Faraday Isolators and Electro-optical Modulators:

A Progress report

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LSC-Meeting
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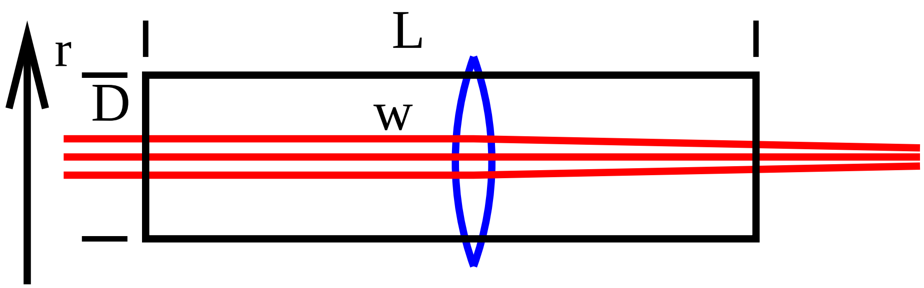
Temperature Distribution:



- $w \ll D \ll L$
- TEM_{00} **Input Beam**

$$\Delta T(r) = \frac{P_{abs}}{4\pi k_{th}} \left[\sum_{n=0}^{\inf} \frac{\left(-2\frac{r^2}{w^2}\right)^n}{n!n} \right]$$

THERMAL LENSING

3 different effects create thermal lensing:

- **thermal changes in index of refraction** dn/dT
- **refractive index changes due to stress**
- **thermal expansion (curvature in the surfaces)**

$$\begin{aligned}\Delta\Lambda(r) &= \Delta\Lambda_{thermal}(r) + \Delta\Lambda_{stress}(r) + \Delta\Lambda_{expansion}(r) \\ &\approx \Delta T(r) L \underbrace{\left(\frac{dn}{dT} - \frac{n^3}{2}\rho_{12}\alpha\right)}_{\frac{dn}{dT}_{eff}} + 2\alpha n w \Delta T(r)^{a}\end{aligned}$$

Most cases: $\Delta\Lambda_{thermal}(r) > \Delta\Lambda_{expansion}(r)$

[a] Mansell et.al. Appl.Optics 40(3) (2001)

LIMITS ON THERMAL LENSING

First Order:

- **Simple Lens:**

$$\Delta T(w) = \Delta T(0) - \Delta T(r = w) \approx 0.1 \frac{\alpha P}{k_{th}}$$

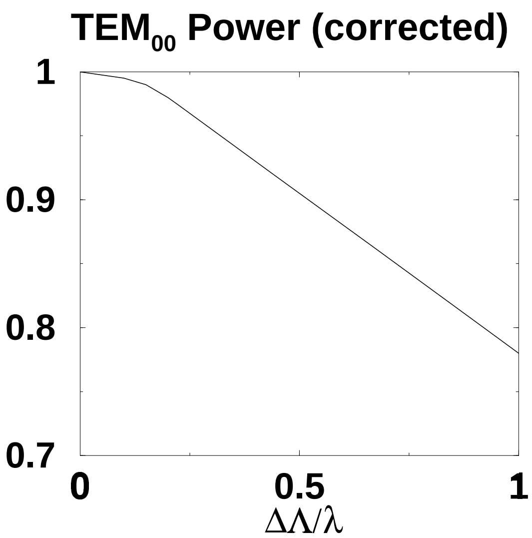
$$\Delta\Lambda(w) = \frac{dn}{dT} L \Delta T(w) \approx 0.1 \frac{dn}{dT} \frac{L P_{abs}}{k_{th}} \qquad \Rightarrow \qquad R_{th} = \frac{w^2}{2\Delta\Lambda(w)}$$

Remarks:

- **Can be included in mode matching calculations**
- **add some uncertainty in the mode matching calculations**
- **mode matching depends now on laser power**
- **bad mode matching for low power alignment states**

LIMITS ON THERMAL LENSING

Second Order:

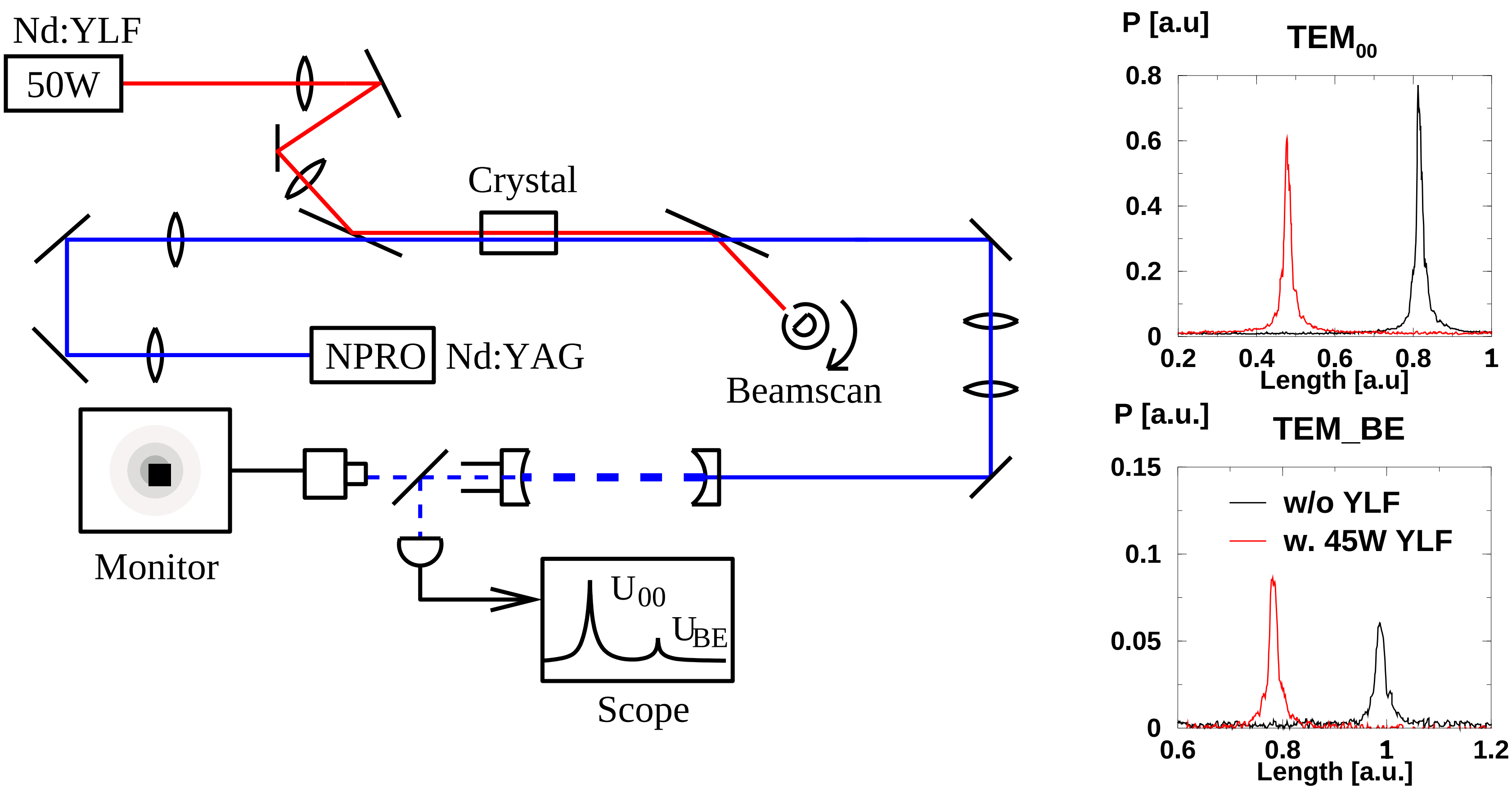


- **Higher Order Modes:**

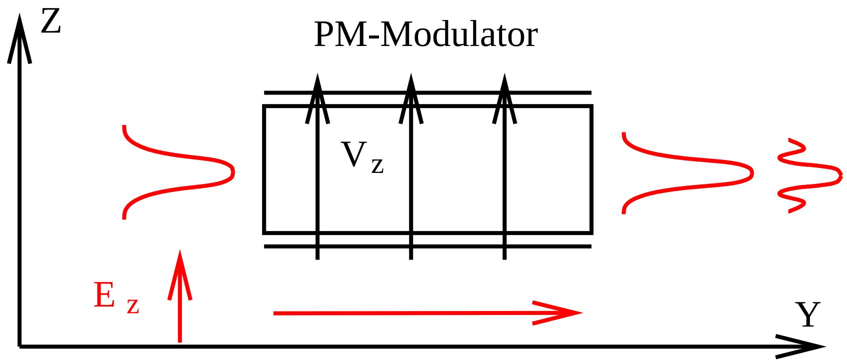
$$\Delta\Lambda(w) < \lambda/6 \;\Rightarrow\; P_{HO} \approx 0$$
$$\Delta\Lambda(w) > \lambda/6 \;\Rightarrow\; P_{HO} \approx 0.24 * \frac{\Delta\Lambda(w)}{\lambda} - 0.03$$

- **Allow 3% higher order modes in each EOM $\Rightarrow$ 3 EOMs $\approx$ 10% losses**
- $> 95\%$ **mode matching between MC and CO $\Rightarrow$ FI $<$ 4% HO-modes (1% goal)**

PUMP-PROBE-EXPERIMENT



MODULATORS: MATERIALS



- **Modulation Index scales with** $n^3 r_{nm}$
- **Thermal Problems scale with** $\frac{dn}{dT}\frac{\alpha}{\kappa}$
- **Figure of merit:** $\frac{n^3 r_{nm}\kappa}{\alpha dn/dT}$

Crystal	$n^3 r_{nm}[pm/V]$	$\frac{dn}{dT}\left[\frac{10^{-5}}{K}\right]$	$\kappa\left[\frac{W}{mK}\right]$	$\alpha[cm^{-1}]$	$\frac{n^3 r\kappa}{\alpha dn/dT}[10^{-14}Am]$	Φ_e
LiNb03	333[a]	3.8[a]	5.6[a]	$<$1.5e-3[a]	327	?
KTP	224[e]	0.83 [c]	13[e]	$<$1e-3[e]	3513	0.7
RTA	273[e]	?	?	$<$1e-3[e]	?	4e-3

LiNb03: k_y, E_z, $n_z = n_e + \Delta n$‘, $n_x == n_0 + \Delta n''$.
KTP: k_y, E_z: **KTiOPO$_4$**
RTA: k_y, E_z: **RbTiOAsO$_4$**

[a]: Crystal Technology, Inc.

[b]: Non linear optics Book, KTP: dn/dT=(1.7), 2.5,3.4 e-5 Kato, IEEE J. of QE 28(10) 1992)

[c]: Wiechman et.al. Opt. Lett. 18(15) (1993) (Sony)

[d]: Karlsson et.al. Opt. Lett. 24(5) (1999) (miss p_4 value, assumed $p_4 = 0$).

[e]: Stolzenberger @ Crystal Associates, Raicol crystals claims $< 50 ppm/cm$ for KTP

MODULATORS: RESULTS

Crystal	Pump[W]	P_{00}	P_{BE}	Ratio	P_{10}	$\frac{P_t}{P_r+P_t}$	Comments
bare beam	0	711±10	40±5	5.6%±1%	51±5	1.5e-4	
RTA (10mm)	0	722±10	33±5	4.6%±1%	40±5		no housing
RTA (10mm)	45	720±10	30±5	4.2%±1%	39±5	2e-4	“
$LiNbO_3$ (40mm)	0	740±10	41±5	5.5%±1%	40±5		no housing
$LiNbO_3$ (40mm)	45	641±10	52±5	8.1%±1%	22±5	1.6e-4	“
$LiNbO_3$ (40mm)	0	768±10	30±5	3.9%±1%	53±5		housing
$LiNbO_3$ (40mm)	45	605±10	110±5	18.2%±1.5%	33±5	6.7e-4	“

Thermal lens in RTA: invisible
Thermal lens in $LiNb0_3$, w/o housing: visible, but tolerable
Thermal lens in $LiNbO_3$, with housing: unacceptable

Guidelines for Design:

- **RTA (or RTP, KTA, KTP)**
- **Power management essential ⇒ Temperature stabilization with Peltier elements**
- **Cooperation with Quantum Technology (Lake Mary, FL) (?)**

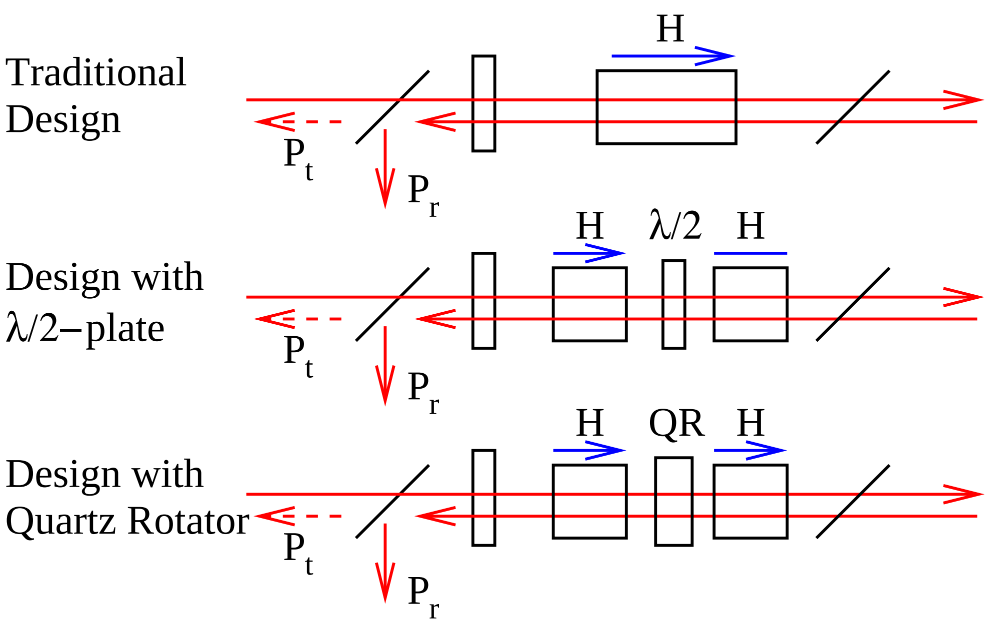
OPTICAL ISOLATION

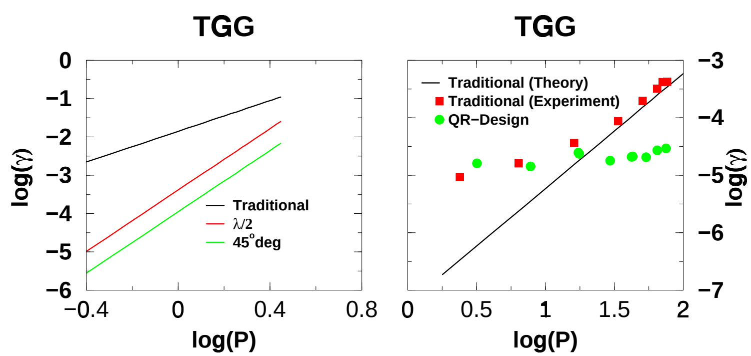
Two Problems:

1. **Birefringence $\Rightarrow$ reduces Isolation Ratio**
2. **Thermal lensing**

1. **two FR-crystal Design compensates birefringence (Efim Khazanov et. al. (LSC-conference 03/01)**
2. **negative thermal lens compensates positive thermal lens (UF-Design)**

Optical Isolation

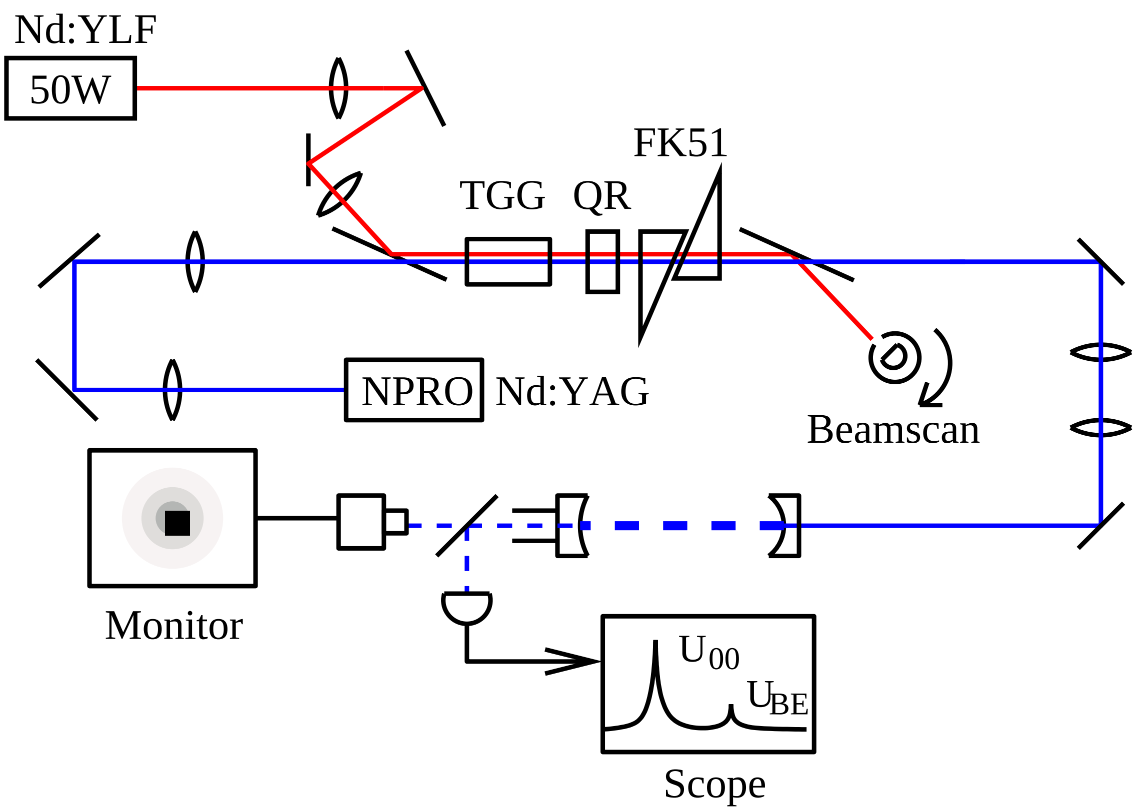


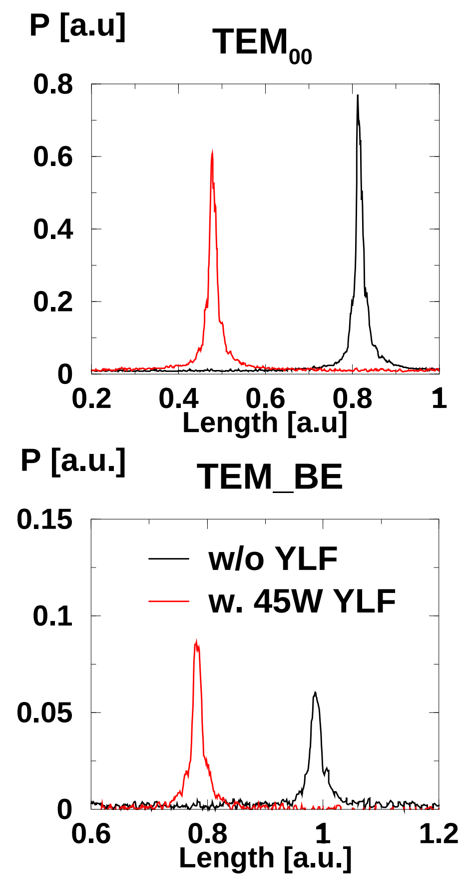


- **45dB isolation at 50W (100W)**

Source: Efim Khazanov et. al. (LSC-conference 03/01)

Pump-Probe-Experiment





Thermal Lensing and Compensation

P	P_{00}	P_{BE}	Ratio	P_{10}	$\frac{P_r}{P_r+P_t}$
0W	771	17	2.2%	62	
45W (no FK51)	620	143	23%	16	2.1e-4
0W (w.FK51)	674	27	4.0%	42	
45W (w. FK51)	641	17	2.6%	43	8.3e-4

20% thermal lensing $\Rightarrow$ 2% HO-modes
150W $\Rightarrow$ 12% HO-modes (w/o) compensator

Result

- **Thermal lensing could be reduced by a factor 8**
- **beam distortions/higher order modes ?**
  (Experiment still limited by elipticity in input beam)

Summary Isolator:

- **Two Element Isolator compensates birefringence**
- **dn/dT $<$ 0 element compensates thermal lensing**
- **Start to look into different materials (BBO ?)**

Thermal Lensing measurements and Compensation:

G.M., Rupal Amin, Donovan McFeron, Ramsey Lundock
David Guagliardo, David Tanner, David Reitze
University of Florida

Birefringence compensation - New Faraday Design

Efim Khazanov,Nikolay Andreev, Oleg Palashov, Alexander Sergeev
Inst. of Applied Physics, N. Novgorod, Russia

Theory:

Mansell, Hennawi, Gustafson, Fejer, Byer, Clubley, Yoshida, Reitze
Appl. Opt. 40(3), pg. 366 (2001)

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