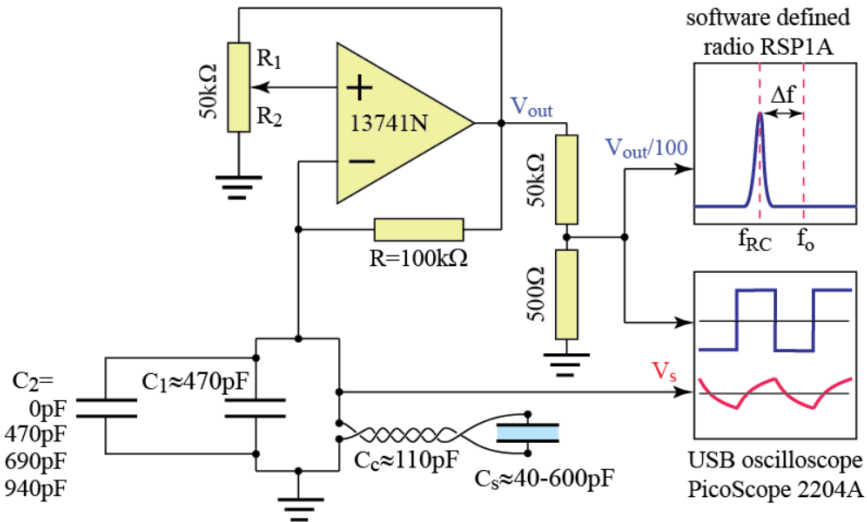


Fig.17. Detailed scheme of the RC op-amp oscillator.

Calibration of the RC oscillator was made by connecting successively, in parallel to  $C_1$ , additional capacitors of capacitance  $C_2 = 470, 690$  and  $940\text{pF}$ . The period  $T=1/f$  of the signal  $V_s$ , measured with the USB oscilloscope PicoScope 2204A, is plotted with plain circles in Fig.18 and fitted to a linear law.

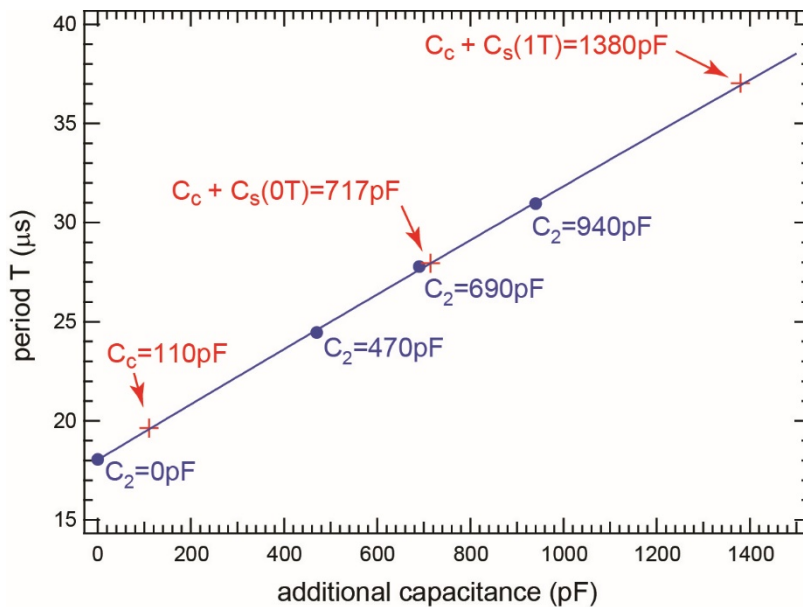


Fig.18. Calibration of the RC oscillator and determination of the capacitance of the nematic cell (19mm x 25mm x 0.05mm).

After the calibration, the sample cable was connected in parallel to  $C_1$  and the period  $T$  was measured again. The capacitance of the cable, read from the linear fit, is  $C_c = 110\text{pF}$ .

Finally, the cell (19mm x 25mm x 0.04mm) filled with the nematic 5CB was connected to the cable. In the absence of the magnetic field, the capacitance of the cell, read from linear fit, is  $C_{s0} = 607\text{pF}$ .

For  $B=0$ , the expected capacitance of the nematic cell is given by

$$C_{s0} = \epsilon_o \epsilon_{\perp} \frac{A}{d}$$

With  $\epsilon_o = 8.85\text{pF/m}$ ,  $\epsilon_{\perp} \approx 6$ ,<sup>1</sup>  $A = 19\text{mm} \times 25\text{mm}$  and  $d = 0.04\text{mm}$  one obtains  $C_{s0} = 630\text{pF}$ . This expected value is larger than the measured one because the real thickness  $h$  of the nematic cell is likely larger than the thickness of spacers.

Next, the cell was submitted to the field, orthogonal to the cell, of a large cuboid neodymium magnet (30mm x 30mm x 15mm) producing the field of the order of 1T. Fig.18 shows that as a result, the capacitance of the sample increases from 607pF to 1270pF.

In the limit  $B \rightarrow \infty$ , the expected capacitance of the cell is given by

$$C_{s\infty} = \epsilon_o \epsilon_{\parallel} \frac{A}{d}$$

or, using  $\epsilon_{\parallel} \approx 17.5$ ,  $C_{s\infty} = 1840\text{pF}$ . As this value is significantly larger than 1270pF, measured with the field of the cuboid magnet, one can conclude that reorientation of the director by the magnetic field is not complete. This result is not surprising because the planar anchoring on the PVA coatings hinders the reorientation of the director there.

To measure precisely the permittivity  $\epsilon_{\parallel}$ , one should built a cell using slides with the homeotropic anchoring, *i.e.* orthogonal to the ITO electrodes.

#### *II.4. Construction of a cell with homeotropic anchoring.*

A simple method for production of the homeotropic anchoring consists of coating the ITO electrodes with the egg lecithin. This can be done by hand using a fine powder of the yolk from a cooked egg, sprinkled on a soft disposable tissue.

The coating process:

- 1° - Slides are first cleaned with soap and hot water and dried with a clean air stream.
- 2° - The ITO electrodes are then gently "polished" (by circular motions) with the disposable soft tissue carrying the fine yolk powder. After this operation, the slides have a "dirty look".
- 3° - Using fresh disposable tissues, clean gently the ITO electrodes several times.

Using slides treated in this manner, build a cell following the method described above in section I.5 and fill it with 5CB as explained in section I.6.

<sup>1</sup> For dielectric permittivities of 5CB see, for example, *Abe et al.*, J. Korean Physical Society, **46**, 220-223 (2005)

### III. Calculation of the magnetic field

#### III.1. Dipolar approximation

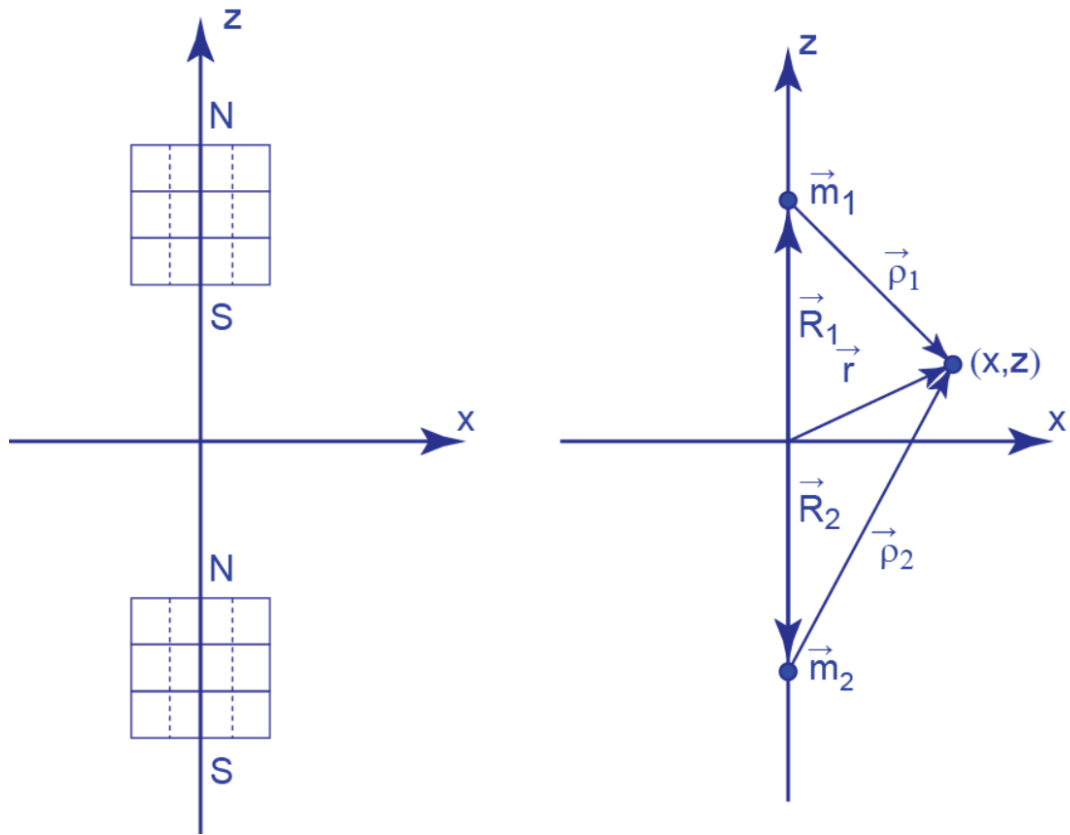


Fig.19. Dipolar approximation: the two annular magnets are represented by identical magnetic dipoles  $\mathbf{m}_1$  and  $\mathbf{m}_2$  located at  $\mathbf{R}_1=(0,1)$  and  $\mathbf{R}_2=(0,-1)$ .

In the local reference frame  $(\xi, \zeta)$  of a dipole  $\mathbf{m}$ , the magnetic field  $\mathbf{B}$  generated by it in the point  $\rho(\xi, \zeta)$  is given by

$$\vec{B} = \frac{\mu_0}{4\pi} \left[ \frac{3\vec{\rho}(\vec{m} \cdot \vec{\rho})}{\rho^5} - \frac{\vec{m}}{\rho^3} \right] \quad (1)$$

In the laboratory reference frame, the dipoles  $\mathbf{m}_1$  and  $\mathbf{m}_2$  are located in points  $\mathbf{R}_1$  and  $\mathbf{R}_2$ , respectively. Using Eq.1 and

$$\vec{\rho}_1 = \vec{r} - \vec{R}_1 \quad \text{and} \quad \vec{\rho}_2 = \vec{r} - \vec{R}_2 \quad (2)$$

one obtains

$$\vec{B}(\vec{r}) = \frac{\mu_0}{4\pi} \left[ \frac{3\vec{\rho}_1(\vec{m} \cdot \vec{\rho}_1)}{\rho_1^5} - \frac{\vec{m}}{\rho_1^3} \right] + \frac{\mu_0}{4\pi} \left[ \frac{3\vec{\rho}_2(\vec{m} \cdot \vec{\rho}_2)}{\rho_2^5} - \frac{\vec{m}}{\rho_2^3} \right] \quad (3)$$

### III.1. Numerical calculation of the magnetic field in dipolar approximation

As our aim was not to calculate the absolute intensity of the magnetic field, we used dimensionless variables  $\mathbf{m}=(0,1)$ ,  $\mathbf{R}_1=(0,1)$  and  $\mathbf{R}_2=(0,1)$ .

A very simple Mathematica program allows to represent graphically the magnetic field generated in the plane  $(x,z)$  by the pair of magnetic dipoles defined in Fig.19.

(4)

```
StreamPlot[{{(3*x*(z-1))/(x^2+(z-1)^2)^(5/2)+(3*x*(z+1))/(x^2+(z+1)^2)^(5/2),
(3*(z-1)*(z-1))/(x^2+(z-1)^2)^(5/2)-1/(x^2+(z-1)^2)^(3/2)+
(3*(z+1)*(z+1))/(x^2+(z+1)^2)^(5/2)-1/(x^2+(z+1)^2)^(3/2)},
{x,-2,2},{z,-2,2}}
```

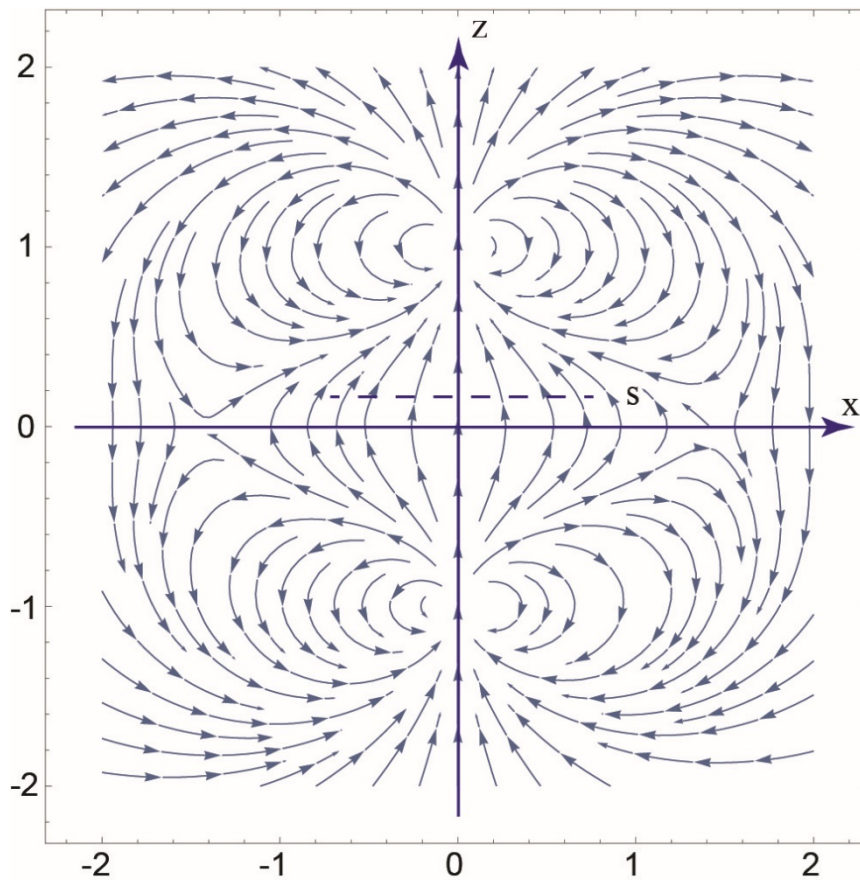


Fig.20. Magnetic field, generated by two magnetic dipoles, calculated using the Mathematica program (4).

## IV. Director field around a disclination

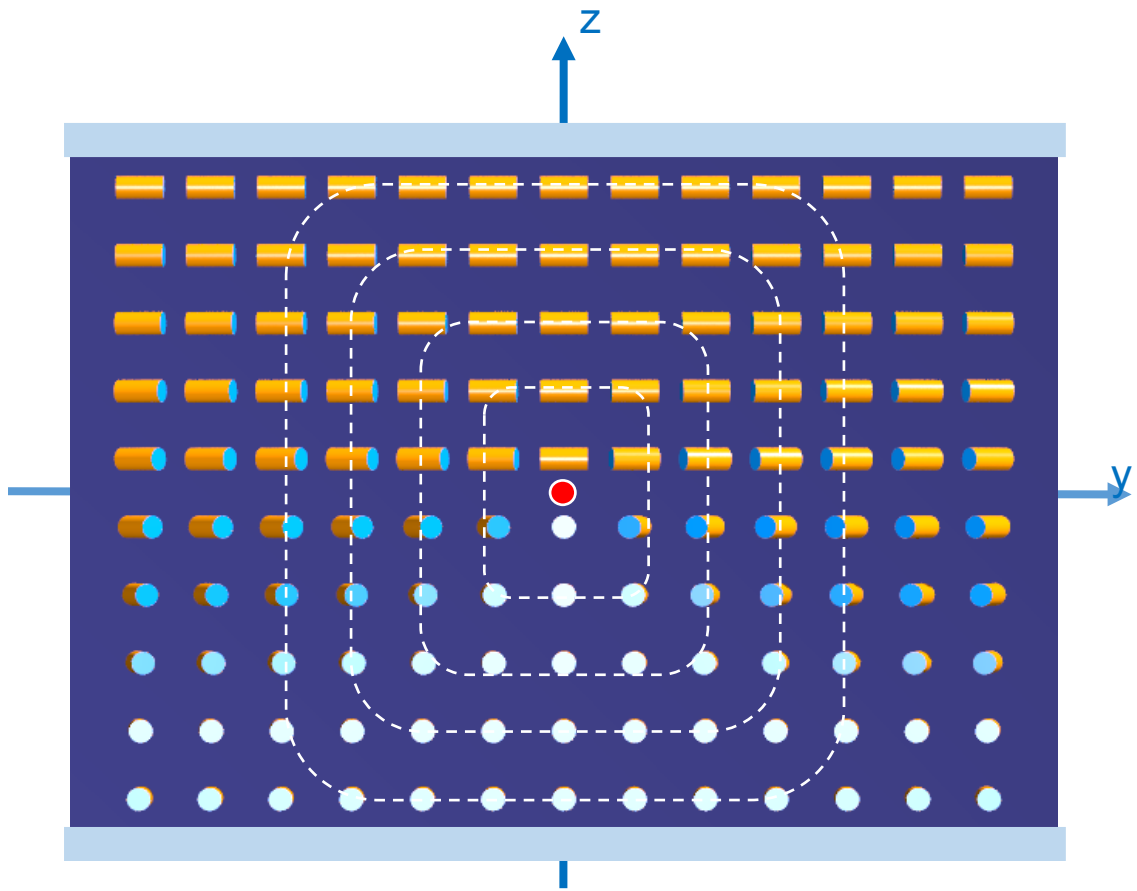


Fig.21. View of the director field surrounding a disclination. The red point in the center corresponds to the intersection of the disclination line with the  $(y,z)$  plane. On any circuit surrounding the disclination, the director represented by cylinders, rotates by  $\pi$ . Therefore, the disclination is a singularity in the mathematical sense: orientation of the director is undetermined on it.

## V. Summary of parts to buy

1° - Software-defined radio RSP1A from SDRplay.....	= 94 €
2°- 10 ITO coated glass slides from Sigma-Aldrich, ref. 576352-10PAK.....	= 185 €
3°- 1g of 5CB from Sigma-Aldrich, ref. 328510-1G .....	= 176 €
4°- 6 annular magnets 19/9,5mm from Supermagnete, ref. R-19-09-06-N.....	= 11 €
5°- USB oscilloscope from Pico Technology, ref. PicoScope 2204A-D2.....	=143 €
6°- Op-amp 13741N from Texas Instruments.....	= 1 €

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Total.....= 610 €