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Holographic Optical Elements (HOE) for high efficiency illumination, solar control and photovoltaic power in buildings

a European project review

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SUMMARY

Integration of holographic optical elements (HOE) into the building envelope of a built environment makes solar radiation as a renewable source of power accessible. The main goal of this research project is the development and production of HOE's for control and directing the radiation of the sun which will give a broad scale of applications with high potential of energy saving and increase of comfort. After detailed simulation studies and laboratory performance tests test rigs have been constructed covering the aspects of sun-shading (facade) and light-directing (light shaft). These test rigs are monitored on a continuous basis with regards to diffraction efficiency, luminance, illuminance, colour temperature and room temperature. The results covering nearly a year will be introduced and critically assessed in the context of the project objectives.

1. Introduction

Sunlight is the source of life on earth. Human well-being is strongly dependent of the availability of daylight and the solar cycle within the year. Researches show that the hormone production is influenced by the conditions of light which effects on the seasonal change in mood. This demonstrates that the quality of light is of a high importance for human physiology as well as psychology. Being able to plan buildings according to the demands for good lighting, especially daylighting, requires a basic knowledge of the principles of light in physics, technical evaluation, appearance and human perception. Architects and engineers can only design a building as an entity in terms of good lighting knowing the background information about light and their high importance for human being. Daylighting design interacts with many design issues of a building, hence it is important to follow an integrated approach. Daylighting in buildings is not only a matter of energy saving and performance, but also of comfort and appearance. A conventional approach considers building issues like daylighting, solar shading and glare separately. Mostly, a conventional approach leads to high energy consumption of a building, e.g. a conventional shading device reduces solar heat gains, but also affects the daylighting by excluding the diffuse light.

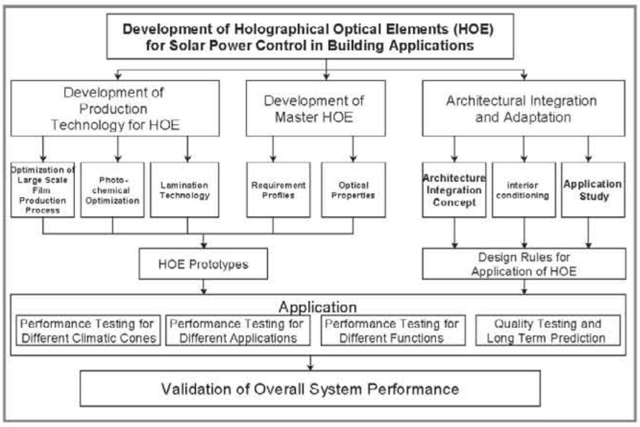
Holographic optical elements (HOEs) have useful properties for diffuse light transmission and radiation control. A shading device with HOEs is an high innovative system allowing "transparent shading". The view to the outside is nearly not affected, but the beam radiation is inhibit to penetrate the building. In combination with an automatic control system the energy consumption for cooling, heating and illumination in buildings can be reduced.

Additionally HOE properties concerning light deflection can be exploited for the redirection of sunlight towards remote areas, which do not have direct access to exteriors, such as basements, enabling their conversion to spaces with new facilities of increased value.

2. Project Methodology and Workplan

In the first phase of the project, requirement profiles, definitions and terms as well as a glossary were defined and an agreement about quality standards and other technical regulatory guidelines was made. Engineering concerning the development and optimization of production technique as well as evaluation and adaptation of concepts for the application of new HOE systems has been undertaken. Performance calculations have been assessed and an overview has been given in the risk and effectivity study. Assessment will be performed in parallel for technological development, economic and environmental development. Key variables for balancing procedures have been defined. HOE systems have been installed in various applications and for defined functions in different climatic zones of Europe. The data are currently monitored and will be assessed and systematically rearranged before extracting balance sheets. Taking into account all data of the balance sheets as described above, a dissemination and exploitation via e Coaching, a script for students of architecture and further education courses are currently realised.

The project methodology is shown in the following diagram:



The project partners are:

- Gesellschaft fur Licht und Bautechnik, Dortmund, DE;
- Hochschule Wismar, Wismar, DE;
- KINON Sicherheitsglas GmbH, Aachen, DE;
- Stilvi GmbH, Athens, GR;
- Umwelt-Campus Birkenfeld Entwicklungs - und Management GmbH, Birkenfeld, DE;
- Universitat Dortmund, Dortmund, DE.
- Universite Blaise Pascal / Centre National de la Recherche Scientifique, Aubiere Cedex, FR ;
- University of Southampton, Southampton, GB;

The role each partner has played within this interdisciplinary project took care of his main knowledge and skills. The well balanced profile of the consortium that consists of experts with an outstanding experience in their special fields represented a multidisciplinary approach and guaranteed that the described objectives could be reached.

3. State of the Art - Holographic optical elements (HOES)

A holographic optical element is a new class of optics that operates on the principle of diffraction. Traditional optical elements use their shape to bend light, but the holographic recording material changes the optical properties by variation of density. This variation causes a type of fin pattern, termed fringe. In order to playback a hologram the reference beam must be shone back through the hologram at the same angle relationship as it had in construction. HOEs are flat and very light, as they are formed in thin films of a few µm thickness only. They can be used to control, focus and select light improving the thermal and lighting perfo-rmance in built environment. Mainly there are four different hologram types:

Grating-HOEs:
Grating-HOEs are holo-graphic diffraction gratings, showing a similar effect as prisms. White light is split into the rainbow colours of the spectrum by passing the grating. This phenomenon can be used to create colour effects in a definite distance of the Grating-HOE.

Display-HOEs:
Display-HOEs are Grating-HOEs, but they are scattered perpendicular to the diffraction plane, so the colour effects appear on the complete hologram surface and less on a surface in a definite distance of the hologram.

Reflection-HOEs:
In a Reflection-HOE reconstruction an incident beam comes from the same side of the hologram. Some parts of the incident light are reflected, some are not, depending on the interference pattern. In a reflection hologram the fringes are packed so closely together that they constitute layers throughout the thickness of the hologram recording material. The spacing between fringes remains constant or differ by the development process. The distance is a function of the wavelength of light used in constructing the hologram and also the angle difference between reference and object beam. The wavelength which matches the fringe spacing will be reflected. All other wavelengths will be transmitted unless the fringe spacing differ by the development process. A Reflection-HOE can be applied for an angle selective shading device.

White-light-HOEs:
White - light - HOEs are transmission holograms. Transmission merely means that the reference beam must be transmitted through the hologram in order for the image to be reconstructed. The holograms should be preferably viewed with a white light source. A typical white light source is the sun. By different fixing between incident and diffraction angle the White-light-HOEs can be applied as light directing systems.

All holograms applied for this project are volume holograms. The production of volume holograms allows in contrast to surface holograms a very high efficiency of diffraction of up to 99%. The known technologies to produce them are silverbromided or dichromated gelatine on a polymer substrate.

For films with silverbromided gelatin AGFA GAEVERT was the only manufacturer, who gave up production and delivery in 1998. A similar material is now offered by the Russian manufacturer SLAVIC, but there are so far no representative experiences with this material as to chemical processing, lamination in glass, and lifetime, although GLB in Cologne has done first tests. GLB holds an international patent for the chemical processing and stabilization against UV-radiation of silverbromid gelatine films.

Dichromated gelatine is general state of the art. GLB in co-operation with Sax3d.com and FilmoTec are optimizing the process and the production of specific types of holographic optical elements on dichromated gelatine. Examination of environmental harmlessness regarding to chromium, yellowing and solar aging of the holograms undertaken by University Blaise Pascal of Clermont-Ferrand are also part of this research project.

Numerous applications of holographic optical elements (independently of the film material) for redirection of light, for solar control, for concentrating photovoltaics, for glare free luminaries, and for displays were developed and patented by GLB. On the basis of joined research and development of GLB with different partners several pilot projects could be realised. Therefore GLB has an advanced know how in the application of holographic optical elements in large glass areas. Similar projects by other research institutions or manufacturers are not known.

To ensure high durability HOEs are laminated between two glass panes. Different quality tests regarding the durability and the load carrying capacity of the laminated glass have been performed by the glass manufacturer KINON and the Structural Design Department of University of Dortmund.

4. Project Results

For the application of HOEs in daylighting and solar control it was necessary to work out different solutions depending on the function, the location in the building envelope (roof, facade) and the climatic zones. In an integrated approach the design of a shading device or a light directing system is a rather complicated task with many parameters involved, from solar geometry to aesthetics or maintenance. Of course solar protection is not just a matter of blocking the direct solar rays: Closely related issues like direct, diffuse and reflected radiation, infrared energy, air flow, or effects on daylight, glare and view needed to be addressed too. A major issue is the balance between opposite seasonal requirements.

GLB built a catalogue of possible solutions with all hologram types. Not all solutions of the complete listing of combinations were good for practical use, but the catalogue allows all project partners to discuss and understand the variety of possible applications of holograms.

Many solutions have been worked out in the framework of the project by calculations for the holographic optical properties under consideration of the solar positions, by detail design for fixed and solar tracked components and by specifications and performance data. Some developments have been stopped by technical problems, other have been developed further on to possible applications.

Common solutions are the absorber construction (shading device), the light directing system for facades and the light directing system for light shafts, atria or courtyards.

Based on this system development for HOE applications, GLB has been adapted the above

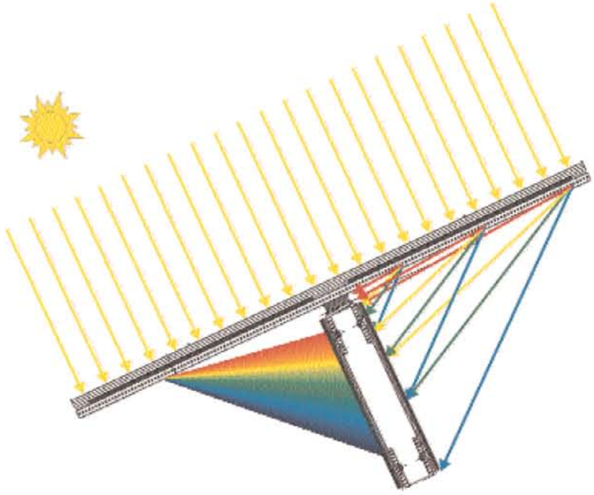


Fig.1: Shading device with grating holograms and absorber profile

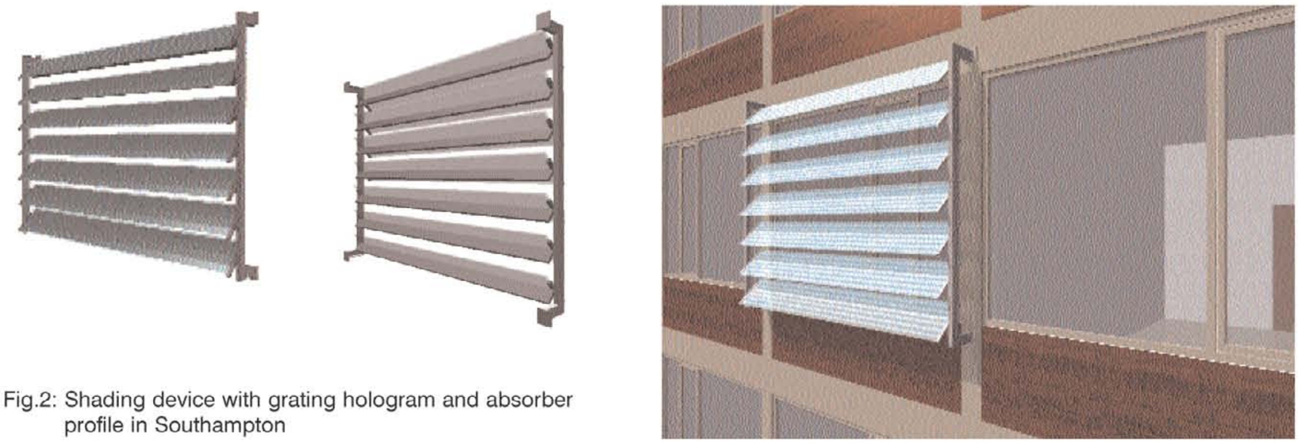


Fig.2: Shading device with grating hologram and absorber profile in Southampton

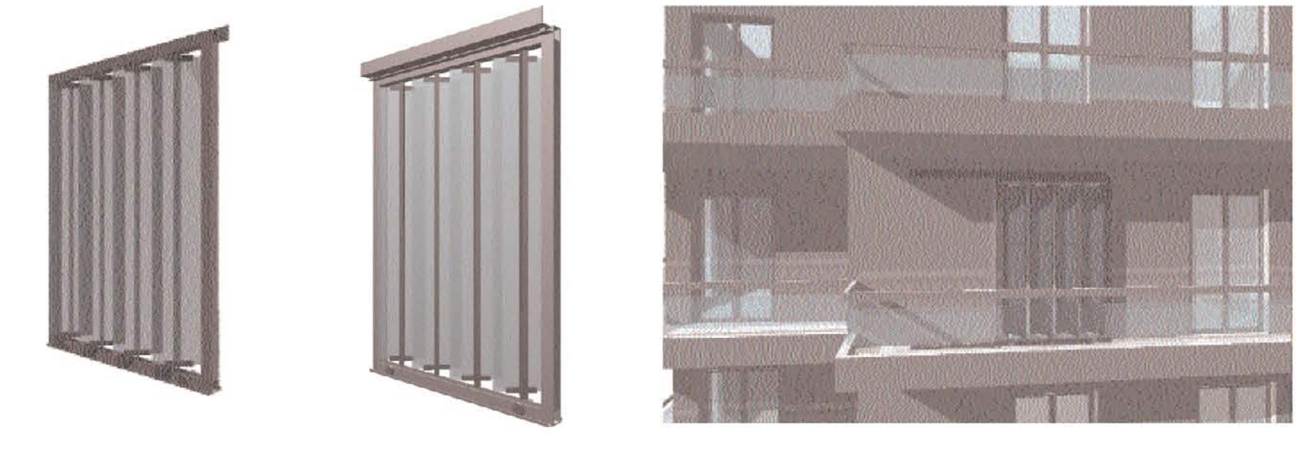


Fig.3: Shading device with grating hologram and absorber profile in Athens

mentioned solutions to three test fields at the University of Dortmund, the University of Southampton and in Athens. In co-operation with UniDo, STILVI and SOTON the best fixing solutions for the HOE units have been worked out.

The absorber construction is a shading device with T-shaped cross section as combination of HOE laminated heat strengthened glass and metal absorber web designed by GLB and University of Dortmund. The use of a silicone adhesive for the linkage of web and flange provides a composite load carrying behaviour of the total cross section. The holograms will diffract the direct sunlight onto an metal absorber, which is perpendicular to the hologram surface (see figure 1).The benefits of the grating holograms are the high diffraction efficiency of over 90%. The diffraction efficiency characterise the performance of the diffraction of the holograms. The left side represents the full colour dispersion from one point while the right shows the superposition of the colours from different points on the surface. Function and geometry is equal for both sides.

The absorber is matt black, sunlight will be absorbed and the arising heat will be conducted to the environment. To protect the room against IR-radiation a selective coating from KINON (resp. Saint-Gobain-Glass), called "Antelio Silver" will be added as hardcoating on position 1, except for one lamella in Southampton for comparison. SOTON could optionally install solar cells on the absorber to test the conversion of sunlight into electrical current. The shading system has to be tracked in horizontal (see figure 2) or vertical direction (see figure 3).

For the test field in Dortmund GLB has developed a one-axis light directing system (see figure 4). Each lamella contains two different white-light holograms. The holograms will be laminated serially between two glass panes. Hereby an maximum area efficiency of 100% is guaranteed. The area efficiency defines the fraction of the total hologram area, which is working at a given time (solar position). After optimization of the expose and development of the white-light holograms a high overall respectively diffraction efficiency (> 50%) has been achieved. HOE 1 covers altitudes of the sun between 100 and 350, HOE 2 between 350 and 700. The limited pivoting range prevents the appearance of additional glare. By optimization of the holograms interference between the serial laminated holograms will not arise. The sunlight will be redirected to the ceiling and into the depth of the room for illumination purposes.

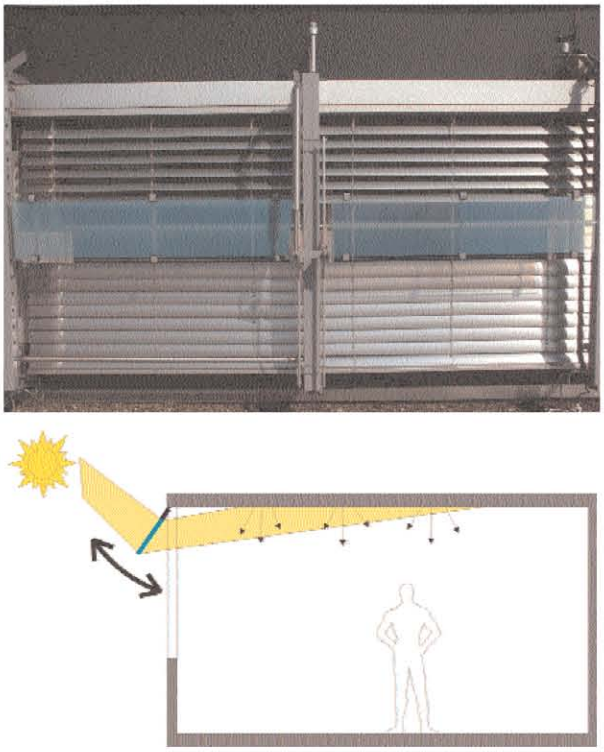


Fig.4: Test facade at University of Dortmund (Light directing system with conventional shading device)

For the light shaft in Athens GLB has developed a light directing system with fixed white-light holograms exposed by a two-axis tracking heliostat (see figure 6). Because the permission for installation was not granted and the project budget was limited the construction was limited to a manual tracking system. However indicative photometrical measurements using a temporarily installed heliostat, according to a redesigned arrangement regarding the sunlight path geometry (see photo 13 financed by STILVI) were carried out.

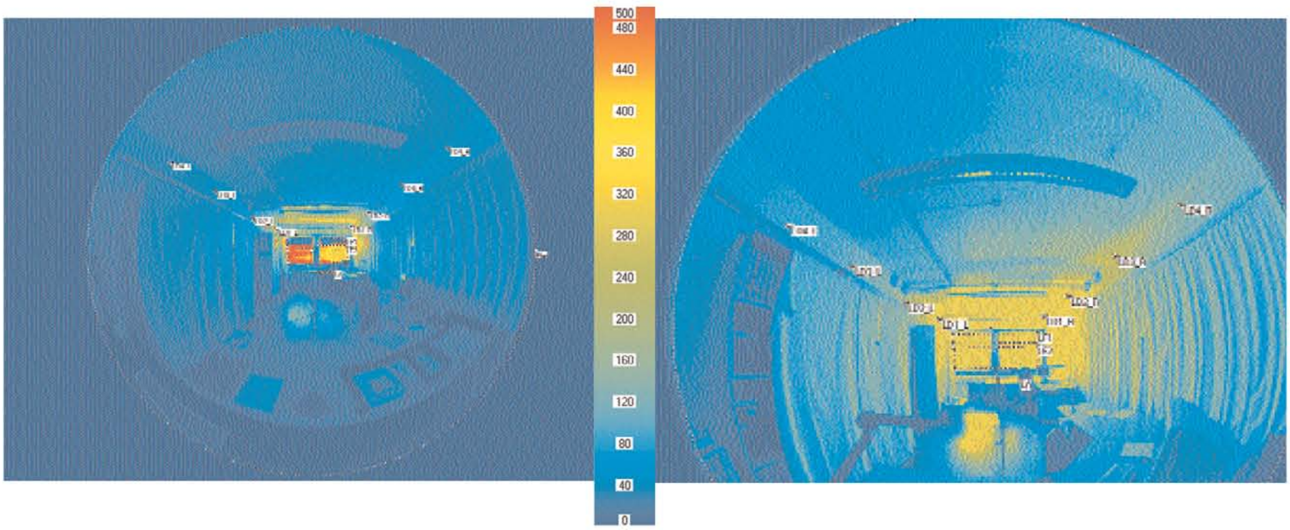


Fig.5: Luminance test results of test facade at University of Dortmund

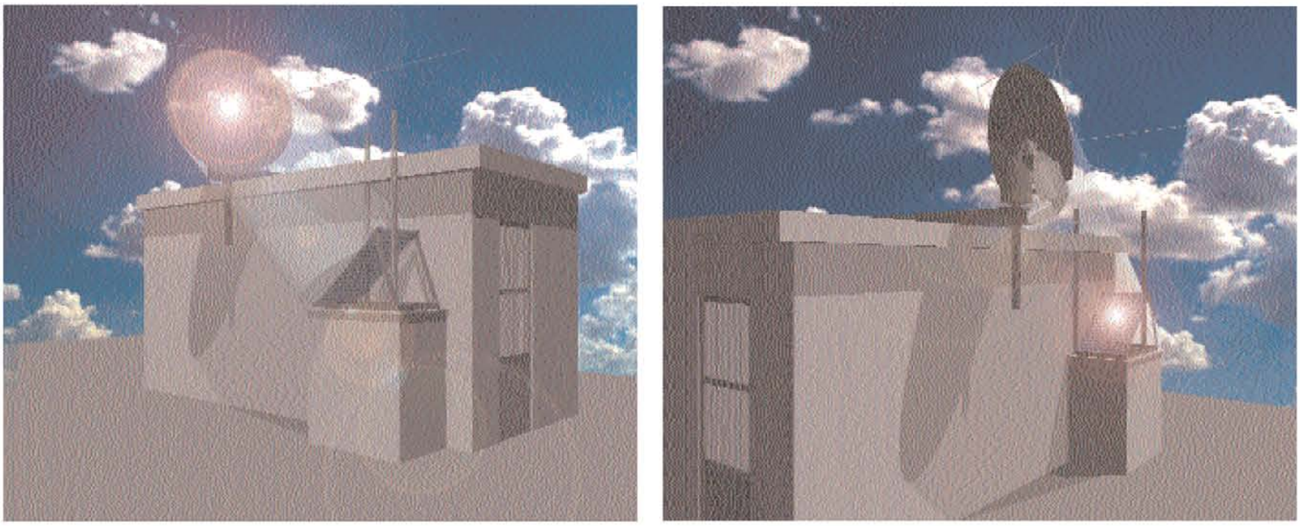


Fig.6: Light Shaft with White-Light-Holograms and heliostat in Athens

GLB has achieved to cover the hole altitude and azimuth of the sun with only two different white-light holograms. The azimuth of the sun is adjusted by the manual tracking of the metal construction (quasi two-axis tracking), the different altitudes of the sun are adjusted by shifting the holograms. Hence HOE 3 and HOE 4 covers altitudes of the sun between 100 and 700. The hologram shifting changes the angle of reflection in the range of +/- 100, but this deviation is tolerable.

The installation of the white-light holograms on the top of the light shaft resulted to an increase, of the average illumination level in a room located 6 m below the hologram, by a factor of 10, while the maximum illumination level measured in the light shaft approached the value of 2,520 lux.

The white-light holograms operate like UV filters at 400nm, since according to the relevant measurements that took place in Athens, the UV radiation is absent in the spectral analysis of the redirected sunlight.

The white-light holograms analyse the sunlight to its spectral components, depending on the light 's incidence angle. Certain applications such as a colour sundial, based on colour changing/ dominant wavelength shift according to the day phase/ solar altitude, respective to the well known shadow based one can be developed using HOEs. Additionally the influence of such dynamic light effects on human health, connected to the stimulation of our biological clock (secretion of melatonin) consist a new field of scientific research on HOEs applications. However the light colour can be stabilized since the incidence angle of light aimed at the hologram can be maintained by means of a heliostat like in the temporary application carried out by Stilvi, where the green colour as typical for the middle of the visible spectrum proves the accurate adjustment of the hologram tilt regarding its efficiency. Additionally the heliostat contributed to a better distribution of sunlight throughout the whole shaft leading to a higher system performance. (see figure 13,14)

The proper use of the different holograms for Athens is shown in the following sun path diagram.

5. Conclusion

The main task of windows is to allow for daylighting and view outside. Conventional shading devices like fixed louvers in horizontal and/or vertical position often affect or spoil these functions, when they control solar heat gains and glare in an effective way. Especially when using an interior shading device, the source of the heat - sunlight hits the glass, the space between the glass and the shading device, and the shading device itself. All three elements have direct contact with the interior space and will heat up

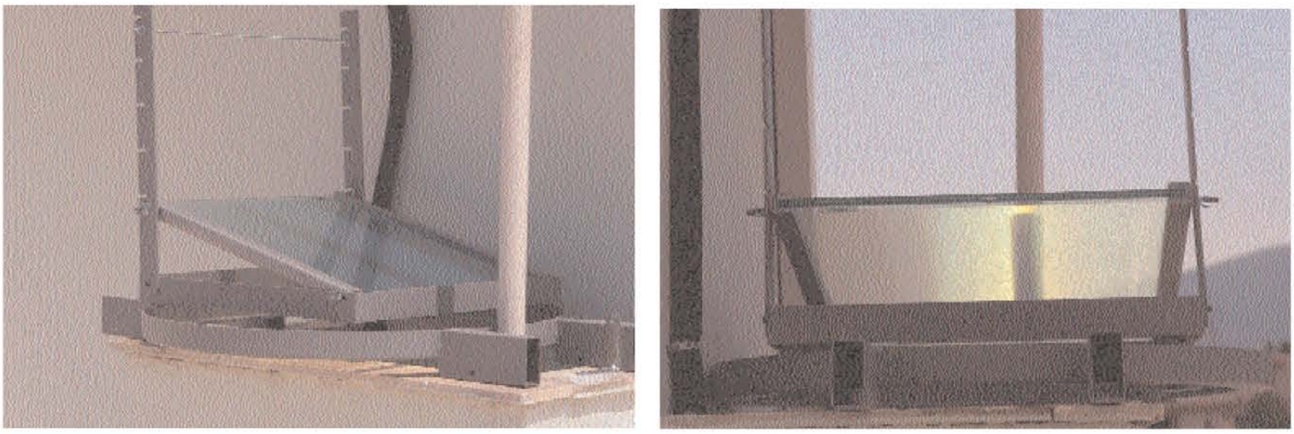


Fig.7: Light Shaft with White-Light-Holograms and manual sun-tracking system in Athens

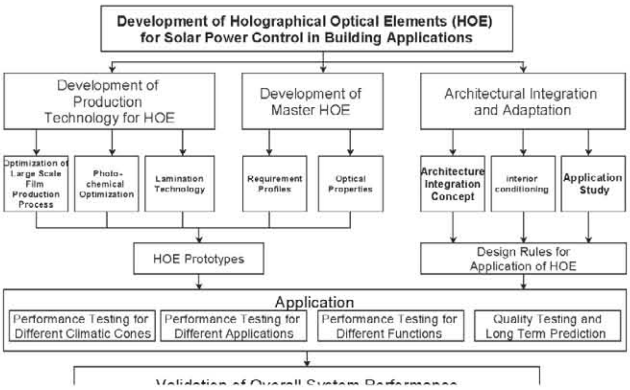


Fig.8: Spectral analysis of the redirected (through HOE) day light in the light shaft

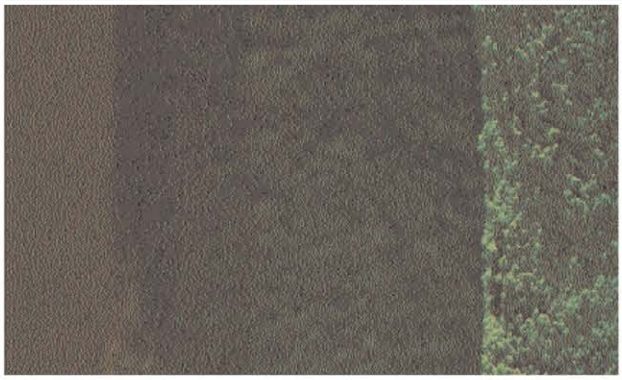


Fig.11: Luminance / colour measurements of redirected sunlight in a light shaft

Max. Luminance without heliostat 15 cd/m2
Dominant colour coordinates x=0.42, y=0.52, z=0.05

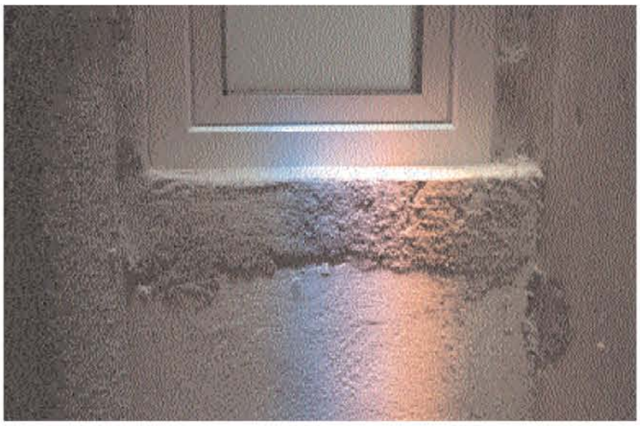


Fig.9: Redirected sunlight analysed to its spectral components.

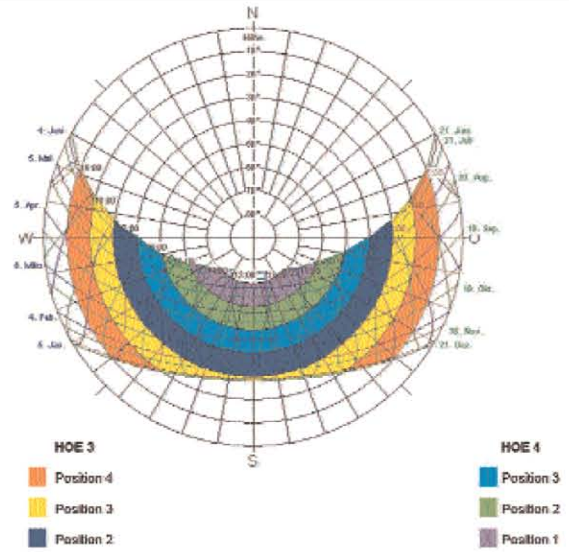
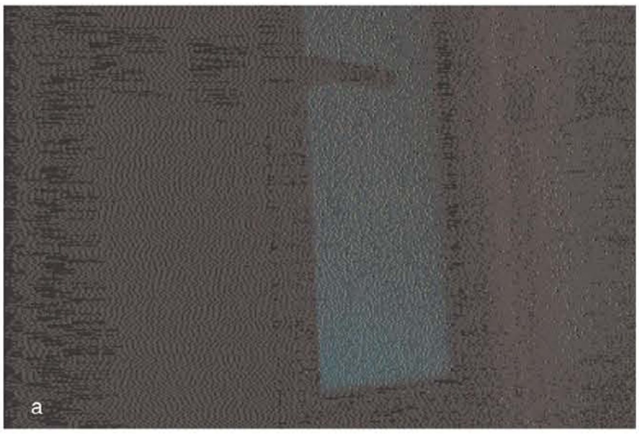


Fig.12: Sun path diagram for Athens



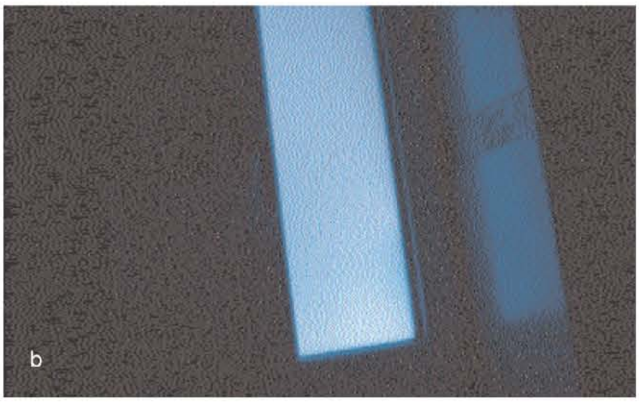


Fig.10 a,b: Light colour adjustment.

Fig.13: Sunlight redirection comprised in a heliostat and a white hologram for a Narrow Light Shaft in the building of STILVI Ltd.

the room extremely at sunny summer times. Conventional shading devices are opaque for direct solar radiation, allowing only a small proportion of diffuse light and reflected sunlight for transmission and illumination of the room. Solar protective glazing with solar gain factors between 0.15 to 0.35 usually have a poor daylight performance (low transmittance and colour effects) and reduces solar heat gains in the winter. External shading devices are exposed to wind and heavy rain, which can affect the performance and life time. Movable devices like blinds and louvers with small dimensions have to be moved automatically into a protected parking position. The light transmittance of conventional shading devices with solar heat gain factors of 0.1 to 0.2 often is below 0.1. Artificial lighting on sunny days is the consequence, increasing the cooling loads and the electricity consumption. Most of the effects can be avoided by a "transparent shading" device with HOEs achieving effective shading and daylighting in combination.

This angle selective shading device is highly efficient and can be looked through, as the HOEs work only for a very narrow angle of incidence (´50). For the remaining range of angles the holograms are not diffracting the light. By combining the shading device with solar cells on or instead of the absorber electrical current can be produced.

The preliminary luminance test results (measurements are still in progress) for the light directing system for facades make clear that the illuminance can increased by a factor of 3-5 or more up to 5 metre depth of the room See figure. On the borders of the redirected light on the ceiling of the room slight colour effects can be observed, but it is undisturbing.

The HOE glass sandwich has been tested on its bond properties as well as on its load carrying behaviour within the research project since it has to suit the safety requirements for glasses applied in buildings. As experiments carried out by the University of Dortmund have shown the shear stiffness of an HOE interlayer developed in this project is higher than of a standard PVB interlayer (PVB = poly vinyl butyral) used in laminated safety glass. This improves composite action of the glass panes resulting in higher load bearing capacity of HOE louvers. Additionally the significant decrease of stiffness typical for PVB interlayers at a temperature of about 200C has not been observed in the tests with HOE interlayers. Because of these favourable properties HOEs are well applicable for external louvers on facades and roofs. Load capacity tests have shown that HOEs suit the requirements for the ultimate load capacity with regard to residual integrity after breakage. Herewith the prerequisites are fulfilled for overhead constructions.

The effect of chromium for the environmental is harmless, yellowing will not occur and the manufactured holograms are quite stable regarding to solar aging (preliminary result, examinations are still in progress).

HOEs, which can be combined with already tested sunlight redirecting systems, such as heliostats and / or hollow light guides, can enhance significantly the quality of the illumination in remote areas, which do not have direct access to the exteriors.

6. Acknowledgement

This project is funded by the European Commission under the Energy, Environment and sustainable development program (EC Contract Number: ENK6-CT-2000-00327).■

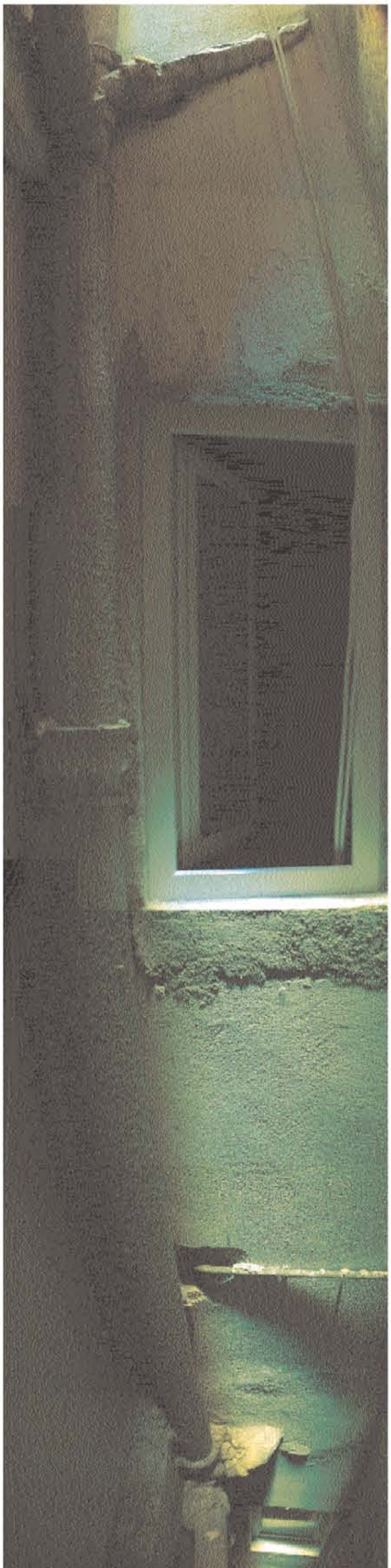


Fig.14: Sunlight dispersion throughout the light shaft. The perception of the dominant wavelength of the spectral distribution is enhanced by the maximum of human eye sensitivity in the photopic range of view.