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Faraday isolators for high average power: achieved results and new ideas

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Introduction

Comparison of the influence of the temperature dependence of the Verdet constant and the photoelastic effect

Measurements of thermooptic characteristics

Comparison of the novel schemes of faraday isolators and traditional one

- isolation ratio
- first pass losses

New ideas

- absorbing phase plate
- TGG crystal orientation optimization
- Use of photoelastic effect

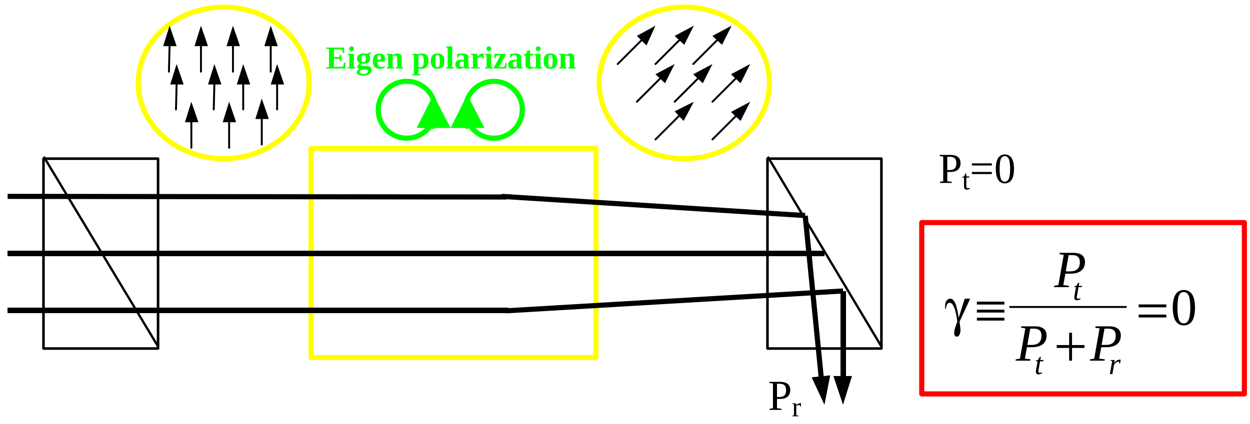
Conclusions

Measurement of small wave front distortions

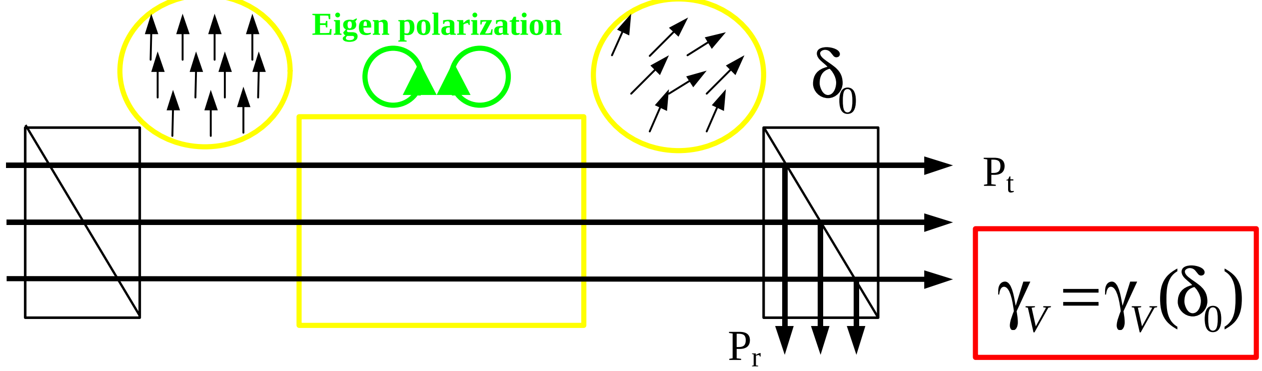
Introduction

The **light absorption in optical elements of Faraday rotators** causes nonuniform cross-section distribution of temperature, which has three physical mechanisms of influence upon laser radiation;

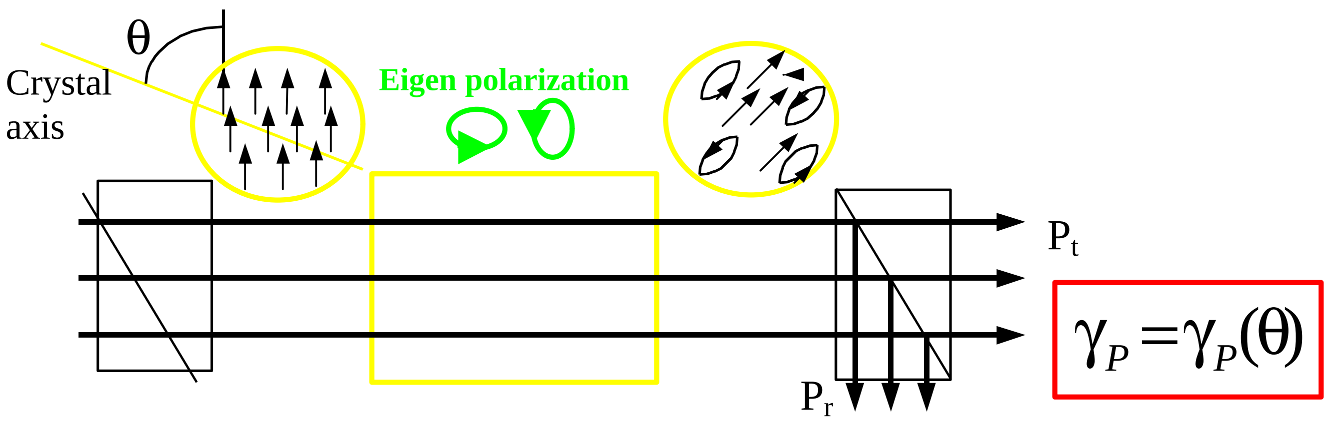
1) wavefront distortions, or thermal lens, caused by the dependence of the refraction index on temperature;



2) nonuniform distribution of the rotation angle of the polarization plane caused by the temperature dependence of Verdet constant;



3) simultaneous appearance of circular (Faraday effect) and linear birefringence as a result of mechanical strains due to temperature gradient (photoelastic effect).



I. Comparison of the influence of the temperature dependence of the Verdet constant and the photoelastic effect

In case of small depolarization, i.e. $\gamma \ll 1$

$$\gamma = \gamma_V(\delta_0) + \gamma_P(\theta)$$

Thus, the depolarization is a sum of two terms representing two physical mechanisms that give rise to the depolarization.

$$g_P^{\min} = \left[\frac{L\alpha P_0 Q}{l\,k}\right]^2 \cdot \frac{A_1}{p^2} \qquad \gamma_V^{\min} = \left[\frac{\alpha P_0}{16\cdot\kappa}\cdot\frac{1}{V}\frac{dV}{dT}\right]^2 \cdot A_3$$

Here indexes "min" indicate values of γ_P and γ_V obtained at optimum values of θ and δ_0, respectively, and

P_0 - laser power
L - length of optical element
α - absorption
κ - thermoconductivity
Q - thermo-optic constant
V - Verdet constant

$$A_1 = \int_0^\infty \left(1/y - \exp(-y)/y - 1\right)^2 \exp(-y)dy \cong 0.137$$

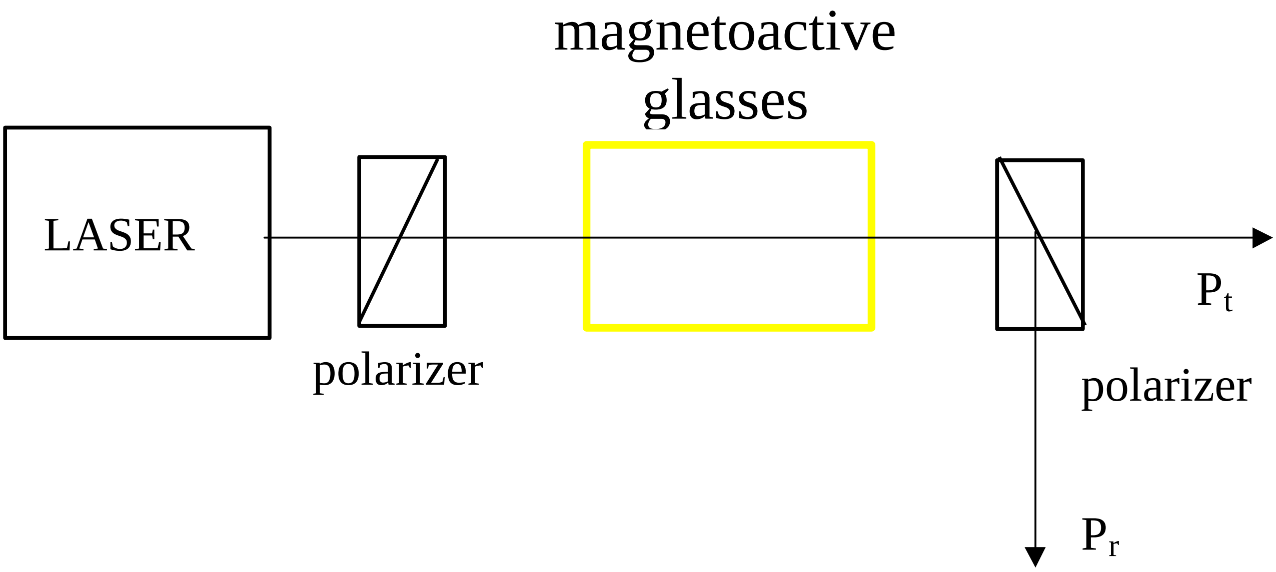
$$A_3 = \int_0^\infty f^2(y)\exp(-y)dy - \left[\int_0^\infty f(y)\exp(-y)dy\right]^2 \cong 0{,}268, \quad f(y) = \int_0^y \frac{1-\exp(-z)}{z}dz$$

$$\frac{\gamma_V^{\min}}{\gamma_P^{\min}} = 2\cdot\left[\frac{\pi}{16}\cdot\frac{\frac{1}{V}\frac{dV}{dT}}{Q}\cdot\frac{\lambda}{L}\right]^2 \le 0.01$$

Thus, the influence of the temperature dependence of the Verdet constant on depolarization is much lower than that of the photoelastic effect.

Investigation of the ways of compensating depolarization caused by photoelastic effect is therefore more promising. In our discussion to follow we shall neglect the temperature dependence of the Verdet constant.

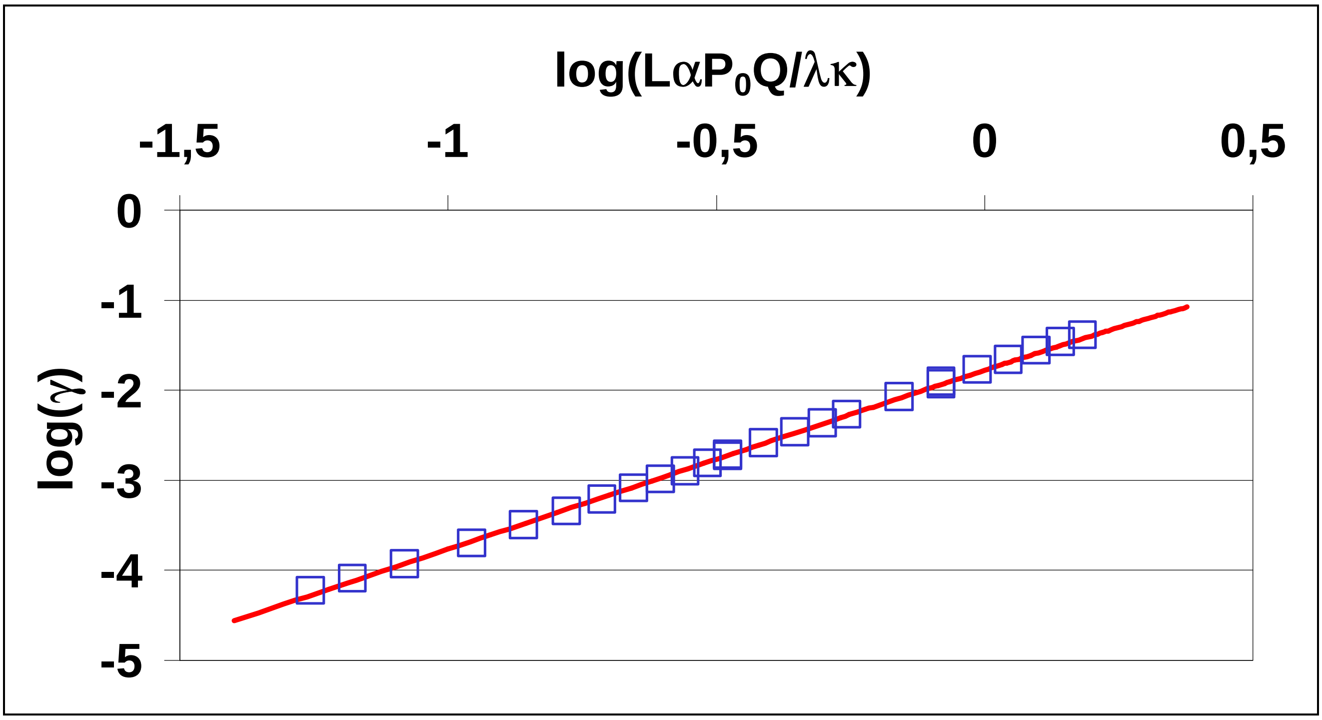
Measurements of thermooptic characteristics of magnetoactive glasses (scheme of measurement)



$$\gamma \equiv \frac{P_t}{P_t + P_r} = 0$$

$$g = 0.017 \cdot \left[\frac{L\, a P_0 Q}{l\, k} \right]^2$$

Measurements of thermooptic characteristics of magnetoactive glasses (results of measurement)



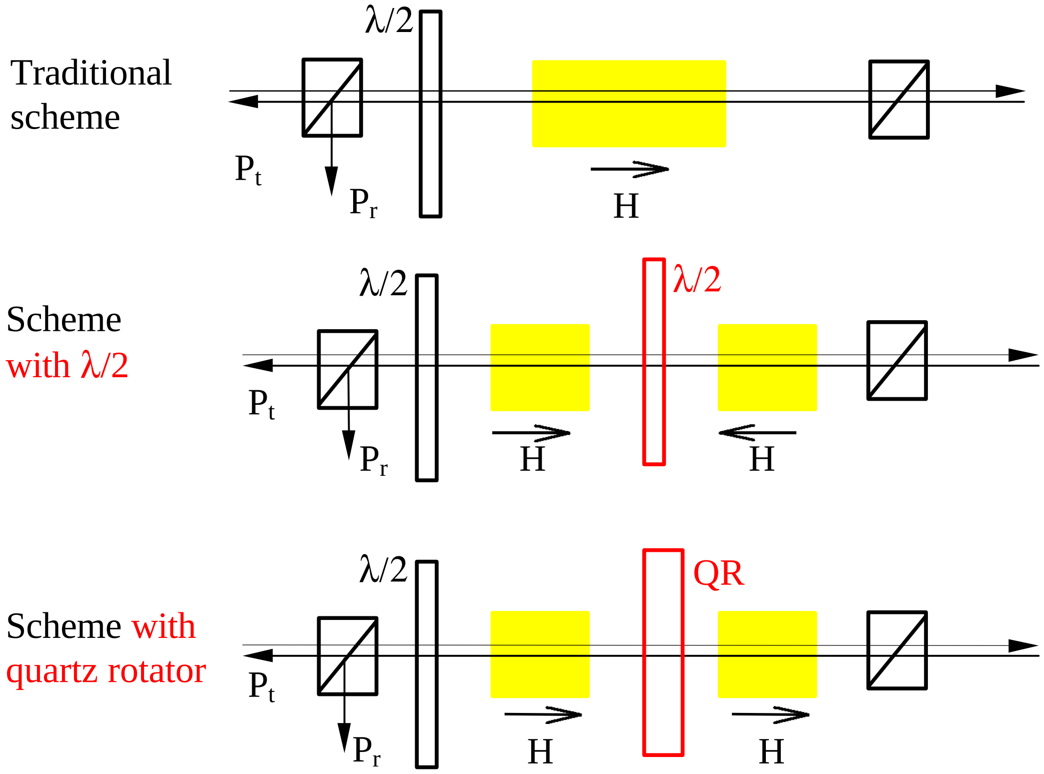
Theoretical (solid line) and experimental dependences of the depolarization ratio γ on power for glass MOC-101.

The measurement results.

Glass mark (Russian)	*Q*/κ, 10^{-6}m/W	Closest western-made analogues (manufacturer)
MOC-101	1.9	-
MOC-105	1.3	M18 (Kigre)
MOC-04	1.3	M24 (Kigre) FR-5 (Hoya)
MOC-10	1.1	M32 (Kigre)

II. Novel schemes of Faraday isolators

The idea of compensating depolarization consists in using two 22.5° rotators and a reciprocal optical element between them instead of one 45° Faraday rotator.



$$\gamma_{0,L,R} \equiv \frac{P_t}{P_t + P_r}$$

Jonse matrices for all optical elements determine the isolation ratio.

$$F = \sin\frac{d}{2} \cdot \begin{pmatrix} ctg\frac{d}{2} - i\frac{d_l}{d}\cos 2\Psi & -\frac{d_c}{d} - i\frac{d_l}{d}\sin 2\Psi \\ \frac{d_c}{d} - i\frac{d_l}{d}\sin 2\Psi & ctg\frac{d}{2} + i\frac{d_l}{d}\cos 2\Psi \end{pmatrix} \qquad \delta^2 = \delta_l^2 + \delta_c^2$$

$$R(\beta_R) = \begin{pmatrix} \cos\beta_R & \sin\beta_R \\ -\sin\beta_R & \cos\beta_R \end{pmatrix} \qquad L(\beta_L) = \begin{pmatrix} \cos 2\beta_L & \sin 2\beta_L \\ \sin 2\beta_L & -\cos 2\beta_L \end{pmatrix}$$

$\delta_l = \delta_l(r, \varphi, Q, \xi_a, \vartheta)$ - phase delay of linear eigen polarization

$\Psi = \Psi(r, \varphi, \xi_a, \vartheta)$ - direction of linear eigen polarization

δ_c - phase delay of circular eigen polarization

β_R - angle of rotation of quartz rotator

β_R - the inclination angle of the λ/2 plate optical axis

$$\xi_a = \frac{2p_{44}}{p_{11} - p_{12}}$$

III. Comparison of the novel and traditional schemes

(case of small depolarization, i.e. $\gamma \ll 1$)

The depolarization ratio $\gamma_{0,L,R}$ can be minimized by

1) **varying the angle $\beta_{L,R}$** i.e., rotating the $\lambda/2$ plate or changing the thickness of quartz rotator

$$b_{optL} = p/8 + Np/2 \qquad b_{optR} = 3p/8 + Np$$

2) **varying the angle θ**, i.e., rotating the crystal around beam axis

$$\theta_{opt\,0} = -\pi/8 \qquad \theta_{optL} = \frac{\pi}{16} + \frac{1}{4}\arcsin\left[\frac{a}{b}\cdot\frac{\xi_a^4 - 1}{(1-\xi_a^2)^2}\right] \qquad \theta_{optR} \text{ - any angle}$$

The minimal values of the depolarization ratio $\gamma_{min0,L,R} = \gamma_{0,L,R}(\theta_{opt}, \beta_{opt})$ are

$$g_{\min 0} \cong 0.014\, p^2 ,$$

$$g_{\min L} \cong 0.846 \cdot 10^{-4} \xi_a^2 p^4$$

$$g_{\min R} \cong 0.4 \cdot 10^{-5} (1 + \frac{2}{3}\xi_a^2 + \xi_a^4)\, p^4$$

$$p = \frac{L}{\lambda}\frac{\alpha Q}{\kappa} P_0$$

Parameter p characterizes the force of the photoelastic effect.

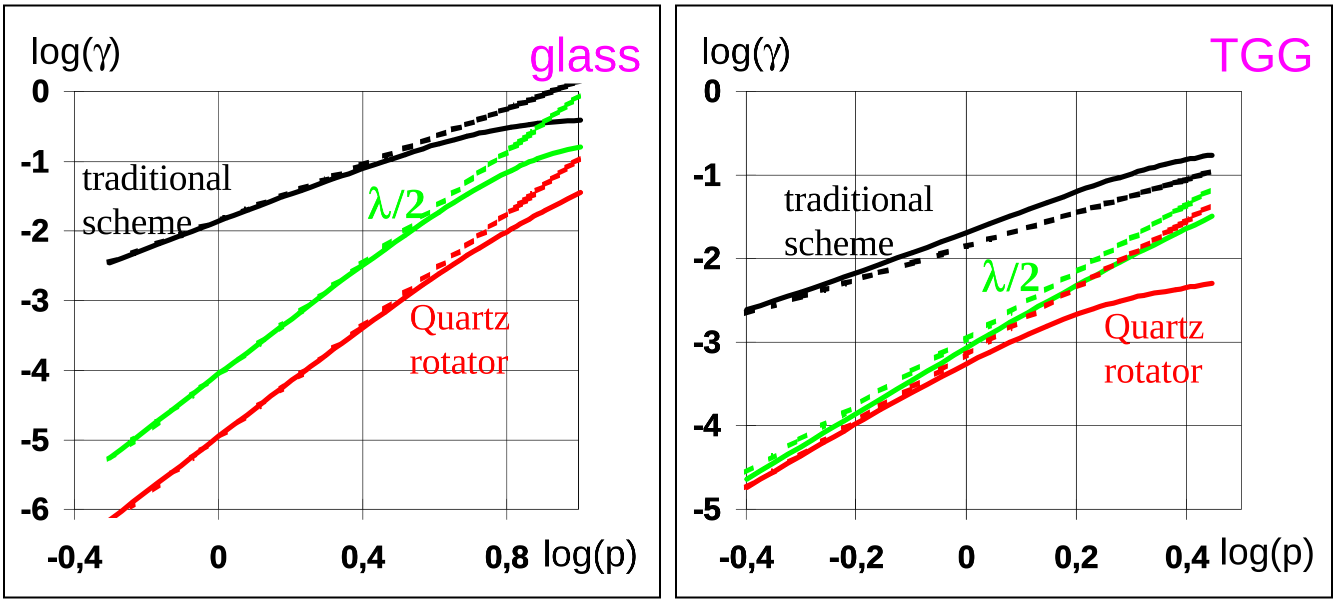
$\xi_a = 1$ for glass $\qquad \xi_a = 3.6$ for TGG

The formulas for $\gamma_{min0,L,R}$ are justified at any ξ_a including $\xi_a = 1$, i.e., for glass magnetooptical media in which the depolarization ratio does not depend on θ.

IV. Comparison of the novel and traditional schemes

(case of large depolarization, i.e. $\gamma \approx 1$)

At a given ξ_a the depolarization ratio of a Faraday isolator, like in the case of the weak linear birefringence, is completely determined by parameter p.



Dashed lines show the formulas for small depolarization.

Approximate estimations show that

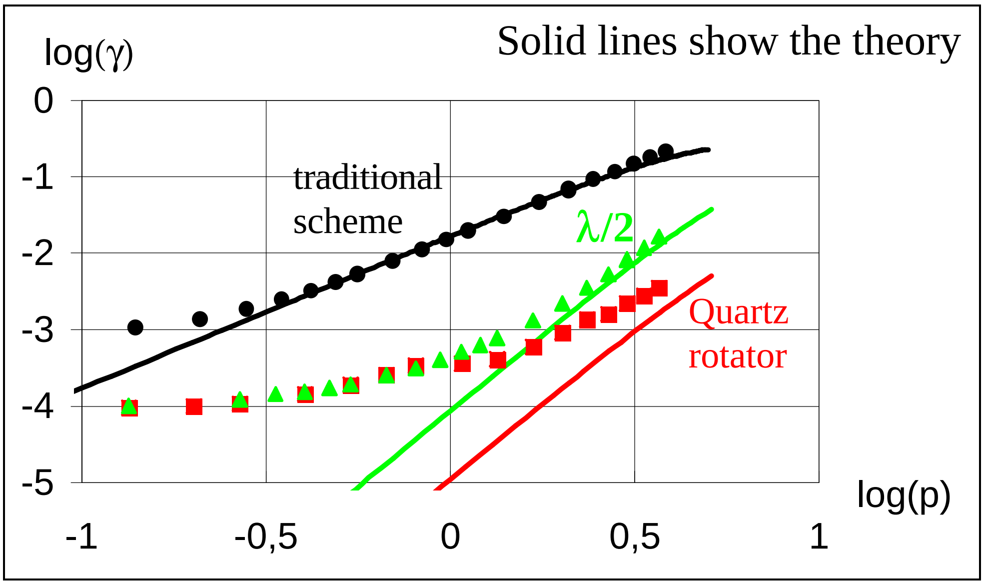
for TGG $p=1$ at power $P_0=2.5$kW
($Q=7\times10^{-7}$/K, $\kappa=7$W/Km , $L/\lambda=2\times10^4$, $\alpha=2\times10^{-3}$ cm^{-1}).

for glass $p=1$ at power $P_0=250$W
($Q\cong5\times10^{-7}$/K, $\kappa=0.5$W/Km, $L/\lambda=4\times10^4$, $\alpha=2\times10^{-3}$ cm^{-1}).

Taking into account these estimations and graph, it is evident that the novel schemes allow construction of Faraday isolators with isolation ratio of 30 dB ($\gamma=10^{-3}$) for average laser power at kW (glass) and multikW (TGG) level.

V. Experimental investigation of novel schemes

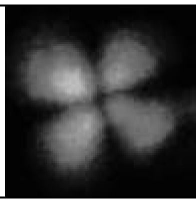
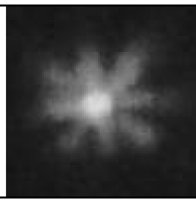
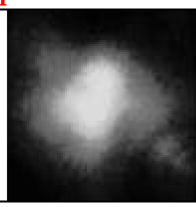
- λ=532nm
- CW Nd:YAG laser
- power up to 5.5 W
- 2 mm diameter Gaussian beam.
- magneto-optical glass
- absorption $\alpha(532nm)=0.05cm^{-1}$



The disagreement between the predictions and experiment at low power is due to the residual, power independent depolarization in magneto-optical elements.

At high powers, however, when the depolarization ratio is mainly determined by self-induced effects, experimental data are in good agreement with theoretical predictions for all three schemes

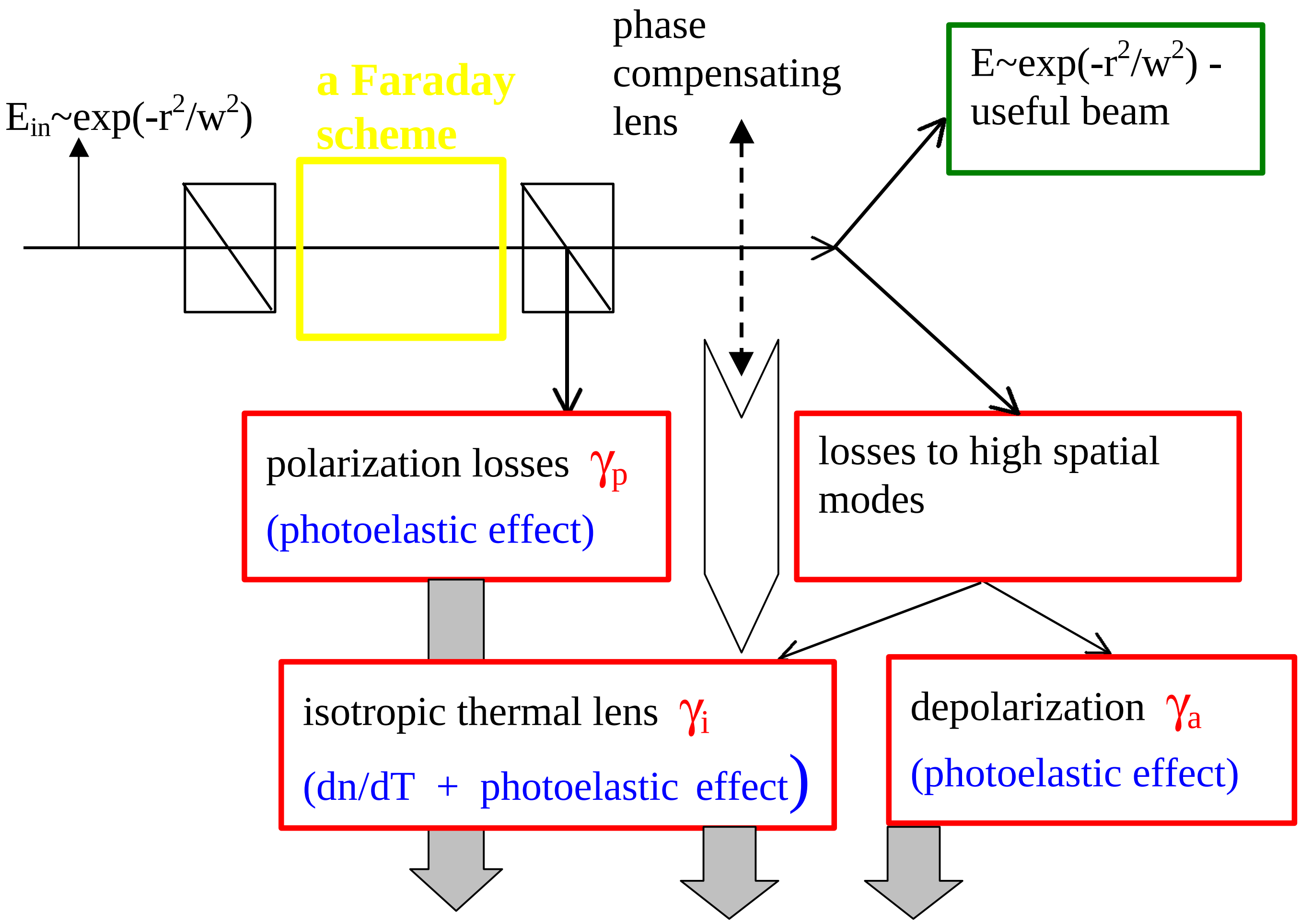
The good agreement of the experiment with theoretical analysis, which assumes only photoelastic-induced depolarization, confirms the theoretical prediction that the photoelastic limits the isolation ratio at high average power. Analysis of the transverse structure of the depolarized radiation also confirms this result:

	traditional	λ/2	quartz rotator
Images of the spatial profiles of the depolarized beams			
Theoretical prediction of period of the dependence of the local depolarization ratio on the polar angle	90^0	45^0	**No** angular dependence

Scheme	$\beta_{\mathbf{opt}}$	$\theta_{\mathbf{opt}}$	$\gamma_{\mathbf{min}}$ **at p<$p_{\mathbf{m}}$ (accuracy 5%)**		$p_{\mathbf{m}}$		$\gamma_{\mathbf{min}}$ **at high* p**	
		TGG	glass	TGG	glass	TGG	glass, p=2	TGG, p=6
Traditional	–	$-\pi/8$	$1.4\times10^{-2}p^2$	$1.4\times10^{-2}p^2$	1.7	0.1	0.29	0.11
with half-wave plate	$\pi/8$	≅0.275 0.90	$0.85\times10^{-4}p^4$	$1.1\times10^{-3}p^4$	2.5	1.0	0.060	0.010
with reciprocal rotator	$3\pi/8$	$\pi/16$	$1.07\times10^{-5}p^4$	$0.71\times10^{-3}p^4$	2.5	0.5	0.0084	0.0034

*) These values of p approximately correspond to power of laser radiation 1.5kW for glass and 5kW for TGG.

First pass losses



$$g_{total\,0,L,R} = g_{p0,L,R} + g_i + g_{a0,L,R}$$

$$g_{p0} = p^2 \frac{A_1}{p^2} x_a^2 \qquad g_{pL} = \frac{p^2 A_1}{p^2} \begin{cases} (2-p/2)(x_a^2+1) & x_a^2 > 1.3 \\ 2(2-\sqrt{2}) & x_a^2 < 1.3 \end{cases} \qquad g_{pR} = \frac{p^2 A_1}{p^2}\left(2-\sqrt{2}\right)$$

$$g_{a0} = p^2 \cdot \frac{A_1}{p^2} \qquad g_{aL} = 0 \qquad g_{aR} = \frac{p^2 A_1}{p^2}\left(2-\sqrt{2}\right) x_a^2$$

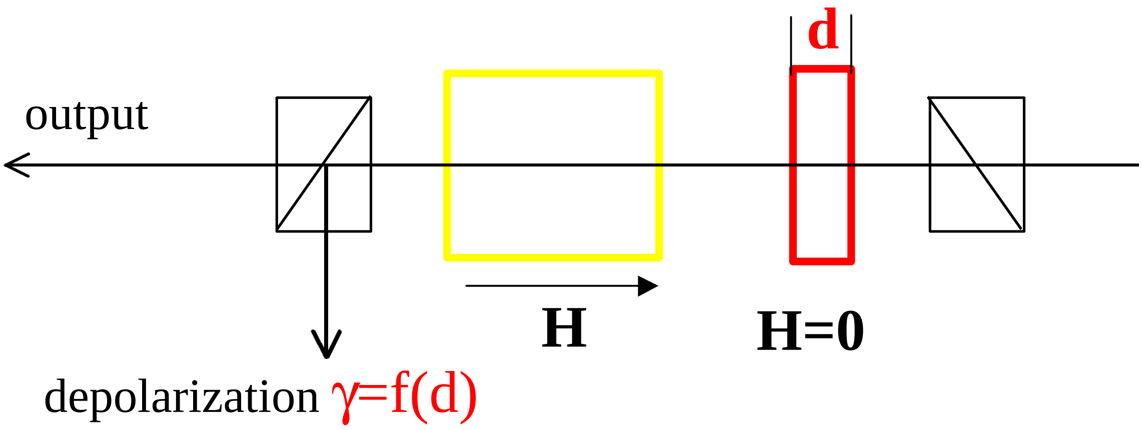
$$g_i = \frac{A_{3,4}}{4}\left(\frac{L}{l}\frac{aP}{k}P_0\right)^2 \qquad P = \frac{dn}{dT} - \left(\frac{1}{L}\frac{dL}{dT}\right)\frac{n_0^3}{4}\frac{1+n}{1-n}\cdot\left(p_{11}+p_{12}\right)$$

A_3=0.268 - no compensating lens

A_4=0.0177 - optimal compensating lens

New ideas

1. Absorbing phase plate



2. TGG crystal orientation optimization

([111] and [110] instead of [001])

$$\gamma = f(Q, \xi_a)$$

Q, ξ_a depend on crystal orientation

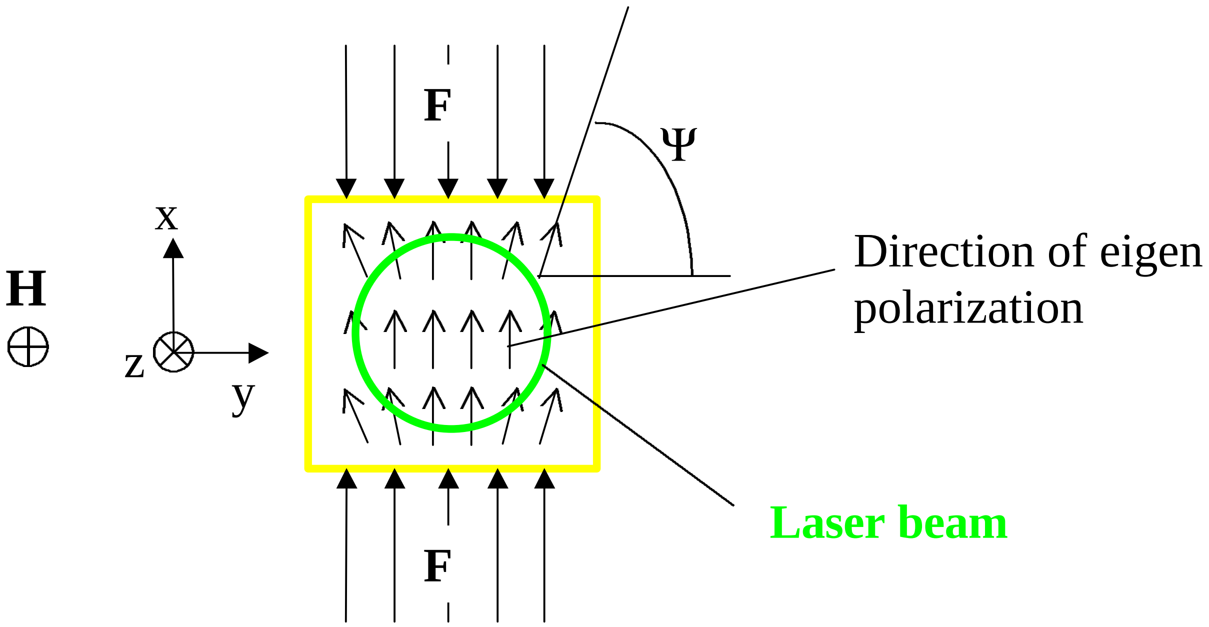
BUT not known for TGG for [111] and [110]

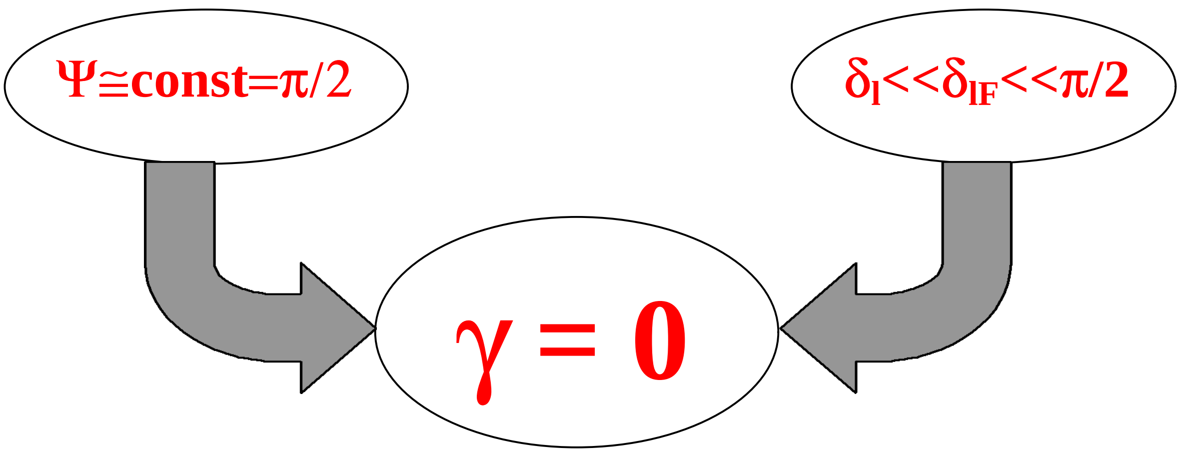
Estimations for YAG give for the best scheme

$$\frac{g_{111}}{g_{001}} = 0.52 \qquad \frac{g_{110}}{g_{001}} = 0.75$$

New ideas (contined)

3. Use of photoelastic effect





Conclusions

- The high power induced depolarization ratio is a sum of two terms which represent two effects: the change in the angle of rotation due to the temperature dependence of the Verdet constant and, more efficient, the birefringence due to the photoelastic effect of thermal strains.
- At optimal values of β and θ the depolarization ratio (and, consequently, the isolation ratio) is determined by dimensionless parameters p and ξ_a.
- Parameter p characterizes the degree of influence of the photoelastic effect on the depolarization ratio. It depends on thermo-optic constant Q which was measured for TGG and number of magnetoactive glasses.
- The depolarization ratio in the both novel schemes is considerably lower than in the traditional scheme at any value of parameters p and ξ_a.
- Novel scheme with reciprocal rotator is best from the viewpoint of isolation ratio and first pass losses and distortions as well.
- **Excellent Faraday isolator for high average power is in progress.**

Note 1, Linda Turner, 08/17/99 07:54:25 PM
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