Study and development of silicon carbide stray light optical components for third generation gravitational wave detectors

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Study and Development of Silicon Carbide Stray Light Optical Components for Third Generation Gravitational Wave Detectors

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Problematic and research objectives

Problematic

Stray light is the light that does not follow the intended path reaching the detector [1]. Subsequently, stray light was considered as an issue because scattered light from surfaces other than the mirrors surface, such as the walls of the cavity, will carry information about the displacement of the wall that will recouple back with the main beam adding a stray light field to the unperturbed field inside the interferometer:

$$E_{total} = E_{in} + E_s = E_{in} + \sqrt{f_{sc}} E_{out} e^{i\emptyset_s(t)} \qquad E_{total} = E_{in} \exp[\sqrt{f_{sc}\frac{P_{out}}{P_{in}}}(\cos\emptyset_s(t) + i\sin\emptyset_s(t))]$$

This final profile of the equation contains a real part and an imaginary part. In this sense, the real part represents the amplitude modulation induced $\frac{dP(t)}{P}$ and the imaginary part represents the phase modulation $n_{\emptyset}(t)$ [1]:

$$\frac{dP(t)}{P} = \sqrt{f_{sc}\frac{P_{out}}{P_{in}}}\cos\emptyset_s(t) \qquad n_{\emptyset}(t) = \sqrt{f_{sc}\frac{P_{out}}{P_{in}}}\sin\emptyset_s(t)$$

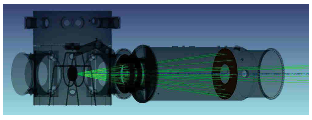
Where E_s is the stray light field, E_{out} is the output field and $\emptyset_s$ is the phase angle thet carries information about the scattered light.

Stray light in the current detectors is being reduced using light shades called « baffles ». In fact, the third generation detector will be using a very high power laser and the test masses will be subjected to a different temperature condition « cryogenic temperature ». Hence, we had to find a new material that can be a replacement for the current baffles and thet can bear these conditions.

[1] Canuel B., and al., Opt Express. 2013 May 6; 21(9):10546-62

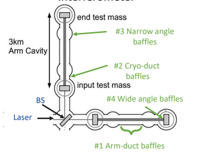
The chamber and the core optics with stray light

Advanced VIRGO core optic chamber system



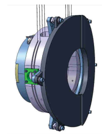
[Credits: J.Marque, Lecture at VESF school 2012, EGO, Italy]

Baffle solutions in KAGRA interferometer



[Akutsu T. and al., Opt Society of America. 2016]

Baffle solutions in Advanced VIRGO



[Credits: A. Moggi (INFN-PISA)]

Research objectives

- Studying and analysing the thermal and mechanical behavior of SiC under interferomrter conditions
- Studying the possibility of stray light reduction or elimination by using SiC as baffles

Methodology

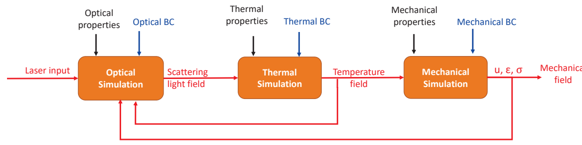
Multiple actions combining

- Optical characterization of the most promising materials (SiC, coated SiC…),
- Analysis of the thermal and thermomechanical changes induced by scattering light flux,
- Analysis of the influence of this changes on the scattering light process (if needed).

All the methodology could be applied to advanced virgo and/or third generation interferometer.

Key points : cryogenic temperature, high laser power density

Methodology of simulation



Optical Work

Optical work

- Material Requirement (SiC is a very promising candidate)
- Optical Characterization
  - Measuring the scattering at room temperature (Advanced VIRGO) and at cryogenic temperature (Einstein Telescope ET)
  - Same conditions for measuring the reflectivity of SiC

	Candidate			
Requirements	SS 304	Al-NiPW	SiC-CVD	SiC
Low Scattering	•(RT)	••	•••	•
High Laser Induced Damage Threshold LIDT	••(RT)		•••	•••
High Thermal Conductivity	•	•••	•••	•••
Low Thermal Expansion	••	•	•••	•••
High Stifness	••	•	•••	•••
High Absorption Coefficient	•	•••	•••	••

••• Most promising candidate

Physical characterization of BOOSTEC® SiC

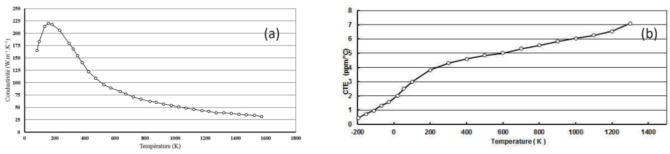


Fig: BOOSTEC® SiC experimental data as a function of the temperature, (a) thermal conductivity, (b) thermal expansion.

Optical characterization of 3 samples of MERSEN SiC

- TIS is calculated as the ratio between scattered output light and input light source

$$TIS^* = \frac{P_{out}}{P_{in}}$$

- TIS measured as a function of the root mean square roughness

$$TIS^{**} = 1 - \exp[-(\frac{4\pi\cos\theta_i\sigma}{\lambda})^2]$$

[Bennett and Porteus]

λ is the wavelength of the laser

σ is the surface roughness of the sample

θ_i is the incident angle (2°-3°)

Polished Sample	Process	Surface Roughness (nm)	TIS** (ppm)	TIS* (ppm)	Reflectivity at Brewster angle(%)	Reflectivity at 3 deg (%)
HIP BOOSTEC® SiC	Hot Isostatic Pressing	5	3487	2120	0.2	21
BOOSTEC® SiC polished (no HIP)	Pressureless sintering	2	558	4360	0.2	19
MERSEN SiC-CVD	Chemical Vaper Deposition	< 1	<<<	50	0.1	19

[V. Bavigadda, and A. Magazzu, EGO, Cascina (Italy)]

Simulation work

Thermal analysis

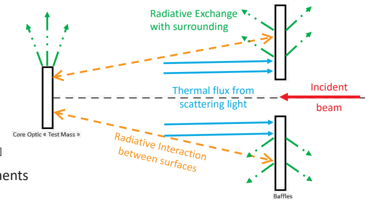
- Steady state thermal analysis
- Open cavity radiation
- View factor interaction
- Radiative interaction with surrounding

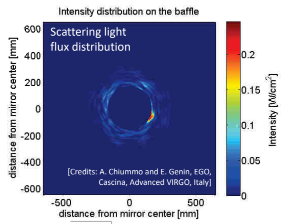
$$\varphi = e\sigma(\theta^4 - \theta_s^4) \quad \text{[Stefan-Boltzmann law for radiation]}$$

- Radiative Interaction between the optical components

$$\varphi_i = \sigma\sum_j e_{ij}F_{ij}[(\theta_j - \theta^z)^4 - (\theta_i - \theta^z)^4]$$

  - e_i and e_j are the emissivities of the facets
  - σ is Stefan-Boltzmann constant
  - F_{ij} is the view factor
  - θ_j and θ_i are the temperatures of the facets
  - θ^z is the absolute zero temperature
- Thermal flux distribution on the baffle obtained from optical simulations





Results

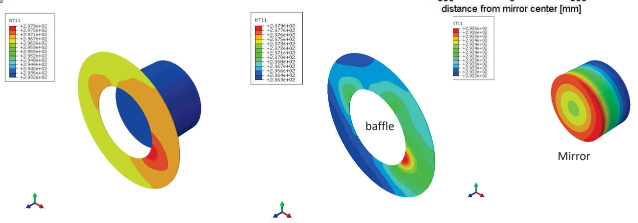


Fig: Temperature field over the baffle and the mirror with room temperature as surrounding one (K)

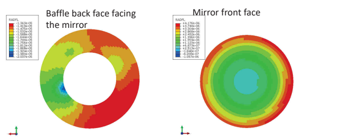


Fig: Radiation flux per unit area on baffle and mirror (W/mm²)

- Maximum temperature attained by SiC at room temperature is T = 297.8 K
- Maximum temperature attained by SiC at cryogenic temperature is T = 141.2 K
- Temperature variation at room temperature and cryogenic temperature is $\Delta T = 2\ K$

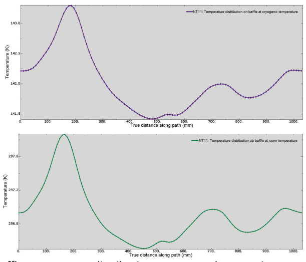


Fig: Baffle temperature distribution at room and cryogenic temperatures (K)

Conclusion & Next Steps

Conclusion

- BOOSTEC® SiC could be a good candidate for baffles for the third generation gravitational wave detectors regarding its thermal and mechanical properties.
- MERSEN SiC-CVD is a very promising material for this purpose due to its agreement with the optical requirements desired.
- Preliminary results of FE modeling interaction between the test mass and the baffle allowing us to study and analyze their temperature variation .

Next Steps

- Studying the characterization process of BOOSTEC® SiC under cryogenic temperature to explore whether the optical requirements are achieved.
- FE Studies of the thermal analysis of the conduction process.
- Mechanical analysis under room and cryogenic temperature of SiC setup must be explored to evaluate displacement, stress; strain and analyze mechanical behavior.
- Evaluating the possibility of using different types of coatings with the same substrate SiC.

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