Optics for Interferometers: Test Masses

Considerations for the surfaces:

- good large-scale flatness, to limit wavefront distortion
- good medium-scale smoothness, to limit scattered light
- small small-scale roughness, to limit losses to optical system

Considerations for the coatings:

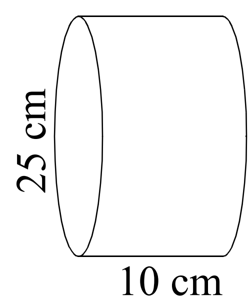
- low absorption, to avoid thermal distortion
- flatness and smoothness comparable to surfaces
- clean environment to avoid contamination

Considerations for the substrates:

- good homogeneity, not to compromize figure above (BS, FP)
- low absorption, to avoid thermal distortion (BS, FP)
- high internal mechanical Q to limit thermal noise (fused quartz)
- form, size, and suspension to limit thermal noise

Process

- Determine performance requirements
- Find connection to mirror specifications
- Research readiness of technology (Pathfinder)
    - substrates, polishing, coating, metrology
- Full-scale fabrication



Performance Requirements

Shot-noise limited sensitivity

- $h(f) = 3 \times 10^{-23}$ at 100 Hz
- with given laser input power (2 W)
- excess phase noise from scattered light less than
    - shot, pendulum thermal noise

Target for GW frequencies

- arm cavity storage time (11 msec, 90 Hz)

Degradation due to contamination

- asymmetry in interferometer insignificant for 'long' times

Mechanical properties

- Internal mode thermal noise below shot noise ($Q > 2 \times 10^{6}$)
- Suspension mode thermal noise minimized

Spatial scales for surface errors

30 mm to 3 mm

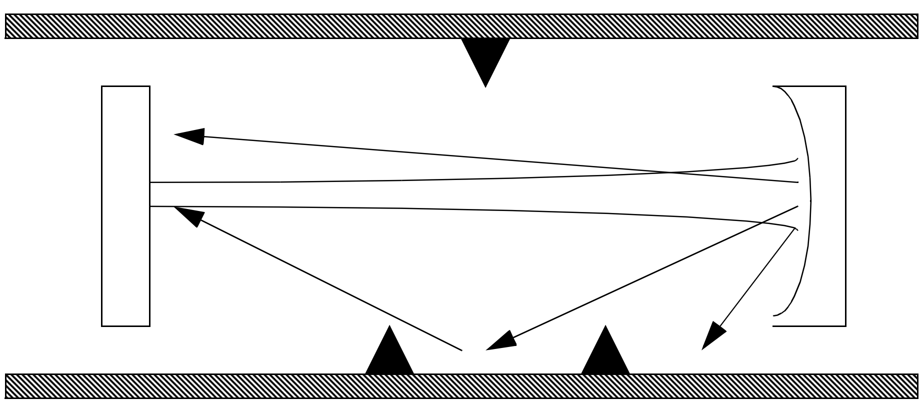
- Scattering angle small compared with (mirror radius)/(arm length)
- Couples light into higher order spatial modes of arm cavity
- Degrades wavefront cancellation at Beamsplitter

3 mm to 80 microns

- Scattered light hits beam tube (baffles) once, or twice
- moving beam tube adds random phase
- light recombines (with low probability), adds phase noise

< 80 microns

- Scattering angle large
- Light lost to baffles, multiple reflections
- Light power lost to system, shot noise degraded



Specification of surfaces

Analytic method, large spatial scale (Weiss, Saha)

- Obtain phase maps of optics: synthesized or measured
- Find basis modes of cavities using Laguerre-Gauss functions
- Analyze surfaces in this modal picture
- Illuminate with LG_oo base mode
- Find projection from <00> into <nm> by imperfect optics
- Calculate resulting optics defect

- Advantage: intuitive, quick for a small number of <nm>
- Disadvantage: ignores cavity coupling, hard to generalize

Specification of surfaces

Numerical method, large spatial scale

(Vinet, Hello; Saha; Hefetz, Bochner)

- Obtain phase maps of optics (surfaces, homogeneity)
- Replicate statistically if needed
- Set up entire optical system as matrices of deviations from flats
- Perform iterative propagation using FFT until field stable
  (in paraxial approx., propagation represented by FFT,
  advance in phase due to propagation, inverse FFT)
- Adjust lengths for resonance conditions (as sensed)
- Analyze for resultant steadystate feilds for
  - performance,
  - impact of defects
- Explore parameter space by scaling input data
- Allows specification of mirrors, and analysis of test data

- Requires 8 hours for 128x128 grid for complete model

Input to FFT modeling

- Phase maps of fused silica substrates for Pathfinder (homogeneity)
  - have sufficient independent measurements
- Hughes-Danbury Calflat polished substrate
  - have only one measurement
  - create ‘new’ surfaces which are statistically similar
- Nominal LIGO interferometer design
  - lengths - 4km, recycling cavity
  - radii of curvature
  - transmission of arm cavity input mirrors - 3%
  - nominal loss (scatter, absorption) - 100 ppm
  - modulation scheme - asymmetry with a phase modulation

Optimization for best GW signal-to-noise

- asymmetry (13 cm)
- recycling mirror transmission (3.2%)
- modulation depth (Γ=0.5)

Parameter searches

- scaling of mirror surface height maps
- variation of nominal loss

Output from FFT model

Scaling laws

- Minimum detectable *h(f)* goes as $\sqrt{RMS}$ of all wavefront defects
- Minimum detectable *h(f)* goes as $PPM^{1/5}$ of additional loss
- Re-optimization recovers much lost GW *S/N*

Acceptable specifications for initial LIGO detectors

- Roughly, $RMS = \frac{\lambda}{600}$ in central 8 cm
    - slightly degraded Hughes-Danbury
- 100 ppm loss acceptable; specifies small-scale micro-roughness
    - simple analytic approximations: $\frac{P_{scat}}{P_{total}} = 16\pi^2\frac{\sigma^2}{\lambda^2}$
    - Thus 0.4 nm micro-roughness acceptable
    - not a super-polish! (probably required for coating)

Other concusions

- Order of 250 mW on photodetector

Scattering to tube walls (medium scale)

- Analytic techniqes for scatter
- Analytic techniques for consequences (Thorne, Vinet)
- Monte-Carlo simulations of light paths

Status for LIGO

Pathfinder Process well underway:

Substrate material available; samples in-house

- Corning grade 0AA meets our requirements
    - homogeneity
    - *Q* probably as well

Polishing feasible

- Hughes-Danbury can produce large, well-figured substrates
- Super-polishing houses may try as well (RFQ)

Coating a challenge

- Same ‘surface’ requirements as for substrate
- Small surfaces (3 cm dia) flat, low-loss, low scatter
- Large highly uniform caoting new for undustry
- American (REO, Boulder) and French firms active