HOLOGRAPHIC OPTICAL ELEMENTS (HOE) FOR HIGH EFFICIENCY ILLUMINATION, SOLAR CONTROL AND PHOTOVOLTAIC POWER IN BUILDINGS

ACRONYM

HIGH EFFICIENCY HOES

SUMMARY (PUBLIC)

CONTRACT NO:	ENK6-CT-2000-00327
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REFERENCE PERIOD:	01.03.2001 - 29.02.2004
DURATION:	36 months

PROJECT FUNDED BY THE EUROPEAN COMMISSION UNDER THE ENERGY, ENVIRONMENT AND SUSTAINABLE DEVELOPMENT PROGRAMM

Introduction

Sunlight is the source of life on earth. Human well-being is strongly dependent on 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.

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 controlling and directing the radiation of the sun which gives a broad scale of applications with high potential of energy saving and increase of comfort.

Holographic optical elements (HOEs) have useful properties for diffuse light transmission and radiation control. A shading device with HOEs is an highly 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.

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 performance in built environment. Mainly there are four different hologram types:

Grating-HOEs:
Grating-HOEs are holographic 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.

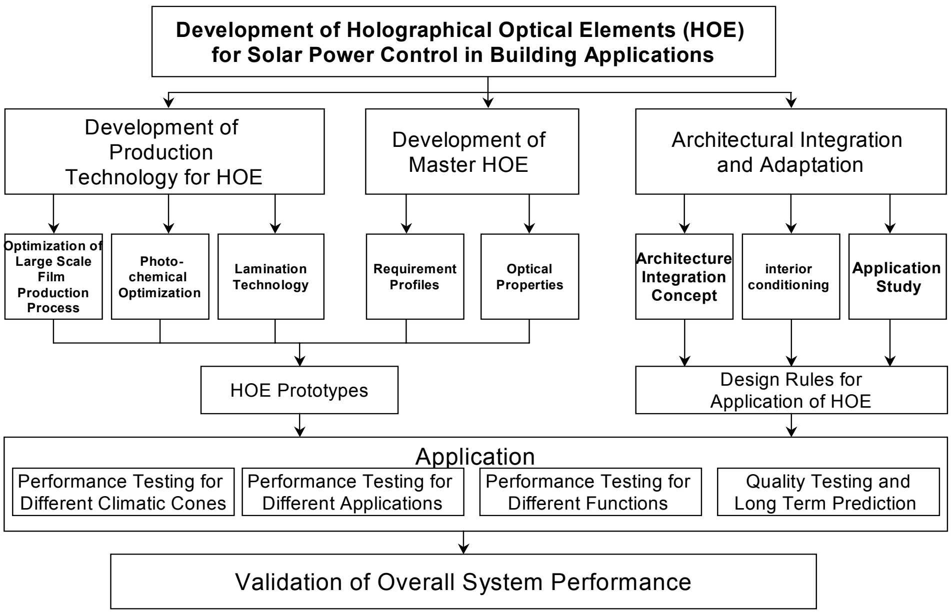
All holograms applied for this project are volume holograms. The production of volume holograms allows in contrast to surface holograms a very high efficiency of diffraction of up to 99%. The known technologies to produce them are silverbromided or dichromated gelatine on a polymer substrate.

Numerous applications of holographic optical elements (independently of the film material) for redirection of light, for solar control, for concentrating photovoltaic, 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.

Project Methodology, partners and workplan

The project workplan was based on three main columns:

- The development of a production technology for HOEs,
- The development of a master HOE and
- The architectural integration and application.



The project partners are:

- Gesellschaft für 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
- Universität Dortmund, Dortmund, DE
- Université 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.

Due to the different involved disciplines, in the first phase of the project the consortium agreed about definitions of project relevant terms, standard operating procedures, requirement profiles and quality standards. This served as basis for the partner's work and guaranteed that scientific results are comparable and reproducable.

The second step was the development of an industrial production technology for HOEs as only an industrialized production guarantees high quality standards in the reproducibility of holograms. This comprised the production of large scale holographic films in a width of 104 cm as well as the development of a lamination process for HOEs as the HOEs are laminated between two glass panes to ensure high durability. Different types of external HOE light guiding louvers have been designed for application on façades and roofs considering structural requirements of serviceability, stability and integrity.

All possible hologram types have been evaluated, whereas some types turned out to be useful and other not. Finally, for the light directing systems white-light holograms and for the sun shading applications grating holograms have been chosen. After the optimization of the film properties and the agreement about the test pilots all necessary film samples have been produced, tested and processed to a laminated glass.

Comprehensive laboratory tests have been carried out to identify the load-carrying behaviour of the louvers with the objective of quantification of the mechanical properties needed for the structural design to assure serviceability and stability of the louvers. For this purpose, the bond effect between the glass panes due to the multi-ply interlayer, the influence of the fixings and the residual integrity in case of broken glass have been investigated in detail. Furthermore, tests concerning weathering and photoageing of the film material have been made as laboratory performance tests and as field tests. Analyses of the environmental harmlessness of the film material and the interlayers rounded off the test series resulting in HOE prototypes for sun shading and light directing.

For the following system development for HOE applications it was necessary to take into consideration different geographical and climate situations as well as the market situation for HOEs in Europe. Therefore climate and market investigations for different European countries have been undertaken. Based on this information, the application possibilities of HOEs in architecture have been examined by laboratory observation studies on a model and by analysing different possible building types. To summarize all possible HOE-system solutions, a catalogue has been developed divided in the three sections “arrangement”, “solution” and “features”. In the process of the system development for HOE applications, the catalogue has been enhanced with different types of holograms and applications for light directing systems and for shading devices.

In the end three different solutions have been developed further on:

- One-axis tracked light directing system (façade):
  This system has the benefits of a high area efficiency (100%) and a high overall respectively diffraction Efficiency (> 50%). The sunlight will be redirected to the ceiling and can be used to illuminate a room. The design (geometry) of the holograms will not lead to any additional glare.
- Two-axis tracked light directing system (light shaft):
  This system has the same benefits as the one-axis tracked light directing system. The second axis is necessary for small light shafts to compensate the sun azimuth too.
- One-axis tracked shading device (façade):
  A grating hologram which will redirect the visible light to an absorber or retro-mirror with is perpendicular to the hologram surface. To protect the room against IR a selective coating has been added onto the glass.

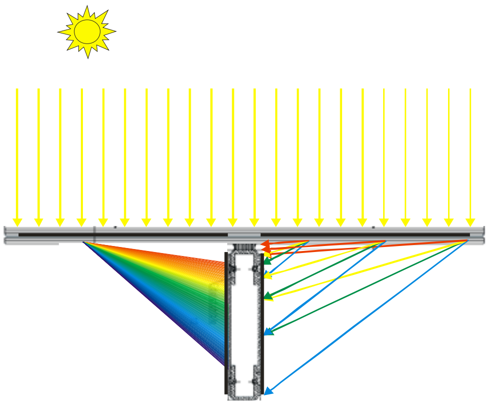


Fig. 1: Shading device with grating holograms and absorber profile

The benefits of the grating holograms are the high diffraction efficiency of over 90%. The diffraction efficiency characterises the performance of the diffraction of the holograms. The left side of Fig. 1 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.

Before installing the test fields, detailed simulation studies for a range of building structures that are likely to be used for HOE applications such as offices, conservatories and attics have been undertaken. These studies have been taken into account a range of European climates focussing on the three test sites in Dortmund (Germany), Southampton (UK) and Athens (Greece).

After the laboratory performance tests and simulations, test rigs have been constructed covering the aspects of sun-shading and light-directing for façades and light shafts. 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. 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 detailed 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. Marketable solutions developed are the absorber construction (shading device), the light directing system for facades and the light-directing system for light shafts, atria or courtyards.

For the test field in Dortmund a one-axis light-directing system has been developed (see Fig. 2). 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 10° and 35°, HOE 2 between 35° and 70°. 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.

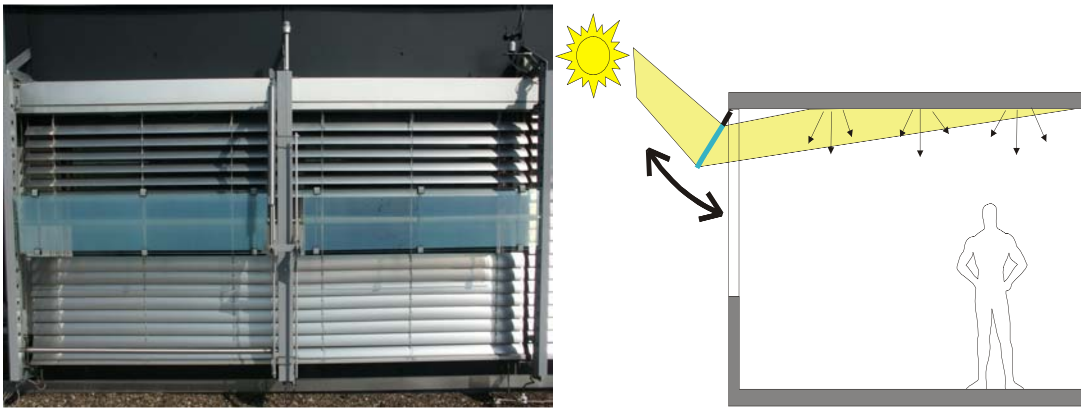


Figure 2 Test façade at University of Dortmund
(Light directing system with conventional shading device)

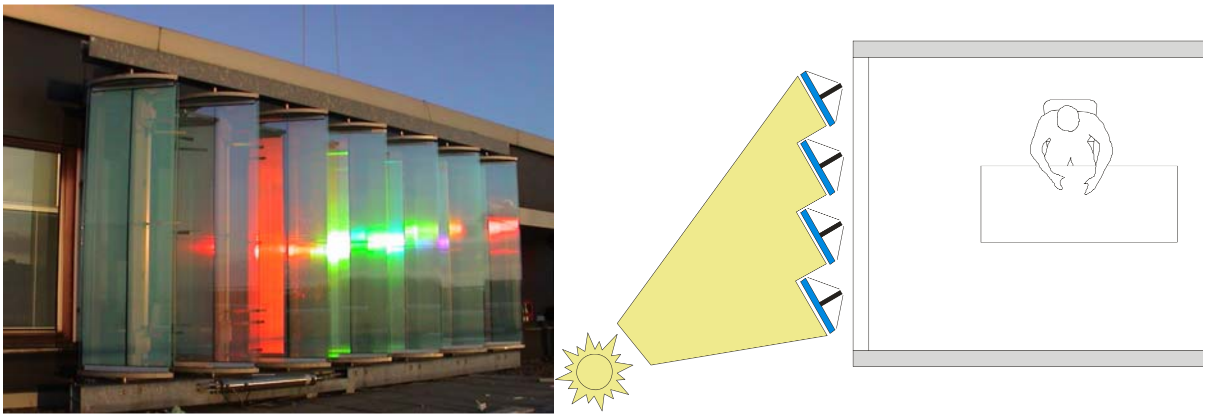


Figure 3 Test façade at University of Dortmund (holographic shading device)

For the light shaft in Athens a light directing system with fixed white-light holograms exposed by a two-axis tracking heliostat has been developed (see Fig. 4). 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 (financed by STILVI) were carried out.

Figure 4 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 10° and 70°. The hologram shifting changes the angle of reflection in the range of +/- 10°, but this deviation is tolerable.

Figure 5 Light Shaft with White-Light-Holograms and manual sun-tracking system in Athens

The test rigs were monitored on a continuous basis with regards to luminance, illuminance, colour temperature and room temperature. Routes for dissemination and exploitation of the results and the know-how about HOEs in architecture via e-Coaching (development of an e-Coaching portal for cooperation, communication and learning) and a script for students of architecture have been implemented.

Results

The main task of windows is to allow daylighting and the 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. This is the case 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 heat up 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 reduce 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 (~ 5°). For the remaining range of angles the holograms are not diffracting the light.

For a safe and efficient implementation of HOE light guiding devices on façades and roofs of buildings the glass louvers must satisfy the requirements for serviceability, load carrying capability (wind, snow, …) and residual integrity in case of broken glass. For this reason, experimental investigations focussed on the stiffness and strength properties of the glass louvers as well as their residual integrity after breakage. The tests have shown that the shear stiffness of the HOE interlayer developed in this project is higher than of a standard PVB-interlayer used in laminated safety glass. This improves the composite action of the glass panes resulting in a higher load-bearing capacity of HOE louvers. Additionally, the significant decrease of stiffness typical for PVB interlayers at a temperature of about 20°C was not observed in the tests with the HOE interlayers. Based on the results of the laboratory performance tests it can be concluded that the requirements for load-bearing capacity, serviceability and residual integrity after breakage are satisfied. Fulfilling the prerequisites for overhead constructions, the HOE louvers are well applicable on façades and roofs.

The effect of chromium for the environmental is harmless as toxic chromium (VI) no longer exists in the films or stabilizers when broken HOE windows are washed out by water. Furthermore, experiments in the laboratory and outdoor exposure showed that the polymeric films enclosed in the KINON window appeared to be well protected from the photo-yellowing. Significant photoageing can not be expected in plus/minus 10 years, yellowing will not occur.

Simulation studies - Facades which suffer from excessive glare (East and West) are probably more applicable for HOE than South facing facades where the higher zenith angle of the sun makes cheaper alternatives such as fixed louvers above the window a possibility. The east facing Southampton test site has clearly highlighted this issue.

The successful application of HOE is clearly location and orientation specific, the current technology only actively interacts with direct (beam) radiation and so is far more attractive for locations such as Athens where the majority of the solar gain is direct.

At present, to justify the application of a tracked HOE system, solely in terms of solar control is difficult. The additional benefits of natural lighting to efficient office working must be quantified. Fixed HOE which reflect incident beam radiation are more attractive from an installation and maintenance viewpoint than tracked louver systems. Simulations predict that significant solar gain reductions can be achieved using this technology. However, the effects of reflected light (glare) and any spectral dispersion of the light that enters the office are potential problems.

Field tests - The luminance test results for the light directing system for façades make clear that the illuminance can be increased by a factor of 3-5 or more up to 5 metre depth of the room. Whereas the illuminance reflects the quantity of light, the luminance is an indicator for the quality of light (direct glare). The results of the luminance camera show a higher luminance at 2 p.m., but between 3 and 5 p.m. the luminance could be reduced by a factor of 2 (from 500 to 250 cd/m²). As a whole, the luminance in the room with the holographic shading device is more even, which leads to a higher comfort (less direct glare). Both are excellent results. On the borders of the redirected light on the ceiling of the room slight colour effects can be observed, but they are undisturbing.

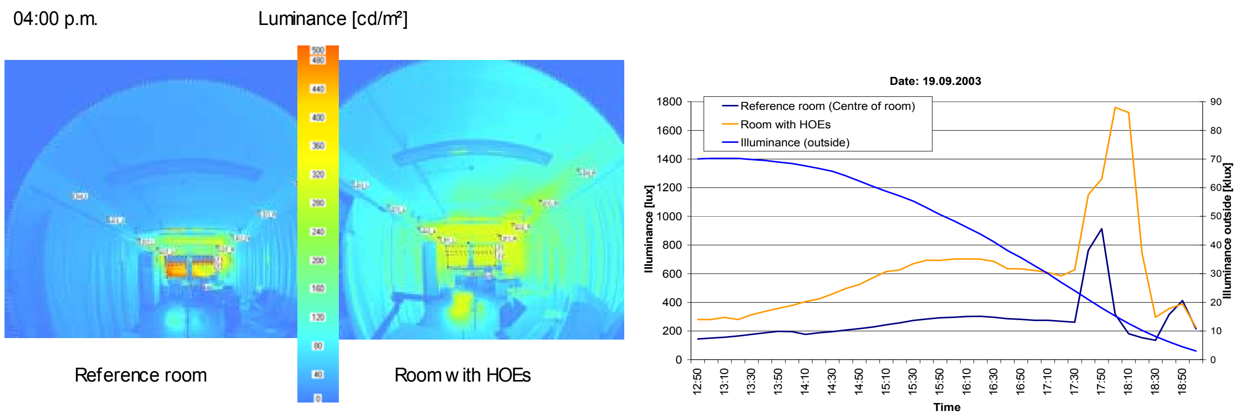


Figure 6 Luminance test results of test façade at University of Dortmund

The remote area measurements showed that the installation of the sunlight redirecting system (white light HOEs) in combination with a Heliostat significantly improved the illuminance level inside the test room and at the room's window at the light shaft. The average illumination level in a room located 6 m below the hologram was increased 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. Furthermore, the HOEs analyze the redirected sunlight to its spectral components while the spectral composition of the redirected sunlight differs from time to time depending on the sun altitude and the incidence angle to the HOE creating interesting lighting effects. 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.

Exploitation and dissemination - During the project life two main routes for dissemination know-how about Daylight in architecture and HOEs have been followed. The partner HWIS developed a detailed script "Holographic optical elements – High efficient system for daylighting and design in architecture" which can be regarded as one of the dissemination documents of the entire research project and may help to position the advanced daylighting system of HOEs on the market. UCBEM developed an e-Coaching portal as platform and instrument for communication and cooperation between project partners and as knowledge-database. With the integration of a learning module this portal can be used for distance learning. By the use of pre-configured standard software with a high degree of dissemination and a high standard of security the portal is a cheap instrument (only costs for the program Intrexx arise) and can be used even in countries where the standard of technology is not as high as in Western Europe. The e-Coaching pilot realized in the framework of the project offers a case study about "Sunshading for a façade of an office building" which shall help students of architecture and engineering, architects and consulting engineers as well as manufacturers to plan and build buildings by integrating HOEs. But the construction and functionality of the system not only offers the possibility to build different user groups (Extranet- and Intranet-groups) and screen-designs but also the content can be adapted to different project and learning objectives so that a very flexible and demand-oriented tool has been developed.

Conclusions

Passive energy saving technologies have a decisive benefit: No further elements are required in addition to a conventional building: it is only necessary to construct the components that are used in any case (floors, outer walls, windows, roofs and sun shading systems) to better quality standards than it is usual. Over the medium term, such a quality improvement must not cause higher investment costs than in a standard building. Particularly through the prefabrication of high-quality exterior building elements, such components can be produced very cost-effectively.

The holographic systems for illumination and solar control are applicable in existing and new buildings. They contribute to the decrease of energy demand and CO_2 emissions, depending on local conditions as well as to the increase of comfort for the user:

- As sun-shading systems HOEs enhance significantly the quality of natural illumination in a building by limiting the glare factor, increasing the illumination uniformity factor and providing view to the exteriors without reducing the illumination level as conventional sun-shading systems do.
- HOEs are acting as UV-filters since they do not allow the penetration of the hazardous UV radiation.
- HOE redirecting systems analyze the incident light to its spectral components creating lighting effects that can add value to existing architecture reviving even neutral buildings in a creative way.
- HOE should be considered as a complementary technology to existing light guiding systems (light propagation, light redirection) providing a higher total system performance, since it is apropriately adopted as a useful key component in the development of respective applications. These constructions can enhance significantly the quality of the illumination in remote areas, which do not have direct access to the exteriors.

It can be considered that HOEs in the future can be extensively used in light applications under the condition that appropriate documentation is available, so that widely used light simulation programs can calculate and predict the daylight results in a space based on related documentation HOE-files of suitable format. It can furthermore be stated that entirely new concepts for building design are not needed for HOE application whereas an integrative planning respecting the demands for daylighting is required right from the beginning. Due to their functional complexity HOEs cannot be implemented as an add-on solution but need to be planned in accordance to the building design.