The influence of magnetooptical crystal linear birefringence on the parameters of an optical isolator

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ABSTRACT

Theoretical considerations have been realised by using a matrix method and by investigating a magnetooptical crystal under simultaneous influence of two magnetic fields: the first one, parallel to the direction of the light propagation (Faraday configuration) and the second one orthogonal (Cotton-Mouton configuration). An experiment confirms theoretical expectations, namely the possibility of extending the isolation magnitude by parallel arrangement of transmission axis of the input polarizer to the birefringence axis.

1. INTRODUCTION

An optical isolator acts in a similar way to a diode in an electrical circuit, that is it allows light to propagate in only one direction. The major application of the isolator is to protect laser from light reflecting from subsequent optics (Fresnel reflection, Rayleigh scattering inside the fiber) and returning back into laser cavity. This phenomenon known as the optical feedback causes deterioration of laser parameters (amplitude fluctuation, frequency instabilities, limitation of modulation bandwidth, noise) and even causes optical damage in case of high power lasers.

Optical isolators have been an important component in systems utilising the high power lasers as the light source. The commonly used optical isolators are based on application of Faraday rotation of linearly polarized light passing through the crystal along the external magnetic field. The parameters of the isolator depend on properties of magnetooptical crystal as well as polarization parameters of light passing through the crystal. In the paper the influence of linear birefringence of magnetooptical crystal on the parameters of the optical isolator is discussed and results of the experiments are presented as well.

2. MAGNETOOPTICAL ISOLATION

Magnetooptical isolator consists of two polarizers between which there is a Faraday rotator. Polarizer transmission axes are oriented at 45 degrees with respect to each other. The most important component of the rotator is the magneto-optically active material (in the near and far infrared region it is most commonly to utilise an yttrium iron garnet known as YIG). The crystal is formed as a rod and put into magnetic field parallel to the axis of the rod and parallel to the direction of the light propagation. The source of this field is a permanent magnet or electromagnet. Magnetic field strength and length of the rod are chosen so as to achieve the 45 degree polarization rotation (in respect with the equation describing angle of Faraday rotation $\Theta = V H l$, where V- Verdet constant, H- magnetic field strength, l- length of the crystal).

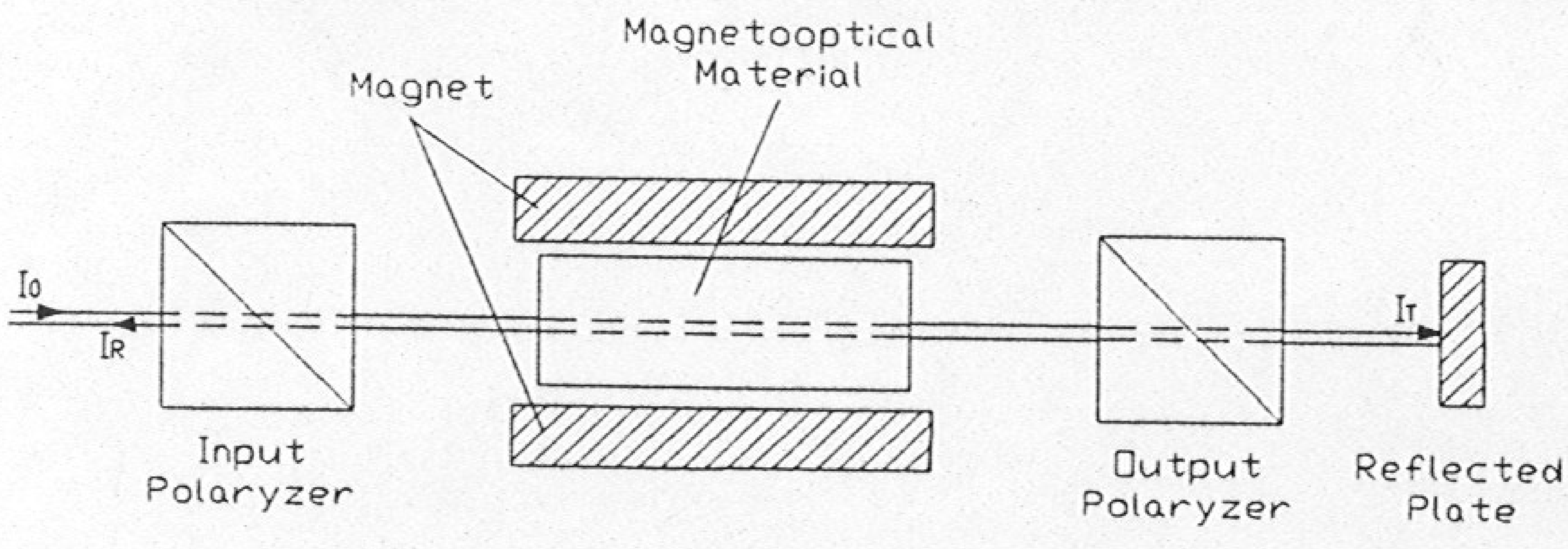

Fig. 1 Scheme of the magnetooptical isolator
I_0, I_R, I_T- Intensity of the incident, back reflected and transmitted beam

Magnetooptical material placed in magnetic field parallel to the direction of the light propagation shows a specific circular birefringence, a phenomenon known as the Faraday rotation (direction of the polarization rotation after passing through this material is independent of the direction of light propagation and depends only on the direction of magnetic field and the sign of a Verdet constant).

Laser light leaving the input polarizer is linearly polarized. Faraday ratator rotates the plane of polarization by 45 degree. In this way it is parallel to the transmission axis of the output polarizer and the transmitted light passes practically through isolator without any losses.

After passing through the output polarizer the reflected beam is linearly polarized. Faraday rotator produces another 45 degree of rotation in the same direction as previously. In this way the light falling on the input polarizer is parallel to the transmission axis of the polarizer and is absorbed by it.

So the magnetooptical isolator serves its purpose - to extinguish back reflection light from components of optical system, thus prevents laser active region from its return and make possible stable work of the laser.

3. PARAMETERS OF THE OPTICAL ISOLATOR

The isolator activity is determined by many parameters. The isolation and the insertion losses come first. They are defined as follows:

Isolation (backward transmission loss)

$$L_B = -10\log(I_R/I_T)\,, \tag{1a}$$

Insertion loss (forward transmission loss)

$$L_B = 10\log(I_T/I_0)\,, \tag{1b}$$

where I_R - intensity of back reflecting light ,
I_T - intensity of transmitted light ,
I_0 - intensity of incident light.

These parameters describing an isolator depend on the quality of the polarizers, the Faraday rotator and the adjustment of an isolator.

Magnetooptical material should introduce no ellipticity of the light beam passing through it and should exactly 45 degrees rotate of linear polarized light. However we must bear in mind that a certain derivation of 45 degrees rotation may occurs as the Verdet constant describing rotation angle is conditioned by wavelength and temperature.

On the isolator, parameters influence also magnetooptical phenomena other than the external induced Faraday rotator. In real magnetooptical material occurs natural birefringence and dichroism (linear and circular).This phenomena caused that the polarization of the light after passing through that crystal becomes not linear but elliptical polarized and changes the angle of rotation.

4. ELIMINATION OF THE INFLUENCE OF LINEAR BIREFRINGENCE ON THE ISOLATION MAGNITUDE OF THE ISOLATOR

For the best effectiveness, magnetooptical materials should not show dichroism and natural birefringence (linear and circular). In reality it is difficult to find such perfect material. It is possible however to eliminate the influence of linear birefringence of the crystal on the isolation magnitude of the isolator. This can be achieved by suitable arrangement of the transmission axes of the polarizers with respect to birefringence axis of the crystal.

Theoretical consideration concerning influence of the crystal linear birefringence on the parameters of the optical isolator have been realised by using a matrix method. In this method the state of light polarization is described as the four-component Stokes vector, whereas any optical component is characterised by Mueller matrix. To achieve the state of polarization of the light after passing through whichever optical component of the isolator the Mueller matrix [7] describing this component should be multiplied by Stokes vector describing incident light.

In order to calculate the Stokes parameters of transmitted $[S^T]$ and reflected $[S^R]$ light beams it is necessary to know the Stokes parameters of incident light beam $[S^P]$ and Mueller matrices of all optical elements of the isolator.

It may be described of follows:

$$[S^R]=[M^{P1}][M^{ROT}][M^{P2}][M^R][M^{P2}][M^{ROT}][M^{P1}][S^P] \quad (2a)$$

$$[S^T]=[M^{P2}][M^{ROT}][M^{P1}][S^P] \quad (2b)$$

where

$$[M^{P1}]=\begin{bmatrix} 1 & \cos(2\Theta) & \sin(2\Theta) & 0 \\ \cos(2\Theta) & \cos^2(2\Theta) & \cos(2\Theta)\sin(2\Theta) & 0 \\ \sin(2\Theta) & \cos(2\Theta)\sin(2\Theta) & \sin^2(2\Theta) & 0 \\ 0 & 0 & 0 & 0 \end{bmatrix}$$

$$[M^{P2}]=\begin{bmatrix} 1 & -\sin(2\Theta) & \cos(2\Theta) & 0 \\ -\sin(2\Theta) & \sin^2(2\Theta) & -\cos(2\Theta)\sin(2\Theta) & 0 \\ \cos(2\Theta) & -\cos(2\Theta)\sin(2\Theta) & \cos^2(2\Theta) & 0 \\ 0 & 0 & 0 & 0 \end{bmatrix}$$

$$[M^R]=\begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix}, [S^P]=\begin{bmatrix} S_0 \\ S_1 \\ S_2 \\ S_3 \end{bmatrix}, [S^R]=\begin{bmatrix} S_{0R} \\ S_{1R} \\ S_{2R} \\ S_{3R} \end{bmatrix}, [S^T]=\begin{bmatrix} S_{0T} \\ S_{1T} \\ S_{2T} \\ S_{3T} \end{bmatrix},$$

$[M^{P1}]$,$[M^{P2}]$-Mueller matrix of polarizer P1 and P2,
$[M^R]$-Mueller matrix of reflecting plane,
$[M^{ROT}]$-matrix of Faraday rotator with linear birefringence,
$S_0=I_0$, $S_{0R}=I_R$, $S_{0T}=I_T$-intensity of incident reflected and transmitted light beams

The calculations have been realised with assumption that the magnetooptical crystal is affected by two magnetic fields: parallel to the direction of the light propagation (Faraday configuration) and orthogonal (Cotton-Mouton configuration).

Then the Mueller matrics for Faraday rotaded is as follows:

$$[M^{ROT}]=\begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & \cos(2\alpha) & -\sin(2\alpha) & * \\ 0 & \sin(2\alpha)\cos(2\beta) & \cos(2\alpha)\cos(2\beta) & * \\ 0 & \sin(2\alpha)\sin(2\beta) & \cos(2\alpha)\sin(2\beta) & * \end{bmatrix}$$

where α-circular birefringence
β-linear birefringence

Isolation and transmission losses of the isolator may be calculated from equations (2a), (2b) and definition of isolator parameters:

for $\Theta=0$

$$L_B = -10\log[(1-\sin 2\alpha)] \neq L_B(\beta),$$

$$L_F = 10\log\left[\frac{1+\sin(2\alpha)\cos(2\beta)}{2}\right],$$

for $\Theta=45^{o}$

$$L_B = -10\log\left[\frac{1-\sin(2\alpha)\cos(2\beta)}{2}\right],$$

$$L_F = 10\log\left[\frac{1+\sin(2\alpha)}{2}\right] \neq L_F(\beta),$$

Theoretical results permit to draw the following conclusions :

- Parameters of the isolator depend on:

- magnitude of the linear birefringence,
- the angle between transmission axes of the polarizers and the axis of crystal birefringence ,

- Changes of this parameters are periodic according to :

- magnitude of the linear birefringence $\beta = n\pi$,
- the angle between the axis of birefringence and the transmission axes of the polarizer $\Theta = n\pi$,

- It is possible to distinguish two particular cases of the position of the input polarizer transmission axis in relation to the birefringence axis:

- if the angle between these axes is 45 degrees then transmission losses should not depend upon magnitude of birefringence induced by the external magnetic field, but in this case the isolation still yields to deterioration ,
- if both axes are parallel then linear birefringence of the crystal does not influence the isolation magnitude.

5. EXPERIMENTAL RESULTS

An experiment confirming theoretical expectations has been realised in a scheme consisting of magnetooptical crystal (yttrium iron garnet in shape of a cylinder with 10 mm length and 1 mm diameter) placed between two polarizers. Laser He-Ne with 1.15 μm wavelength was used as a light source. To create Faraday rotation an induction coil was wound directly on the crystal. Linear birefringence of the crystal was created also by an external electromagnet. For convenience, the isolator measurement has been carried on in the same scheme as the measurement of transmission losses, it did contain the reflection plate.

When measuring transmission losses, the transmission axis of the output polarizer was placed parallel and when measuring isolation - orthogonal to the polarization plane of the light after passing through Faraday rotator. Experienced dependence of isolation and transmission losses on intensity of current creating magnetic field orthogonal to the direction of beam propagation is shown on fig. 3 a, b and 4 a, b. There are marked curves for the different angles between birefringence axis of the crystal and transmission axis of the input polarizer.

Experiment results are in general consistent with theoretical expectation and confirm the possibility of extending the isolation magnitude by parallel arrangement of transmission axis of the input polarizer to the birefringence axis (fig 3 a, curve 0^0). An optimum arrangement of the scheme for achieving maximum value of isolation unfortunately resulted in increasing transmission losses (fig. 4 a, curve 0^0).

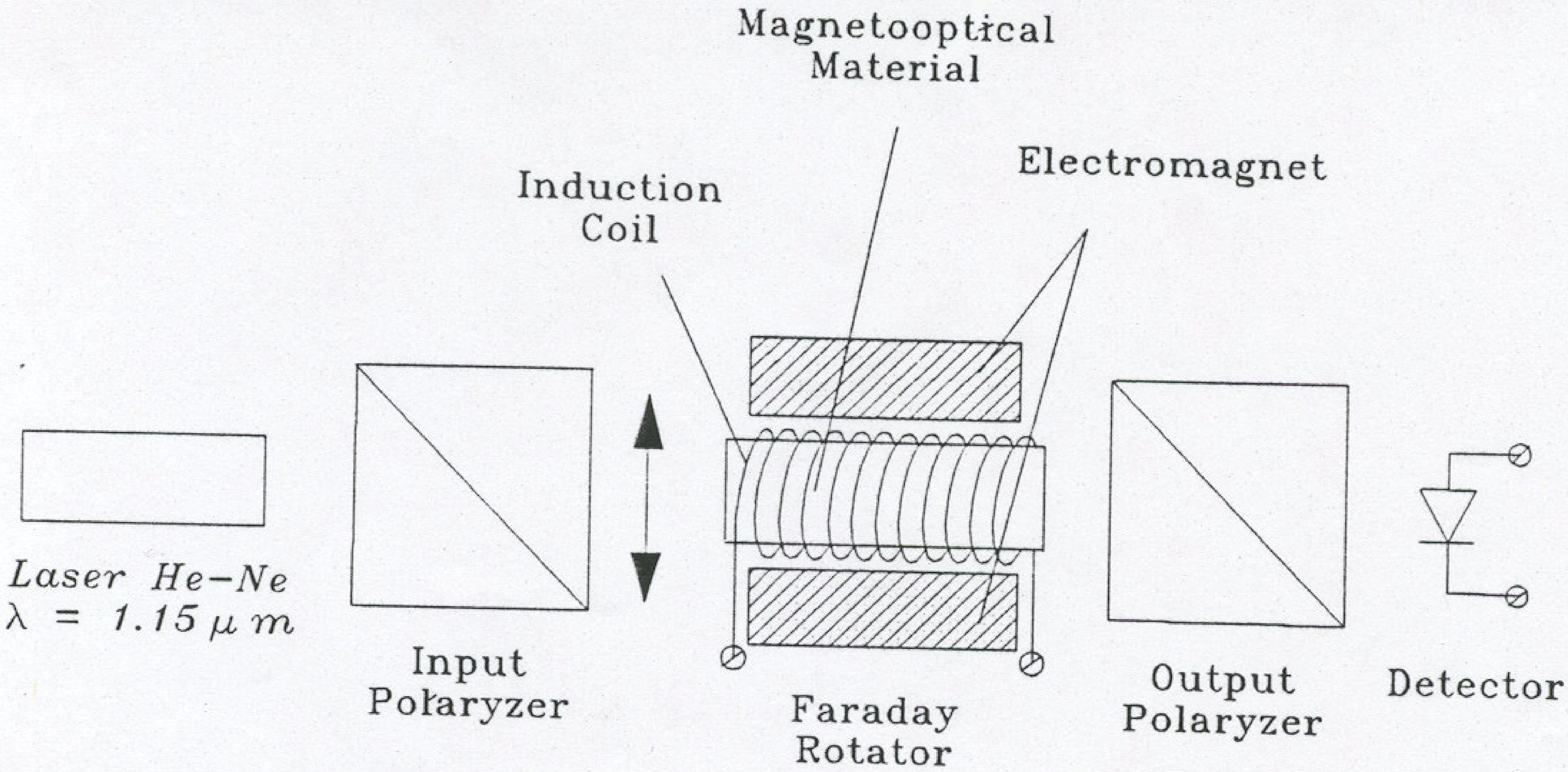

Fig. 2 Experimental scheme

6. CONCLUSIONS

Main result of the paper is conclusion that influence of linear birefringence of magnetooptical crystal on the isolator parameters may be diminished by parallel orientation of the birefringence axis of the crystal and axis of input polarizer. It was also proved that Mueller matrix and Stokes vector methods are well fitted for analysis of the optical isolator. In this way there are possibility to analyse influence of other phenomena like dichroism, magnetic linear birefringence, circular natural birefringence (optical activity) on the isolator parameters.

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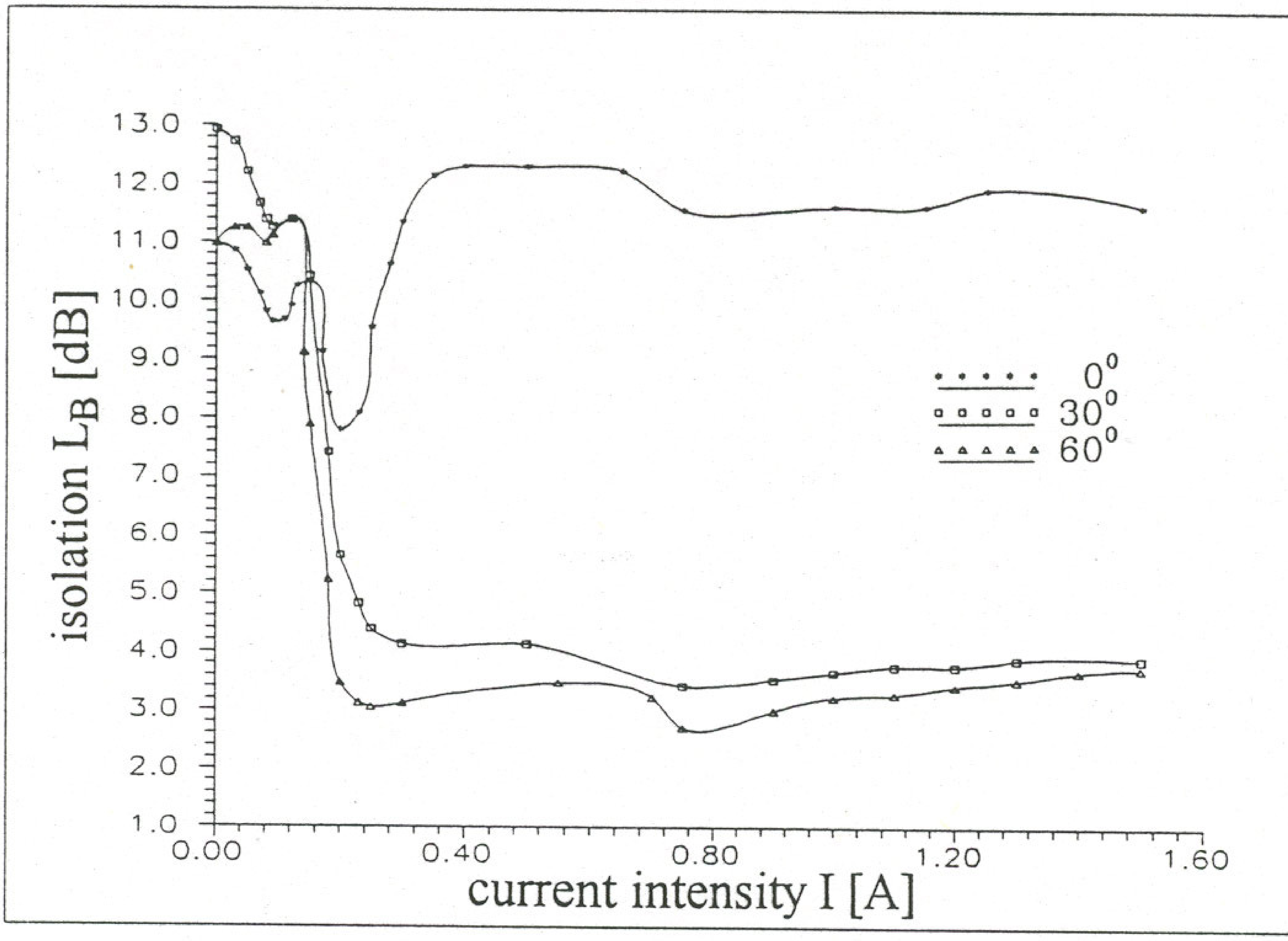

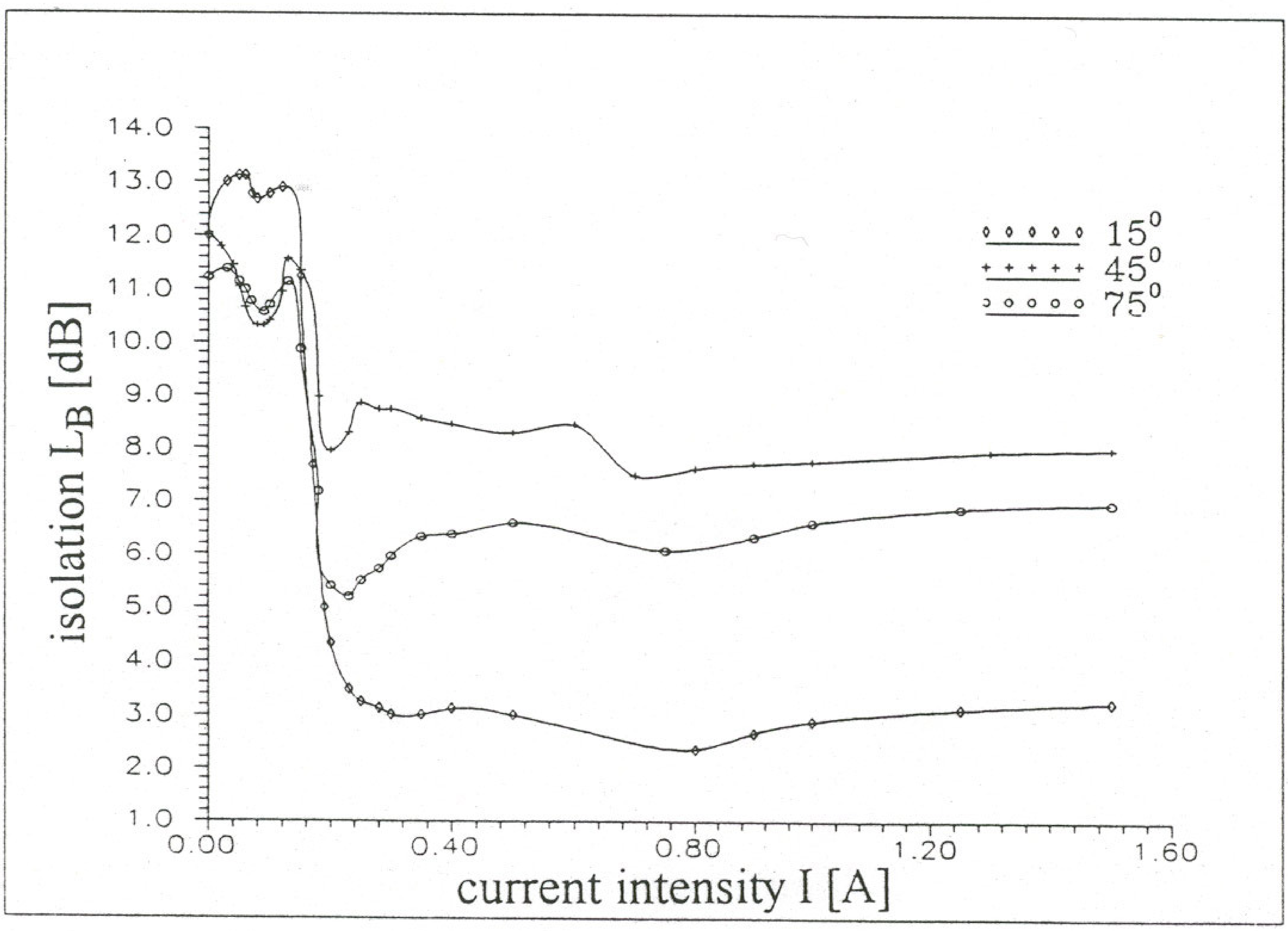

Fig. 3a,b Isolation dependence upon linear birefringence

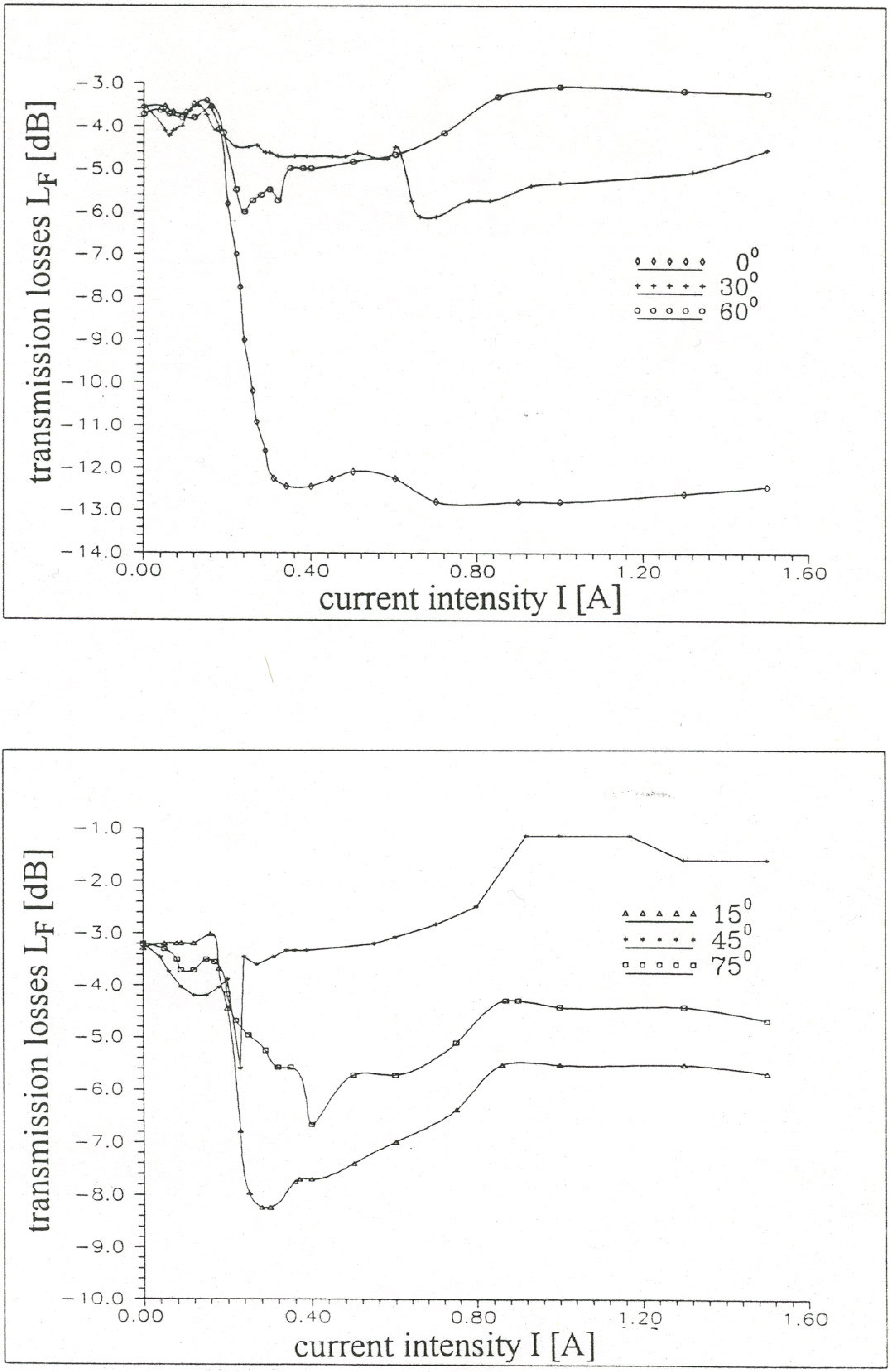

Fig. 4a,b Transmission losses dependence upon linear birefringence