ISC meeting

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Polarization issue in PRC

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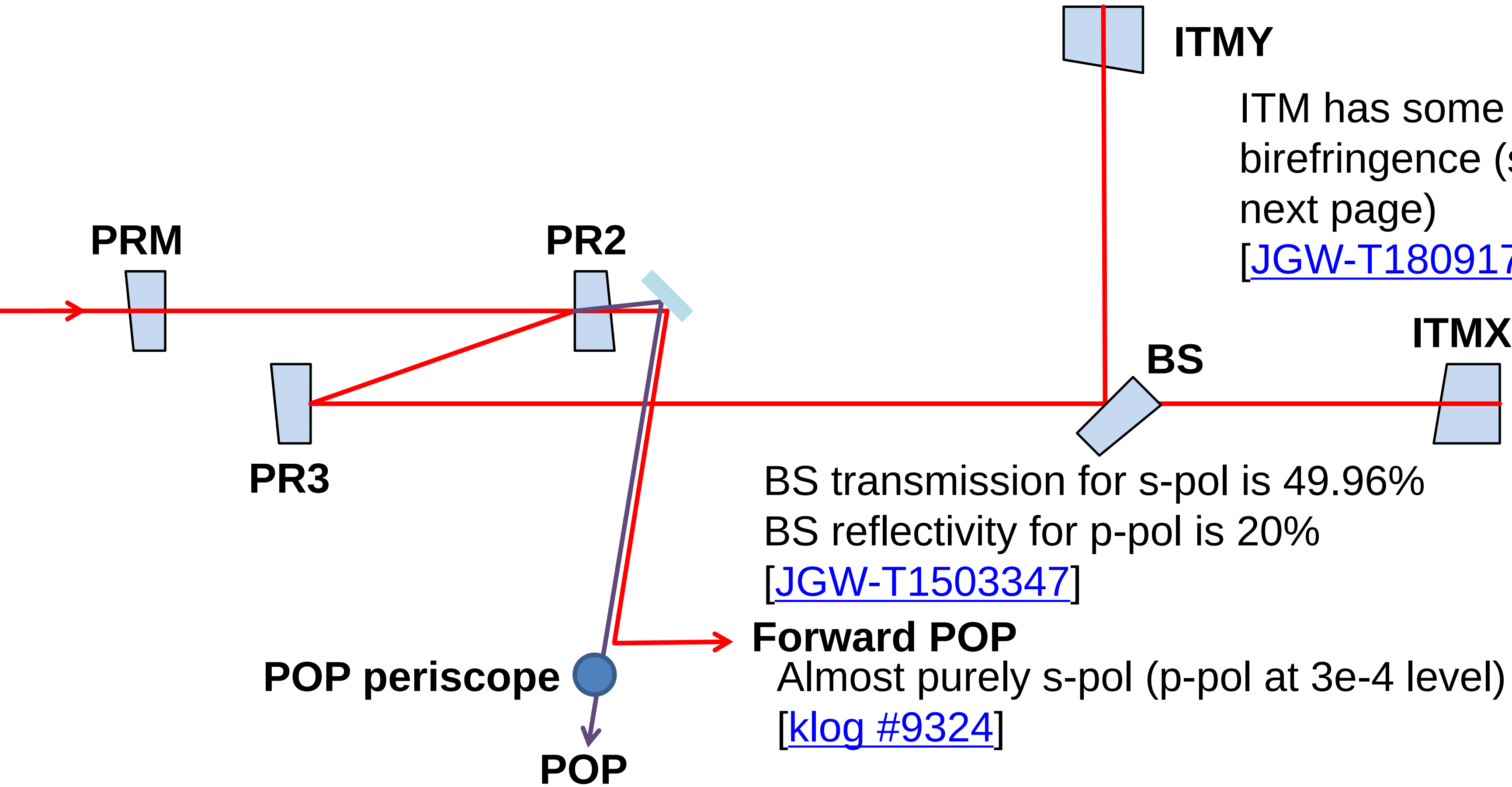
The Situation

- ITM reflection has some p-pol, while forward beam is almost purely s-pol



9.4 % p-pol from ITMX single bounce
4.6 % p-pol from ITMY single bounce [klog #9314]

ITM Birefringence

- Vendor measured transmission wavefront error (TWE) with circular polarization, but TWE measured with s-pol was different

JGW-T1809173

	specification	vendor report	measured
ITMX	< 6nm	3.47	25.9nm
ITMY	< 6nm	4.07	30.1nm

Table 6. figure error of TWE at 140mm aperture

- This suggests that ITM has some birefringence
- Optical path length difference between two polarizations Δl_{b} gives phase difference of

$$\alpha = 2\pi\Delta l_{\mathrm{b}}/\lambda$$

ITM Birefringence

- If we treat RMS linearly, Δl_b can be written as
  $$\Delta l_\mathrm{b} = l_\mathrm{o} - l_\mathrm{e'} = 2l_\mathrm{u} - 2l_\mathrm{e'}$$
  where $l_\mathrm{u/o/e'}$ are the optical path length measured with circular polarization (~5 nm RMS by vendor) and polarization aligned with o/e' axes (~30 nm RMS by Caltech)
- *Maximum* power loss due to s-pol turning into p-pol is $\rho = (1-\cos 2\alpha)/2 \simeq \alpha^2$ (2 for round-trip in ITM)
- The power loss will be 7.0% for X and 9.5% for Y
- This corresponds to the power ratio at POP (p/(s+p)) of 10.8 % for X and 4.0 % for Y (note that BS reflectivity is different between polarizations) * corrected on June 30
- This seems to (amazingly) agree with the measurement (9.4% for X and 4.8% for Y)

Implications

- We need both uniform l_s and small Δl_b but this cannot be achieved by surface corrections
- Using ordinary and extraordinary refractive indices, Δl_b can be written as

$$\Delta l_\mathrm{b} = d n_o (n_o^2 - n_e^2)\theta^2/(2n_e^2)$$

where θ is angle between c-axis and beam axis, JGW-T0400030 and d is ITM thickness (15cm)

For sapphire @ 1064 nm

$$n_e = 1.747$$

$$n_o = 1.754$$

Note that they are different in cryogenic temperatures and there might be additional birefringence due to stress or something

- If we require loss to be smaller than a threshold,

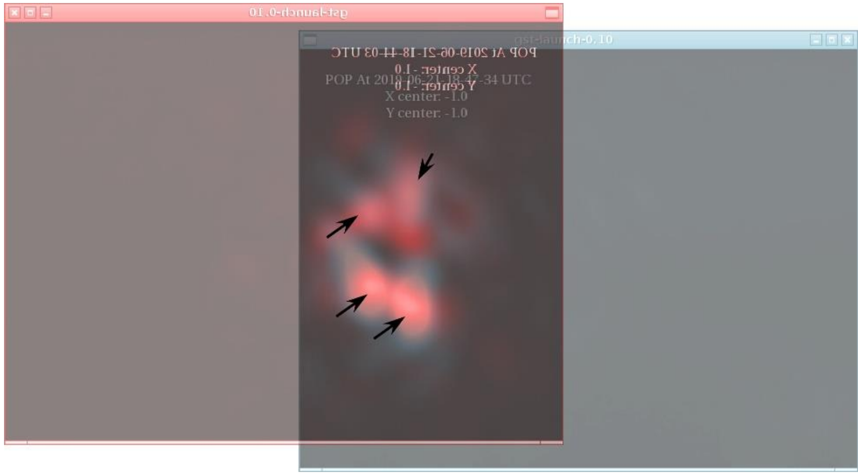
$$\Delta l_\mathrm{b} < \sqrt{\lambda^2 \rho_\mathrm{th}/(2\pi)^2}$$

$$\theta < \sqrt{\frac{2n_e^2\sqrt{\lambda^2\rho_\mathrm{th}/(2\pi)^2}}{d n_o(n_o^2 - n_e^2)}}$$

For 10% (1000ppm) loss, these will be 54 nm (5.4 nm) and 0.41 deg (0.13 deg)

Other Possibilities

- The shape of p-pol beams from ITMX and ITMY seems similar which implies common p-pol generation? [klog #9329]
  Common stress due to suspension?



- Beam height changes could create p-pol beam? (we have 1/300 inclination)
- Beam clipping creates p-pol beam somehow?
- Birefringence in ITM coating? (might be able to check by measuring the amount of p-pol at room temperature)

Sapphire Axes

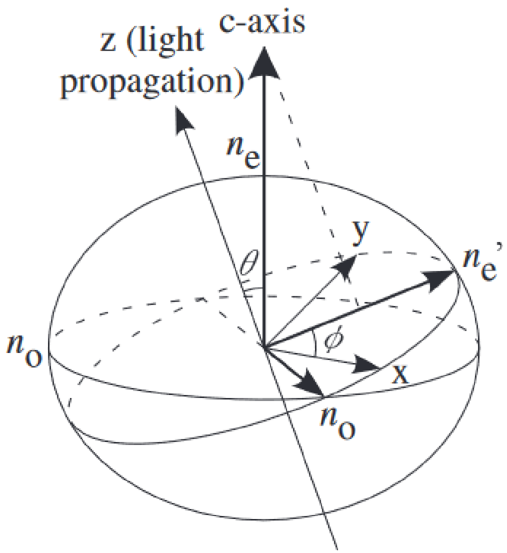
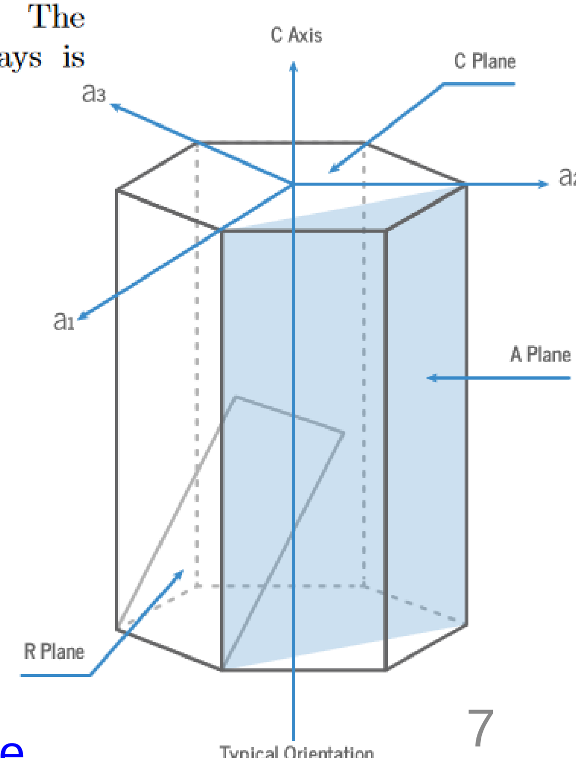


Figure 1. If the c-axis of the sapphire sample inclines by an angle θ from the z-axis, the phase speed of light propagating along the z-axis depends on the direction of its electric field vector **E**. The phase speed of a beam whose electric field is parallel to the projection of the c-axis onto the xy-plane, which inclines by an angle ϕ from the x-axis, is c/n'_e and the phase speed of a beam whose electric field is perpendicular to the direction is c/n_o. The phase retardation between these two rays is given by Eq. 2.

Tokunari+, [JPCS 32, 432 (2006)]

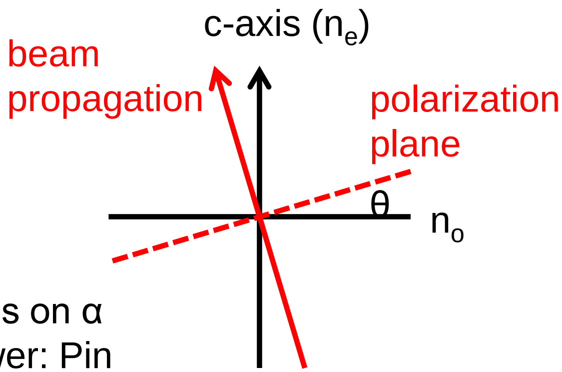


http://jp.rubicontechnology.com/company/sapphire

Calculation Details

- Phase difference between o-axis and e'-axis

$$\alpha = 2\pi d(n_o - n_{e'})/\lambda$$



- p-pol power after ITM reflection

$$\begin{aligned} P_p/P_{\rm in} &= (1-\cos^2 2\phi)(1-\cos 2\alpha)/2 \\ &\leq (1-\cos 2\alpha)/2 \\ &\simeq \alpha^2 \end{aligned}$$

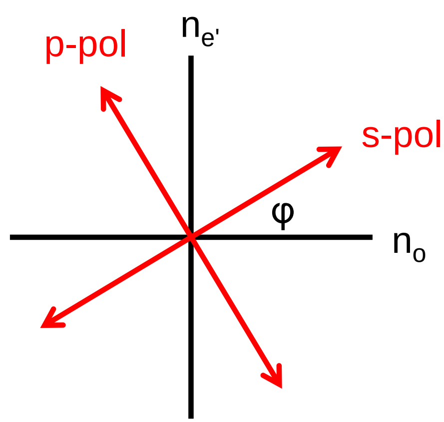
s-pol power depends on α
Maximum s-pol power: Pin
Minimum s-pol power: Pin*cos^2(2φ)

- Transmission wavefront error

$$d(n_o - n_{e'}) = 2(\underline{d(n_o + n_{e'})/2} - \underline{dn_{e'}})$$

Measured with circular polarization, and this is minimized by polishing

Not directly measured. RMS measured with s-pol shows small dependence on mirror orientation, and this suggests $dn_{e'}$ map is similar to dn_o map in RMS



θ < 0.2 deg (JGW-T1809173)
But φ is totally unknown

Note (added on Apr 18, 2020)

- Actually, φ can be estimated from TWE map difference between (0 deg map & 90 deg map) and (45 deg map & 135 deg map)

$$\frac{\alpha(\pi/4)}{\alpha} = -\tan 2\phi$$

See JGW-T1910380

- Therefore,

$$\begin{aligned} P_p/P_{\rm in} &= (1-\cos^2 2\phi)(1-\cos 2\alpha)/2 \\ &\simeq \alpha^2 \sin^2(2\phi) \\ &\simeq \alpha(\pi/4)^2 \end{aligned}$$

where α(π/4)=2π(TWE[45 deg] – TWE[135deg])/λ