Modulators and Faraday isolators
- what we learnt from LIGO I –

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- Contents -

- Thermal lens in EOM and Faraday Isolator
- RFAM
- Isolation at high power

LIGO-G000146-00-D

Experimental setup for EOM

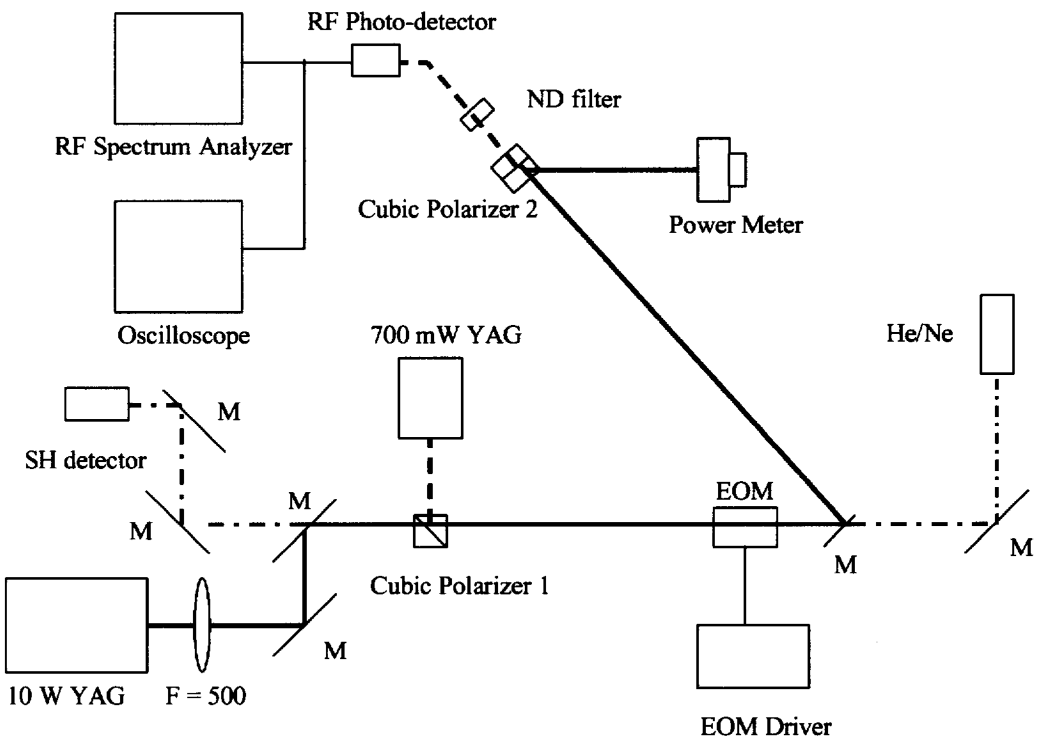

Fig.1 Experimental arrangement

Shack-Hartmann wavefront detector

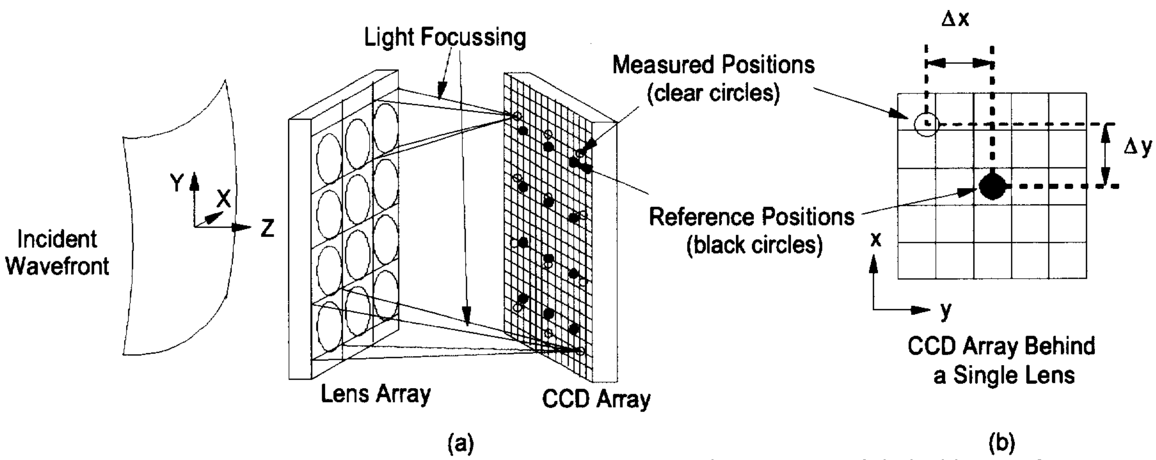

Figure 1 - Schematic of the operation of the Shack-Hartmann wavefront sensor. Light incident on the sensor propagates along the z-axis, as shown in (a). The CCD array and the lens array are shown tilted relative to each other only to illustrate the operation of the device. In reality, the lens array and CCD array are parallel. The measured position change of the focal spots illustrated in (b) as Δx and Δy gives the average wavefront tilt over a lens aperture when divided by the separation between the lens array and the CCD.

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Thermal wavefront distortion in EOM (1)

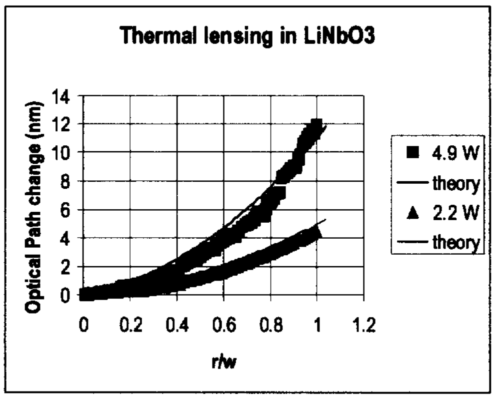


Fig.3 Thermal lens

$$\Delta OPL(r) \approx 0.07741\frac{P_{abs}L}{k_{th}}\left(\frac{dn}{dT}+\alpha n\right)\left(\frac{r^2}{w^2}+0.4\frac{r}{w}\right) \quad 1)$$

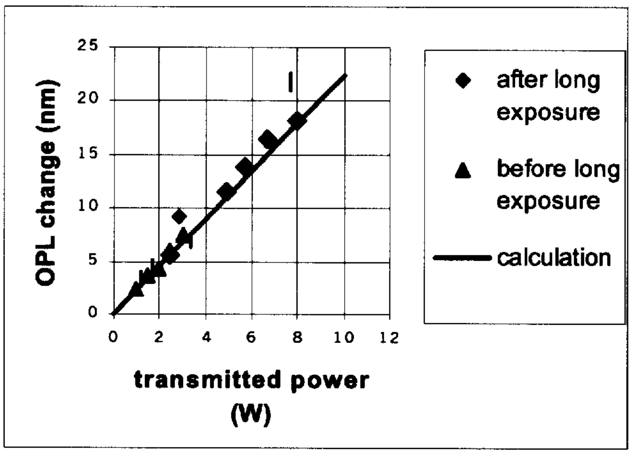
1) Justin Mansell, private communication (1997)

$$\Delta T(r) = \left|T(r) - T_0\right| = \frac{-aP}{4\pi k_{th}}\left(\Gamma + \ln\left[2\left(\frac{r}{w}\right)^2\right] + E_1\left[2\left(\frac{r}{w}\right)^2\right]\right) \quad 2)$$

$$= \frac{aP}{4\pi k_{th}}\left(\sum_{n=0}^{\infty}\frac{(-1)^n\left(2\frac{r^2}{w^2}\right)^n}{n\cdot n!}\right)$$

2) K. A. Strain, K. Danzmann, J. Mizuno, P.G. Nelson, A. Rudiger, R. Schilling, and W. Winkler. "Thermal lensing in recycling interferometric gravitational wave detectors," Phys. Lett. A, **194**, 124-132 (1994).

Thermal wavefront distortion in EOM (2)



Thermal lens before and after long exposure (r=w)

$$\Delta OPL(r) \approx 0.07741\frac{P_{abs}L}{k_{th}}\left(\frac{dn}{dT}+\alpha n\right)\left(\frac{r^2}{w^2}+0.4\frac{r}{w}\right) \quad 1)$$

ΔOPL(w) = const * P

const = 2.2 x 10^{-9} (m/W)

P_{abs}= absorption coeff * P

Thermal wavefront distortion in EOM (3)

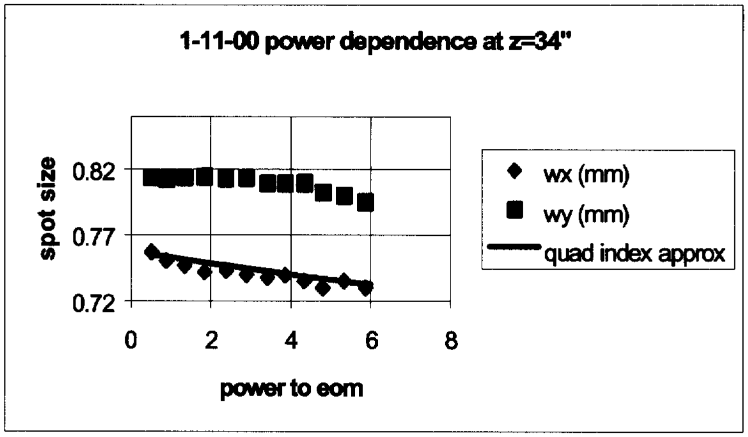


Fig.5 Measured and calculated spot size of a cw, Nd:YAG beam transmitted through EOM

$$\begin{pmatrix} A & B \\ C & D \end{pmatrix} = \begin{pmatrix} \cos\left[\sqrt{(n2/n)}\, L\right] & \sqrt{(n/n2)}\, \sin\left[\sqrt{(n2/n)}\, L\right] \\ -\sqrt{(n2/n)}\, \sin\left[\sqrt{(n2/n)}\, L\right] & \cos\left[\sqrt{(n2/n)}\, L\right] \end{pmatrix}$$

$n(r)=nc - n_2 r^2/2$

The optical path measured at the spot size w can be related to n2 as

$n_2 = 2\, \Delta OPL / (w^2 L)$

and from previous Fig, ΔOPL can be expressed as a linear function of power P as

$\Delta OPL = 2.2 \times 10^{-9}\, P$

RFAM (1)

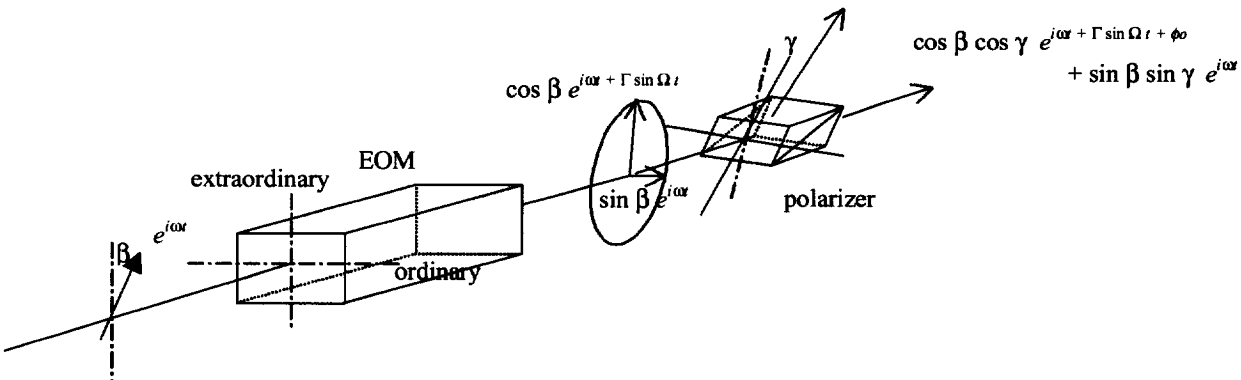


Fig. 6. Residual intensity modulation caused by angular misalignment.

$$I=I0\{\cos^2\beta \cos^2\gamma + \sin^2\beta \sin^2\gamma + 2\cos\beta \cos\gamma \sin\beta \sin\gamma \cos(\Gamma \sin \Omega t + \phi o)\}$$

S. Kawamura, A. Abramovici and M. E. Zucker, Rev. Sci. Inst. 68, 223 – 229 (1997)

RFAM (2)

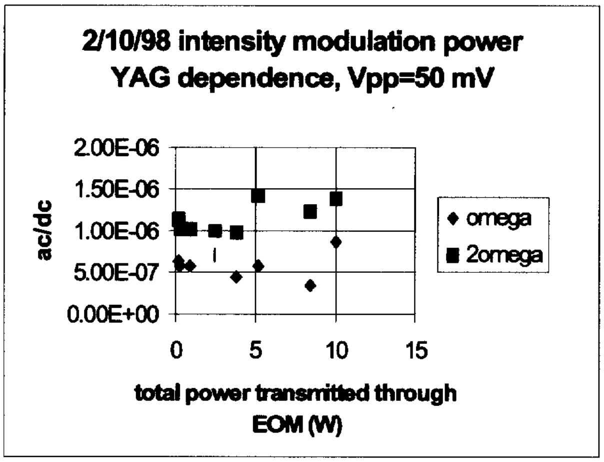
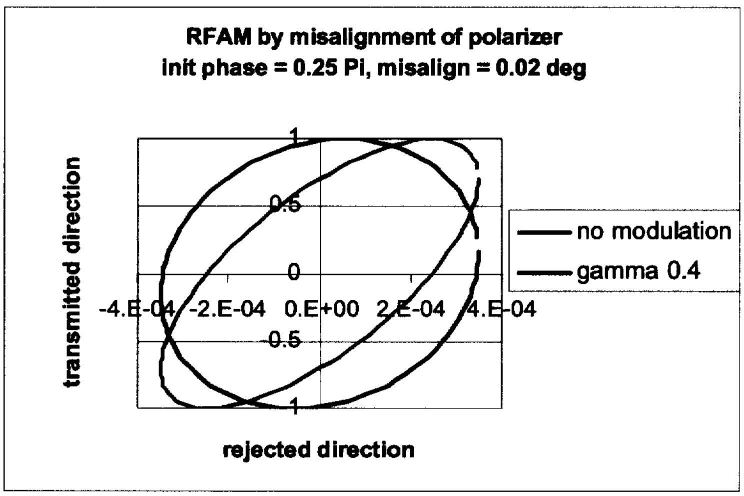
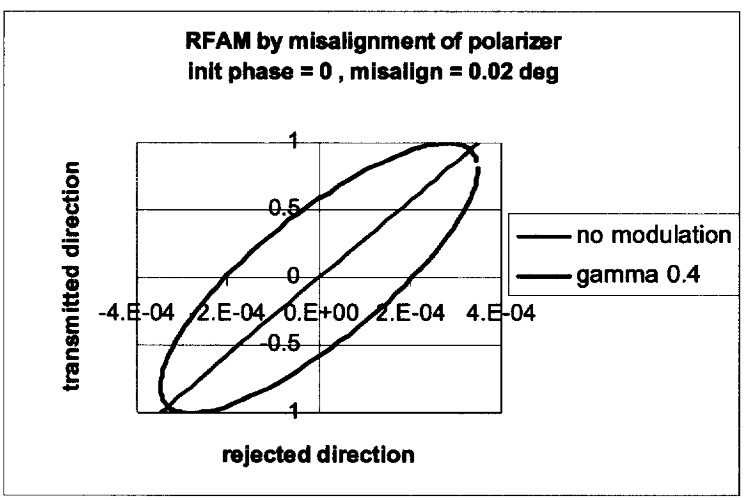


Fig.9 Power dependence of residual intensity modulation

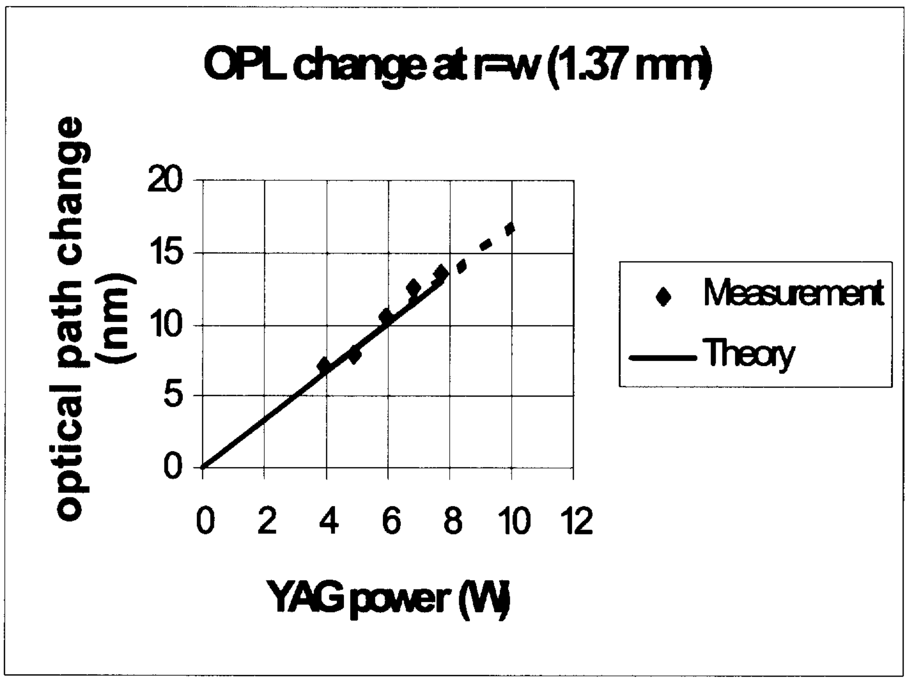
$$I=I0\{\cos^2\beta \cos^2\gamma + \sin^2\beta \ \sin^2\gamma + 2\ \cos\beta \ \cos\gamma \sin\beta \ \sin\gamma \ \ \cos(\Gamma \sin \Omega\ t + \phi o)\}$$

RFAM (3)

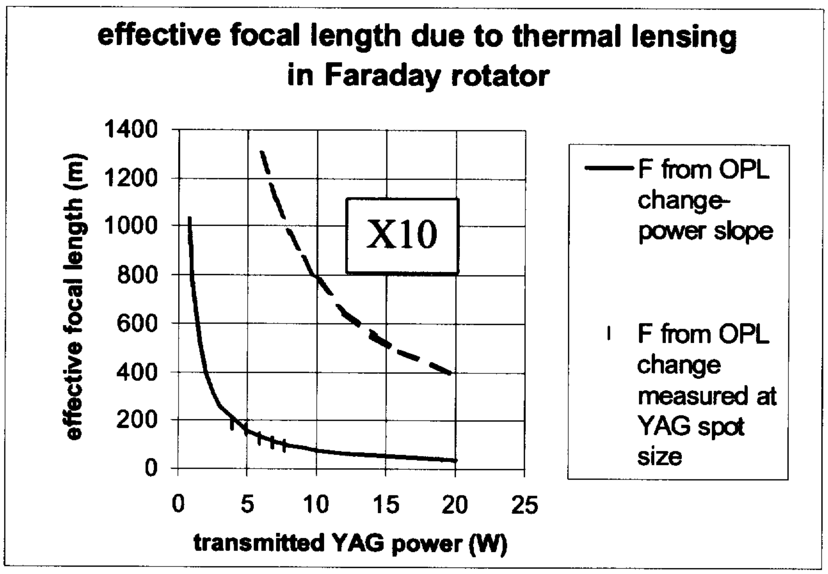

RFAM by misalignment of polarizer
init phase = 0.25 Pi, misalign = 0.02 deg
transmitted direction
rejected direction
1
0.5
0
-0.5
-1
-4.E-04
-2.E-04
0.E+00
2.E-04
4.E-04
no modulation
gamma 0.4


RFAM by misalignment of polarizer
init phase = 0 , misalign = 0.02 deg
transmitted direction
rejected direction
1
0.5
0
-0.5
-1
-4.E-04
-2.E-04
0.E+00
2.E-04
4.E-04
no modulation
gamma 0.4

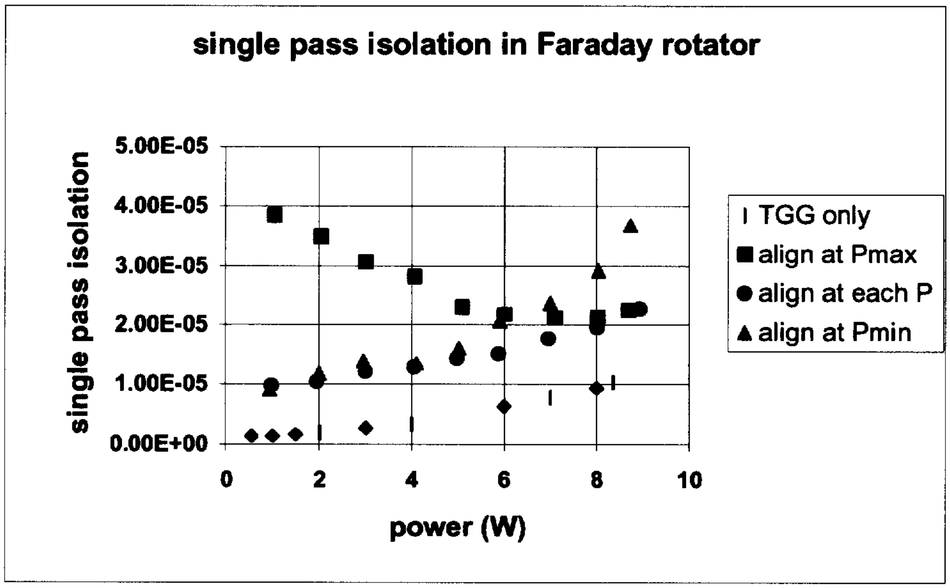
Faraday isolation (1)



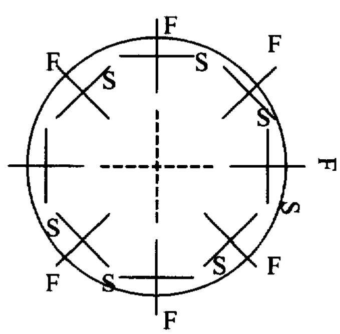
Faraday isolation (2)



Faraday isolation (3)

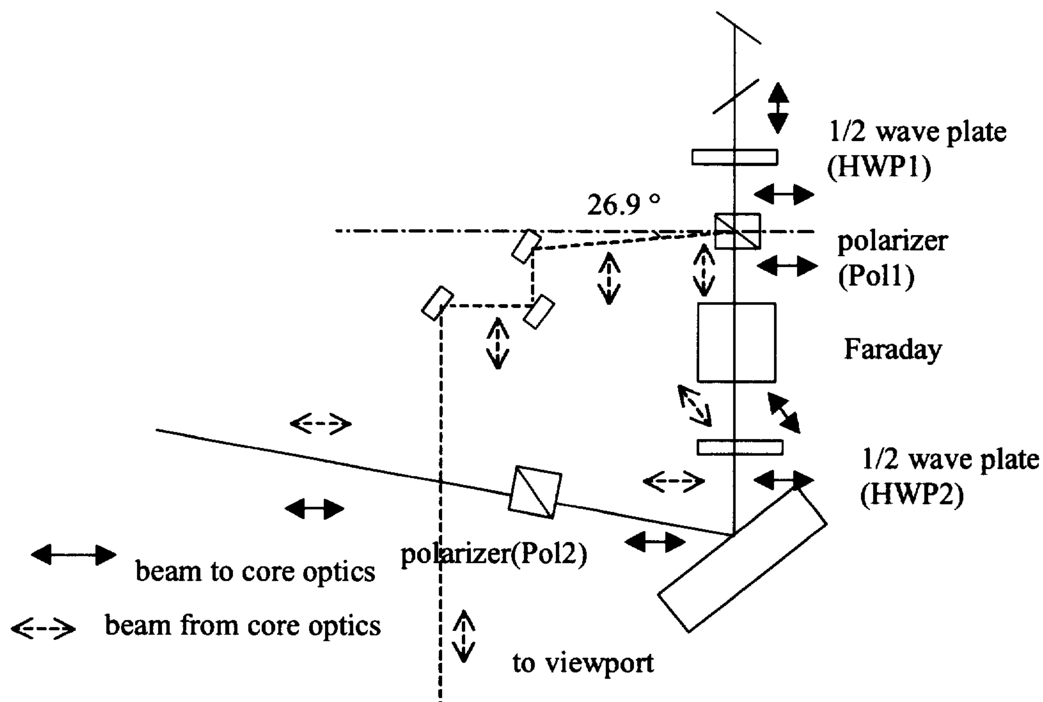


- Thermal depolarization in TGG
- Temperature dependence of Verdet constant



E. A. Khazanov, O. V. Kulagin, S. Yoshida, D. B. Tanner, and D. H. Reitze, IEEE J. Quant. Elect. 35, 1116 – 1122, (1999)

Faraday isolation (4)



Faraday isolation (5)

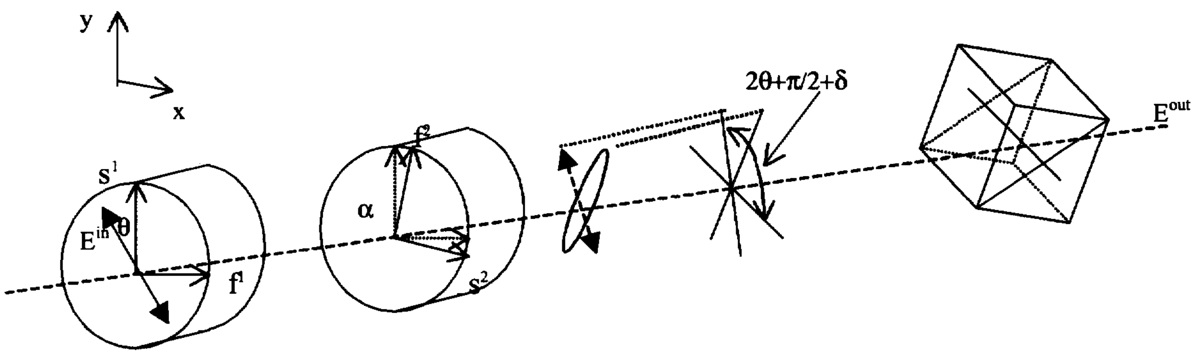


Fig.1 zero-order HWP and an analyzer cross-polarized to slightly elliptical output polarization.

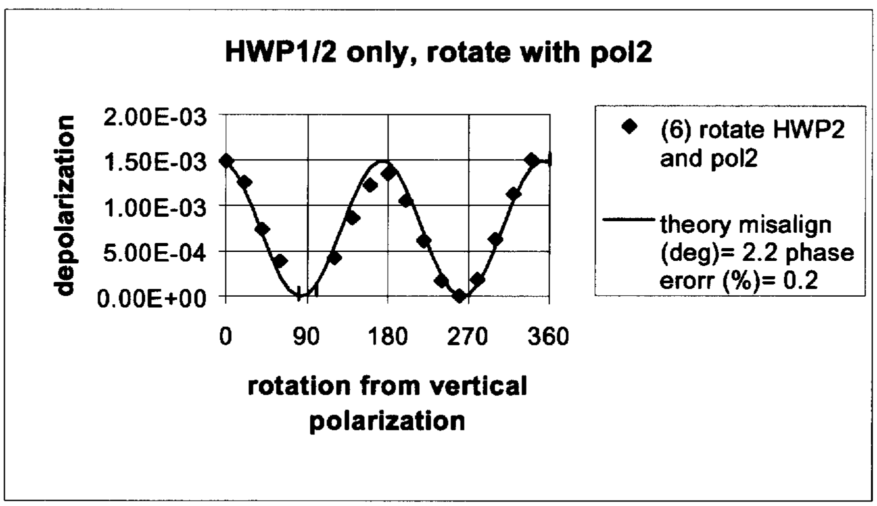
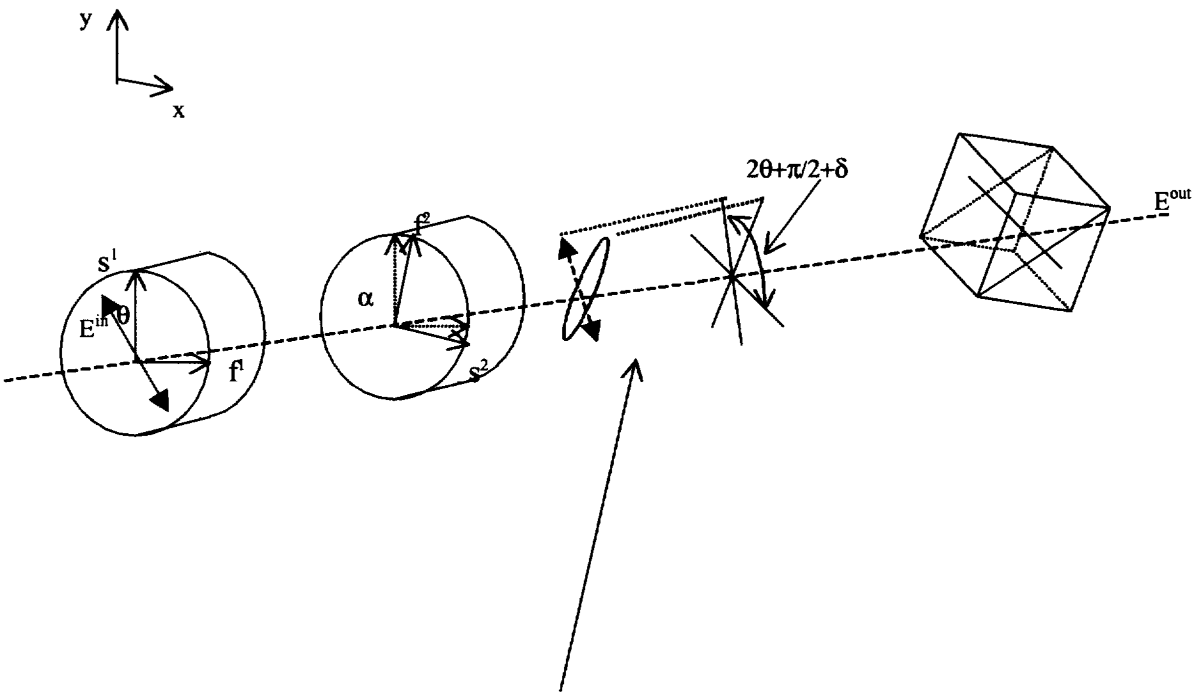
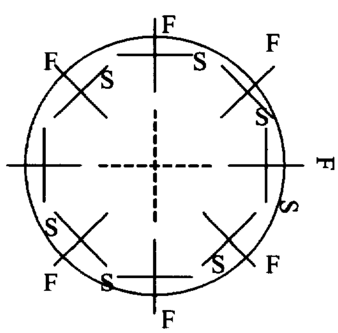


Fig.3 Depolarization due to imperfection of a half-wave plate

Faraday isolation (6)



+



Thermally induced birefringence in TGG

Faraday isolation (7)

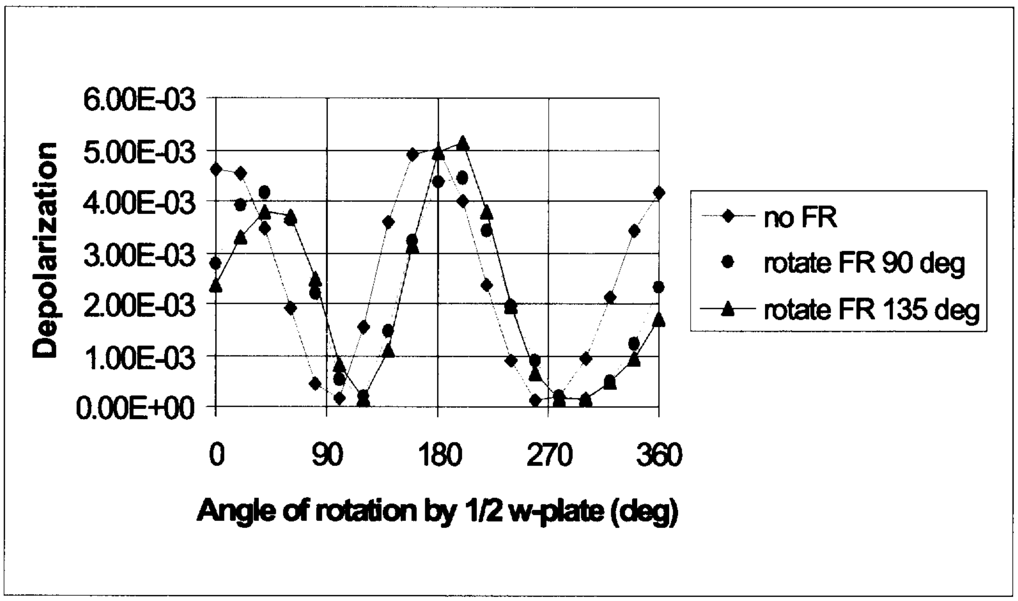


Fig.6 Overall depolarization

Overlap integral

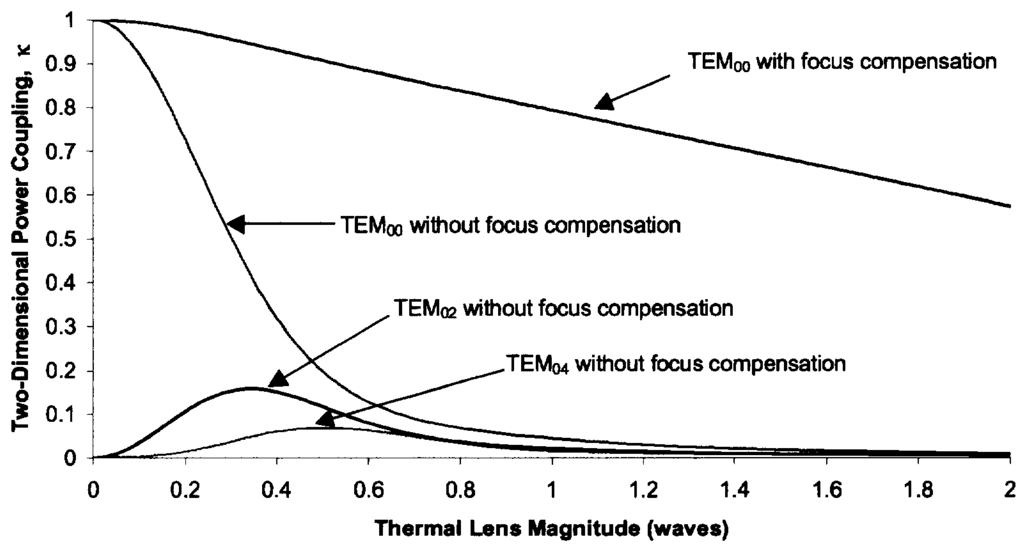


Figure 2 - Two-dimensional power coupling, κ, between a gaussian beam with a thermal lens and an ideal TEM_{00} beam with and without optimal focus compensation. The power coupling of the aberrated beam with optimal focus compensation to the TEM_{20} Hermite-Gaussian mode is also shown.

Measured and calculated thermal lens

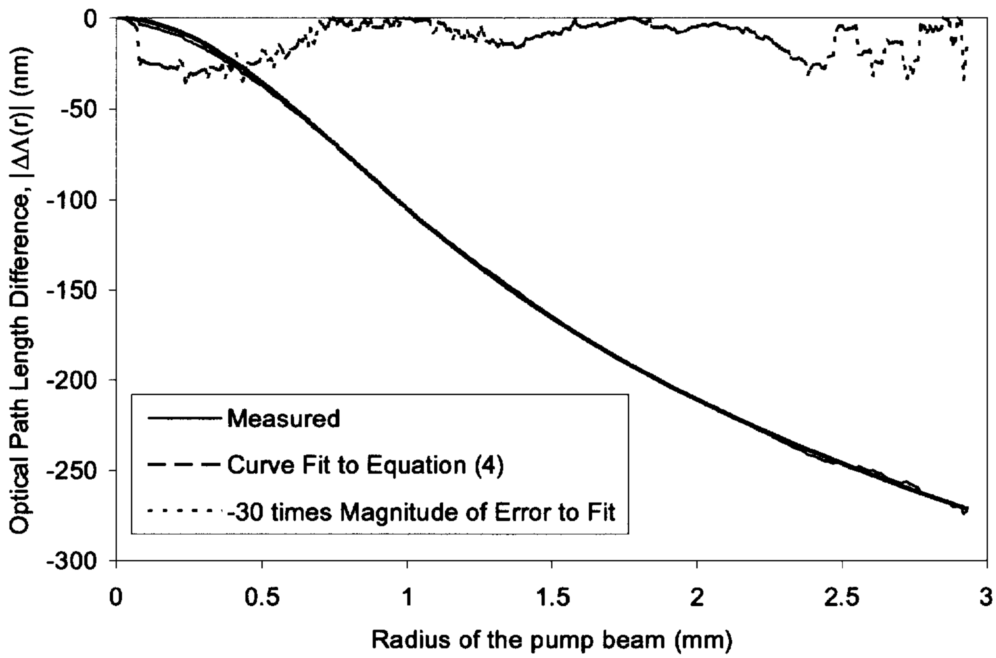


Figure 3 – Optical path length difference versus the radius of the pump beam for NG5 Schott glass when exposed to a 190mW Nd:YAG beam with a gaussian waist of 1.02mm. Shown is the measured data, the fit to the theoretical shape given by Equation (2), and the absolute value of the difference between the two curves expanded thirty times to make the difference visible.

Measurement of coupling to reference

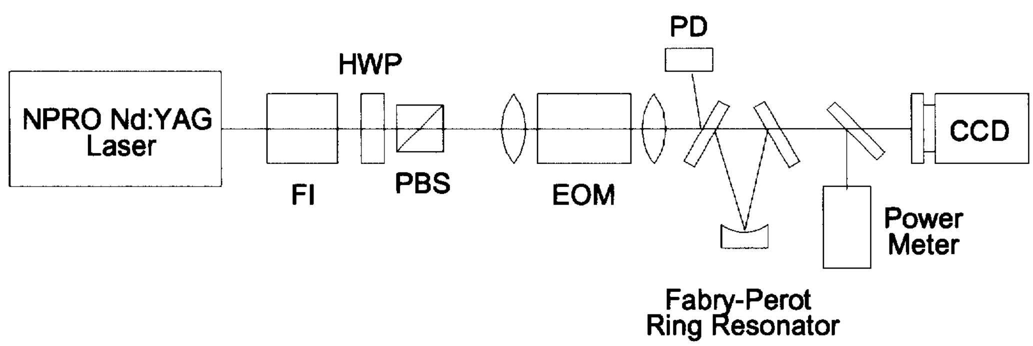


Figure 4 - Schematic of optical setup used to measure the effect of transmissive optic thermal lensing on coupling to the TEM00 mode of a cavity. Note that the wavefront conditioning optics were not drawn. An absorbing piece of filter glass, also not shown, was placed at different locations relative to the cavity waist.

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Measured and calculated power coupling

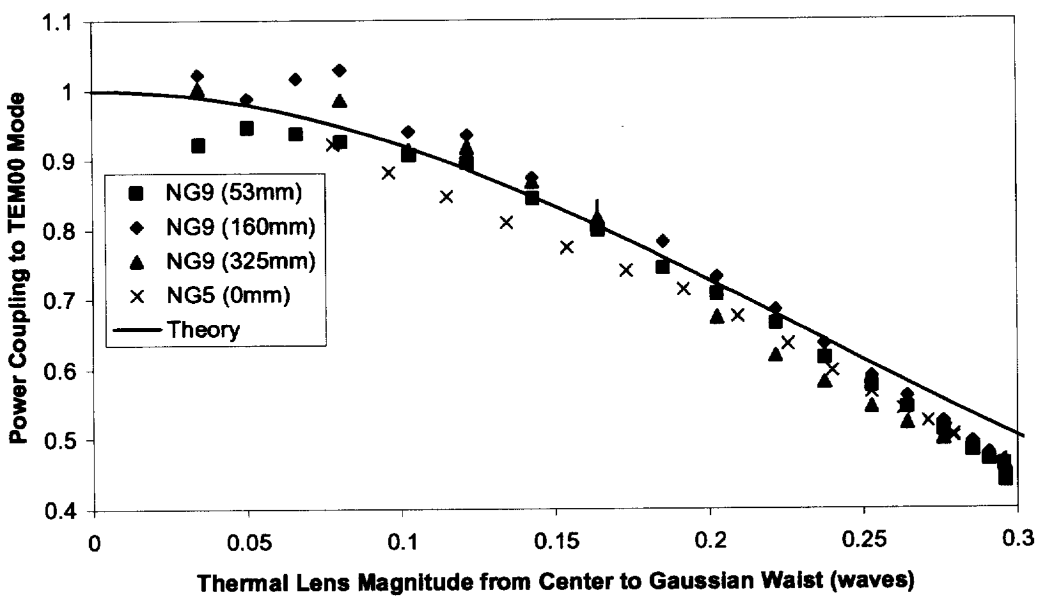

Figure 5 - Power coupling of a thermally distorted TEM00 mode to a ring Fabry-Perot mode cleaner cavity versus the thermal lens magnitude induced in different types of filter glass (NG9 or NG5) at different distances from the cavity waist. For the measurement using the NG5, the thermal lens was reimaged into the cavity to eliminate any change in the gaussian beam intensity profile. The thermal lens magnitude was calculated using the known material parameters and Equation (11).

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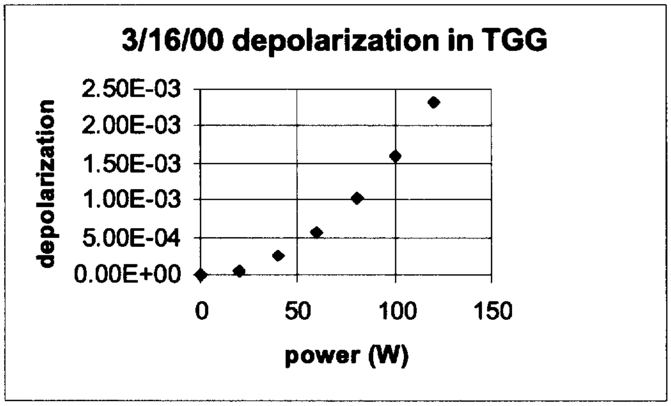
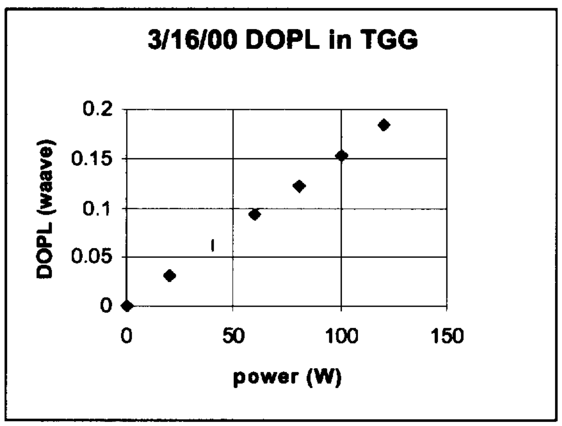
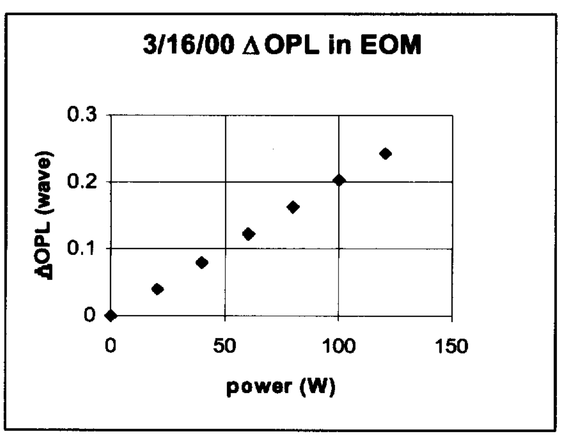
Scale to LIGO II power level







Note 1, Linda Turner, 05/17/00 10:30:16 AM
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