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STUDY OF THE OPTICAL PROPERTIES OF THE MIRRORS OF THE DIRECTIONAL OPTICAL MODULE FOR THE NEMO NEUTRINO UNDERWATER TELESCOPE

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Abstract

The reflectivity properties of different materials have been studied in order to select the best material to be used in the NEMO Directional Optical Module. The Cherenkov light produced in water by muons has been simulated with a monochromatic coherent laser of 476 nm of wavelength; to reduce refractive effects, a semi-cylinder shaped piece of Plexiglas has been used to simulate the light guide. Different reflecting materials have been matched to the Plexiglas and reflected light power has been measured by a photodiode as a function of incident light angle.

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1 INTRODUCTION

The NEMO Collaboration is studying the design of an optical module sensitive to the direction of the detected Cherenkov light. The optical module is based on a glass sphere containing a 4-anods 10" photomultiplier coupled to a set of mirrors. In order to match the refraction index of the photomultiplier and the glass sphere, the volume between the photomultiplier and the glass sphere must be filled with a transparent material like plexiglas or optical gel. Two prototypes of such a photomultiplier have been manufactured by Hamamatsu and the measurement of their optical properties is in progress. A conceptual design of the optical module is reported in Figure 1.

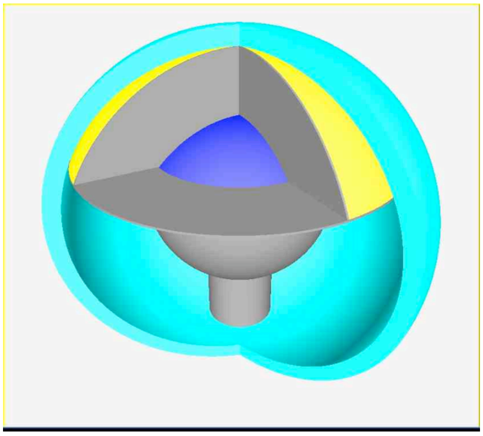

Figure 1: The conceptual design of the directional module showing the photocatode (blue), mirror system (gray), the Plexiglas (yellow).

The aim of this study is to find out the best reflecting material to be employed in the NEMO Directional Optical Module light-guide system. In order to choose the candidate material, an experimental setup has been assembled in order to measure the power of an incident coherent laser beam reflected by different selected materials, as a function of beam incident angle.

The result of this study should give indications about reflecting properties of the different materials and sort out the most reflecting material of the ones considered.

2 THE EXPERIMENTAL SETUP

A picture of the experimental setup is reported in Figure 2. It consists of:

- **The light source**: Laser beam (Innova 304, Coherent, USA).
- **The target**: semi-cylinder shaped Plexiglas with strips of different reflecting materials matched on its surface. The target has been fixed upon a rotating graduated support and it can be moved up and down to select the particular reflecting material.
- **The optical system**: two focalizing lenses and a beam deflector to guide the reflected beam to the acquisition sensor.

- **The detector**: a photodiode (LM-2, Coherent, USA) matched with a Wattmeter (Fieldmaster, Coherent, USA).

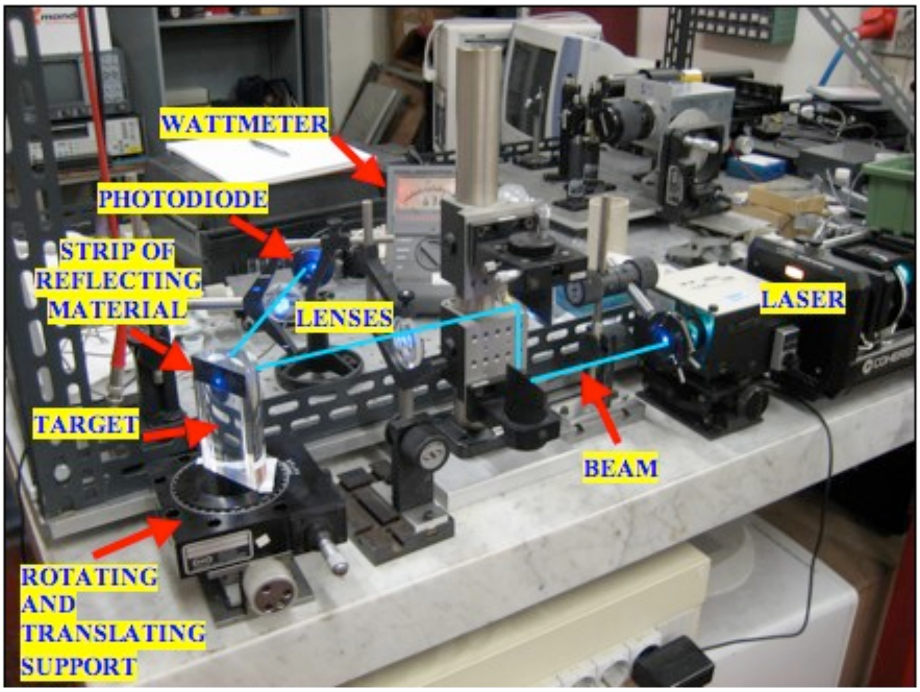

Figure 2: The experimental setup.

2.1 The light source

The Innova 304 can deliver a coherent laser beam at three different wavelengths. For the measurements discussed in this report we selected 476 nm wavelength, 200 mW output power, corresponding to the shortest wavelength that the device can deliver. This particular wavelength has been selected because it is next to the wavelength of Cherenkov light emitted in water by incoming muons.

The beam has been focalized by lenses before and after being reflected by the target in order to have point-like beam hitting the target and the photodiode.

2.2 The target

The target consists of a semi-cylinder shaped piece of Plexiglas matched to strips of different reflecting materials. The strips have been placed side by side vertically on the surface opposite to the surface of incident light, with reflecting side facing the direction of incoming beam as shown in Figure 3b. The choice of the semi-cylinder shape for the Plexiglas is due to the fact that, when hitting the curve surface of the target, the beam is not refracted at the air/Plexiglas interface, because it is perpendicular to the surface in every point.

According to the *Snell law* :

$$n_1 \sin\theta_1 = n_2 \sin\theta_2 \qquad (1)$$

where n_1 and n_2 are the refraction indexes of air and Plexiglas, θ_1 is the beam angle of incidence and θ_2 is the angle of refraction of the beam. The semi-cylinder is oriented in such a way that the incident laser beam hits the curved surface of Plexiglas always with an incident angle equal to 0° and the reflected beam exits the curved surface with an angle equal to 0 as well, In this way the beam is transmitted through the material without being deviated from its path (Figure 3a) and without reflections. The reflected beam is then focused with a lens system in order to concentrate the intensity on the photodiode.

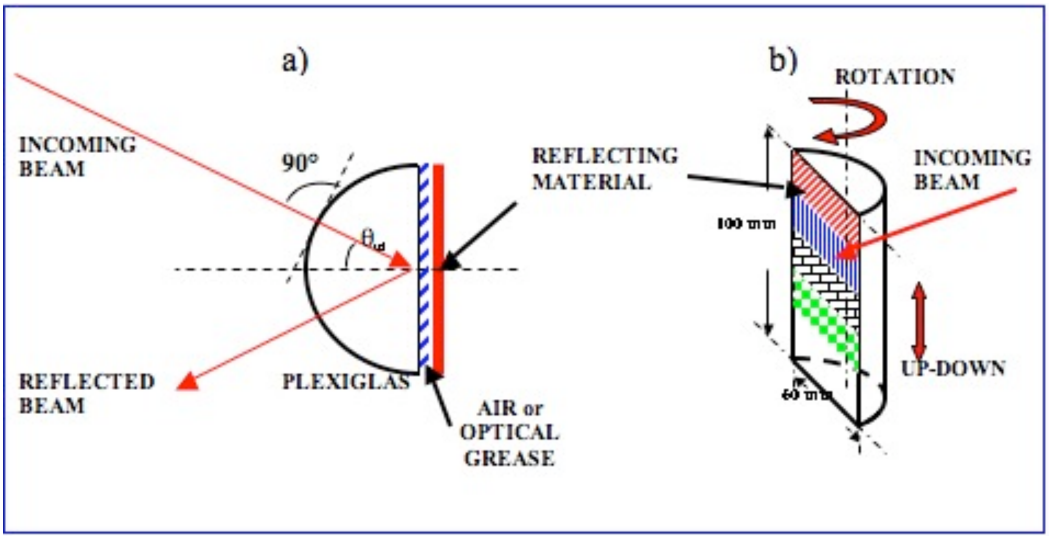

Figure 3: a):The laser beam hitting the target (top view). b):The target (side view).

Six different reflecting materials have been studied in this measurement:

- **3M (adhesive)**: it is a multi-layer polymeric adhesive film.
- **3M**: it is a similar multi-layer polymeric film without adhesive film.
- **HiFi MEX02C**: it is a single-side metalized polyester film with a highly reflecting mirror finish.
- **Aluminum**
- **Teflon**
- **Aluminated Mylar**

The strips of reflecting materials have been matched to the Plexiglas in two different ways:

- Air
- Optical grease

and data acquisition has been replicated for the two cases, in order to investigate the differences.

The target lays upon a graduated rotating support which makes possible to select the angle of incidence of the beam. The target can also be moved in the up-down direction in order to select the particular strip of reflecting material to be measured without modifying the beam path (Figure 3b).

2.3 The optical system

Three different wavelength component are generated by the laser. The 476 nm wavelength used in these measurement is selected with a collimator after a dispersing device. The beam is then deflected to reach the correct height and focused on the reflecting material located behind the semi-cylindrical Plexiglas. A second lens is used to focus the reflected beam on to the photodiode.

2.4 The acquisition sensor

A photodiode calibrated for the selected laser wavelength has been used to measure the intensity of the reflected beam. The sensor is connected to a wattmeter which directly indicates the power of reflected light.

3 THE MEASUREMENT

The power of the reflected light has been recorded as a function of the angle of incidence of the beam. The angles have been selected with the help of a graduated rotating support fixed to the target.

The same data acquisition has been made for two different kinds of matching between Plexiglas and the reflecting materials. In the first case, strips of reflecting materials have been applied to the plastic surface without any matching substance, thus having *air* between Plexiglas and reflecting material. In the second case, *optical grease* has been used to match the reflecting materials and the plastic surface.

3.1 The first set of measurements with the *air* gap

The plot in Figure 4 shows the power of the reflected laser beam as a function of angle of incidence of the beam for the six different reflecting materials in the case of *air* between the Plexigal and the reflecting materials. The values of each measurement are also reported in Table 1.

The *3M* material is a permanent adhesive material therefore the *air* gap could be considered negligible. As can be seen from the plot in Figure 4, it appears to be the most reflective material among the ones selected.

However, the intensity of the beam reflected by the *3M* foil seems comparable to that reflected from the other materials, for incidence angles greater than 40 degrees. This effect is particularly evident for poor-reflecting materials, such as *Teflon* and *Aluminum.* In fact, their reflected power is pretty low in the region below 40 degrees of incidence angle, but rises up to be comparable with others, beyond that point.

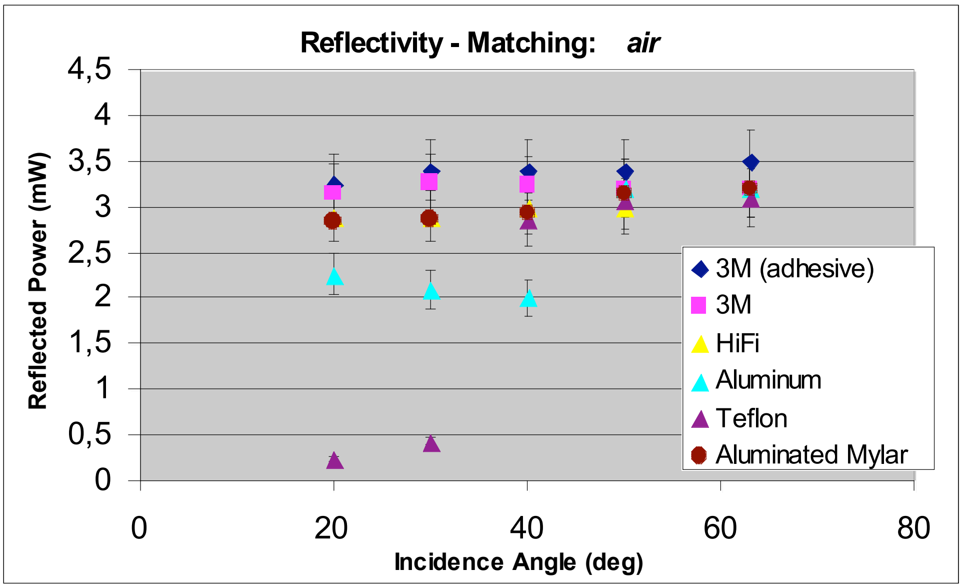

Figure 4: The reflected light power as a function of angle of incidence of the beam in the presence of air between the Plexiglas and the reflecting materials.

Table 1: Values of the reflected power (mW) as a function of the beam incident angle for different materials (*air*).

	20°	**30°**	**40°**	**50°**	**63°**
3M (adhesive)	3.25	3.40	3.4	3.4	3.5
3M	3.15	3.26	3.24	3.2	3.2
HiFi	2.9	2.9	3.0	3.0	3.2
Aluminum	2.26	2.1	2.0	3.2	3.2
Teflon	0.225	0.43	2.86	3.07	3.1
Aluminated Mylar	2.84	2.87	2.94	3.14	3.2

This can be explained with the *total reflection* effect on the Plexiglas plane surface, due to the different refraction indexes of the two different materials at the interface: *Plexiglas* (n=1.52) and *air* (n=1).

The diagram in Figure 5a clearly shows what happens in the region below 40 degrees of incidence angle. The incoming beam travels through the *Plexiglas* and hits the interface with angle θ_1. According to the *Snell law* (1) it is refracted and transmitted through *air* with an angle

$$\theta_2 = \arcsin\left((n_1/\, n_2) * \sin\theta_1\right) \qquad (2)$$

Then it hits the reflecting material, it is reflected back with an angle θ_2 and again meets the interface. Here the beam is newly refracted and goes through the *Plexiglas* with an angle θ_1 towards the photodiode.

Refraction occurs at incident angles lower than the Brewster angle. The limit angle (*Brewster Angle*) is obtained from the *Snell Law* (1) where the function *sin* has its maximum equal to 1. Its value is given by the expression:

$$\theta_{\lim} = \arcsin\left(n_2/\, n_1\right) \qquad (3)$$

that in our case becomes

$$\theta_{\lim} = \arcsin\left(1/\, 1.52\right) \sim 41.1° \qquad (4)$$

When the incident angle exceeds the Brewster angle the beam is totally reflected at the interface as shown in Figure 5b.

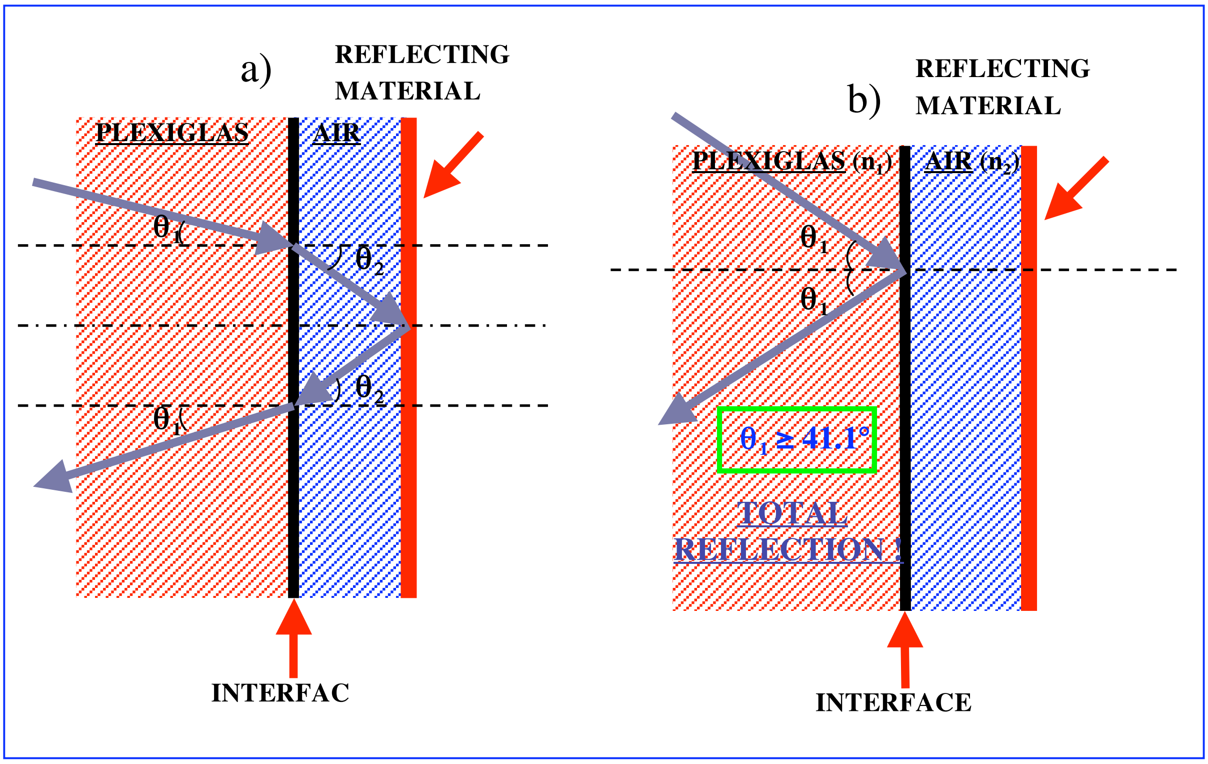

Figure 5: a) In the case of *air* gap, for incidence angles below 41.1°, the beam is refracted through air; b) for incidence angles above 41.1° the beam is totally reflected at the Plexiglas plane surface.

3.2 The second set of measurements with *optical grease*

The plot in Figure 6 shows the power of the reflected light as a function of the angle of incidence of the beam for six different reflecting materials in the case of *optical grease* as matching mean at the interface. The values of each measurement are also reported in Table 2.

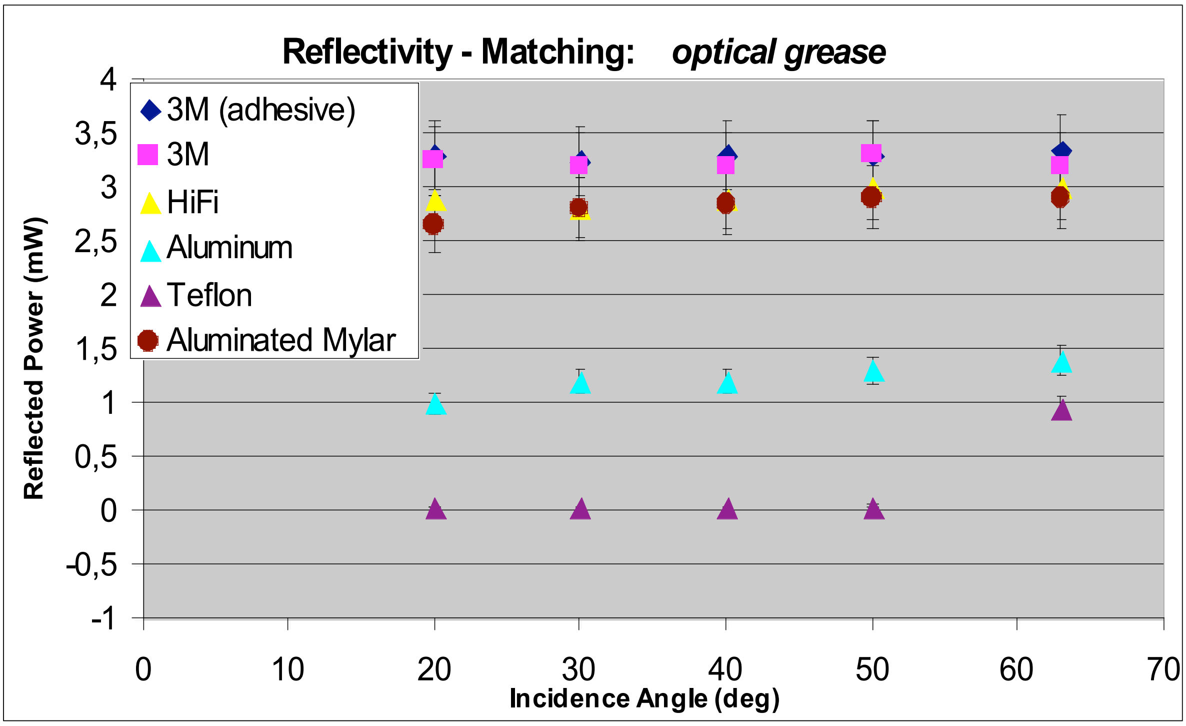

Figure 6: The reflected light power as a function of angle of incidence of the beam in the presence of optical grease between the Plexiglas and the reflecting materials.

As can be seen from the plot, the reflected power shows no dependence from beam angle of incidence. This can be explained by the fact that, in this case, the materials have been matched to the plastic surface by optical grease. The latter has a refraction index approximately equal to that of the Plexiglas. Therefore there is a continuum at the interface and no appreciable refraction or total reflection effect can take place. The path of the beam is clearly schematized in the diagram in Figure 7. The incoming beam hits the *Plexiglas*, goes through it, it is transmitted through the optical grease without suffering any refraction and it is then reflected back by reflecting material.

Also in this configuration the 3M materials show reflecting properties better than the other studied material. The *Aluminated Mylar* and the *HiFi* present rather good reflective properties but their performance are 90% that of the 3M foils.

Table 2: Values of the reflected power (mW) as a function of the beam incident angle for different materials (*optical grease*).

	20°	**30°**	**40°**	**50°**	**63°**
3M (adhesive)	3.30	3.25	3.3	3.30	3.35
3M	3.25	3.20	3.20	3.30	3.20
HiFi	2.90	2.80	2.90	3.00	3.00
Aluminum	1.00	1.20	1.20	1.30	1.40
Teflon	0.030	0.041	0.042	0.045	0.956
Aluminated Mylar	2.65	2.81	2.85	2.90	2.90

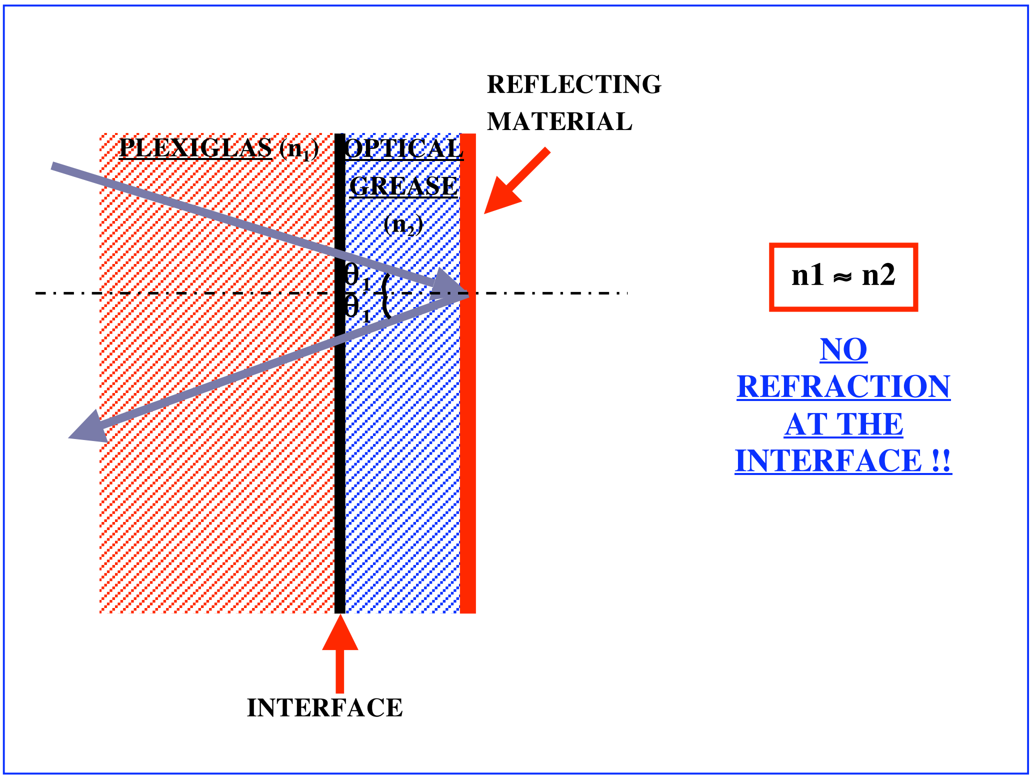

Figure 7: In the case of the *optical grease* the incoming beam is not subdued to refraction effects at the interface.

3.3 Comparison with other reflecting materials

Finally the *3M* material has been compared with a prototype of the Cherenkov light detector part of the CEBAF Large Adron Spectrometer (CLAS) at Jefferson Laboratory (Virginia, USA).and with a 1/10 wave mirror.

The prototype is made of a thin aluminum layer deposed by evaporation method upon a polycarbonate substrate and the 1/10 wave mirror (Valumax, Newport Co., USA) has a certificated reflectivity greater than 96% in the range 480 nm – 2000 nm.

The comparison has been realized without Plexiglas and at 0° incident angle. The result of the measurements are reported in Table 3 and the 3M material shows better reflective properties than the mirrors.

Table 3: Comparison between reflectivity of 3M material and two different kind of mirrors .

	Reflected Power (mW)
Cherenkov mirror	3.53
1/10 wave mirror	3.80
3M material	4.10

4 CONCLUSIONS

We studied the reflecting properties of several materials searching for a good candidate to realize the collecting light system of the prototype of the directional optical module designed for the NEMO experiment. We tested six different materials in different configurations and for different reflective angles. According to the results, it clearly appears that *3M* is the best candidate.

3M seems to be the best reflective material even if compared to two different kind of highly-reflective mirrors.