Advanced Faraday isolator designs for high average powers.

Efim Khazanov, Anatoly Poteomkin, Nikolay Andreev,
Oleg Palashov, Alexander Sergeev

Institute of Applied Physics, N.Novgorod, Russia

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Advanced Faraday isolator designs for high average powers.

Introduction

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

II. Measurements of thermooptic characteristics of TGG and glasses. FOM of magneto-optical materials.

III. Novel two-element Faraday isolator designs and its comparison to the traditional one

IV. Novel one-element Faraday isolator design.

V. Novel Faraday rotator design and its comparison to the traditional one

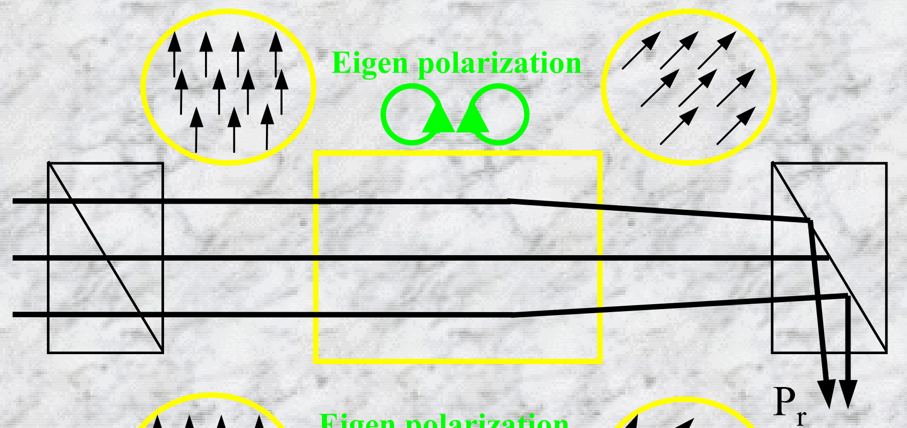
VI. Faraday isolator at the unlocked IFO.

Conclusions

Introduction

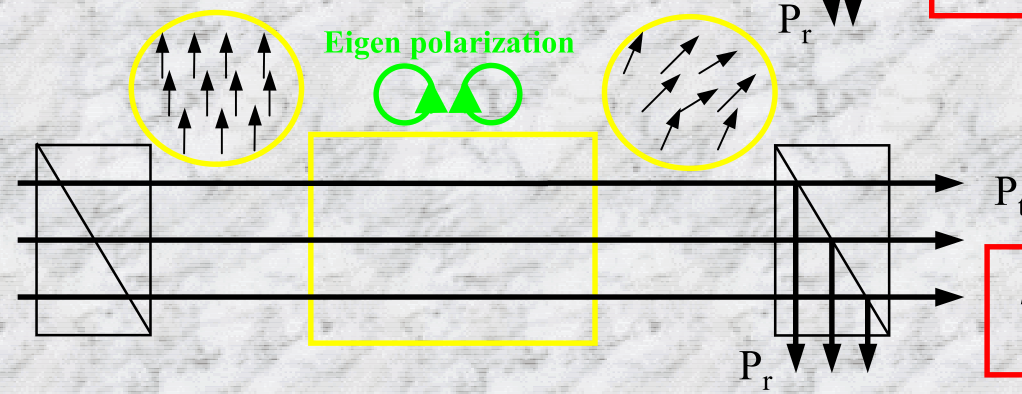
Three physical mechanisms of influence upon laser radiation:

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



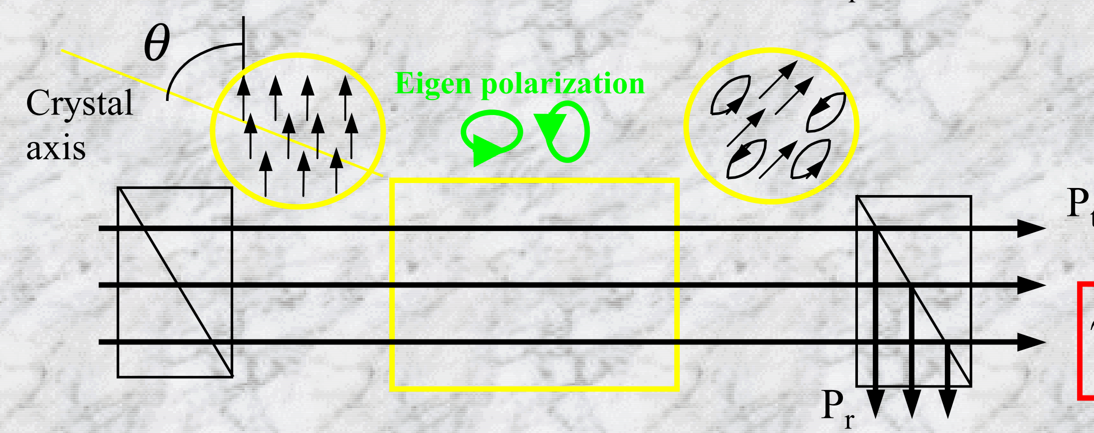
$$\gamma \equiv \frac{P_t}{P_t + P_r} = 0$$

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



$$\gamma_V = \gamma_V(\delta_0)$$

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



$$\gamma_P = \gamma_P(\theta)$$

I. Comparison 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.

$$\gamma_P^{\min} = \left[\frac{L\alpha P_0 Q}{\lambda\kappa}\right]^2 \cdot \frac{A_1}{\pi^2}$$

$$\gamma_V^{\min} = \left[\frac{\alpha P_0}{16\cdot\kappa}\cdot\frac{1}{V}\frac{dV}{dT}\right]^2 \cdot A_3$$

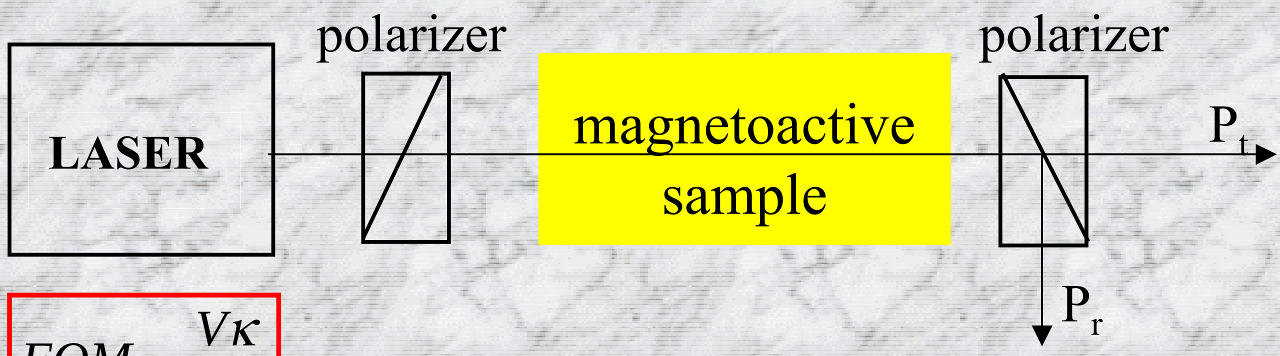
Here indexes "min" indicate values of γ_P and γ_V obtained at optimum values of θ and δ_0, respectively,

P_0 - laser power	Q – thermo-optic constant
L - length of the element	V - Verdet constant
α - absorption	A_1=0.137
κ - thermoconductivity	A_2=0.268

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

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

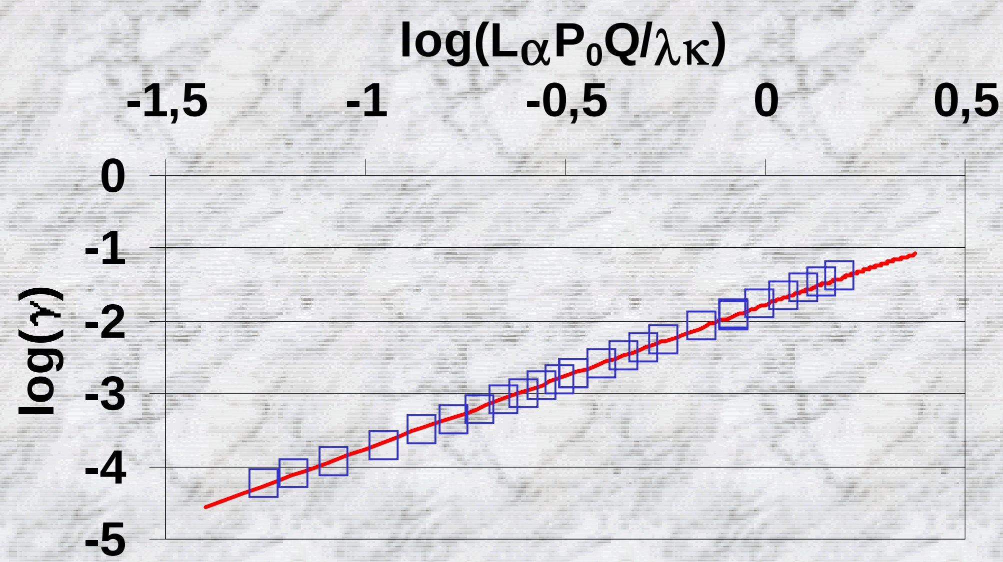
II. Measurements of thermooptic characteristics. Glasses



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

$$\gamma = 0.017 \cdot \left[\frac{L\alpha P_0 Q}{\lambda \kappa} \right]^2$$

$$FOM = \frac{V\kappa}{\alpha Q}$$



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

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

II. Measurements of thermooptic characteristics. TGG

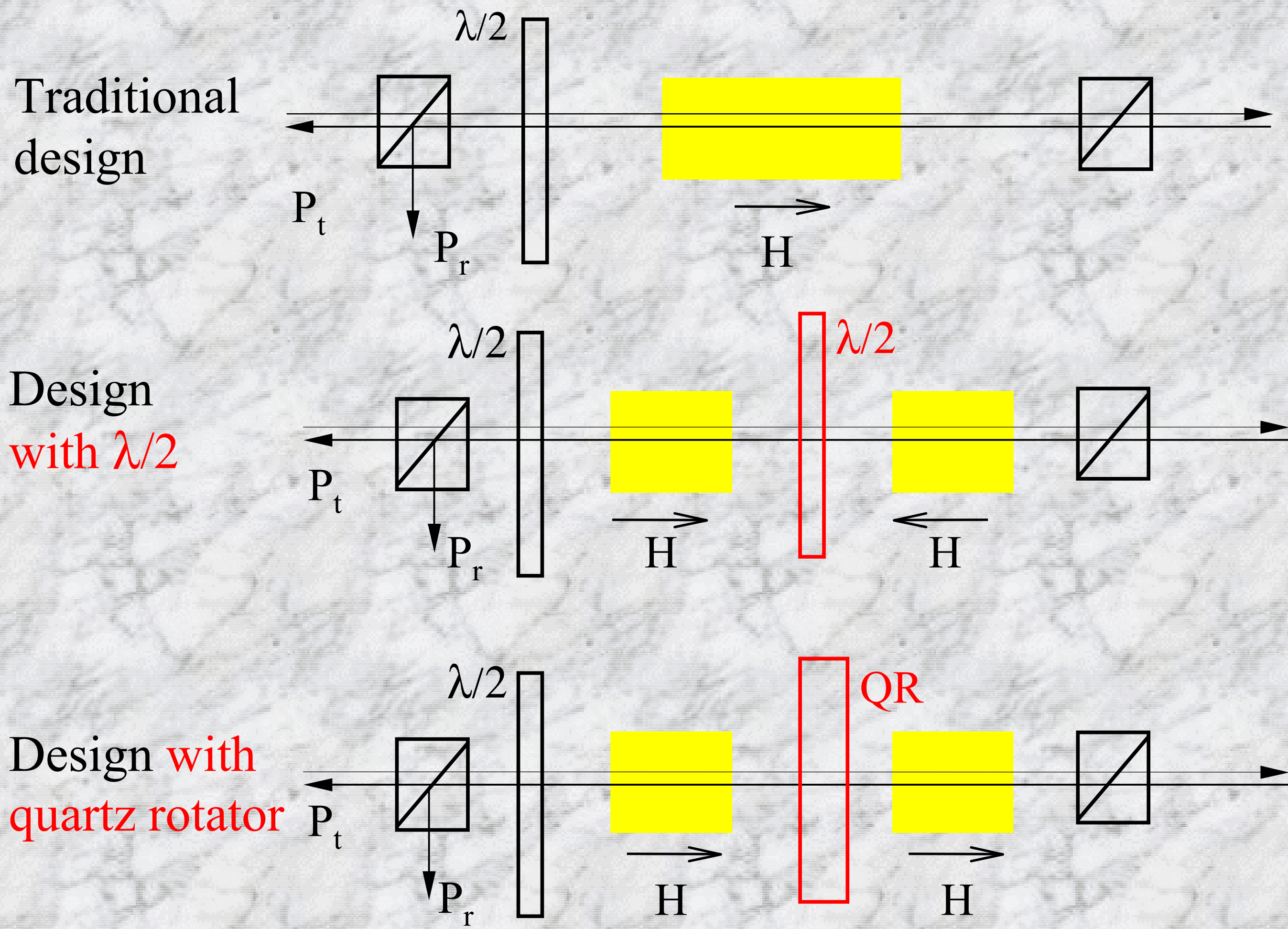
No	Diameter (length), mm	orientation	vendor	λ, nm	$Q\alpha$, 10^{-7}/Км	ξ
1	15 (36)	[111]	Litton (USA)	1080	11	-
2	15 (36)	[111]	Litton (USA)	1080	3.7	-
3	15 (36)	[111]	Litton (USA)	1080	9.3	-
4	10 (20)	[111]	Litton (USA)	1053 1080	6.0 6.2	- -
5	5 (54)	[111]	OFR (USA)	1053	3.2	-
6	5.5 (29)	[111]	Deltronix (USA)	1053	5.2	-
7	13 (20)	[001]	EOT (USA)	1053 1080	5.4 6.5	2.3 2.2
8	11 (11)	[001]	Lynx (Russia)	1053	7.7	2.2
9	11 (11)	[001]	Lynx (Russia)	1053	7.0	2.3
10	11 (11)	[001]	Lynx (Russia)	1053	7.8	2.1

[001]-orientation is the best for traditional design and [111] is the best for novel design.

III. Novel two-element Faraday isolator designs. Idea.

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.



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

III. Novel two-element Faraday isolator designs.

Theoretical comparison with the traditional design.

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

$$\gamma_{\min L} \cong 0.846 \cdot 10^{-4} \xi^2 p^4$$

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

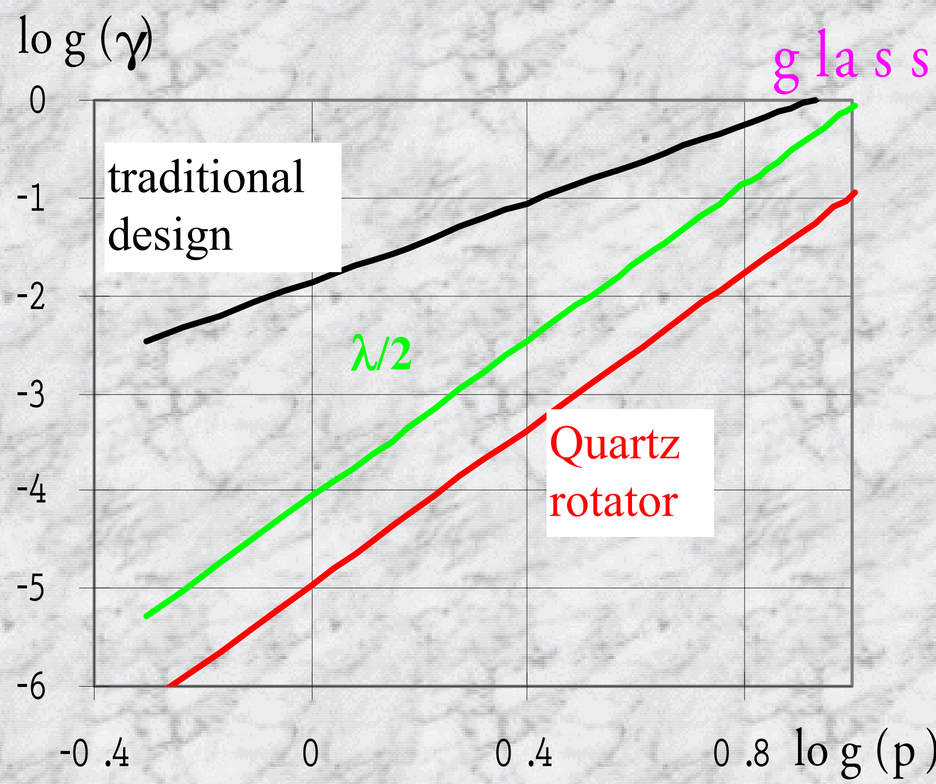
$$p = \frac{L}{\lambda} \frac{\alpha Q}{\kappa} P_0$$

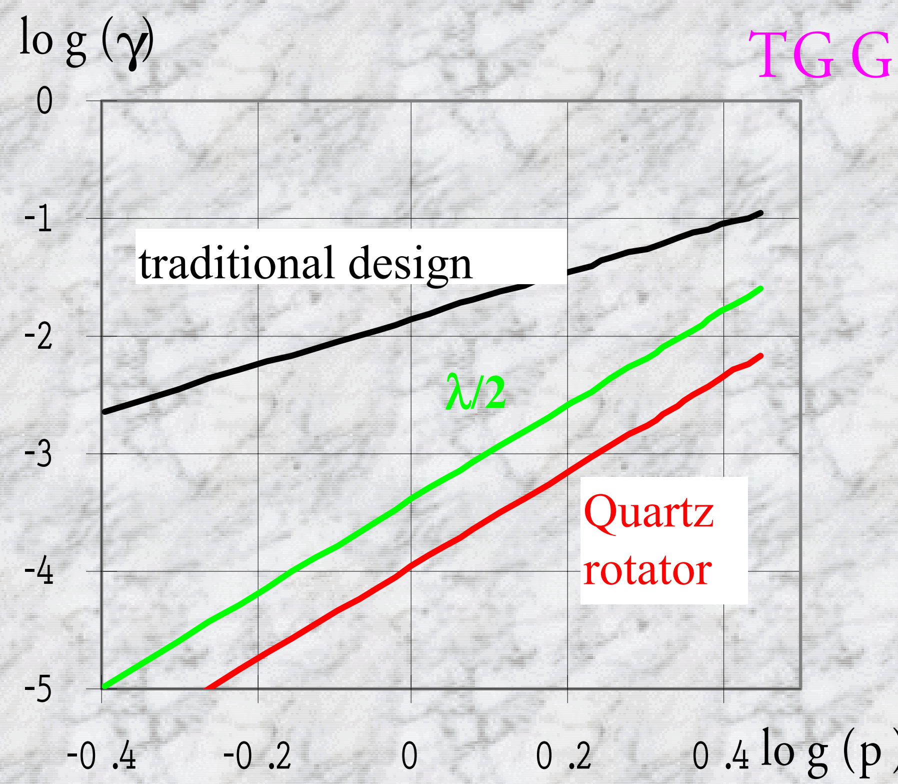
parameter p characterizes the force of the photoelastic effect.

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

ξ=1 (glass) ξ=2.2 (TGG)

At given ξ the isolation ratio is completely determined by parameter p.

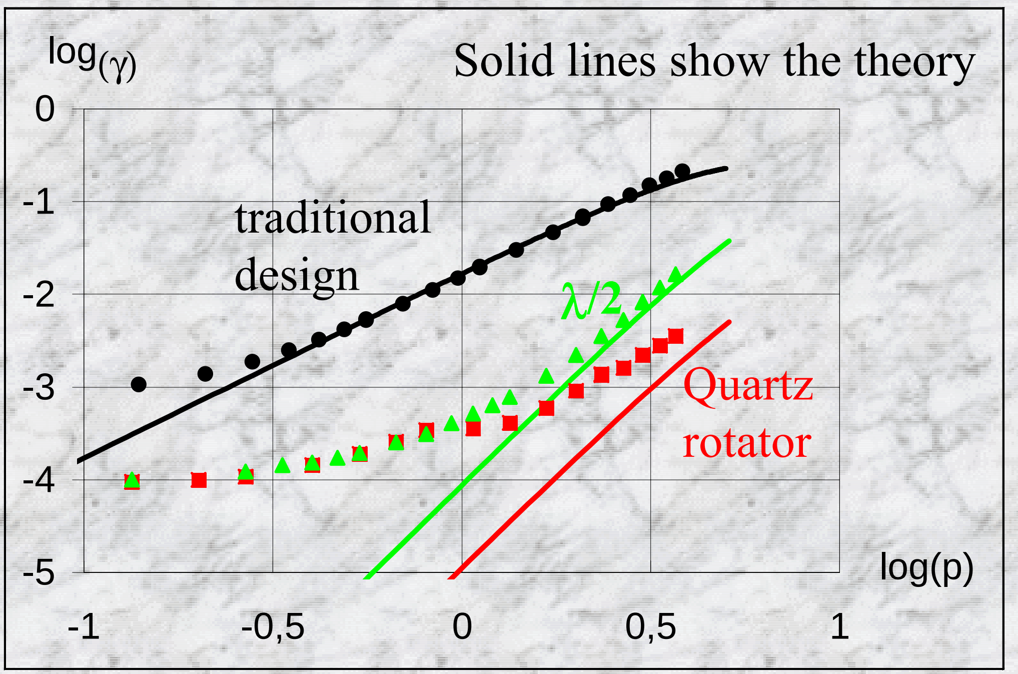




III. Novel two-element Faraday isolator designs.

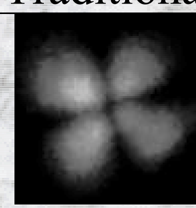
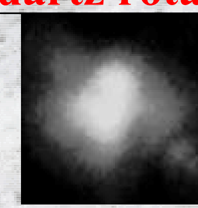
Experiments with glass.

λ=532nm	CW Nd:YAG laser	power up to 5.5 W
2 mm dia. beam	glass	absorption (532nm)=0.05cm^{-1}



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

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:

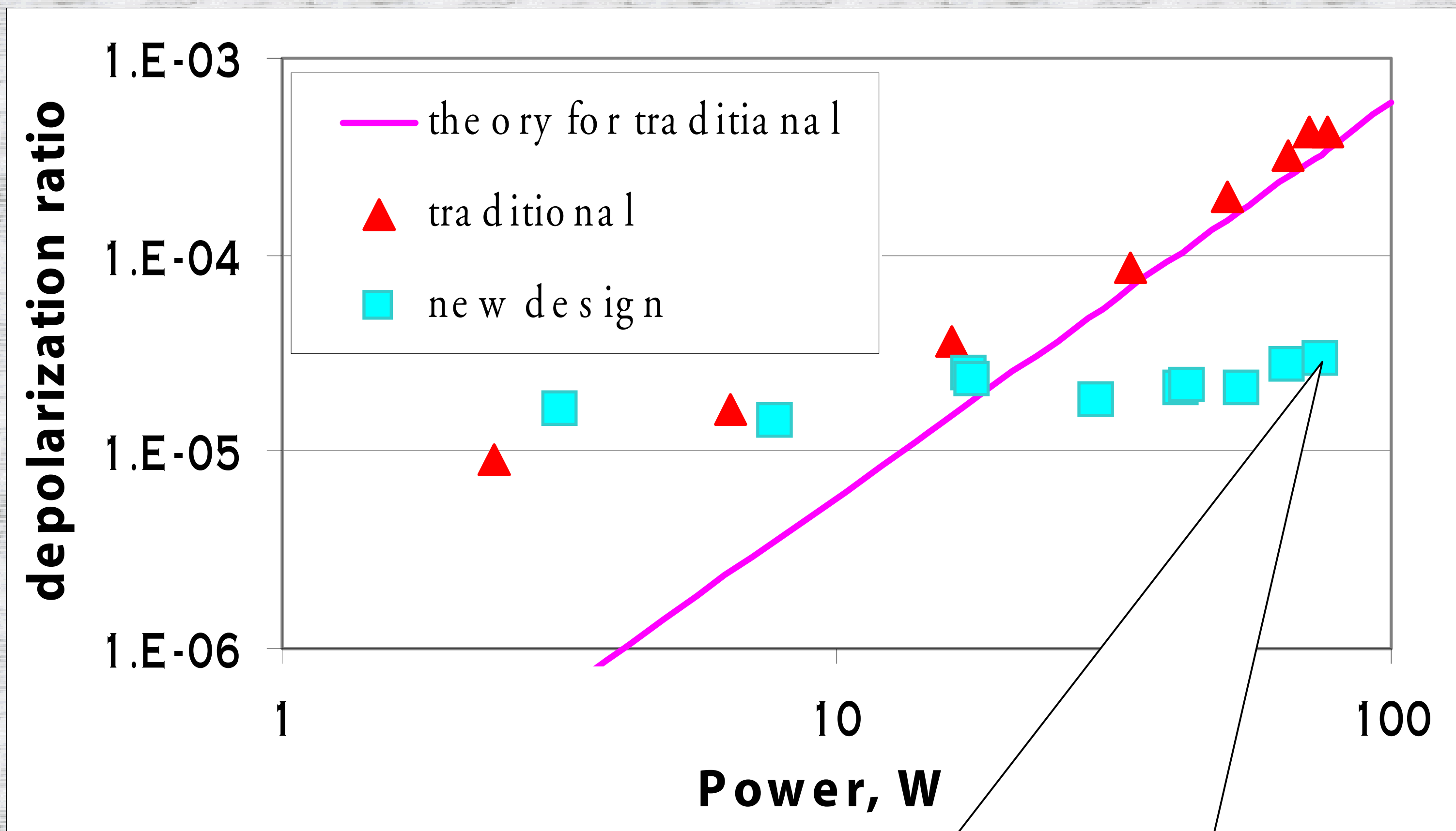
	Traditional	$\lambda/2$	**quartz rotator**
Images of the spatial profiles of the depolarized beams			
Theoretical prediction of period of the dependence of the local depolarization ratio on the polar angle	90^{o}	45^{o}	No angular dependence

III. Novel two-element Faraday isolator designs.

Experiments with TGG.

λ=1054nm **CW Nd:YLF laser** **power up to 55 W**

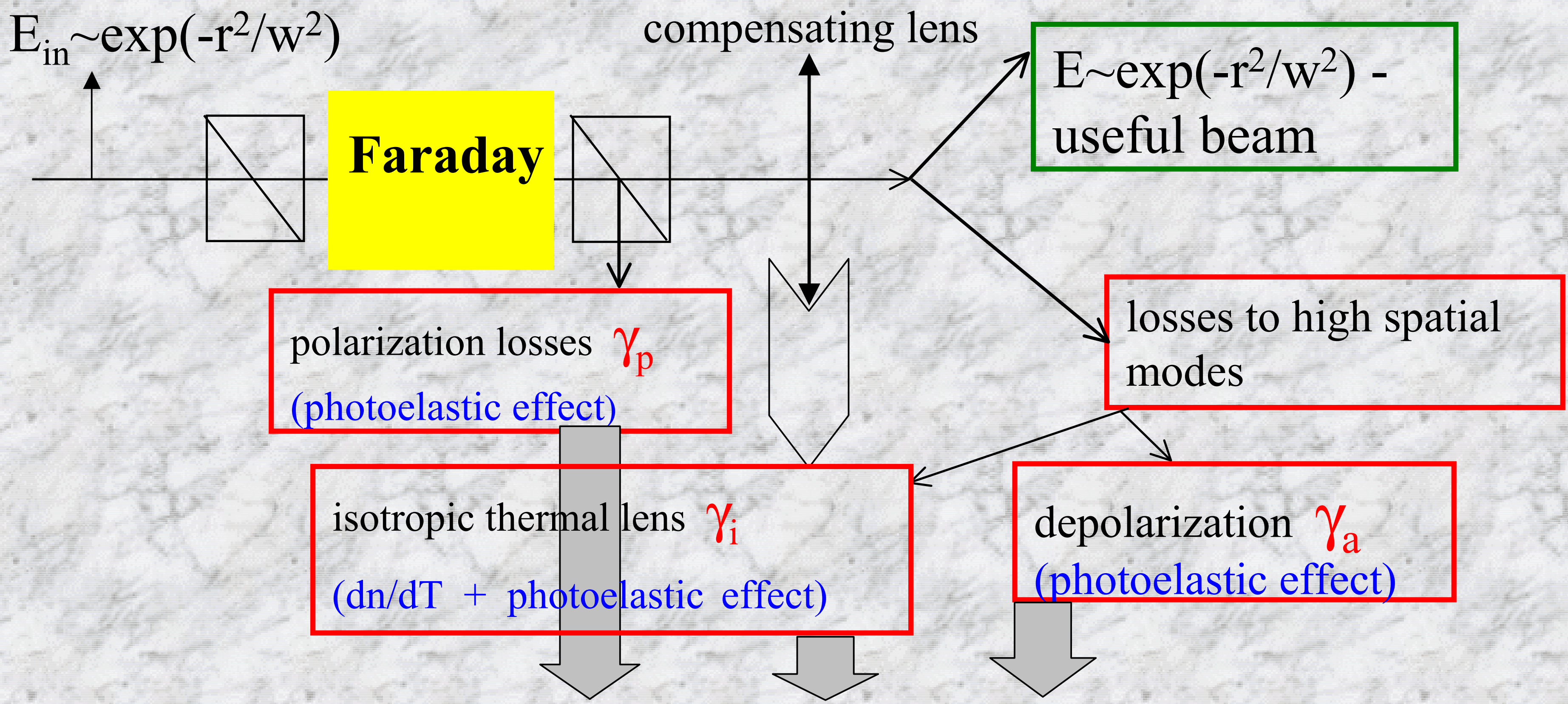
2 mm dia. Gaussian beam **TGG**



45dB isolation ratio at 100W laser power

III. Novel two-element Faraday isolator designs.

First pass losses.



$$\gamma_{total\ 0,L,R} = \gamma_{p\,0,L,R} + \gamma_i + \gamma_{a\,0,L,R}$$

$$\gamma_{p0} = p^2 \frac{A_1}{\pi^2}\xi_a^2 \qquad \gamma_{pL} = \frac{p^2 A_1}{\pi^2}\begin{cases}(2-\pi/2)\left(\xi_a^2+1\right) & \xi_a^2 > 1.3\\ 2(2-\sqrt{2}) & \xi_a^2 < 1.3\end{cases} \qquad \gamma_{pR} = \frac{p^2 A_1}{\pi^2}\left(2-\sqrt{2}\right) \qquad \gamma_i = \frac{A_{3,4}}{4}\left(\frac{L}{\lambda}\frac{\alpha P}{\kappa}P_0\right)^2$$

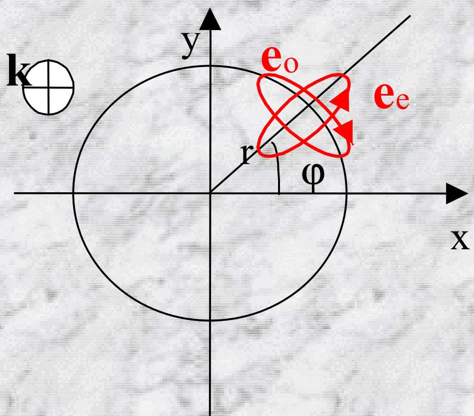
$$\gamma_{a0} = p^2 \cdot \frac{A_1}{\pi^2} \qquad \gamma_{aL} = 0 \qquad \gamma_{aR} = \frac{p^2 A_1}{\pi^2}\left(2-\sqrt{2}\right)\xi_a^2 \qquad P = \frac{dn}{dT} - \left(\frac{1}{L}\frac{dL}{dT}\right)\frac{n_0^3}{4}\frac{1+\nu}{1-\nu}\cdot(p_{11}+p_{12})$$

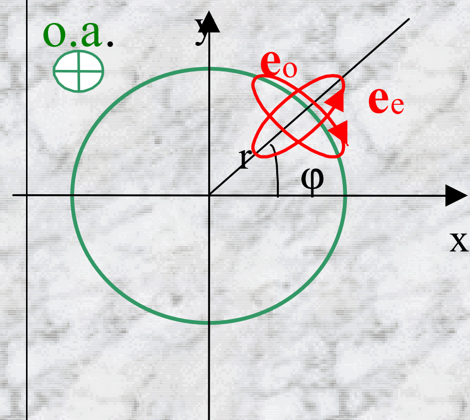
A_3=0.268 - no compensating lens A_4=0.0177 - optimal compensating lens

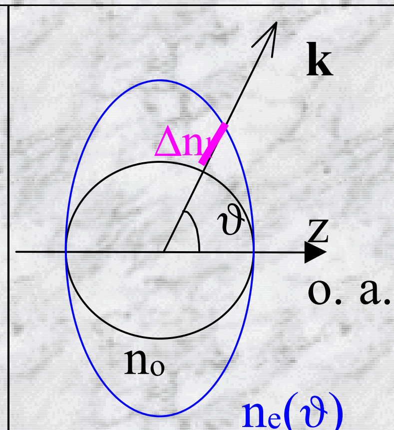
IV. Novel one-element Faraday isolator design.

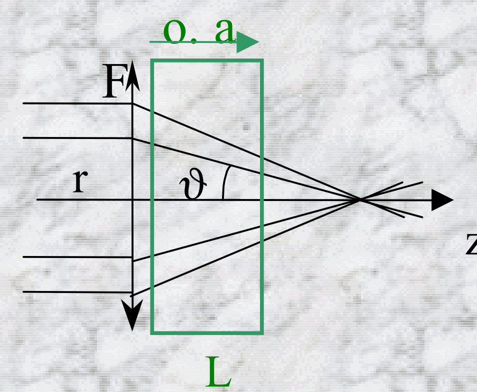
Diverging beam in quartz - how it works.

Heated sample (in magnetic field)	Crystal quartz.	









$$\Psi_T = \varphi \quad \xleftrightarrow{1} \quad \Psi_{cr} = \varphi$$

$$\Delta n_l \approx A(n_0 - n_e)\vartheta^2 \qquad \vartheta \approx \frac{r}{F}$$

$$\delta_{T\_l} = C \cdot QP \begin{cases} r^2 & step-shaped \\ f(r^2, r_0^2) & Gaussian \end{cases}$$

2

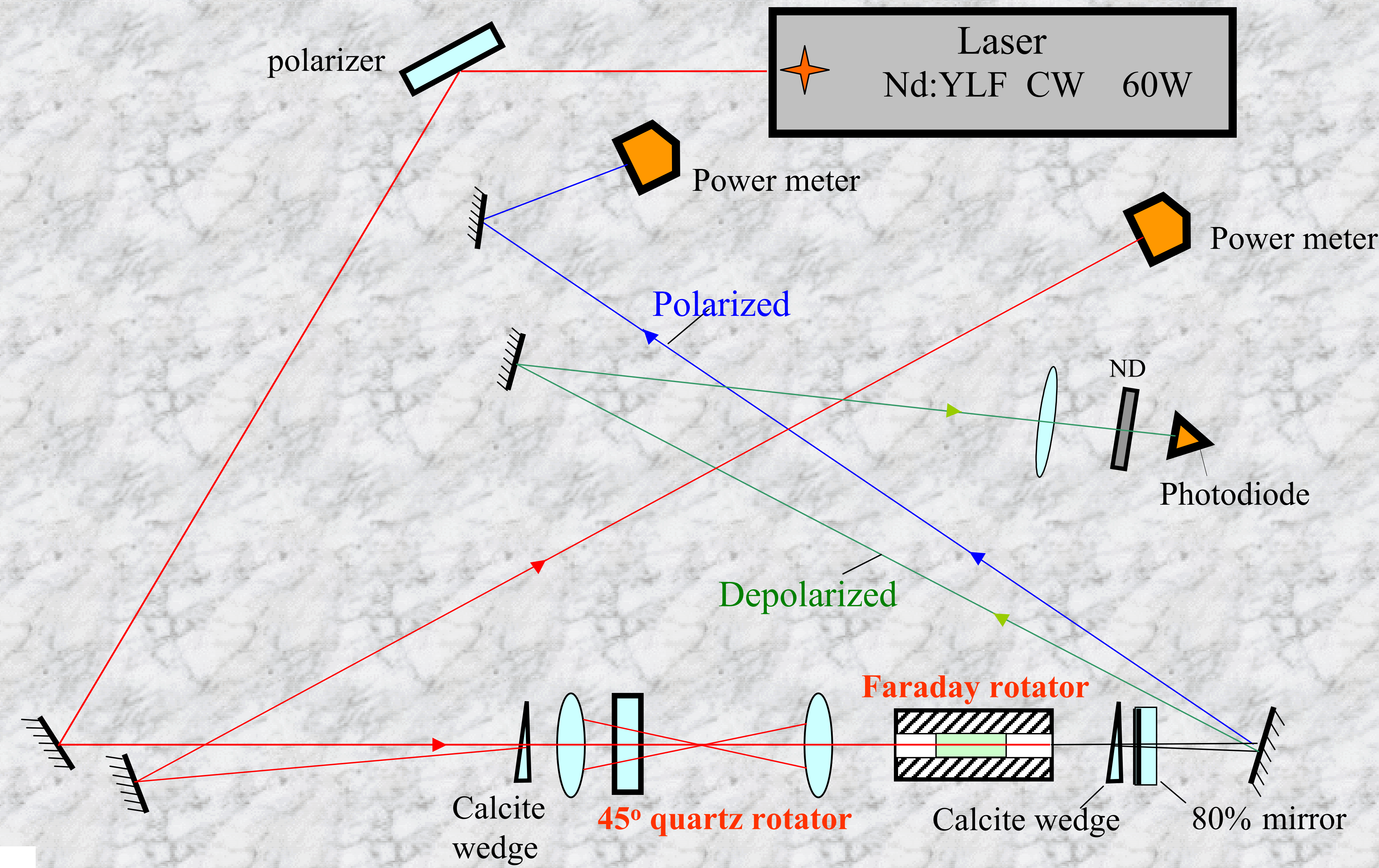
$$\delta_{cr\_l} = \Delta nkL \approx BL(n_0 - n_e)\frac{r^2}{F^2}$$

$$f(r^2, r_0^2) = 1 - \frac{1 - \exp(-\frac{r^2}{r_0^2})}{\frac{r^2}{r_0^2}}$$

$$\delta_c = 2VLH = \pm\pi/2 \quad \xleftrightarrow{3} \quad \delta_c = kL(n_{left} - n_{right}) = \pm\pi/2$$

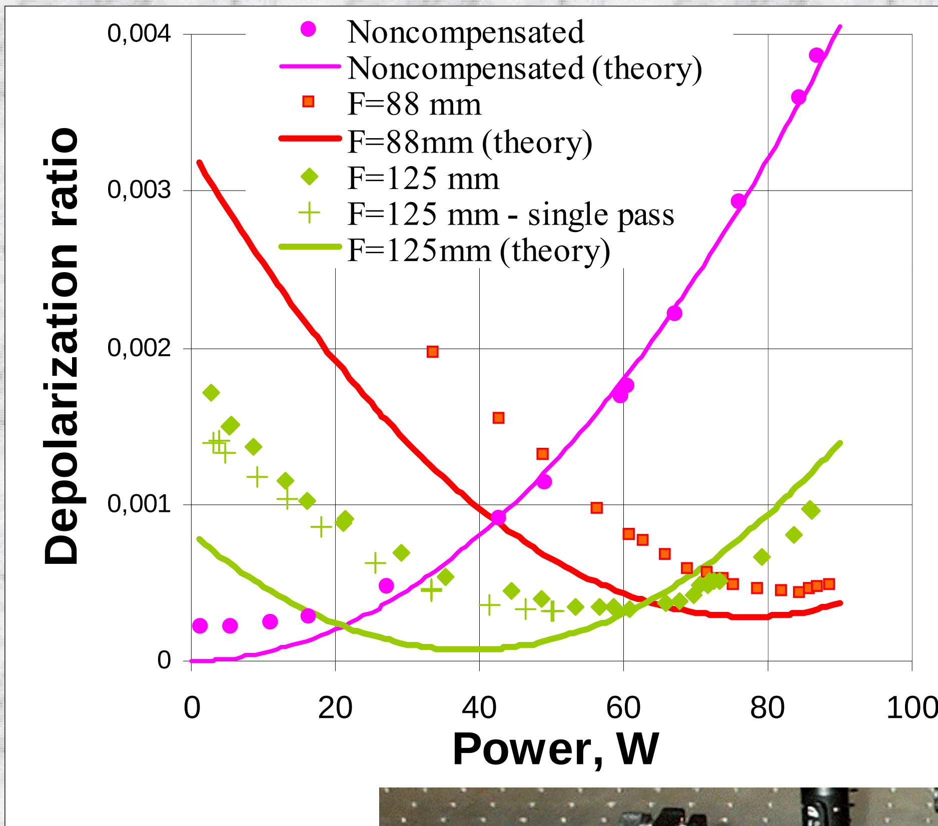
IV. Novel one-element Faraday isolator design.

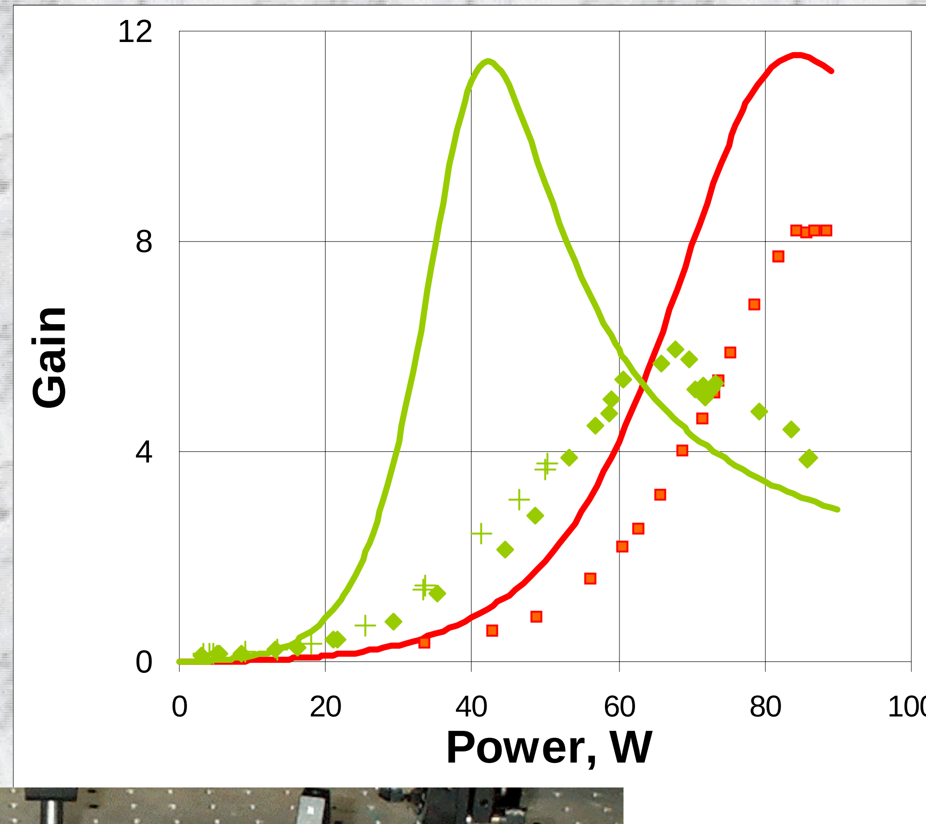
Experimental setup.

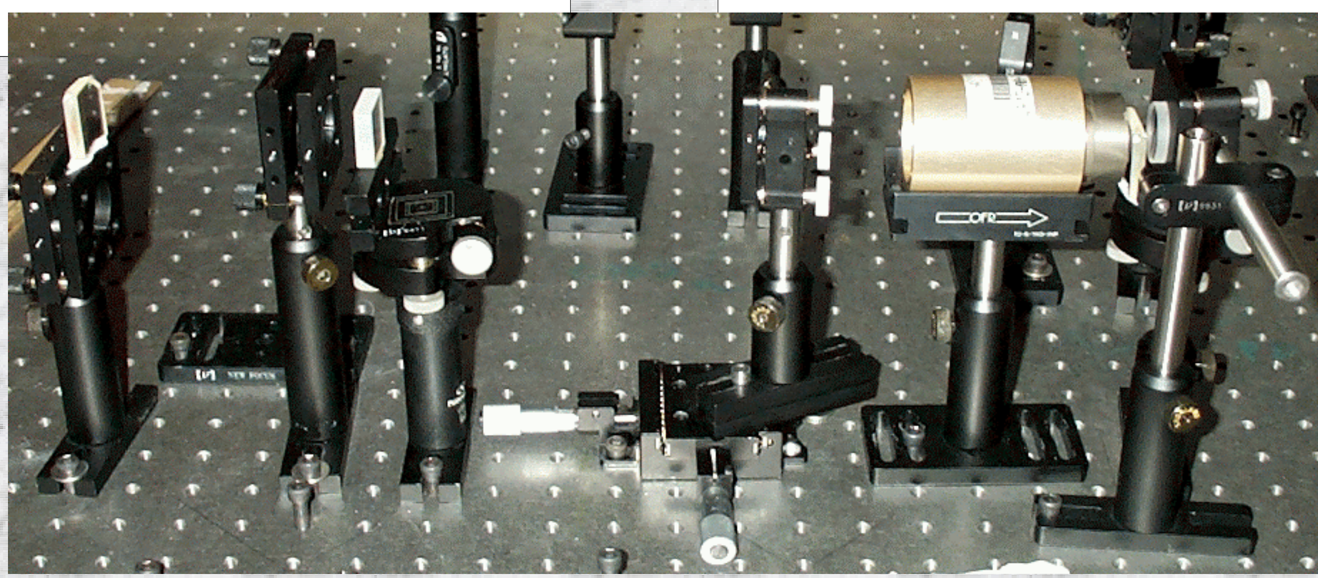


IV. Novel one-element Faraday isolator design.

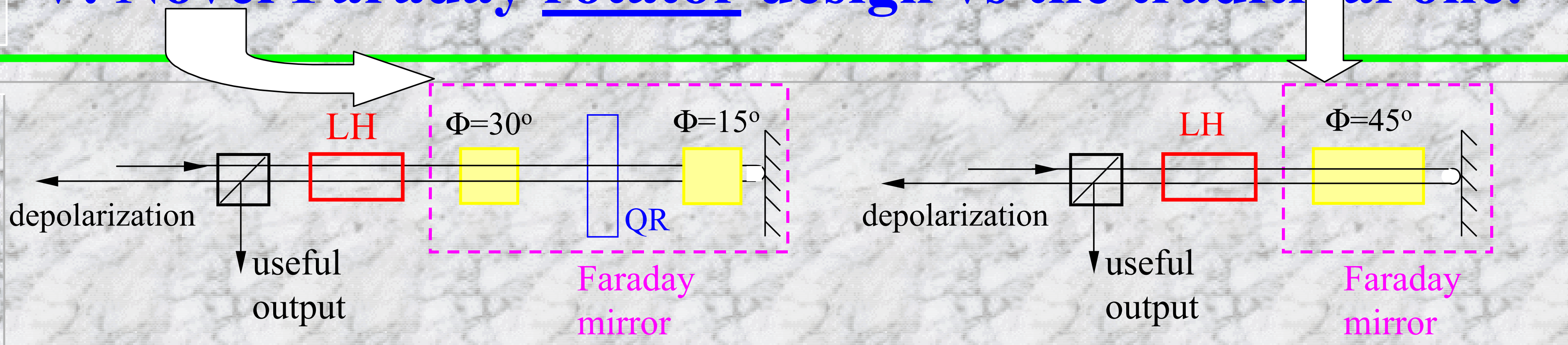
Experimental results.





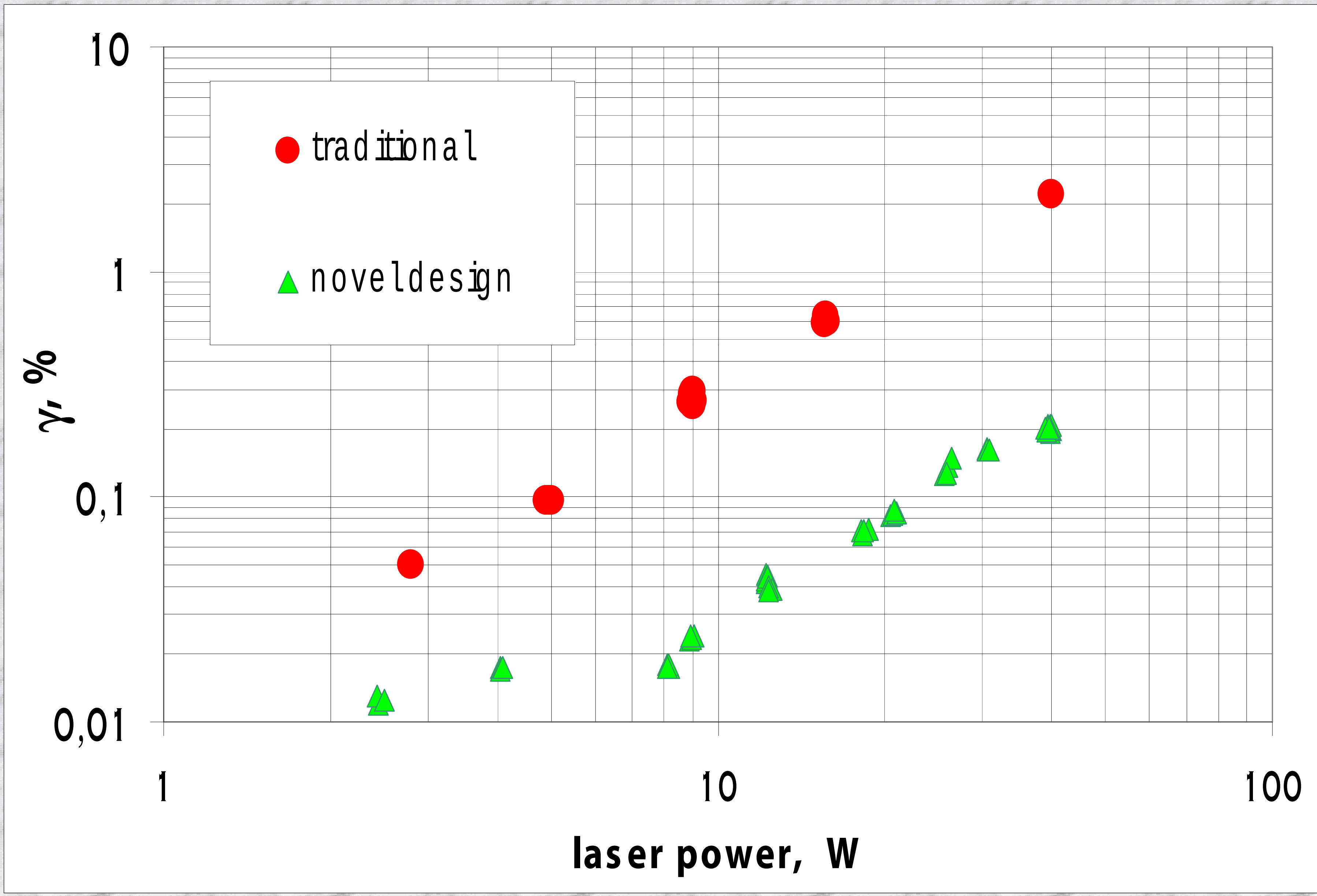


V. Novel Faraday rotator design vs the traditinal one.

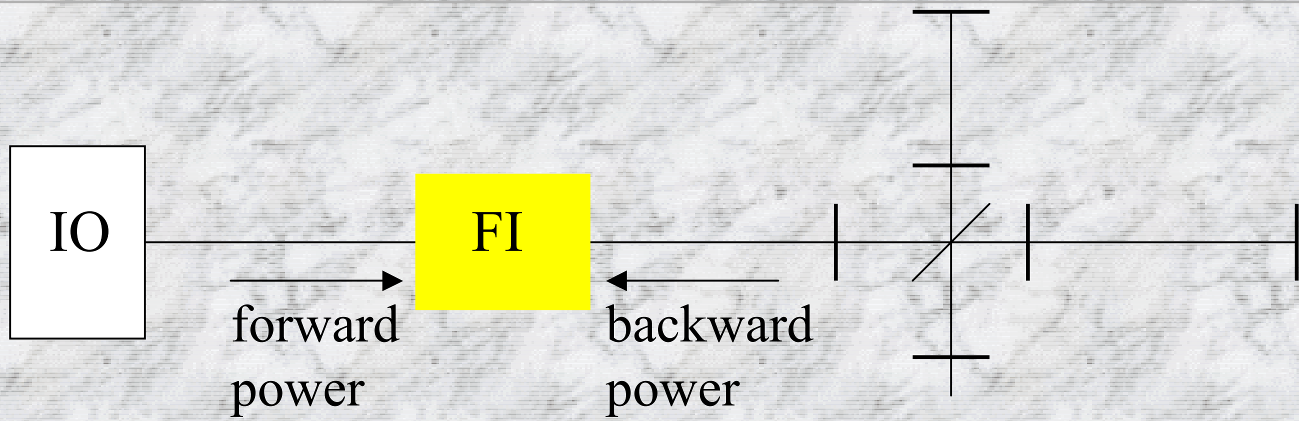


V. Novel Faraday rotator design vs the old one.

Experimental results.



VI. Faraday isolator at the unlocked IFO. Problem.



	forward, W	backward, W	total, W	τ
Normal regime. Steady-state regime with the locked IFO.	125	5	130	∞
Regime A. Power stored in the IFO is coming away from it into both IO and dark port.	125	125…500	250…625	ms
Regime B. Unlocked steady-state regime after power stored in the IFO has came away.	125	125	250	s…min
Regime C. Transient regime at the locking procedure.	0…125	0…125	0…250	ms...s

VI. Faraday isolator at the unlocked IFO.
Further investigation.

characteristic thermalization time - nanoseconds or less
characteristic mechanical stress time (beam radius/speed of sound) - microseconds
characteristic time of thermo-diffusion - tenths of second.

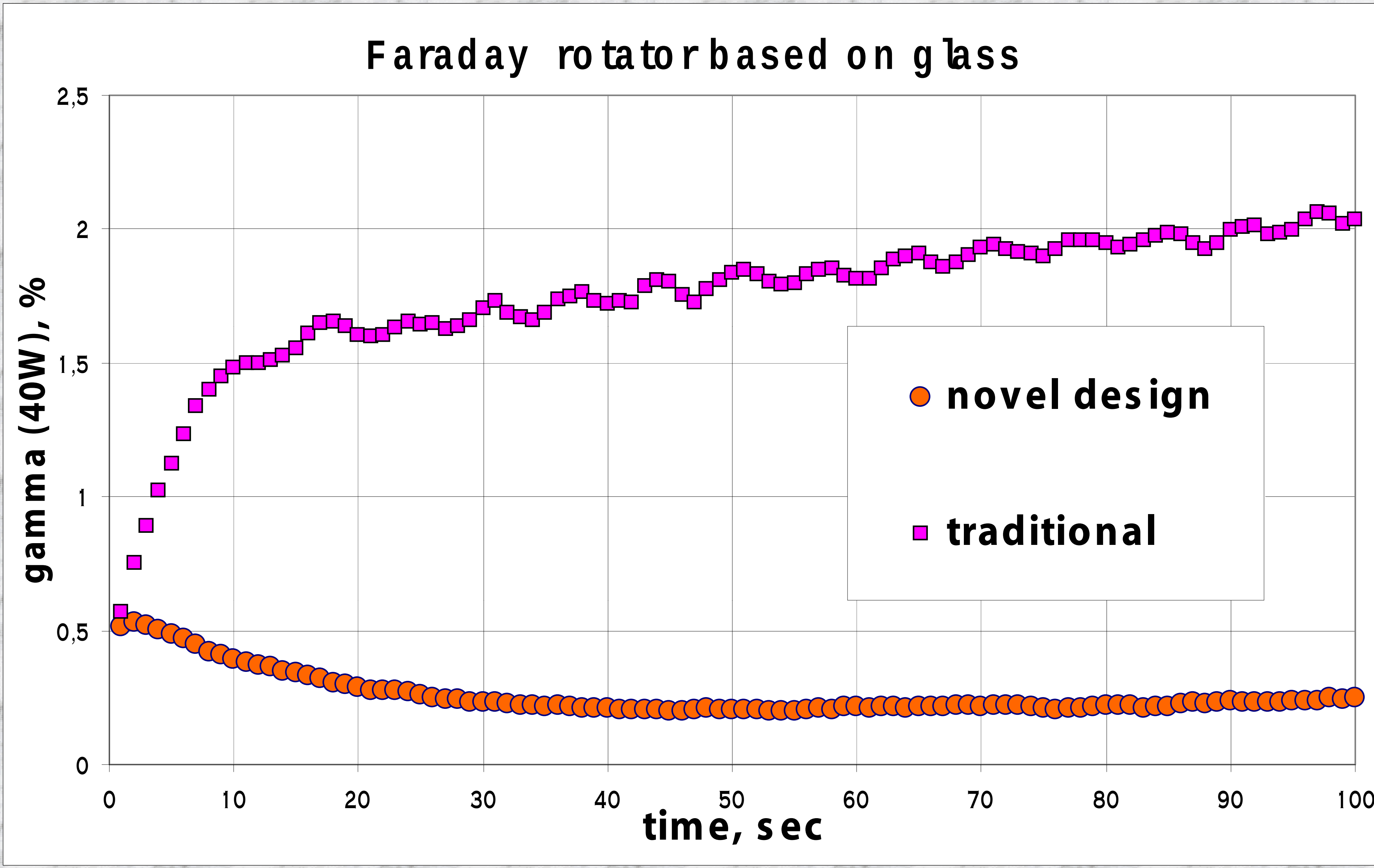
All self-induced effects (dn/dT, dV/dT, photoelastic effect) will take place, and not in steady-state regime only.

The following R&D should be done to make sure
the FI will work safety in LIGO II even when interferometer is unlocked.

- **Computer simulation of different scenarios of unlocking and locking processes in order to define the worst condition in LIGO II which FI can come in.**
- **To complete the FI specification from the viewpoint of unlocked IFO.**
- **Investigation of characteristics of all existing FI designs at the conditions defined above (#1) and comparison them to the above specification (#2).**
- **If the specification is not completely satisfied by any of FI designs, searching a solution (develop new FI designs, use a Pockels shutter and etc.).**
- **Formulation of recommendations for the locking procedure taking into account non steady-state behavior of FI.**

VI. Faraday isolator at the unlocked IFO.

First measurements.



Conclusions

- The high power induced depolarization ratio is a sum of two terms which represent two effects: the temperature dependence of the Verdet constant and, more efficient, the birefringence due to the photoelastic effect of thermal strains.
- The isolation ratio is determined by two dimensionless parameters: normalized laser power *p* and combination of photoelastic coefficients ξ.
- Thermo-optic caracteristics of TGG and number of magnetoactive glasses were measured.
- It is shown that [001]-orientation of TGG is the best for traditional design of Faraday isolator and [111] is the best for novel design.
- The isolation ratio of the both novel Faraday isolator designs is considerably higher than in the traditional one at any value of parameters p and ξ.
- Novel design with reciprocal rotator is the best from the viewpoint of isolation ratio and first pass losses and distortions as well. 45dB isolation ratio at 100W laser power is implemented.
- Compensation of birefringence in laser head by means of new Faraday rotator is much more efficient at high laser power.
- Behavior of Faraday isolator at the unlocked IFO should be investigated.
- High efficient Faraday isolator and rotator for 1kW power may be implemented.