LASER INTERFEROMETER GRAVITATIONAL WAVE OBSERVATORY
-LIGO-
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Polarization Scatter Through Sapphire Substrates

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1. Introduction

The bulk index inhomogeneities in large, LIGO candidate boules of synthetic sapphire have been much studied (LIGO-P010014). Without surface polish correction, these inhomogeneities induce aberration scattering of light out of the primary detection mode beam, so diminishing the instrument strain sensitivity(LIGO-T020103-05-D). Since a perfect [sapphire] crystal would have no intrinsic inhomogeneities nor Rayleigh scatter, it may be considered whether the existent inhomogeneities, which show remarkable directional correlation with the crystal axes, are due to non-uniform birefringence effects in the actual, imperfect boules. That is, for a perfect crystal aligned (as a wave plate) to an ingoing beam polarization, there would be uniform retardation across the transmitted beam. However we suppose that the actual plate has wandering of the local mean optic axis. In this way ingoing beam polarization can only be exactly aligned to in some global mean. The transmitted beam will 1. have some orthogonal (to the input) “scattered” polarization component, and 2. the primary polarization field will have an aberrated wave front (indistinguishable from inhomogeneity induced). Previous measurements on sapphire boules have measured the net wave front aberration in *one [primary] wave front polarization only* (thus including effect 2.). For a simple model where measured primary transmitted aberration is entirely due to this optical axis wandering effect, scatter to the orthogonal polarization (effect 1.) can be unacceptably large. Here we report a direct measurement of effect 1 through a typical sapphire sample (“Sapphire B” test substrate, 15 cm diameter; 10 cm thick with 1 degree wedge, “***m***” axis orientation) which exhibits strong characteristic inhomogeneity banding(LIGO-P010014) At the level of the experimental sensitivity no correlation of local polarization rotation with apparent inhomogeneity was found. This sensitivity is sufficient to exclude polarization scatter from concern for advanced LIGO application.

2. Concern: ITM transmission modal loss.

Figure 1 shows
the transmitted optical path inhomogeneity (OPD) through the sapphire substrate (“sapphire B”) studied here. Strong banding in the inhomogeniety is associated with the c/m axis of the crystal structure. This inhomogeniety will scatter light out of the GW carrier mode thus diminishing an interferometer’s strain sensitivity by

$$\frac{\Delta h}{h} \approx -\left(k_0\sigma\right)^2 \qquad (1)$$

where k_0 is the laser wave number ($2\pi/\lambda_0$) and σ is the rms of the transmission OPD (suitably weighted over the Gaussian beam profile). For s~ 50nm (per Fig 1) we have $\delta h/h$~ 0.1 (~30% diminution in astrophysical reach). This effect can be acceptably ameliorated by compensation polishing of an AR surface.

Our OPD derterminations (Fig 1) strictly measure the aberration in only one (primary) polarization. In sapphire it could be possible also to diminish the primary mode via polarization scatter, which we have no previous data on. This can be modeled as a "waveplate" of wrong oriented optic axis material within a bulk crystal otherwise perfectly aligned to the primary polarization vector. The effect of transmission through this inclusion relative to neighboring normal paths may be described by two parameters: 1. the inclusion differential phase depth, δ (i.e. $\delta=\pi$ would be a $\lambda/2$ plate); and 2. the inclusion optic axis deviation, ϕ (plate rotation angle). Then

$$\mathbf{T}_{JONES} = \begin{pmatrix} 1 & 0 \\ 0 & e^{i\delta} \end{pmatrix} - \phi(1-e^{i\delta}) \begin{pmatrix} \phi & 1 \\ 1 & -\phi \end{pmatrix} \qquad (2)$$

for $\phi<<1$, through $O\left(\phi^2\right)$. For a presumed pure $\begin{pmatrix} 1 \\ 0 \end{pmatrix}$ primary polarization incident wave, both a transmitted primary field aberration:

$$(\mathrm{OPD}) \sim \mathrm{Arg}[\mathbf{T}_{00}]/k_0 \qquad \text{(effect 2)}$$

and a polarization scattering:

$$E_\perp \sim \mathbf{T}_{10} \qquad \text{(effect 1)}$$

result. This later implies an *additional* mechanism reducing strain sensitivity:

$$\frac{\Delta h}{h}_{Polz} \approx \left\langle \left\langle \left| \mathbf{T}_{10} \right|^2 \right\rangle \right\rangle_{Gaussprofile} \qquad (3)$$

However the *observed* OPD (Fig 1) poses no constraint on (3). For instance, near $\delta=\pi$ the value of (3) could dominate (1). Furthermore effect 1 cannot be compensated as effect 2 can be by refiguring of an AR surface. Therefore a direct measure of effect 1 was conducted, and reported here.

3. Measurement

The setup for scanning "sapphire B" in $\left|E_\perp\right|^2$ measurement is sketched in figure 2. The crystal is mounted horizontally on an X-Y scanning stage ("RTS" instrument in the Caltech OTF). Alignment is critical for minimizing residual $E_\perp$ contamination in the detection. This is complicated by the wedged crystal's birefringent deviation and variable thickness (δ). Setup alignment is facilitated by observing the *natural* waveplate $E_\perp$ oscillations in the wedge direction (noticeable in figure 4). These have a spatial period:

$$\lambda_{surface} = \frac{\lambda_0}{\alpha \Delta n} \qquad \alpha = \text{wedge angle}$$

(where Δn = 0.0077 is the birefringent index difference) and vanish at perfect optic axis alignment. A systematic procedure is then:

1. Mount “sapphire B” tip-tilting it so that the beam is perpendicular to the exit surface.
2. Rotate (about the beam axis) “sapphire B” until the natural $E_\perp$ oscillations vanish. This establishes $\overline{\phi} = 0$.
3. Rotate the exit $\lambda/2$ plate such that the $E_\perp$ PD signal is minimum.

Deliberate (known) rotations of the exit $\lambda/2$ about that fixed in 3. then calibrates the sensitivity. A rotation curve containing this calibration is shown in figure 3. Note that the detection was not balanced (primary polarization all through to “power detector”). This configuration sufficed to set the good upper limit achieved.

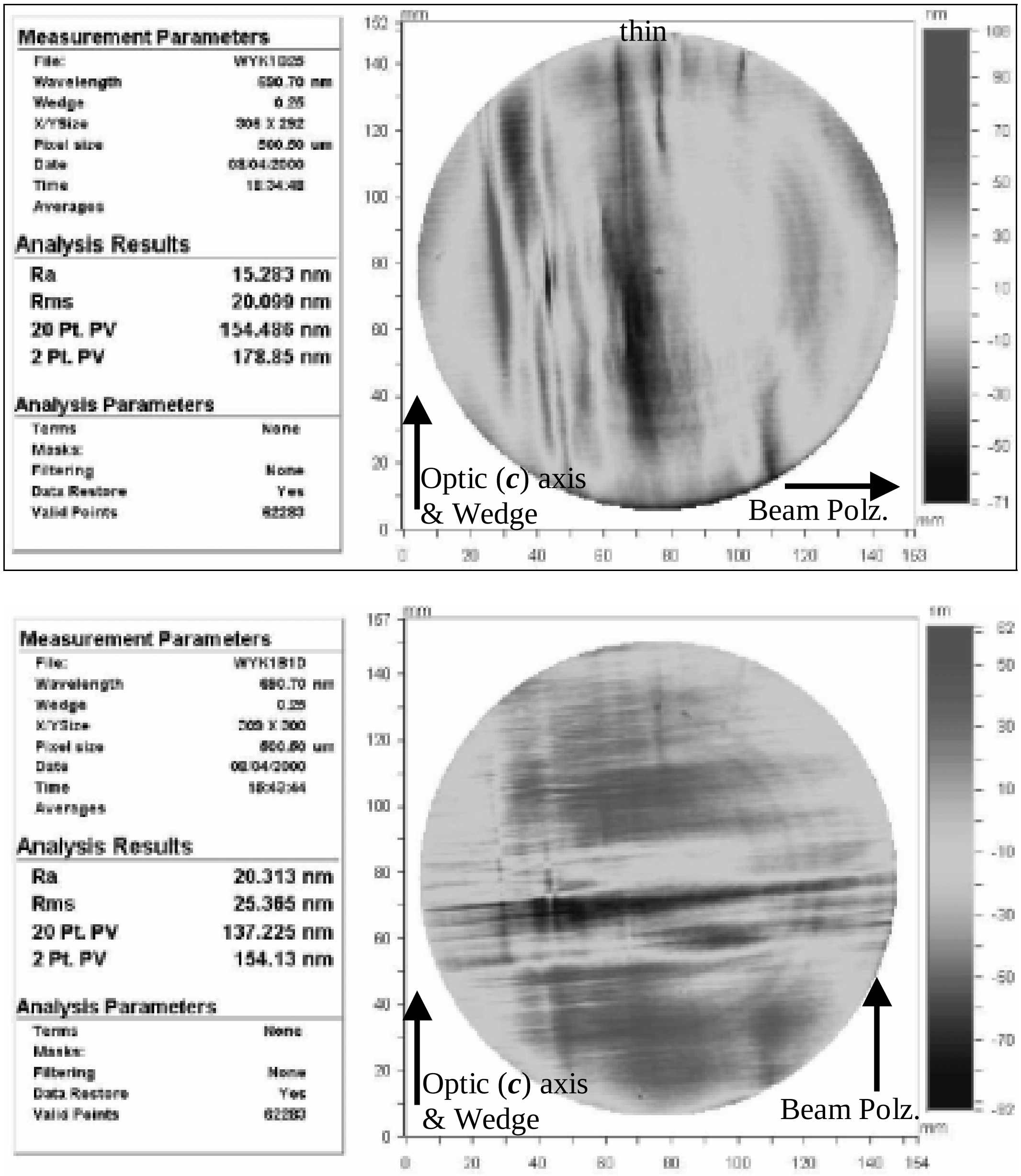
4. Results, conclusions

Final data for “sapphire B” consists of the calibration curve of Fig 3 and the full scan shown in Fig 4 ($\lambda/2$ plate set to minimum at ~ 10.0^o). The $\left|E_\perp\right|^2$ scan still has features. However, except for a systematic ~constant Y gradient, the only clearly resolved feature is a residual of the natural oscillation described in section 3 (due to drift in the instrumentation over the several day setup-scan interval). This residual, being just at the threshold of resolution gives an approximate benchmark upper limit to additional polarization scatter. Certainly no pattern that correlates to that of Fig 1 is identifiable. In terms of (3) this sets a limit:

$$\frac{\Delta h}{h}_{Polz} < \text{ 50 ppm}$$

This may be contrasted to the prediction from Fig 1 via (1) of $\Delta h/h$~ 10,000ppm. Although this measurement explicitly observes the relevant quantity (scatter to wrong polarization), it must be kept in mind that it does not give any limit to possible optic axis deviations (say ϕ_{max}). For instance, the null result reported here for effect 1 and ascribing the full observed inhomogeniety of Fig 1 to effect 2, could be consistent if the crystal had very thin (δ<<1) inclusions of large optic axis deviation (ϕ_{PV}~1).

We also note that step 2. in the setup prescription (section 3) implies that any installed sapphire TMs would be hung exactly such that $\overline{\phi} = 0$. Clearly this implies a tolerance for rotational alignment at installation. A systematic rotational misalignment $\overline{\phi} = 1^o$ would result, via equations (2) and (3), due to the natural oscillations of section 3 to a strain diminution fo
0.1% ($\Delta h/h = 2\overline{\phi^2}$).



Measurement Parameters

File:	WYK1025
Wavelength	690.70 nm
Wedge	0.25
X/YSize	306 X 292
Pixel size	500.50 um
Date	08/04/2000
Time	18:34:48
Averages	

Analysis Results

Ra	15.283 nm
Rms	20.099 nm
20 Pt. PV	154.486 nm
2 Pt. PV	178.85 nm

Analysis Parameters

Terms	None
Masks:	
Filtering	None
Data Restore	Yes
Valid Points	62283

Measurement Parameters

File:	WYK1B10
Wavelength	690.70 nm
Wedge	0.25
X/YSize	309 X 300
Pixel size	500.50 um
Date	08/04/2000
Time	18:42:44
Averages	

Analysis Results

Ra	20.313 nm
Rms	25.365 nm
20 Pt. PV	137.225 nm
2 Pt. PV	154.13 nm

Analysis Parameters

Terms	None
Masks:	
Filtering	None
Data Restore	Yes
Valid Points	62283

Figure 1

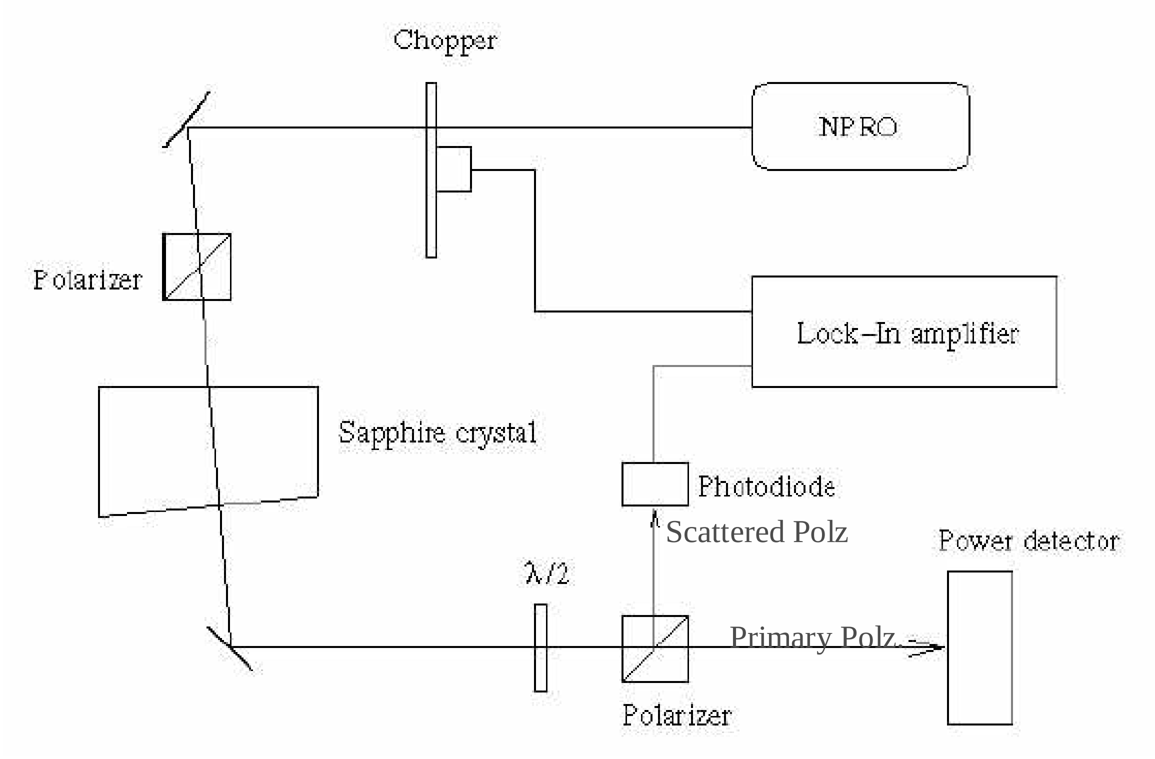
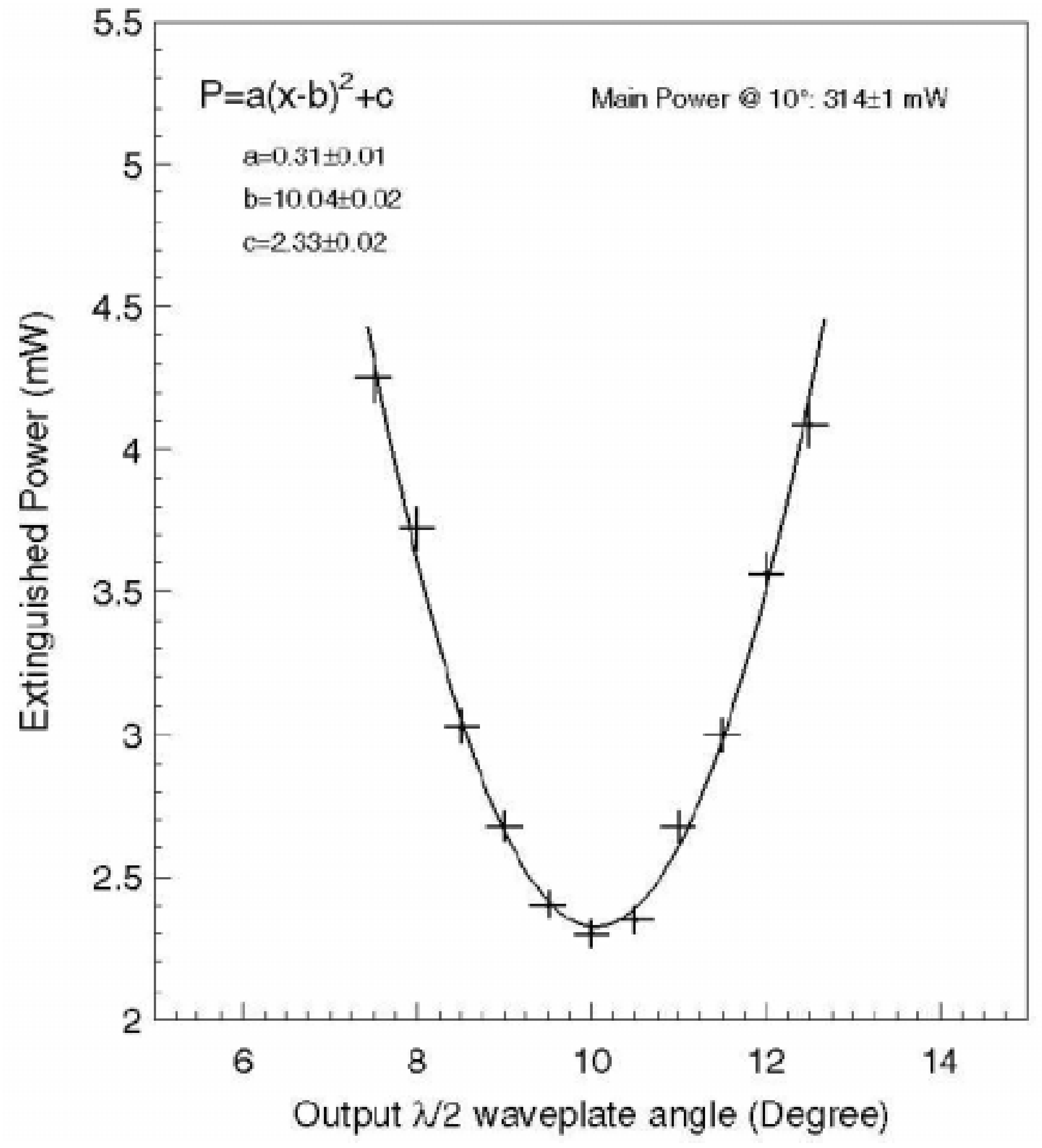
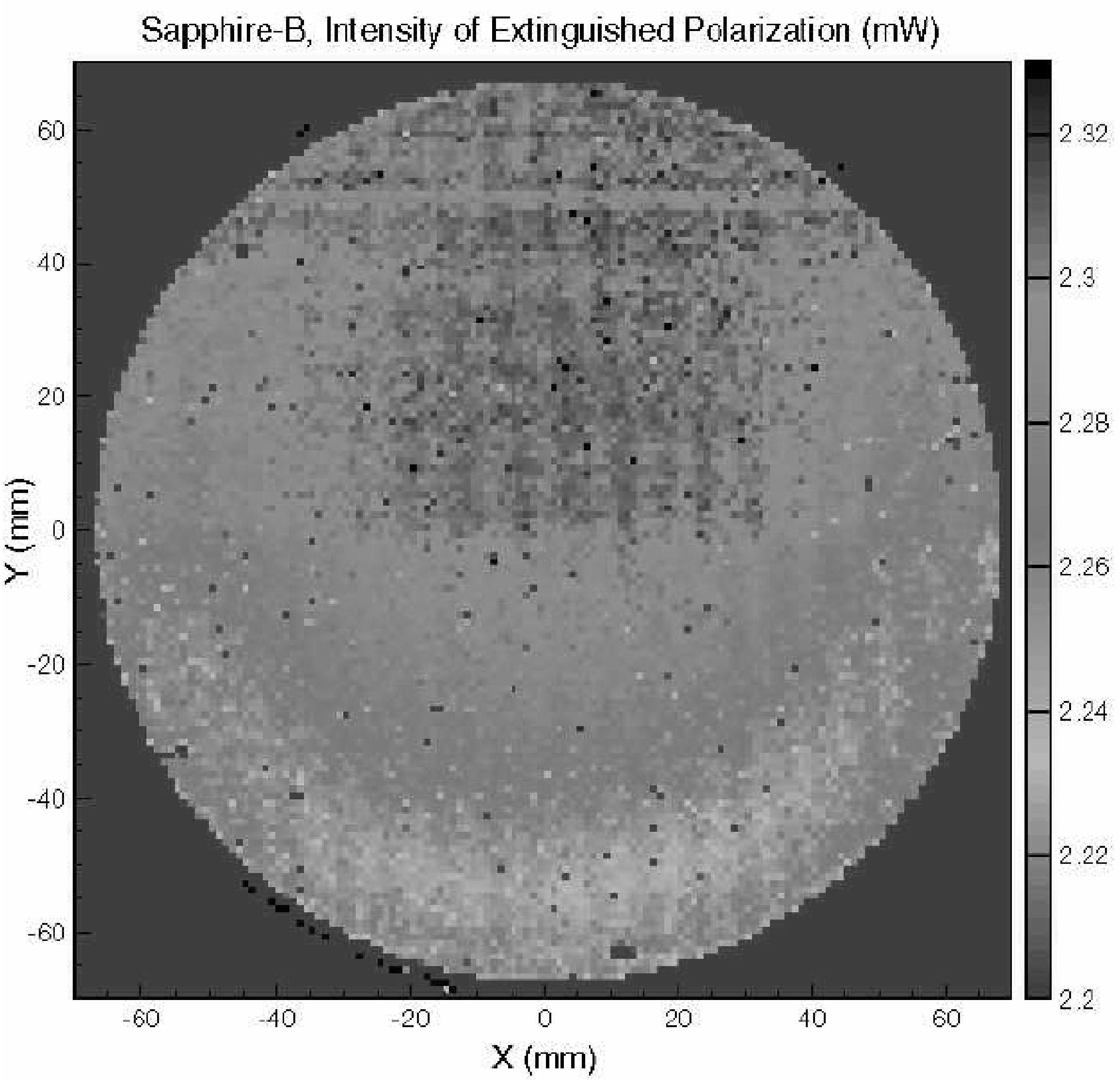

Chopper
NPRO
Polarizer
Lock–In amplifier
Sapphire crystal
Photodiode
Scattered Polz
Power detector
λ/2
Primary Polz.
Polarizer

Figure 2



$P=a(x-b)^2+c$
a=0.31±0.01
b=10.04±0.02
c=2.33±0.02
Main Power @ 10°: 314±1 mW
Extinguished Power (mW)
5.5
5
4.5
4
3.5
3
2.5
2
6
8
10
12
14
Output λ/2 waveplate angle (Degree)

Figure 3



Sapphire-B, Intensity of Extinguished Polarization (mW)
Y (mm)
60
40
20
0
-20
-40
-60
X (mm)
-60
-40
-20
0
20
40
60
2.32
2.3
2.28
2.26
2.24
2.22
2.2

Figure 4