Topical Survey on Daylighting System

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Abstract Over ages science and technology has grown a lot. In day to day life new inventions and discoveries are made. Science and technology has reached into every sector of our life. From quite a few time there has been a need for the introduction of new technology, utilizing daylight in building and to monitor their performance for the benefit of those concerned with the building design practitioners lighting engineers, builders, product manufacturers, building owners and property managers. There are many different options and systems which serve many different purposes. Henceforth it is difficult to find the apt product. The overview and the description of the product help a lot to choose the desired daylighting system for the given conditions. In the present work theoretical design of holographic optical element has been done to filter out ultraviolet and unwanted portion of solar radiation and to allow only visible spectrum to enter inside the interior of the room. Such system provides even distribution of sunlight within the interior of the building which is hygienic and supportive to human health and activities as well as to reduce energy demands. To redirect the uniform daylight diffracted by the HOE into the remote interiors of a building, light pipes or optical fibres are quiet promising. For cost effectiveness, Plastic Optical Fibres (POFs) are used as wave guide for daylighting.

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1 Introduction

In this ever growing technological era, people prefer easier, quicker and cheaper means to accomplish their endeavours without having concerns about the aftermath. To meet out the demands of residential as well as commercial building in urban area with growing population towering and crowded buildings are being constructed as a result sunrays do not reach every nook and corner of the building. Using artificial lights during daytime, which seems to be a trivial issue to moot, is in fact causing a major energy drain and environmental break down.

The estimation of energy consumption due to electric lighting in buildings has soared up to an appalling figure of approximately 40–50% of the total energy cost [1]. Buildings employing efficient daylighting techniques have plummeted electric lighting energy consumption by 50–80% [2]. Moreover, these light sources lack in the distribution needed for complete biological functions. The three light sources namely incandescent lamp, energy efficient fluorescent light and cool white florescent lamp is widely used in daylighting system. Presently these lamp lack blue portion of the spectrum which is very beneficial part for humans. Thus redirecting the sun rays which contains all spectrum beneficial to human health becomes necessary. Our prepared system regarding implementation of holographic optical elements to redirect sun rays into the interior of a building is capable of redirecting the entire spectrum of sun rays into interior of building [3].

In the sphere of physical sciences, daylighting points out to a system that delivers, in a given space, well administered and occupant responsive lighting with favourable environmental attribute and reasonable financial value. A given area is said to be day lit when not only it is swamped with natural light as primary source of illumination but also when it renders thermally and visually comfortable place which also manifests outdoor views. Further, scientists at the Lighting Research Centre (LRC), in Troy, N.Y. have reported the enhanced productivity and comfort levels of daylight-exposed occupants. Also, it caters to the mental and visual stimulation that tunes human circadian rhythms [4].

The obvious visual dividends of daylighting include its broad electromagnetic spectrum with excellent colour rendering property. The non-visual benefits of daylighting are too efficacious to ignore. This is particularly true in case of psychological and physiological outcomes. Daylighting significantly scales down the psychological sadness or Seasonal Affective Disorder (SAD) stimulated by the artificial light [5]. Energy savings is one of the most crucial benefactors of daylighting. The benefits run the gamut from reduction of fossil fuel consumption, reduction in greenhouse gas emission to the decreased heating and cooling load from artificial light. Above all, it avoids double conversion of energy i.e. transforming solar energy into electricity using PV cells and then into artificial light. Daylighting can be successfully employed not only in residential and commercial buildings but also in educational facilities, laboratories, workshops, healthcare facilities, photo bioreactors etc.

This work focuses on daylighting solution with the help of optical fibres and HOE's. Daylighting can be vaguely split into three categories namely, visible light, Ultra-Violet (UV) rays and Infra-Red (IR) waves. In our circumferential solar radiation, ultraviolet (UV) accounts for 7% and infrared accounts for 46% of radiation. However 46% of the solar radiation falls under visible range [6, 7]. IR radiation of the solar spectrum is responsible for producing heat inside the interior which is not suitable for hot climate. Further, prolonged exposure to solar UV radiation may result in acute and chronic health effect on skin, eyes and immune system. Therefore, visible light should reach the interior free from UV and IR to avoid spatial heating and for protection of optical fibre.

1.1 Various Daylighting Systems

While considering a daylighting system for a building three important factors should be considered are (i) solar shading, (ii) glare control and (iii) Redirecting the sunlight inside the building [8–10].

Daylighting with shading and without shading are the two major classification of daylight systems [11]. Both the categories are operational with direct and diffused sunlight. Shading strategy consists of installing Louvers and blinds, light shelves, turnable lamellas, lasercut panels are systems for direct sunlight application whereas prismatic panels, anidoliczenithal opening, mirror elements, prisms and venetian blinds for diffused skylight.

Daylighting without shading method is in cognate with the optical system modus operandi. Zenith light guiding elements with holographic optical elements, fish system, anidolic ceiling, light shelf comes under diffused light guiding system whereas prismatic panels, laser cut panels, lighting guiding glass, HOE falls under direct light guiding system. A holographic optical element is a new class of optics that operates on the principal of diffraction. Conventional optical elements use their shape to bend light but holographic recording materials changes the optical property by variation of refractive index. Mostly conventional method of daylighting techniques are bulky and require maintenance and adjustments for optimal performance unlike HOE system, which usually have no moving part and require low maintenance.

HOEs qualify to fulfill all the requirements which must be met by an ideal light delivery system. A single HOE can be used to redirect the sunlight to the interior part of a building and can also be used as solar shading and glare controlling device [12–14].

Use of as holographic windows [14] for daylighting application in buildings is quite attractive for last three decades. Holographic windows redirect sunlight from the immediate window area into the rear of the room so as to illuminate the darker regions with reduced glare. Main feature of HOEs are large optical apertures, light weight, thin film geometry, and cost effectiveness. HOEs are wavelength selective and hence they can also be made to operate over a narrow wavelength band.

Further, holographic optical elements (HOE) are used advantageously as filters [15–17] to filter out ultraviolet and unwanted portion of solar radiations while remaining portions of useful solar radiation are made to diffract into interior of buildings with reasonably good diffraction efficiency. From the architectural point of view, HOEs have certain useful properties for light transmission and radiation control.

Now in these days people are utilizing solar energy for daylighting application in various means using HOEs [13, 14], fiber optics [5, 18] and others ways [19]. Each technique has its own limitation. A comparative study has been given by Ullah and Wang [20].

2 Theoretical Background

In order to analyze the spectral characteristics of volume phase transmission holograms, we use the coupled-wave theory [21] which gives analytical equations for the diffraction efficiency assuming refractive index variation to be sinusoidal. When the wavelength of the reconstructing beam satisfies Bragg's law the diffraction efficiency is given by

$$\eta = \frac{\sin^2\left\{\left(\xi^2 + \upsilon^2\right)^{\frac{1}{2}}\right\}}{\left(1 + \frac{\xi^2}{\upsilon^2}\right)} \tag{1}$$

where, parameters ξ and υ are defined by the following relations

$$\xi = \delta \frac{2\pi n}{\lambda} d \sin\theta \quad \& \quad \upsilon = \frac{\pi n_1 d}{\lambda \cos\theta} \tag{2}$$

where n_1 is the depth of refractive index modulation, d is the film thickness, n is the average refractive index of the medium, λ is the free space wave-length of the reconstruction light beam and δ is the angular deviation in radians with respect to Bragg's angle θ.

Bragg's angle θ is related to the fringe spacing Λ recorded in the hologram through the relation given by

$$\sin\theta = \frac{\lambda}{2n\Lambda} \quad \& \quad \cos\theta = \left\{1 - \left(\frac{\lambda}{2n\Lambda}\right)^2\right\}^{\frac{1}{2}} \tag{3}$$

When the illumination is made at Bragg's angle (i.e. $\delta = 0$) we have from (1)

$$\eta = \sin^2 v \tag{4}$$

$$\eta = \sin^2\left(\frac{\pi n_1 d}{\lambda \cos\theta}\right) \tag{5}$$

$$\eta = \sin^2\left(\frac{\pi n_1 d}{\lambda\left\{1 - \left(\frac{\lambda}{2n\Lambda}\right)^2\right\}^{\frac{1}{2}}}\right) \tag{6}$$

Using (6) variation in diffraction efficiency (η) for a holocon with wavelength at Bragg's angle for different values of depth of refractive index modulations of holocon recording has been plotted. While drawing the curves care has been taken to ensure that criteria for thick phase transmission holographic lens are fulfilled for which (6) holds good. A holographic lens is said to be thick if its Q parameter $\left(Q = \frac{2\pi\lambda d}{n\Lambda^2}\right)$ is greater or equal to 10 [22].

3 Experimental

3.1 Holographic Lens Recording and Reconstruction

Experimental setup for recording holographic lens is shown in Fig. 1. For present work a holographic lens has been recorded on commercially available high resolution silver halide plate PFG-01 (film thickness d = 8 μm and average refractive

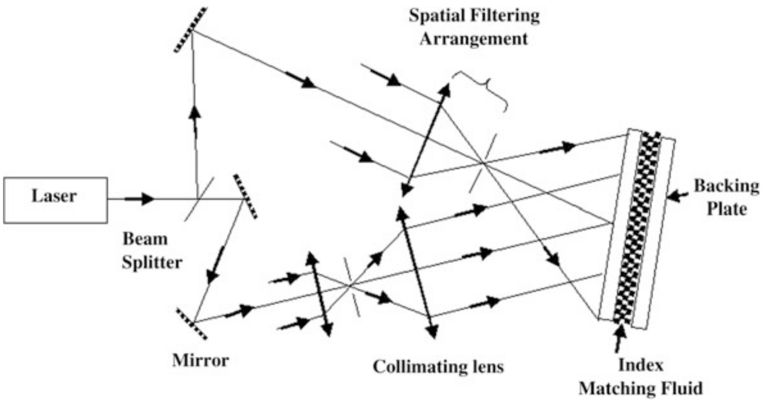

Fig. 1 Schematic of the geometry for recording holographic lens

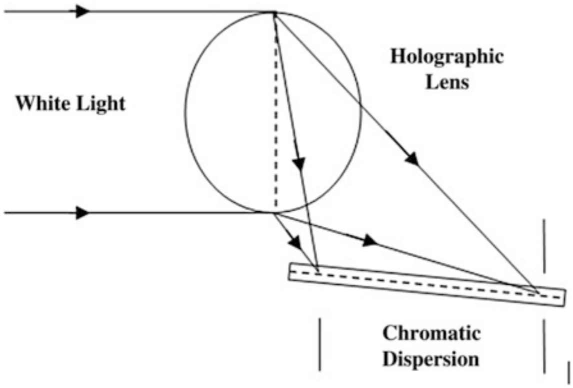

Fig. 2 Schematic of the reconstruction setup of holographic lens

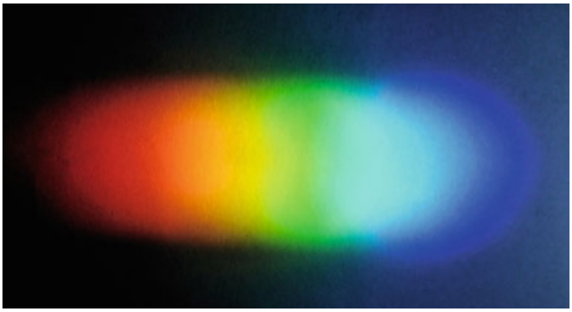

Fig. 3 Photograph of the Spectrum of white light diffracted by a typical holographic lens

index n = 1.61) using a He–Ne Laser (λ = 0.6328 μm) of power 12 mW. The recorded hologram is processed using standard procedure.

When recorded holographic lens is illuminated with white light, chromatic dispersion will occur. Schematic of chromatic dispersion through hololens is shown in Fig. 2 whereas experimental evidence is in Fig. 3.

4 Results

Theoretical curves for diffraction efficiency ‘η’ versus wavelength ‘λ’ for holograms of different fringe spacing Λ, depth of refractive index modulation ‘n_1’ and film thickness ‘d’ recorded in holographic film has been presented in Fig. 4. For the curves of Fig. 4 designing parameters have been optimized such that diffraction efficiency of these holograms is appreciable over visible region whereas diffraction efficiency of these holograms is poor for ultraviolet region. Such holograms are suitable for cold climate. Diffraction efficiency versus wavelength curves can be optimized for IR region and are suitable for hot climate condition.

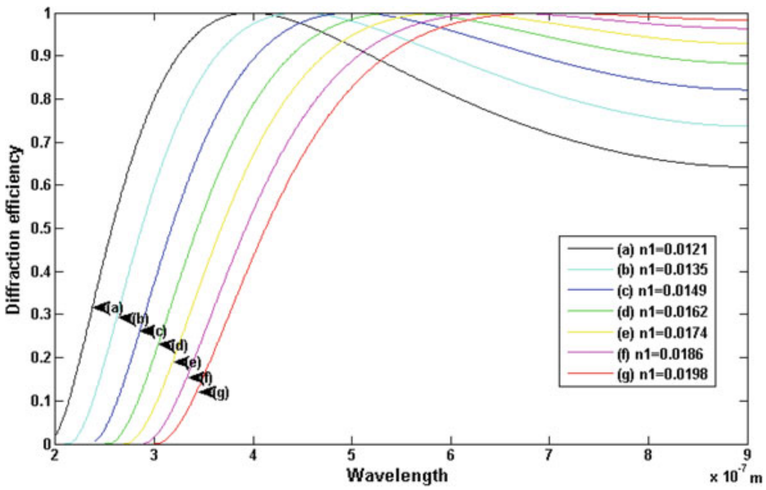

Fig. 4 Variation of diffraction efficiency with wavelength for different values of depth of refractive index modulation (n_1) at fixed value of Λ = 0.51 μm, n = 1.61 and d = 16 μm

5 Application of Holographic Filter in Daylighting Using Optical Fibre

Fibre optic cables by means of thin solid fibre transmits light with high efficiency by total internal reflection. Apart from its ease of installation, absence of mirrors at bends and uniform illumination throughout, fibre optics shows incomparable colour rending property. What makes optical fibre a strong contestant in daylighting systems is its controllability and ease of application. Apart from this, it also gains control over glare, heat gain and consistency issues that besets the conventional daylighting designs. Additionally, it steers sunlight quite deep into buildings without altering space layout or introducing complications like heat gain, glare, disruption of the intensity and variability in lighting, duration of exposure to light etc., which generally leads to fatigue, mood shifts such as Seasonal Affective Disorder.

Silica has a very good light transmission, but it is expensive, especially for bundle production and quartz fibres are fragile and rigid. Glass fibres have light attenuation higher than silica fibres, but they are considerably cheaper and more flexible.

Generally Plastic Optical Fibre are used as fibre bundles as they have low-bending radii, high levels of flexibility, low cost, higher strength and better acceptability for complex wiring in buildings [23]. A light guide material, Polymethylmethacrylate polymer, is employed in POF [24, 25]. It has good light transmission properties, especially for white lights.

An ideal daylighting system should cut down all sorts of spatial heating causes. One of them is exposure by UV and IR waves. Another reason to filter out IR waves is their prolong exposure to POFs can drastically deteriorate the performance of plastic fibre. Hence suitable filtering should be employed so that the fibre is unaffected by UV and IR radiations. In this work, we have proposed the use of HOE filter to do the required task [26, 27].

Furthermore, the light collected by HOE has to be concentrated to pass through the aperture made up of fibre ends.

6 Discussion and Conclusion

Present investigation reveals that properly designed HOEs fulfils all the necessary conditions regarding redirection of solar radiation into the interior of a building so as to ensure cost effectiveness daylighting supportive to human health. Further designing parameters of daylighting holograms can be optimized to filter out unwanted portion of solar radiation depending upon the requirement of hot or cold climate condition thereby minimizing the cost of cooling or heating the interior of a building. Such filters may advantageously be implemented to optical fibres used to redirect the filtered solar radiation to the remote interior of a building.

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