Open Questions for Crystalline Coating Materials

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- Motivation
  - Reduced mechanical loss: see talks by
    - Angie Lin
    - Garrett Cole
- History
  - March LVC meeting:
    - Crystalline coatings discussion
    - Coatings workshop

Crystalline coatings show promise, but we are missing a lot of expertise and experience. There are a lot of unknowns.

How do we get from our current state to a crystalline coating interferometer?

Goals of this talk/week:

1: List some possible issues
(show-stoppers)

2: Eliminate the obviously unimportant ones
(back of envelope)

3: Make plans to measure the unknown
properties and effects
(to do list)

Things we know are important

- Brownian Noise
- Thermo-Optic Noise
- Absorption
- Scatter

Any show stoppers?

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  - Measurements (JILA, Glasgow, American, etc.)
  - Y, σ fairly well known
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Formulation for high thermal conductivity coatings?

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Missing theory for anisotropic materials!

Formulation for high thermal conductivity coatings?

Things that May be Important

- Two Photon Absorption
- Birefringence/Elasto-Optic
- Piezo-Electric Effect
- Electro-Optic Effect
- Nonlinear Effects

Any show stoppers?

Lets do some BOEs!

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- Two-Photon Absorption
  - Second order ~Intensity^2
  - β = 26 cm/GW for GaAs @ 1064 nm
  - Less @ 1550 nm
  - Less for AlGaAs
  - Much less for GaP, but not measured at IR
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  - Creates polarization-dependent frequency splitting
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How well can we align polarization?

In paper[1], Δf = 4 MHz.
If AdLIGO, $\Delta f \approx$ 60 Hz.

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  - Change in thickness from stray E-fields
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Generally,
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$\Delta n = -n^3 * r_{41} * E/2$

$r_{41} \sim -10^{-12}$ m/V @ 1064 nm
Possible cancellation with Elasto-Optic?

Similar for GaAs, AlAs, GaP, 1550 nm

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- Nonlinear Effects
  - Second-order Harmonic Conversion
  - Multiple Wave Mixing
  - Second order nonlinear optical coefficient d_{14}~300e-12 m/V
    - Larger than most materials
  - Higher Order Effects???

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Most values measured, just need some calculations!

Other Issues

- Purity/Defects
- Surface treatments
- Growth Conditions
- Crystal Orientation

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Mostly Important for absorption, but how do they affect other properties?

Other Issues

- Purity/Defects
- Surface treatments
- Growth Conditions
- Crystal Orientation

Mostly Issues for Angie and Garrett

Anything Else?

Next up:
To Do list

To Do:

- Short term:
  - Back of the Envelope (this week?):
    - Elasto-Optic
    - Electro-Optic
    - Higher-Order effects
  - Modeling (FEM):
    - Brownian & Thermo-Optic
      - do we need better theory?
  - Measure Scatter

To Do:

- Medium Term:
  - Theory
    - Brownian & Thermo-Optic
    - Noise terms left over from previous slides
    - Add to GWINC
  - Measurement
    - Mech. loss vs orientation, alloy
    - Properties of AlGaP
      - β, r_{41}, d_{14}, etc.
    - Absorption vs Growth Conditions/Surface Treatment, etc
  - Production
    - Improve purity
    - Larger scale
    - Better buffer/bond layer

To Do:

- Long Term:
  - Look into other crystalline materials for other wavelengths
  - Full-scale production
  - Pick a material

Volunteers?

Talk Over, notes below.

Common Issues

- Most material properties known:
  - (At least for AlGaAs)
  - Incl. κ, C, α, n, ϕ (sort-of/in progress)
  - Absorption: being measured
- Unknowns:
  - ϕ in various directions (Is this necessary?)
    - Dependence on Alloy concentration?
  - dn/dT (especially at cryo)
  - Scatter

Common Issues

- Measuring ϕ
  - Do we need a theory that takes into account anisotropy?
  - Easy experiment to make: grow different orientation crystals, deposit on cantilevers, measure.
    - For AlGaP: Depends on substrate
  - Might be useful to recreate the Penn et al. 2003 measurements.
    - Different layer structures, # of layers, etc., to narrow down areas of interest.
- dn/dT
  - Existing LSC Experiments
  - Using multilayer optical cavities: Talghader and Smith, Appl. Phys. Let. 1995.
- Scatter
  - Measure TIS
  - Identify scatter centers: surface, boundary, internal defects?

Uncommon Issues

- Crystalline Orientation
- Non-linear effects
- Birefringence
- Raman Scattering
- Electo-optics
- Piezo-electric
- Opto-mechanic

Uncommon Issues

- Non-linear effects
  - Two-Photon Absorption
    - At 800 kW power, 5.5cm beam radius, GaAs absorption <0.2ppm, scales with power.
    - Less for 1550
    - Much less for AlGaAs
    - How do we test these?

Boggess, et al. Quantum Electronics, IEEE Journal of , vol.21, no.5, pp.488,494, May 1985

A. Villeneuve, et al. Appl. Phys. Lett. 62, 2465 (1993)

Optical Properties

- Absorption

  – Best values so far <5 ppm at 1064 nm; actually limited by absorption of HeNe probe (measured by A. Alexandrovski, SPTS). Further measurements with transparent probe in the works…

  – Source of absorption that we might be concerned about:

  – Free carriers: impurities or dopants contribute free carriers to the material. How to deal with this? MBE is the best growth approach in terms of getting the most pure III-V thin films (I'm not just saying this b/c I do MBE, it really is the best growth technique if we want high-purity DBR structures :). Both AlGaAs/GaAs and AlGaP/GaP approaches use MBE-grown material for this reason. The only other plausible technique is MOCVD, but it tends to incorporate C and O impurities from the gaseous sources. May be worth comparing with an MOCVD-grown structure through just to see how big the difference is. This would be something to think about in terms of scaling up to larger mirrors (but there are large enough MBEs to do what we want, the limit is size of GaAs substrate or size of float-zone silicon).

LIGO Optical Properties (cont'd)

- Scatter – Typical post-bond roughness of 1.3-1.5 Å corresponds to a scatter loss of <3 ppm
- Purity? Not sure how to quantify this??
  - Very few techniques are available to measure the impurity levels we desire in crystalline films. In fact, PCI measurement for absorption is probably the most sensitive. Or could measure resistivity, although this is also more difficult for low resistivity material.

Brownian Noise

- What is the loss function (micro-resonator and cavity measurements)
  - Frequency dependence? Resonators: ~constant at cryo, Q ranges from 110k (1-4 MHz) to a best of 225k (200 Hz to a few kHz); RT resonator response complicated by thermoelastic effects…
  - Temperature Dependence? RT: 2.5×10-5 (Q 30-40k); Cryo: 4.4×10-6 (Q up to 225k)
  - Anisotropy? unknown

Brownian Noise (cont’d)

- Does JILA measurement measure freq. Dependence? Kind of, see averaging time dependent plots in paper
  - Will Tara's?

Interface losses

- Bonding no additional losses seen in tests with JILA, tests with Gregg and Steve may show excess loss – high amplitude issue? Not clear…
  - Would be interesting to study with TEM what the interface is like between bonded AlGaAs/Silicon to get an idea of what kind of interface you can “get away with” that doesn’t affect mechanical loss, or show that interface doesn’t matter

Interface losses (cont'd)

- Epitaxial integration (with buffer layers)
  - GaP: Will have mechanical loss measurements on GaP film on Si cantilevers by GWADW. This will give an indication of whether or not mech loss is coming from this buffer layer. This is definitely something that we'll focus on because we expect it to be the dominant source of mech loss due to atomic-scale antiphase domain defects (wrong bonds) generated from growth.
  - GaAsP: will have some initial structural (XRD) data at GWADW, probably nothing on mech loss or absorption. For this buffer layer, we expect this to be a larger source of mech loss (compared to GaP buffer layer) because of dislocations from the difference in lattice mismatch between GaAsP and Si. The advantage of this approach is to be able to get to the lattice constant of GaAs and therefore use the GaAs/AlGaAs DBR system on Si. I'm not very optimistic towards this approach, but it's something to try, even just to understand what the source of mechanical loss is in crystalline materials.

Thermo-Elastic

- Relevant values:
- CTE, Heat Capacity, thermal conductivity
- AlGaAs
- See paper, this should all be covered…
- Not many values for GaP/AlGaP (ioffe probably has best ones). These values are dependent on doping/impurity concentration. In any case, many of the measurements were done in the 1970s-80s with doped material (they couldn't grow very high-purity films back then and semiconductor industry doesn't care about undoped material).

Thermo-Refractive

- Also covered in paper and I have sent you literature before…

Piezo-Electric

- I can send some references…
- For GaP, this paper: D.F. Nelson, E.H. Turner, APL 39 (1968) and list of most values in Springer Materials pdf, both attached to email.

Production Scale

- How big can we make them? Limited by current GaAs wafer size at 200 mm diameter. Bonding and growth both possible over 450-mm diameter…
  - Just curious- who is doing 450-mm III-V deposition? I didn't know anyone has demonstrated on that scale. Current largest production MBE chambers are outfitted for 3x200mm wafers. For GaAs, this is the largest available wafer size anyway. Conceivably this could be custom fit for 1 larger-sized Si optic. Again, this goes back to whether you need to use MBE (likely) or whether MOCVD films have low enough absorption.
- How small can they be while still giving improvement? Not sure what you mean…
  - I guess this depends on how low the absorption is, how large the beam is, and all the other effects in the preceding and following slides? Can we do back of envelope calculation with just absorption and beam size?

Non-linear effects

- Two Photon effects? Can provide references or simply search for this, values readily available
- General note: almost all nonlinear effects are strongly dependent on wavelength and carrier concentration, so need to be careful when citing/using values.
- GaAs suffers from two-photon absorption (TPA) at 1550 nm (band edge is 870 nm). [W.C. Hurlbut et al., Opt. Lett. 32 (2007)]
- AlGaAs, esp. high Al content does not have significant TPA.
- GaP has indirect and large bandgap (2.25 eV) which prevents TPA. Only measured values available at 532 nm [S.J. Rychnovksy, U of Iowa thesis (1994)] or other nonrelevant wavelengths.

Birefringence

- See paper: Appears to be unavoidable as it comes from thermal-expansion-mismatch strain between mirror layers; note that 100-oriented GaAs/AlGaAs is in-plane anisotropic, but strain breaks symmetry…
- Proportional to E field

Electro-Optic Effect

- Electro-gyration not familiar
- What's the Electric Susceptibility? Easy to look up
- Kerr effect same, quadratic with E field
- Pockels effect same

Raman Scattering

- No prior experience
- Dependent on third-order nonlinear susceptibility and is similar to a four-wave mixing process. For all nonlinear stuff, I'd refer to Boyd's "Nonlinear Optics". Both GaAs and GaP have similar third-order nonlinear susceptibility.

Effect combinations

- Piezo-electro → make stress → Birefringence
- Optical rectification → make electric field → electro-optic effect
- Second-order harmonic generation → frequency doubling → parametric down-conversion
-

Annealing effects

- None apparent so far in both microresonators and cavity mirrors. Annealing is necessary for decent bond strength. Does not seem to change optical properties either.
- Mechanical loss of silicon has noticeable differences for different annealing conditions (but maybe this is a surface effect and not bulk effect?). Not much compelling reason to look at annealing of GaP/AlGaP since the growth itself is basically a long, high-temperature anneal already.

Bulk vs Coatings

- Can we measure these properties on bulk samples instead of coating samples?
- Most of these properties are already measured, GaAs/AlGaAs has been studied since the 1960s… Best bet is to not re-invent the wheel here… Let's just make bonded mirrors (big or small) and measure everything directly.
- We are measuring bulk GaP (and plan for bulk AlGaP) for mechanical loss, Young's modulus, radius of curvature, etc. These values are not well known for GaP/AlGaP.