Short translation

Patent name:

Apparatus for measurements of magneto-optical properties, non-reciprocal optical properties and non-linear optical properties and operational principle.

Abstract:

The apparatus, which measures the difference of optical properties between two opposite directions of light propagation through a studied object, is disclosed. Using the disclosed method, the magneto-optical properties, non-reciprocal optical properties and non-linear optical properties of the studied object can be measured with a high sensitivity and a high precision.

Prior-art

Measurements of the magneto-optical and non-linear properties of an object with a high precision and high-sensitivity is important for a variety of the application including biology and spintronics. At present, the magneto-optical instruments for measurements of Faraday rotation angle, Kerr rotation angle and magnetic circular dichroism are conventional measurement equipment in biology, spintronics and other fields.

Measurements of the non-reciprocal properties of the studied object may disclose an important information about the object, because the non-reciprocal response exists only when the time-inverse symmetry is broken in the studied object. An instrument for measurements of non-reciprocal properties has not been developed yet, but if it would be available, it could be used in different fields. When the refractive index and absorption coefficient are different for two opposite directions of light propagation, the optical properties of the object are called to be non-reciprocal. The break of the time-inverse symmetry is a key for an object in order to have a non-reciprocal response.

The Faraday rotation, Kerr rotation and the magnetic circular dichroism (MCD) are magneto-optical properties, which are measured to characterized the magneto-optical properties of an object.

Figure 1 shows the conventional setup for measurements of Faraday rotation. Light is passing from the light source to the detector through the sample, which is placed between crossed polarizer and analyzer. When polarization of light is not rotated by the sample, light is blocked by the analyzer and it can reach the detector. When the polarization is rotated, a small amount of light can pass the analyzer and it can be detected. The demerit of this setup is a bad sensitivity, because of the following reason.

Figure 2 shows the transmission of light through a polarizer and an analyzer as function of angle between them. The angle of 90 degrees corresponds to the crossed polarizer and analyzer. For this angle the 1st derivation of the transmission with respect to the angle equals zero.   This means that the change transmission as function of a rotational angle is small and it is proportional to square of rotation angle and the second derivation. This is reason of a bad sensitivity of the conventional setup for the Faraday rotation measurements. The sensitivity of the conventional setup usually does not exceed 1 mdeg and often it is larger than 10-50 mdeg.

Figures 3 shows the conventional setup for measurements of magnetic circular dichroism (MCD). The photo-elastic modulator (PEM) makes the polarization of light modulated between left- and right- circular polarizations. The   difference in absorption between left- and right- circularly polarized light is detected by the detector using the lock-in technique. Because of the use of a lock-in technique, this setup for MCD measurements has a high sensitivity. However, there is a high MCD signal only in the case when wavelength of light is close to material absorption edge. A transparent material has no any MCD response. This limits the amount of information about the sample, which could be obtained by the MCD measurements.

Figures 4 shows the conventional setup for measurements of Kerr rotation angle. Polarized light is reflected from the sample and it is detected by the detector. In the front of the detector there is a polarizer P2, which axis is 90 degrees with respect to the axis of the polarizer P1. In the case when there is no polarization rotation, light is blocked by polarizer P2 and it can not reach the detector. When after the reflection the polarization is rotated, some light can reach the detector. Since the magnitude of the detected light is proportional to the rotation angle (the Kerr rotation angle), the rotation angle can be evaluated.

Similar to the setup of Fig.1, the demerit of this setup is a low sensitivity. The reason of the low sensitivity is the same. It is zero derivation of transmission when polarizers are crossed (See Fig. 2).

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disclosed invention

In the disclosed measurement method the optical properties of a sample is measured for two opposite directions of light propagation. Since the direction of light is changed by a 2x2 optical switch without any change or distortion of the optical alignment, a tiny difference of optical properties for opposite propagation directions can be measured with a high precision.

Figure 5 shows the disclosed setup for measurements of the non-reciprocal loss as it is disclosed in the present invention. Figures 5(a) and 5(b) show two switch states of the 2x2 fiber switcher. Both the light source and the light detector are connected to one side of the switcher. Other side of the switcher is connected to two opposite sides of the sample. The fiber collimators are used for light coupling between fibers and free space. The two switching states are absolutely identical except propagation directions of light in the sample are opposite. In the case of Fig. 5(a) the propagation direction is from up to down. In the case of Fig. 5(b) it is from down to up. The difference of the detected light for two switching states corresponds to the non-reciprocal absorption in the sample.

Figure 6 shows the disclosed setup for measurements of the non-reciprocal loss using the lock-in technique. The pulse generator generates a sequence of electrical pulses, which switch the 2x2 switcher between its two states. Also, the pulses are used as the reference signal for the lock-in amplifier. The detected signal is modulated at the same frequency as the switcher is switched.. The amplitude of the modulation is proportional to the value of the non-reciprocal loss of the sample. The lock-in amplifier is able to measure this modulation with a high precision and a high sensitivity.

Fig.7 the disclosed setup for measurements of the Faraday rotation. It is similar to the setup shown in Fig.6 except two polarizers are inserted at each input of the sample. The angle between axes of the polarizers is 45 degrees. Since the Faraday effect is a non-reciprocal effect, the polarization rotates in opposite directions for opposite propagation directions of light. For example, if in case of the propagation in the up-direction the Faraday rotation is positive, the polarization of light at the polarizer will be larger than 45 degrees and the detection signal will be smaller (See Fig.2). In the case of the propagation in the down-direction the polarization of light at the polarizer will be smaller than 45 degrees and the detection signal will be larger. Measuring the difference of detected light between two opposite propagation direction by the lock-in technique, the Faraday rotation angle can be evaluated with a high precision and a high sensitivity. The angle of 45 degrees between polarizers corresponds to the highest sensitivity for measurement of the Faraday rotation angle, because the derivation of the transmission between polarizers (See Fig.2) with respect to the angle between polarizers is the largest in this case.

Figure 8 shows the disclosed setup for measurements of the MCD. It is similar as the setup shown in Fig.7 except two quarter-wave plates are inserted between polarizers and the sample. The axes of the polarizers are in the same direction. The angle between the axes of the quarter-wave plates is 90 degrees. The angle between axes of the polarizers and the quarter-wave plates are 45 (-45) degrees. In one propagation direction the polarization of light is left-circularly polarized and the opposite direction it is right-circularly polarized. The measured difference of the detected light is proportional to the difference to absorption between left- and right-circularly polarized light or the MCD signal.

The MCD signal for the opposite propagation direction can be measured using the same setup. It can be done by 90-degree rotating of the polarizers. The 90-degree rotation of the polarizers corresponds to the flipping of the propagation direction for the left circularly polarized light from up-direction to down-direction and for the right circularly polarized light from down-direction to up-direction. By averaging the MCD signals, which are measured in the opposite direction of light propagation, any parasitic signal in measured MCD can be excluded. This is merit of this setup comparing to the conventional setup of Fig.3.

It should be noticed that using 90-degree angle between polarizers and same axis angle of the quarter-wave plates the identical measurements can be done.

Figure 9 shows the another disclosed setup for measurements of the MCD. A polarized light source, polarization-maintaining fibers and fiber switch are used in this case. The quarter-wave plates QW1 and QW2 are inserted between collimators and sample. When the angle between the polarization axes of both input/output fibers and the axes of the quarter-wave plates equals +45 degrees, the absorption of left-circularly polarized light can be measured with a high precision. When the angle equals to -45 degrees, the absorption of right-circularly polarized light can be measured with a high precision. When the angle is +45 degrees at one side of the sample and -45 degrees at another side, the difference of the absorption between the left and right circularly polarized light can be measured.

The merit of this setup comparing with the setups shown in Figs. 3 and 7 is that it can measure individual absorption of left- and right- circularly polarized light with a high precision additionally to the difference in absorption between the left and right circularly polarized light, which only can be measured by setups of Figs. 3 and 7.

Figure 10 shows the disclosed setup for measurements of non-linear absorption. Figures 10 (a) and (b) show two switch states of the switcher. The attenuator is inserted between the sample and the fiber switcher. For one switching state of the switcher, light is passing the absorber at first and next the sample (Fig.10 (a)). For another switching state of the switcher, it is opposite. Light is passing through the sample at first and next through the absorber (Fig.10 (b)). Therefore, light of different intensity is passing through the sample for the different switching states. In contrast, at detector the intensity of light is nearly-same for both switching states. It is because for both switching states, light is passing through all the same elements on the path from the source to the detector. In the case when the absorption of the sample does not depend on the light intensity, the intensity of light at the detector is exactly the same for both switching states. In the case when the absorption of the sample is dependent on the light intensity, there is a tiny difference in intensity of light at the detector. This difference can be measured with a high precision using the lock-in technique and the non-linear absorption of the sample can be evaluated. In the case when an tunable attenuator is used, the dependence of the non-linear absorption on light intensity can be measured.

Figure 11 shows the disclosed setup for measurements of the Kerr rotation angle. It is similar to the conventional setup shown in Fig.4, but a 2x2 fiber switch used between the sample and the detector/source. Because of the usage of the lock-in technique for the Kerr rotation measurements, the sensitivity and measurement precision of this setup can be significantly enhanced comparing to the conventional setup of Fig.4.

The polarizers and quarter-wave plates are inserted after the fiber collimators. They makes input light circularly-polarized. For one input the incident light is left-circularly polarized. For another input the incident light is right-circularly polarized. Therefore, the switcher switches incident light between left and right circular polarizations. In the case of non-zero Kerr rotation, after the reflection there is a conversion between the left and right circular polarization, which can be detected using the lock-in technique and the Kerr rotation angle can be evaluated with a high precision.

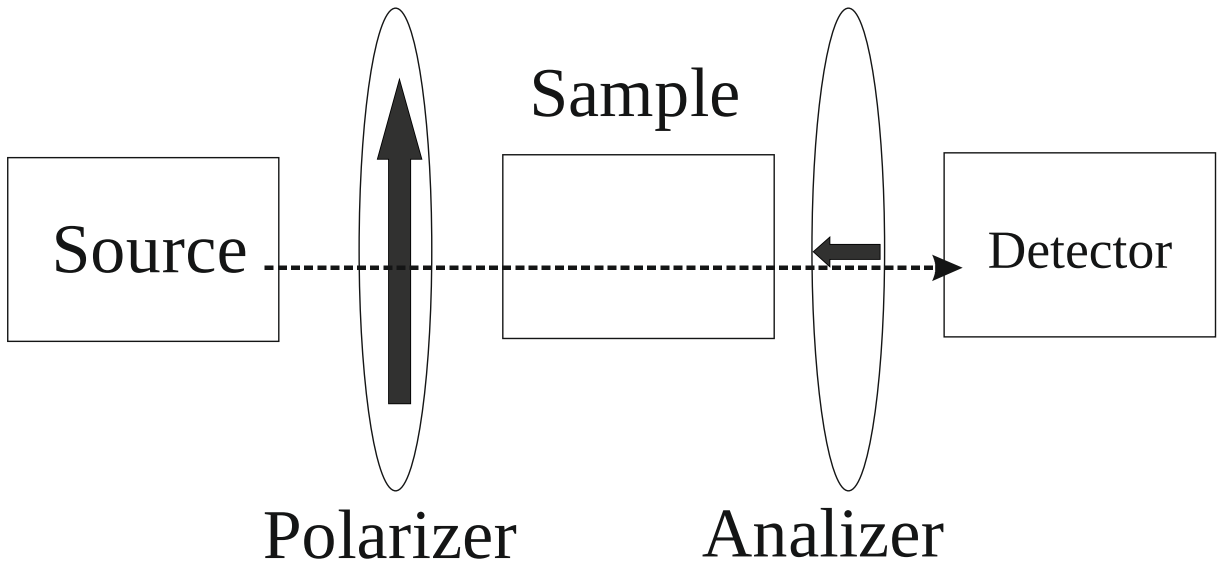

Fig.1 Prior Art. Conventional setup for measurements of Faraday rotation. The sample is placed between crossed polarizer and analyzer, which block the light propagation from the source to detector. When the polarization is rotated by the sample, light can reach the detector and the rotation angle can be evaluated.

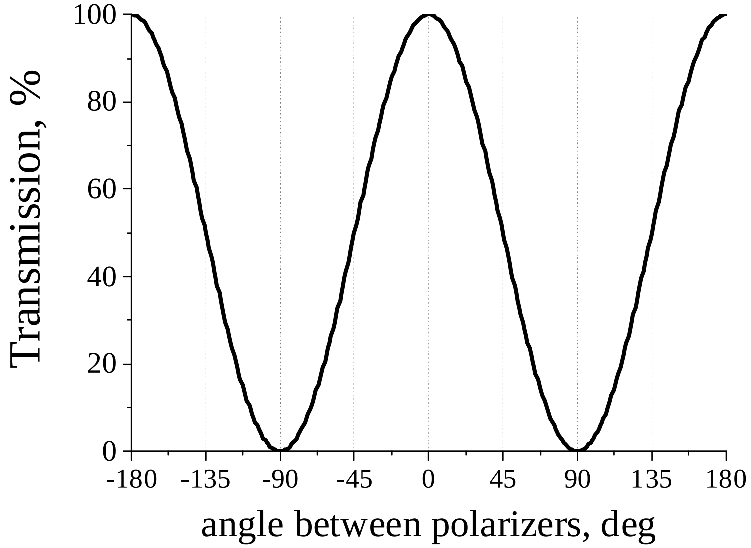

Fig.2 Prior Art. The transmission of light as function of angle between polarizer and analyzer. The angle of 90 degrees corresponds to the crossed polarizer and analyzer. For this angle the 1st derivation of the transmission with respect to the angle equals zero. This is reason of a bad sensitivity of conventional setup for the Faraday rotation measurements. In the disclosed invention the angle between polarizer and analyzer is 45 degrees, where the derivation and the sensitivity are the largest.

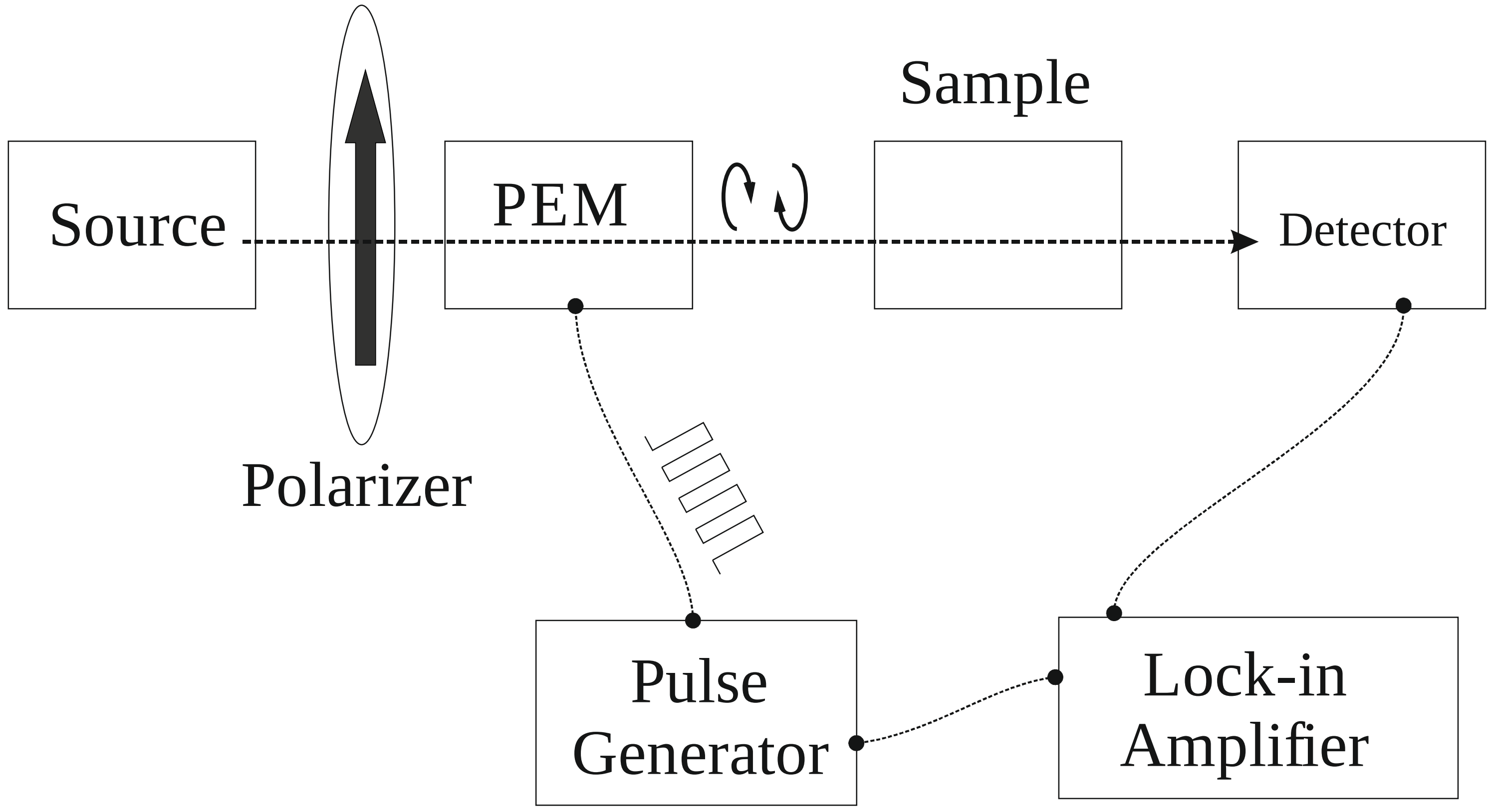

Fig.3 Prior Art. Conventional setup for measurements of magnetic circular dichroism (MCD). After the photo-elastic modulator (PEM) the polarization of light becomes modulated between left- and right- circular polarizations. The difference in absorption between left- and right- circularly polarized light is detected by the detector using the lock-in technique.

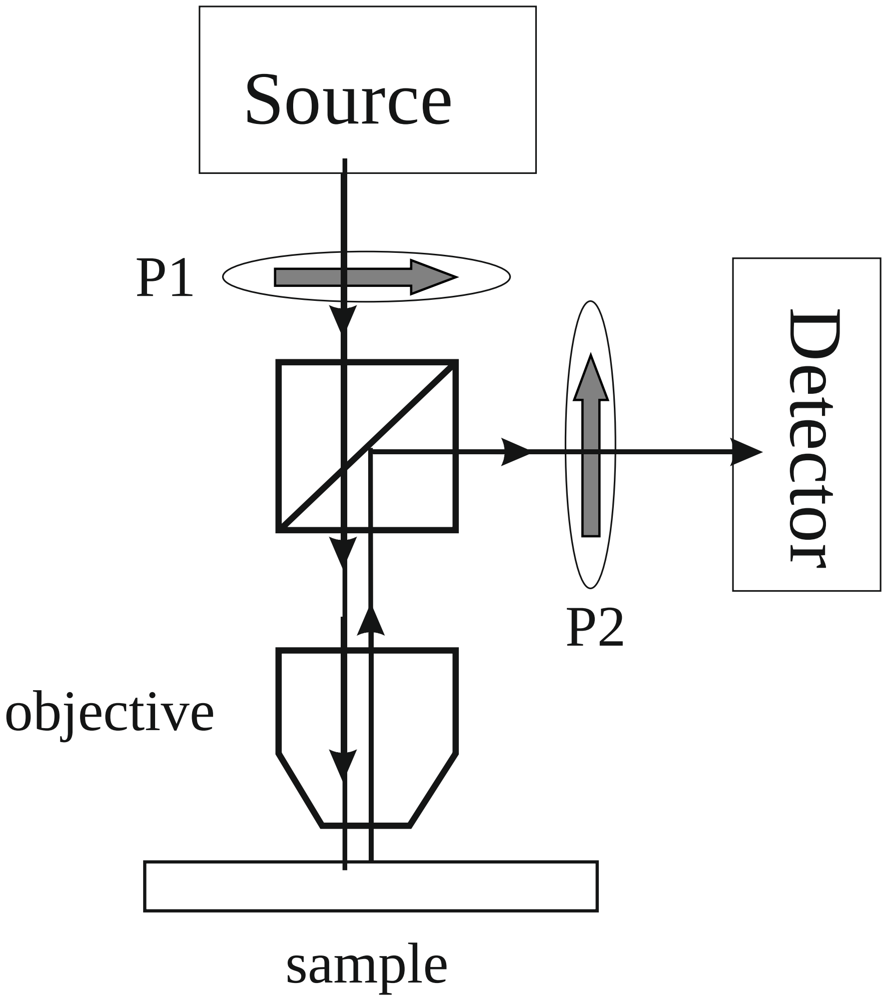

Fig.4 Prior Art. Conventional setup for measurements of Kerr rotation angle. Polarized light from the source is reflected from the sample and it is detected by the detector. The angle between axes of polarizer (P1) and analyzer (P2) is 90 degrees and light is blocked. Only when the polarization is rotated after the reflection, light reaches the detector and the rotation angle can be evaluated.

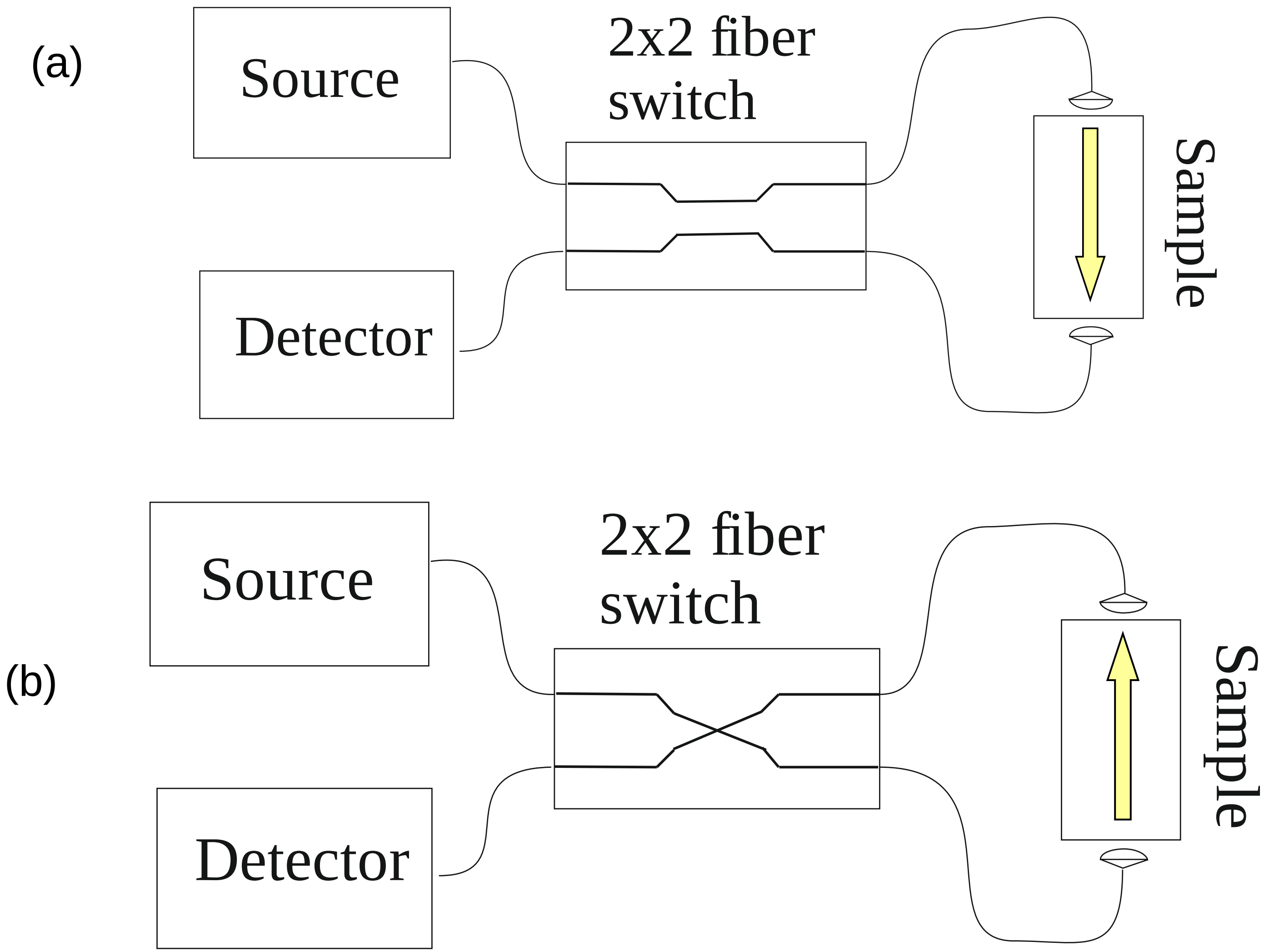

Fig.5 the setup for measurements of the non-reciprocal loss. Fig. 5 (a) and (b) show two switch states of the switcher. The yellow arrows indicate the directions of light propagation.

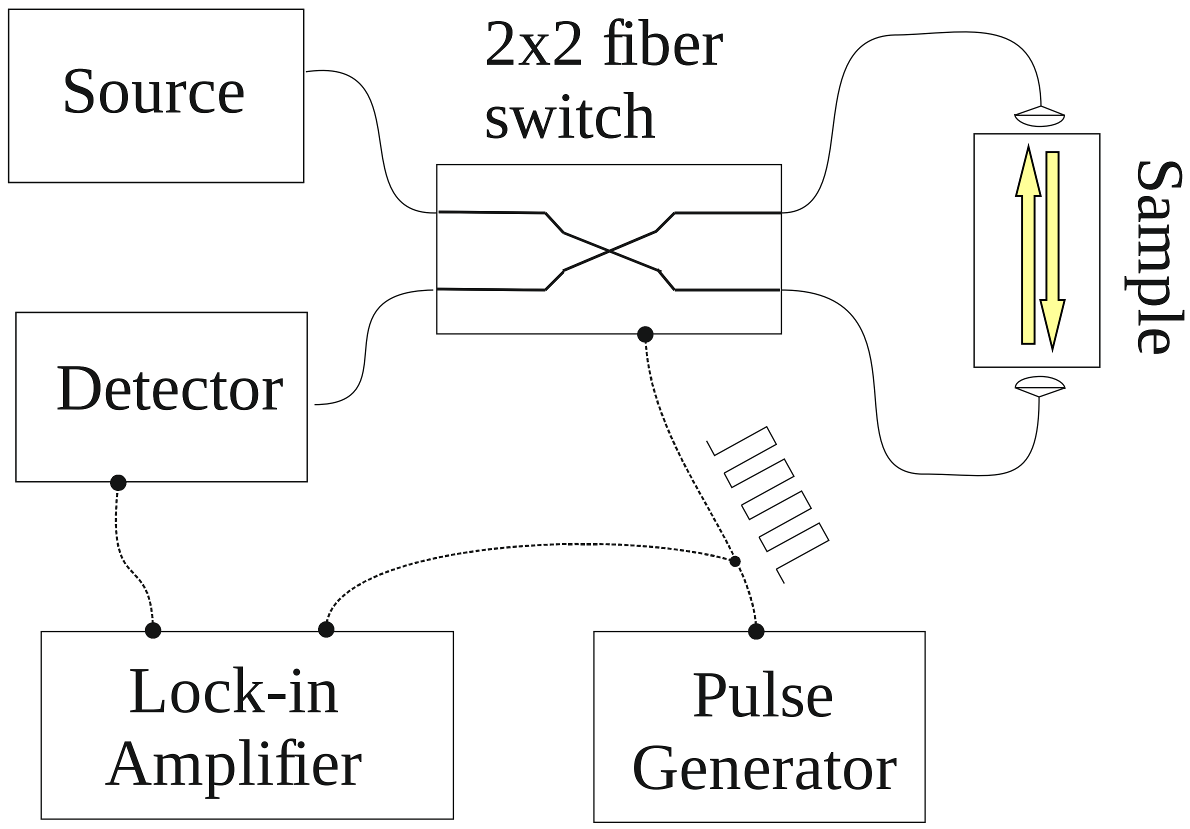

Fig.6 the setup for measurements of the non-reciprocal loss using lock-in technique

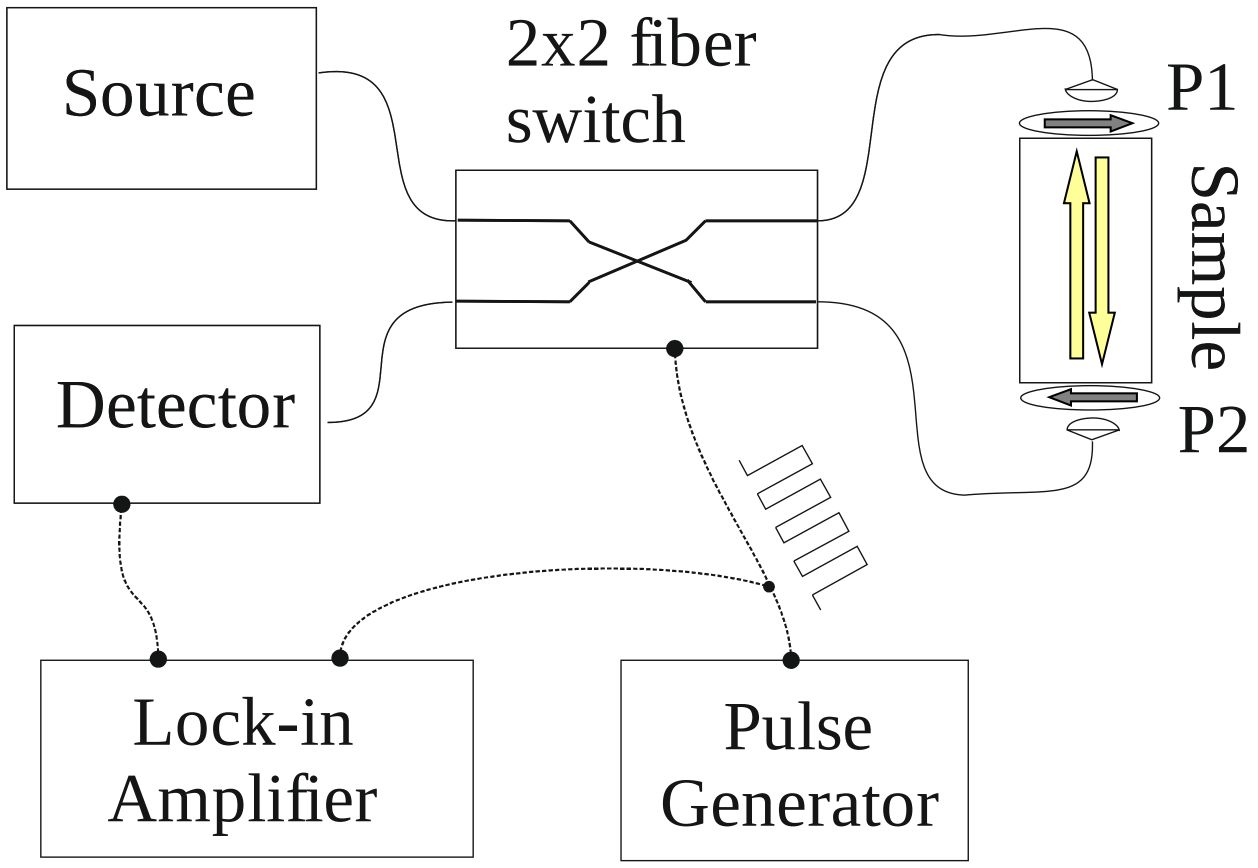

Fig.7 the setup for measurements of the Faraday rotation. The polarizers P1 and P2 are inserted between the fiber collimators and sample. The angle between axes of the polarizers is 45 degrees.

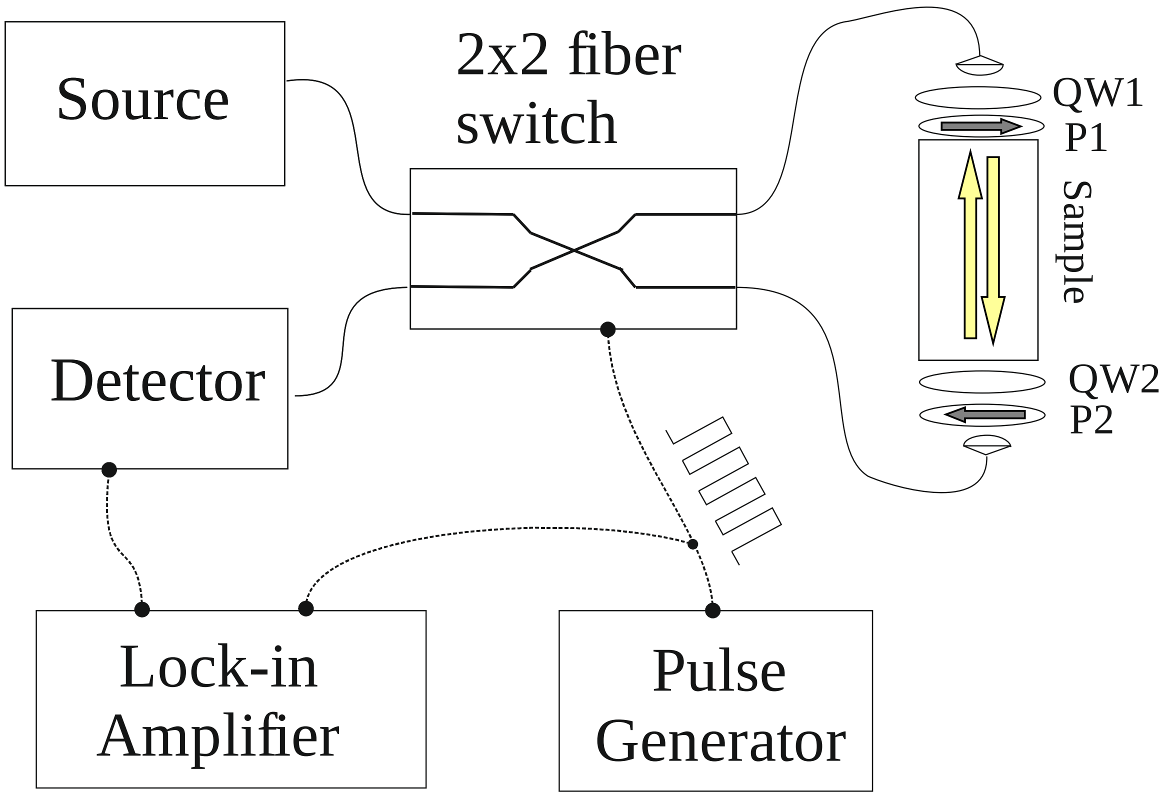

Fig.8 the setup for measurements of the MCD. The quarter-wave plates QW1 and QW2 are inserted between polarizers P1 and P2 are and sample. The axes of the polarizers are in the same direction. The angle between axes of polarizers and QW1 is 45 and between polarizers and QW2 is -45 degrees

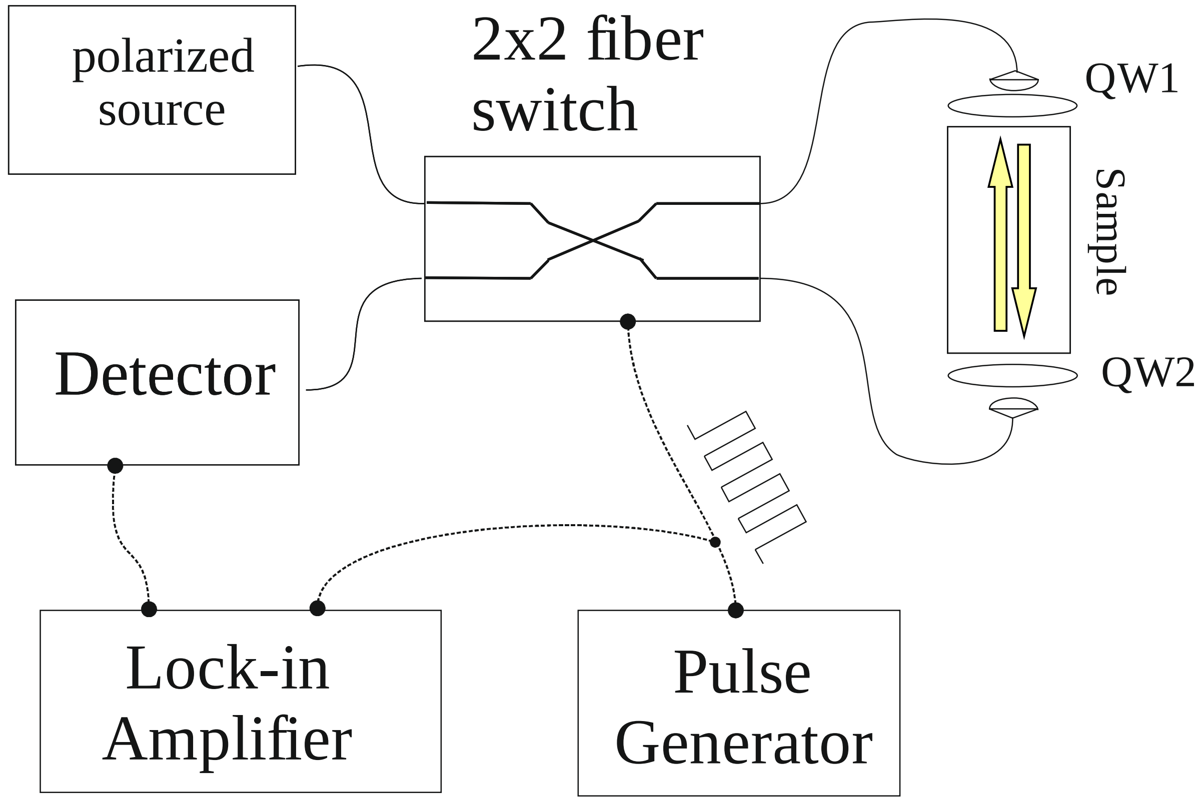

Fig.9 the setup for measurements of the MCD. A polarized light source, polarization-maintaining fibers and fiber switch are used. The quarter-wave plates QW1 and QW2 are inserted between collimators and sample.

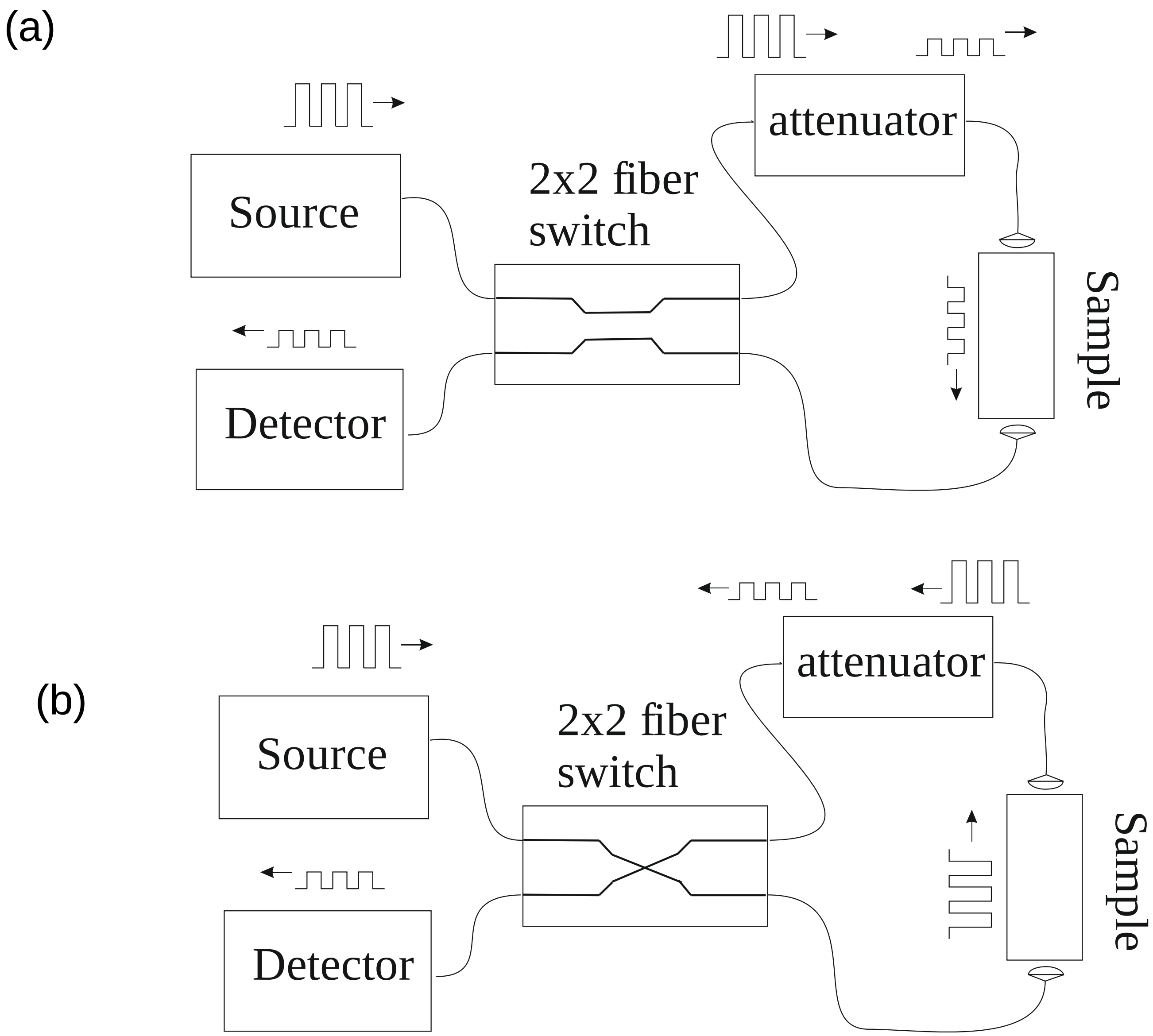

Fig.10 the setup for measurements of non-linear absorption. (a) and (b) show two switch states of the switcher. For different switching states, light of different intensity passes through the sample, but light of nearly- same intensity reaches the detector. A train of pulses shows the intensity of light at different points

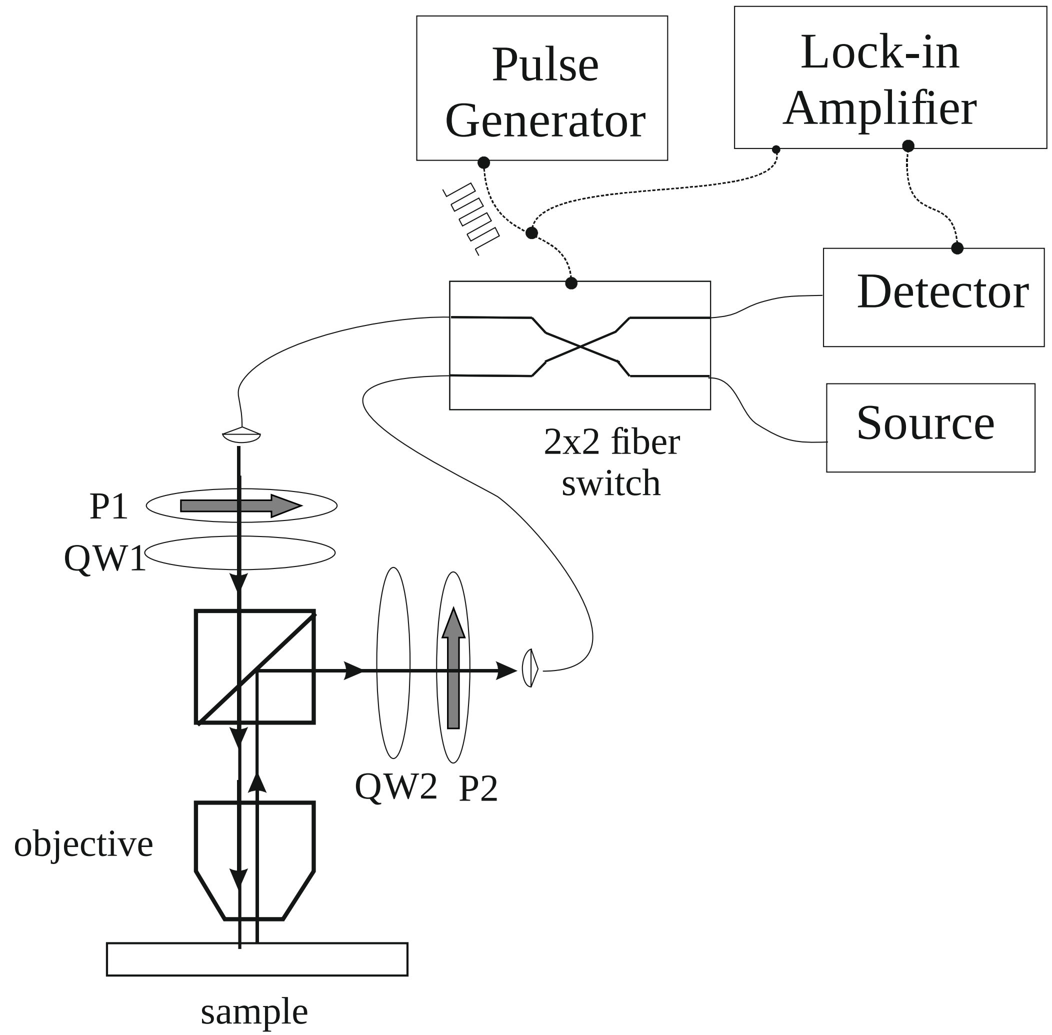

Fig.11 the setup for measurements of Kerr rotation angle. The angle between axes the polarizers P1, P2 is 45 degrees. The angle between axes quarter-wave plates QW1,QW2 and the polarizers are + 45 and -45 degrees.