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V. Loriette, J. Roger, A. Boccara, Ph. Gleyzes, J. Mackowski. Probing of low loss materials at $1.064\ \mu\text{m}$ for interferometric gravitational waves detection. Journal de Physique IV Proceedings, 1994, 04 (C7), pp.C7-631-C7-634. 10.1051/jp4:19947149 . jpa-00253207

HAL Id: jpa-00253207

<https://hal.science/jpa-00253207>

Submitted on 1 Jan 1994

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Probing of low loss materials at 1.064 μm for interferometric gravitational waves detection

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Abstract : Within the framework of the Virgo project, characterisations of low-absorption high reflectivity multilayers coatings by collinear mirage effect at 1.064 μm are reported. All the tested samples have absorption losses lower than 20 ppm and the lowest observed average absorption loss is 0.99 ppm.

1. INTRODUCTION

Today, energy absorption inside multilayer dielectric coatings is becoming a limiting factor for apparatus that require very low energy losses and/or a precise control of a light beam's wave front shape. In the case of a Virgo type giant interferometer, a high absorption inside the optics coatings gives rise to thermal lens effects and thus to wave front deformation and contrast loss. For the time being, the quality level of the Virgo optics is still higher than what is commercially available. Today, mirrors absorbing less than 5 ppm and homogeneous to within 20% on a few millimetres square are of current use, but Virgo will have to use seven hundred centimeters square mirrors, with absorption below 1 ppm and homogeneity better than 10% on the whole mirror surface. Our goal has been to realise a test bench that would allow us to reach a sensitivity better than one tenth of a ppm, to check the coatings homogeneity of $R_{\text{max}} 0^\circ @ 1.064\mu\text{m}$ mirrors and to allow us intensive and fast testing. We opted for a mirage bench in a collinear configuration.

2. THE VIRGO PROJECT

Virgo is a franco-italian project for a giant Michelson-type interferometer with three kilometers long arms. This interferometer will detect gravitational waves, which are local deformations of space-time, created by violent astrophysical events, that propagate at the speed of light. The effect of such a wave on an interferometer is a relative variation of the two arms lengths of about 10^{-20} . In order to reach a sufficient sensitivity to detect those extremely small signals, almost perfect optics are required.

3. MEASUREMENT PRINCIPLE^[1]

In every mirage bench, whatever the beams geometry, one laser beam (the pump beam) heats the sample and its surroundings, thus produces variations of the different refraction indices inside the heated region. By using a modulated pump, those variations become periodical. A second beam, much weaker than the pump, crosses the heated region and is periodically deflected. The deviation's amplitude is related to the variations of the refraction indices, which are themselves proportionnal to the amount of energy lost by the pump beam. By measuring the probe beam deviation with the help of a quadrants detector and a lock-in amplifier, the sample's absorption coefficient can be found. The signal amplitude not only depends on the sample's absorption, but on many other thermal and geometrical parameters, so in practice only measurements relative to a known standard, and with the same beam geometry, are performed.

4. SET UP

In our particular case, energy from a modulated TEM₀₀ Nd-YAG laser is lost inside the first layers of the mirrors coatings and heat diffuses in the air and in the silica substrate. The probe beam, which is a low power He-Ne laser, crosses those two regions and strikes a quadrants detector placed behind the sample. An interference filter in front of the detector prevents spurious light from the pump beam from entering the detector. The two beams are focused on the same point of the sample's surface, the beams waist sizes are

150 μm for the pump and 70 μm for the probe. Thanks to a suitable sample holder, the sample's front surface position is fixed independently of the substrate shape. This permits to avoid realigning the beams each time the sample is changed, *see fig 2*. The quadrants detector and the probe beam are part of a commercial mirage bench^[2]. The use of a CCD camera helps to position roughly the two beams and the maximum signal amplitude, which is obtained when the probe beam

FIG. 1. Beams geometry. The maximum deviation is obtained when the distance e between the two beams equals 0.5 times the pump beam waist size.

crosses the region of highest gradient of the index of refraction, is found by translating the pump beam. By using the rotation stage we are able to scan circles on the samples and thus to test the coatings homogeneity. Once again, the precise positioning of the sample keeps the two beams crossing point exactly on the front surface while the rotation stage is in use.

FIG. 2. Set up.

5. RESULTS

5.1. 5 to 20 ppm range

In this range of absorption our setup gives fair results. We suppose that absorption only occurs inside the coatings and neglect volume absorption in the air. As we test Rmax mirrors, there is no volume absorption inside the substrate. Our absorption standard is a 9ppm absorbing coating on fused silica. Without any special care, such a bench allows measurements with a sensitivity of one tenth of a ppm on mirrors with some tens ppm absorption. We tested two years old mirrors from Sextant Avionics. The samples were cleaned with acetone and methanol. Some results are summarised in table 1.

Sample	Mean abs./1ppm	homogeneity/1ppm	sensitivity/1ppm
Rmax	6.44	0.9	7.5E-2
Co91	9.29	0.6	6.5E-2
Co92	5.80	1.5	3.9E-2
AR	9.69	-	1.6E-1
C201	17.9	1.1	6.1E-2

TABLE 1. Absorption values of various multilayer coatings on silica substrate.

Pump power 880mW, modulation frequency 2405Hz.

The AR sample is an anti-reflective coating on fused silica, so absorption also takes place inside the substrate. In order to eliminate the bulk absorption contribution we performed two measurements, one on the coated and one on the uncoated side. The difference between the two results gives the value of coating absorption alone.

5.2. 0 to 5 ppm range

In order to test very low absorbing mirrors, we focused on the ways of increasing the signal to noise ratio by increasing the signal while lowering the noise.

5.2.1. Signal to noise ratio increase

As the signal amplitude only depends on the incident power value, one may think of increasing it a lot. In fact, if the pump beam power is higher than 1W on a 150 μ m radius spot, some mirrors are damaged. We didn't find any relation between the damage threshold and the absorption level, the proof being that one of the weakest mirrors was the less absorbing one.

The two main noise sources are atmospheric convection that induce beam pointing fluctuations, and laser power fluctuations.

5.2.2. Beam wander

This first effect has been greatly decreased by simply protecting the beams in plexiglas tubes and by working with a modulation frequency higher than 1kHz, where beam wander effect is negligible. The sole fact of protecting the beams increased the SNR by 30%. When the modulation frequency increases the heat diffusion length decreases, and so does the signal amplitude. One may then think that increasing the frequency would lower the SNR. It's not the case because the signal loss is compensated by a faster noise decrease. When the diffusion length becomes comparable to the pump beam size, the signal decreases no more, and as the beam wander effect becomes negligible at frequencies higher than 800 Hz, the SNR is not improved by working at a frequency much higher than 1 kHz.

5.2.3. Power fluctuations

The second main noise source is long term laser power fluctuations. It induces important (up to 15%) signal fluctuations on a thousand seconds timescale. As our lasers are not intensity stabilized the only method to get rid of these fluctuations is to test our standard before each measurement.

We tested 1" diameter mirrors made by PMS and used the previously tested Co91 sample as our standard. We worked at 1208Hz.

Sample	Mean abs./1ppm	homog./1ppm	sensitivity/1ppm	pump power/1W
Rmax 0°@1.064 μ m ρ =1m	2.5	0.3	8E-3	2.0
Rmax 0°@1.064 μ m ρ = ∞ on fs	0.99	0.2	6E-3	0.85

TABLE 2. Absorption values of various PMS mirrors. The second mirror substrate was made of superpolished fused silica.

By working under those optimal conditions ($f \geq 1$ kHz, protected beams) the sensitivity reached 6 ppb.

5.2.4. Air absorption

When testing mirrors with losses below 1ppm, air absorption can't be neglected anymore. In effect, absorption by unit length by water vapour around 1.064 μ m varies from 60ppm/m up to 350ppm/m depending on ambient moisture. One can get a rough estimate of air absorption by considering the length of the beams overlapping region.

$\delta l \approx (\text{pump waist}) / \tan(\text{angle between the two beams})$. Taking an angle of 25° $\delta l \approx 320 \mu\text{m}$ which leads to an absorption between 0.02 and 0.11 ppm whatever the sample. This absorption is eliminated by replacing air by dry nitrogen.

6. CONCLUSION

We have tested two sets of Rmax 0° multilayer dielectric mirrors with absorption levels ranging between one and twenty ppm. None of the samples reached the Virgo specification either on absorption or on homogeneity. We have shown that collinear mirage detection, when performed under optimal conditions, permits to obtain a sensitivity better than one hundredth of a ppm and that, even with low absorbing mirrors, a mirage bench is easy enough to use to be considered as a valuable optical shop tool.

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