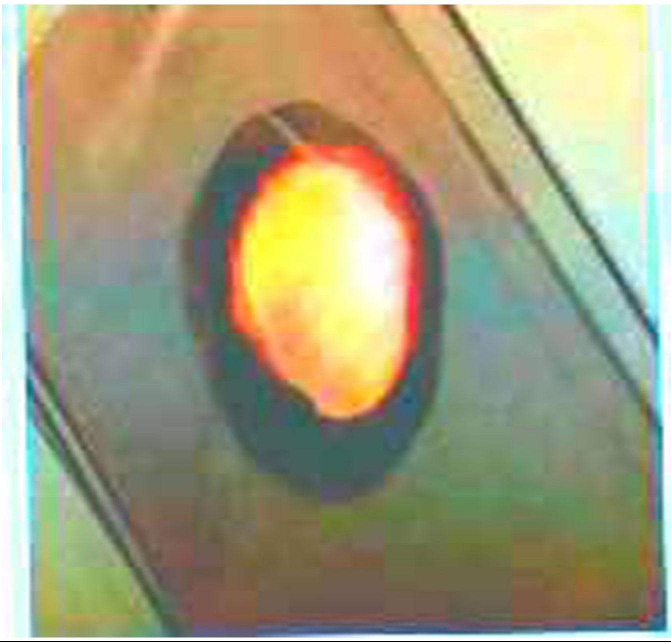
DEVELOPMENT OF HOLOGRAPHIC LENS TO USE IN CONJUNCTION WITH SOLAR CELLS

Project report



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Woman Scientist:

Sreebha A.B.
Research Fellow
Department of Optoelectronics
University of Kerala

Scientist Mentor:

Dr.V.P. Mahadevan Pillai
Professor and Head
Department of Optoelectronics
University of Kerala

A project report

on

“ Development of Holographic Lens to use in conjunction with Solar Cells”

Submitted before Women Scientist Division, Kerala State Council for Science Technology & Environment (KSCSTE), Thiruvananthapuram

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Reference No: 023/wsd-BLS/2012/CSTE

Project Period: 25/04/2013 to 24/04/2016.

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Department of Optoelectronics
University of Kerala

AUTHORIZATION

The project work entitled "Development of Holographic Lens to use in conjunction with Solar Cells" by Ms. Sreebha A.B. was carried out under the "Back to lab programme" of Women Scientists Division, Kerala State Council for Science Technology and Environment, Govt. of Kerala. The work was carried out at Department of Optoelectronics, University of Kerala, Kariavattom Campus, Thiruvananthapuram, Kerala - 680 581 under the guidance of Dr. V.P. Mahadevan Pillai, Professor and Head, Department of Optoelectronics, University of Kerala. The project was initiated wide Council (P) Order No. 445/2013/KSCSTE dated 27/03/2013. The duration of the project was 3 years (from 25/04/2013 to 24/04/2016) and the financial expenditure for the implementation of the project was Rs. 14, 60,704/-

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Sreebha A.B.

Contents

1. Abstract

The project work primarily focused on the development and characterization of recording media for the fabrication of holographic optical elements. PFG 01 Silver halide holographic recording materials are procured and holographic lenses are recorded on the material. The holographic lenses are coupled with a Dye Sensitized Solar Cell (DSSC) by keeping the holographic lens vertically to the solar radiation like window pane of buildings. Enhancement of 32.89 % in the power conversion efficiency of DSSC is achieved.

As a next phase, a red sensitive photopolymer with enhanced shelf life, storage life and diffraction efficiency is successfully fabricated in our lab. Influence of cross –linker in the polymer composition is studied. Various parameters like thickness of the photopolymer material, recording geometry, recording angle, laser exposure energy etc. are optimized to enhance the results. The fabricated red sensitive photopolymer accomplished more than 80 % diffraction efficiency and 6 months shelf life and storage life. The performance of the fabricated photopolymer is compared with a commercial grade red sensitive photopolymer and it is found that the fabricated photopolymer is better in terms of shelf life and diffraction efficiency.

Several holographic optical elements like gratings and lenses are recorded on the fabricated photopolymer. These elements are coupled with Dye Sensitized Solar cells under various illuminance conditions. Enhancement in the power conversion efficiency of solar cells is achieved under all illuminance conditions. Photopolymer based holographic gratings are employed for the efficiency enhancement of solar cells under low illuminance conditions for the first time. When holographic gratings are used, the enhancement in the power conversion efficiency is very high (about 154 %) for the lowest illuminance of 500 lux. When

photopolymer holographic gratings are used, the enhancement in the power conversion efficiency of about 69 % is achieved for the lowest illuminance of 500 lux The aptness of using photopolymer holograms for solar applications is also revealed. The photopolymer based holographic lenses are also coupled with solar cells by keeping them both horizontally and vertically to solar radiation and efficiency enhancement of solar cell is achieved in both cases .

A green sensitive photopolymer with good diffraction efficiency is also fabricated in our lab. Commercial grade green sensitive photopolymer is also procured and holographic lenses are recorded on it to use in conjunction with solar cells. Green sensitive photopolymer based holographic elements are also capable of enhancing the power conversion efficiency of solar cells.

The well exploitation of the present research work will be breakthrough advancement towards green and sustainable energy.

2. Approved Objectives

a) The fabrication of a Holographic Lens to use as solar concentrator

b) To enhance the efficiency of the solar cell.

c) To identify the suitable materials for recording Holographic Lens

d) Publication of the results in reputed journals.

3. Need for the study

The emissions created by conventional energy-use are very high and there is a big requirement of non –polluting renewable energy sources. Solar energy is the major free source of inexhaustible obtainable energy among the various renewable energy sources. Solar energy is available in great intensity in our country. In most parts of India, clear sunny weather is experienced 250 to 300 days a year. The solar energy potential is about 6,000 million GWh per year. But, so far the solar energy utilization in India is very small. The main constraint of solar power generation now is the high cost of photovoltaics. One approach to overcome this problem is to reduce the total area of photovoltaics by concentrating sunlight using optical components and focus it on to the solar cells. The concentrators can be used as roof top concentrators or window concentrators to collect the impinging solar power.

The traditional solar concentrator finds limitations due to its bulky nature and its need for some mechanical tracking system to face the sun directly. It also heats up the solar cells and requires a cooling system. Hence an alternative is needed. Holographic lens is a better alternative to conventional concentrators. Holographic lens is an optical element fabricated by holographic methods. It has several advantages like light weight, handy, low cost in mass production, wavelength sensitivity and ability to perform multiple functions simultaneously. A single holographic lens can split the solar spectrum and concentrate the radiation of desired wavelength and diffract away the heat radiation. The cooling system can be avoided in such systems and the mechanical tracking system can be avoided as holograms have the ability to focus light falling at different angles to the solar cells.

4. Introduction to Holography:

Light sensors such as eyes, photographic film and electro optic detectors record only the intensity of light waves and cannot record the information about the phase as it oscillates from crest to trough and back (1). The entire wave field can be defined in space if the amplitude and the phase of a wave are registered in one plane (2). Holography does this by mixing an unaltered reference beam with the object beam on a photographic film. The key to holography is this reference beam (1). The interaction between the object and reference beam develops a pattern of fluctuating intensity (determined by the changes in phase and amplitude of light beams) on the photographic film (3). This interference pattern scatters light while illuminating with the reference beam and forms an image with complete information about the object (3). This interference pattern is called "hologram". The word hologram has originated from two Greek words "holo" and "gram". The word "holo" means "the whole" and "gram" means "record" (4). Even though, holography is admired mainly for its realistic appearance of 3-D images, it has advanced as a tool with enormous potential that appears in many branches of science other than optics such as, material science, magnetism, crystallography, medical science, atmospheric science, many-body physics, super conductivity, quantum gravity, string theory and thermodynamics (5- 13).

A hologram is recorded by creating an interference pattern on a holographic recording medium by the addition of a reference wave, ψ_R with the object wave, ψ_O.

$$\psi_R = A_1 e^{i\phi_1}$$

1.1

$$\psi_O = A_2 e^{i\phi_2}$$

1.2

Where A_1, A_2 are the amplitudes and ϕ_1, ϕ_2 are the phases of reference wave and object wave respectively (14).

The interference pattern is observed on the recording plate with the intensity I, which is defined as the square of the absolute value of all the wave functions (14). Therefore,

$$I = \left|\psi_R + \psi_O\right|^2 = \psi_R^* \psi_R + \psi_R^* \psi_O + \psi_R \psi_O^* + \psi_O^* \psi_O \qquad 1.3$$

$$= \psi_R^* \psi_R + \psi_O^* \psi_O + \psi_R \psi_O^* + \psi_R^* \psi_O \qquad 1.4$$

Where, $\psi_R^* \psi_R = I_R$ and $\psi_O^* \psi_O = I_O$ be the intensities of the reference and object beam respectively (14). Then,

$$I = I_R + I_O + \psi_R \psi_O^* + \psi_R^* \psi_O \qquad 1.5$$

Substituting equations (1.1) and (1.2) in equation (1.4) and replacing $e^{i\phi}$ with $(\cos\phi + i\sin\phi)$, we get (15)

$$I = A_1^2 + A_2^2 + 2A_1A_2\cos(\phi_1 - \phi_2) \qquad 1.6$$

The two interfering waves should be coherent and monochromatic to produce constructive interference fringes and thus we can write the phase difference as

$$\phi_1 - \phi_2 = \pm 2\pi n \qquad 1.7$$

Where, the integer n represents the order of fringes.

Then, $\cos(\phi_1 - \phi_2) = \pm 1$. Substituting the value in equation (1.6) we get,

$$I = A_1^2 + A_2^2 \pm 2A_1A_2 \qquad 1.8$$

$$I_{\max} = (A_1 + A_2)^2 \text{ and } I_{\min} = (A_1 - A_2)^2 \qquad 1.9$$

Thus, in the region of interference, a set of maximum and minimum disturbance surfaces are formed and we get the interference fringes in the recording medium (hologram). During reconstruction, when we illuminate the hologram with the original reference beam ψ_R, the Intensity of the light passes through the hologram attains the intensity given by (16)

$$I' = I\psi_R \qquad 1.10$$

Substituting equation (1.5) in equation (1.10) we get

$$I' = \psi_R I_R + \psi_R I_O + \psi_R \psi_R \psi_O^* + \psi_R \psi_R^* \psi_O \qquad 1.11$$

Here, the first and second terms in equation (1.11) are the unmodulated illumination intensities, the third term represents the conjugate real image of the object formed in front of the hologram and the fourth term represents the optical interpretation of the object which can be written as $I_R\psi_O$. Fourth term is same as the object wave with a constant reference intensity term which is modulated by the object amplitude and forms the virtual image of the object (17, 16).

The schematic representation of recording and reconstruction of hologram is shown in Fig (1) (3).

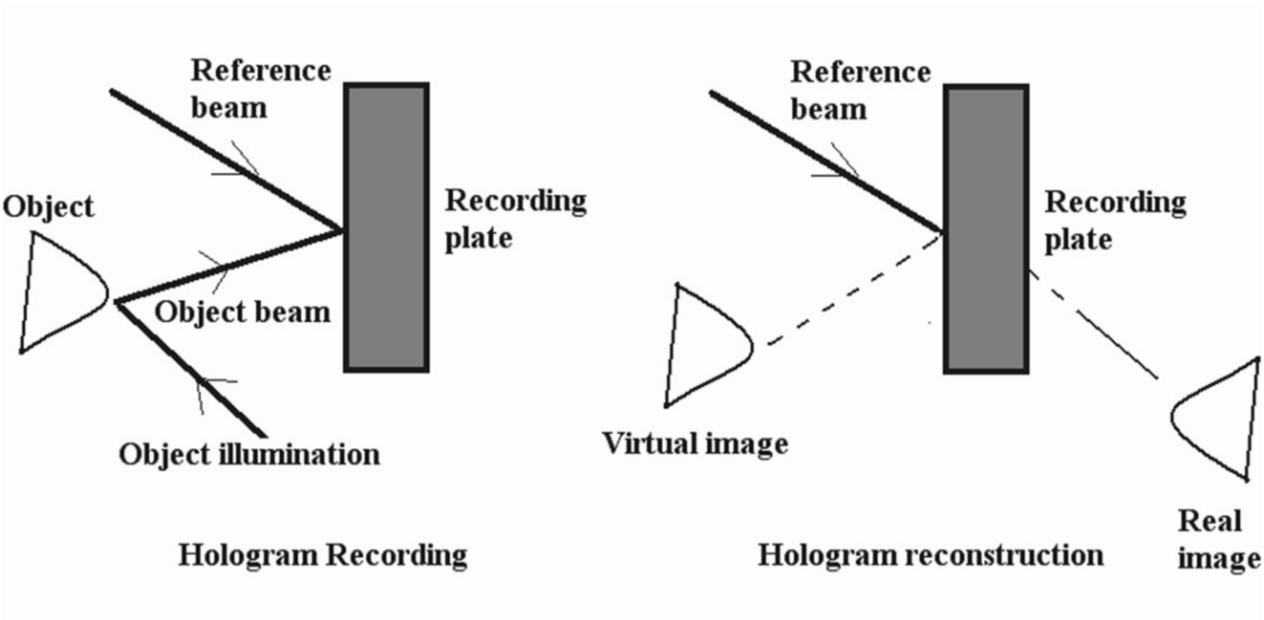

Fig.1 schematic representation of Holographic recording and reconstruction

5. Materials Adopted for the Present Study:

Silver halide and photopolymer are the recording materials used for the present study.

Choice of recording material is very significant in holography. Recording materials for holography should absolutely exhibit high resolution (thousands of lines per millimeter), stability and diffraction efficiency (18). For recording high quality 3D volume holograms, the recording material should possess large physical thickness and negligible shrinkage (19). In order to guarantee the invariability of the fringe structure during any operations under several external factors and post-exposure treatments, recording media should have high physical and mechanical performance (20). Also, the holographic recording media should have sufficient energy sensitivity, good shelf life and storage life, transparency at the operating wavelength, nondestructive hologram reconstruction ability etc. (20). Illumination of light is capable to modulate the optical properties of holographic recording material such as absorption constant, thickness and refractive index (3). In amplitude holograms, mainly the absorption co-effcient gets modulated where as in phase holograms, thickness or refractive index gets modulated. But,

in practical holographic cases, all these parameters get modulated. Also, the material should possess high optical quality and temporal stability (21). Photosensitivity and dynamic range of the recording material should be sufficient to write holograms (21).

The majority of holographic recording materials have been developed for image display applications than data storage applications. Self-developing recording materials with no wet processing are preferred for data storage applications (22). For digital holographic data storage applications, recording media should possess adequate thickness and optical flatness, low scattering performance and negligible shrinkage on exposure (23).

Photographic plates and films with high resolution and sensitivity are the first widely used materials for holography (21). Dichromated gelatin (DCG), photoresists, photopolymers, photothermoplastics (PTP), photorefractives etc. are the other materials used for recording holograms (24). Table (1) below shows different recording materials for holography and their important characteristics (24).

Material	**Resolution (mm^{-1})**	**Diffraction efficiency**	**Sensitivity (J/m^2)**
Photographic Emulsions	5000 Approximately	0.06 for amplitude holograms 0.60 for phase holograms	≈ 1.5
DCG	10000	0.90	100
Photoresist	3000	0.30	100
Photopolymers	5000	0.90	10-10000
PTP	500-1200	0.30	0.10 – 1.0
Photorefractives	10,000	0.20	10

Table 1 : Different holographic recording material and their characteristics

5.1. Silver Halide Photographic Emulsions:

Photographic emulsions such as silver halides are still broadly used for recording holograms as they have high resolution, sensitivity and availability (25). It is used to record both amplitude and phase holograms. But, it is irreversible and created print outs in phase holograms (26). As photographic emulsions require wet processing, they cannot be used in data storage applications and real time holographic applications (27, 28). Furthermore, silver halide materials are absorptive and they have partial linear response and intrinsic noise (26).

5.2 Photopolymers:

Photopolymer is a multi-talented recording material for holography due to its properties such as its suitability for rapid dry processing, low cost, high optical quality, high resolution, low diffusivity, easy preparation techniques, transparency in the visible spectral region, high diffraction efficiency and high angular selectivity (29). Even though, the photopolymer material has a significant role in the advancement of holography, its commercial availability is currently inadequate. A photopolymer recording material in general consists of a binder, a monomer, a photosensitive dye, and an initiator (30, 31). The binder is an inactive component used to grasp the components of the photopolymer film. Monomers are small molecules that also enter into the reaction to produce refractive index modulation (30). Photo-initiator enables the formation of free radicals when exposed to light and reacts with monomers and binders to link them together (30). The sensitizer absorbs light and interacts with the photo initiators to begin photopolymerisation of monomers. We can also supply additional monomers as cross-linkers to stabilize the final hologram recorded on the polymer material (32).

Photopolymer films when exposed to laser light for holographic recording, creates a complex pattern of constructive and destructive interference in the material. In the areas of constructive interference, monomers assembles together to form a growing polymer chain and in the areas of destructive interference, the concentration of monomer stays unchanged. This creates modulation of index of refraction in the material (33).

6. Methods Adopted for the Present Study:

Amplitude transmission holographic recording using in-line geometry and phase transmission holographic recording using off-axis writing geometry are the methods used for the fabrication of holographic optical elements. Different categories of holograms and recording geometries are briefly described below.

The type of the hologram depends not only on the profile of the interference pattern formed over the recording medium but also on the photochemical and physical parameters and dimensions of the recording medium (34). Holograms can be classified in to different types by

considering several parameters such as transmission function of the recording medium, recording configuration and reconstruction, recording geometry, region of diffraction, thickness of recording medium etc (35).Table. 2 shows different types of holograms with the critical parameters for the categorization.

Types of holograms	**Critical parameters of material/ recording set up**
Amplitude and phase holograms	Transmission function of the recording medium
Transmission and reflection holograms	Recording and reconstruction configurations
Inline and off-axis holograms	Recording geometry
Fresnel and fraunhofer holograms	Region of diffraction
Thin and thick holograms	Thickness of recording medium

Table.2: Classification of Holograms

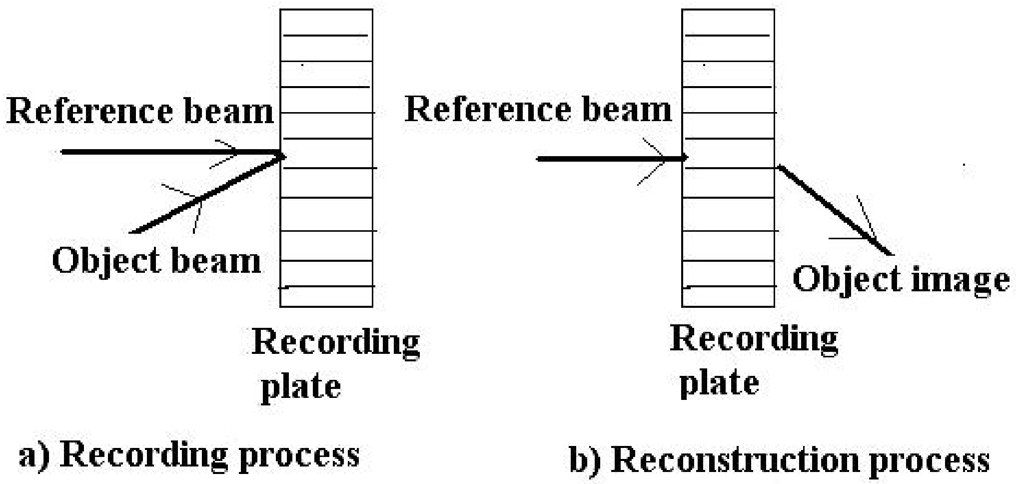

Fig 2 (a) Recording process and b) reconstruction process for transmission holograms

Schematic representation of the recording configuration and reconstructing configuration of transmission holography is shown in Fig.2.(a) and (b) respectively. During holographic recording in transmission type holograms, the object and reference beams reach the recording plate from the same side during holographic recording and the interference fringes are formed perpendicular to the plane of recording plate. Here, the reference beam is to be transmitted through the hologram to reconstruct the image. (36, 37).

6.1 In-line and Off-axis Holograms:

Schematic representation of recording an in-line/on-axis hologram is shown in Fig.3. For in-line holograms, part of the object beam itself can be employed as the reference beam. It is also known as on-axis holograms. In reality, the Fresnel diffraction pattern of an object is recorded by in-line holography methods and the object can be reconstructed at the same Fresnel distance away (38).

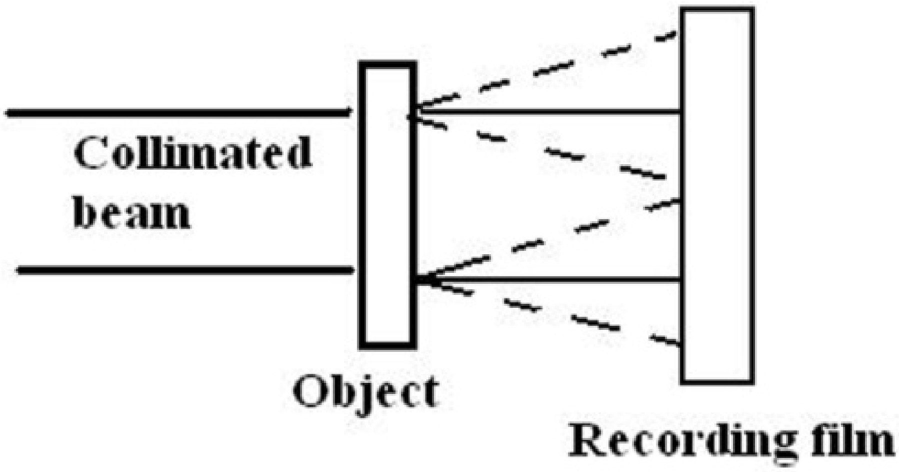

Fig 3. On- axis hologram recording

The in-line holography usually deals with transparent or semitransparent objects that comprise a scattered light field (U_O) in addition with the unscattered light field (U_R) on illumination. The interference between both the light fields occurs in the recording film placed at a small distance away from the object. The films records the intensity distribution, $I(x, y)$ of the interfering wave fields which can be written as (38)

$$I(x, y) = |U_O + U_R|^2$$

$$= |U_O|^2 + |U_R|^2 + U_O U_R^* + U_O^* U_R \qquad 1.12$$

During the reconstruction of in-line hologram (the schematic representation is shown in fig. 4), the light field scattered from the hologram, $U\ (x, y)$ can be represented as the product between illuminating plane reference be (U_R) and transmission function, t(x,y)

$$U(x, y) = U_R \times t(x, y) \qquad 1.13$$

Assuming a linear response to the intensity allied with the holographic recording medium, we can write

$t(x,y) = a + bI(x,y)$ 1.14

Where a and b are the constants and is the intensity distribution formed in the hologram.

Substituting for I(x,y) in eqn (1.14) and for t(x,y)in eqn (1.13), we get

$$U(x,y) = U_R\{a + b(\ |U_O|^2 + |U_R|^2 + U_O U_R^* + U_O^* U_R)\}$$

$$= U_R a + U_R b\,(|U_O|^2 + |U_R|^2) + U_O U_R^* U_R b + U_O^* U_R U_R b$$

$$= U_R a + U_R b\,(|U_O|^2 + |U_R|^2) + U_O |U_R|^2 b + U_O^* U_R^2 b$$ 1.15

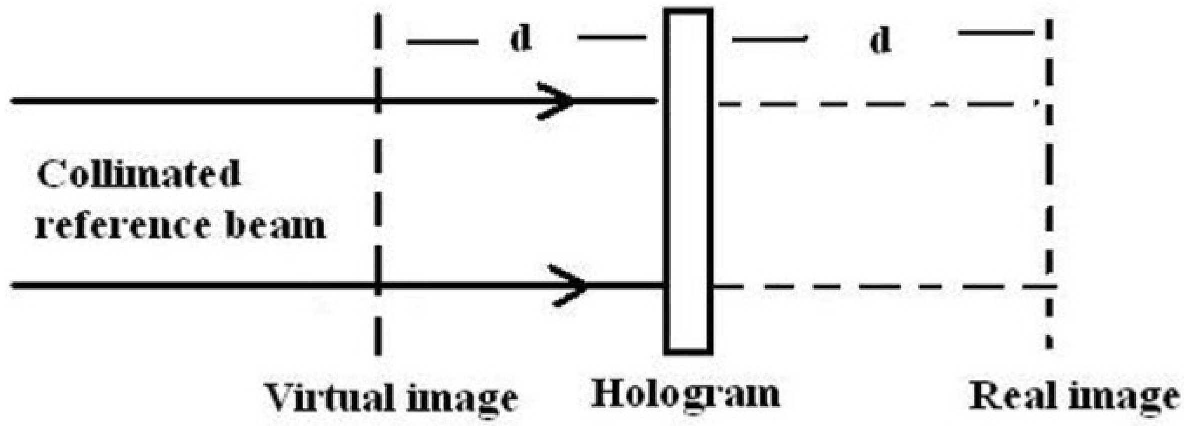

Fig. 4. Reconstruction of in-line hologram.

Since the scattered beam intensity is very low compared to unscattered beam intensity for transparent or semitransparent objects, the second order terms of scattered beam can be neglected. The spatially constant terms are insignificant for hologram and hence only the last two terms which contain scattered field, U_O and its complex conjugate, U_O* in the equation are important. The field U_O* denotes back ward propagation of the object beam to form a virtual image at one side of the recording film. There is also a real image on the other side of the hologram. These real and virtual images are equidistant from the hologram. They overlap during reconstruction and this twin image problem is the main disadvantage of in- line holography (38).

The disadvantage associated with this twin image problem is eradicated with the invention of the off-axis reference holography by Emmett Leith and Juris Upatnieks (39, 40). Leith and Upatneiks divided the laser beam in to two beams, object beam and reference beam.and shifted the reference beam to off- side (39, 40). Off-axis holography not only offers separation of image components, but also affords front illumination of opaque objects; which cannot be possible with in-line holography (41). Also, the intensity ratio between object and reference beams can be modified to get the maximum bright image of the object (41). A typical set up for recording and reconstruction of off - axis holography is in Fig 5 shown below.

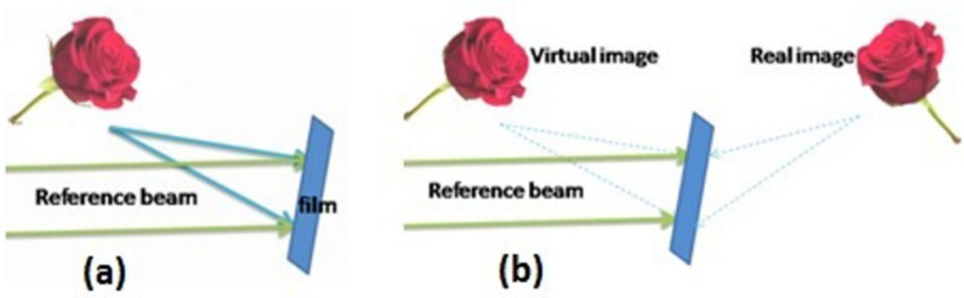

Fig 5 (a) Schematic diagram of recording and (b) reconstructing off-axis hologram

6.2 Amplitude and Phase holograms :

The complex amplitude transmittance of the recording medium for holography can be expressed as (24)

$$t = e^{-\alpha d} e^{-i\frac{(2\pi n d)}{\lambda}} \quad 1.16$$

Where, the parameters α ,d and n be the absorption co-efficient, thickness and refractive index of the recording medium respectively. A change in α with the exposure produces an amplitude hologram, while a change in n or ,d will produce a phase hologram.

Amplitude holograms are formed by the change in absorption constant of the recording medium which results in the spatial modulation of the transmissivity of the recording material (34). The amplitude of the transmitted wave is greatly modulated in such type of holograms. Here, interference patterns are recorded as density variation in the recording media (18). Phase hologram results when the phase of the transmitted wave is more modulated than its

amplitude. Refractive index change is prominent in such type of holograms to create a change in the surface profile of the recording material during holographic recording. Also, when the thickness of the recording medium is large enough to create an optical path length change or refractive index modulation without damaging the material, we get a thickness modulated phase hologram (24, 34). Hence in phase holograms, interference pattern is recorded as change in refractive index, surface profile or thickness of the recording medium (18). Diffraction efficiency of phase holograms is superior to that of amplitude holograms and hence they are widely used for data recording (18).

7. Results and Discussion

7.1 Fabrication of Holographic Optical Elements (HOEs) in PFG 01 Silver Halide Recording Material:

HOEs are basically the optical elements fabricated by holographic methods. They have certain unique functions and characteristics (42). HOEs are wavelength selective elements which can perform multiple functions simultaneously. A single HOE can act as a filter, beam splitter, concentrator, diffractive element etc (42). The properties of HOE depend upon the fringe structure formed in the hologram where as the properties of conventional optical elements depend on the surface shape of the element. Additionally, HOEs are cheap in mass production and are flat, handy and thin (42). Several in-line and off- axis HOEs are fabricated in PFG 01 silver halide material and those are exploited for solar applications to direct and concentrate solar power on to solar cells.

7.1.1 Writing and Reading set up for In-line Silver Halide HOEs:

Recording geometry of in-line holographic optical element is shown in Fig.6a. For recording, the object is illuminated with the laser beam of wavelength 632.8 nm from a He- Ne laser and the hologram is recorded by keeping the recording plate at 11 cm from the object (here, 11 cm). The laser beam is expanded by using spatial filters and the beam area made to1 cm^2 at the recording plate by using a suitable aperture.

The laser exposure energy is kept at 1000 μJ/cm^2 and different in-line HOEs are recorded by using pin holes of different sizes drilled on different glass plates of thickness 5 mm. The in-line holograms of pin holes of different diameters (namely 0.6 mm, 0.7 mm, 0.8 mm, 0.9 mm and 1 mm) are recorded in PFG 01 silver halide material. The in-line holograms of pin holeswith different diameters thus recorded are designated as $d_{0.6}$, $d_{0.7}$, $d_{0.8}$, $d_{0.9}$ and d_1 respectively.

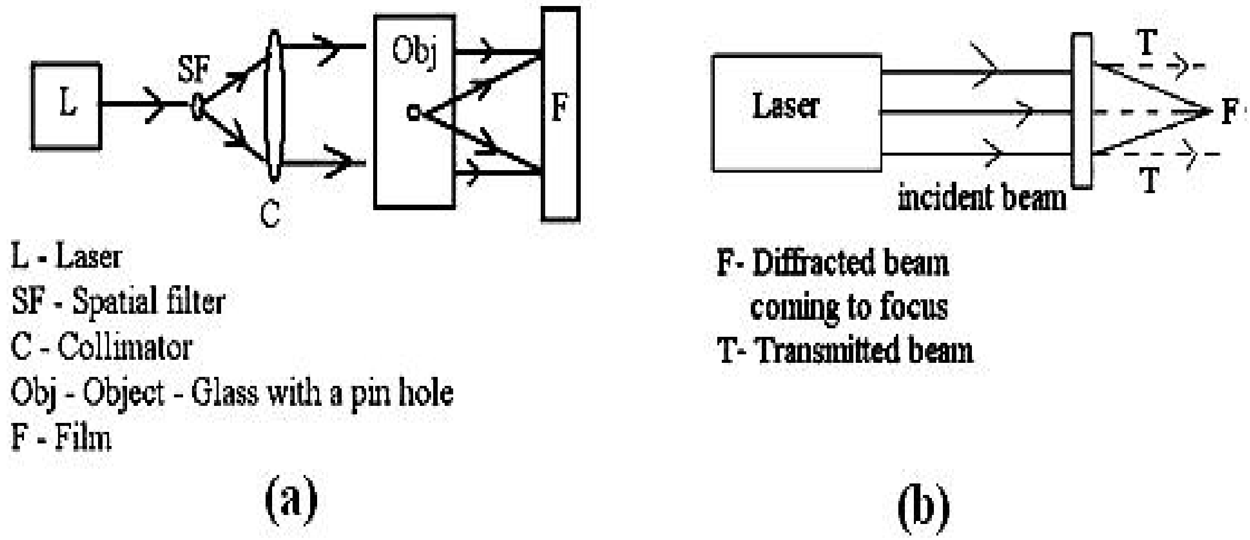

Fig.6. (a) Recording geometry for inline transmission HOE
(b) Schematic diagram for diffraction efficiency measurements

The hologram recorded silver halide plates are developed in cwc2 developer for 3 minutes and then washed for 5 minutes and dried in normal laboratory conditions. During the construction of holograms, only certain regions of PFG 01 silver halide plates are exposed to laser light where as other regions remain unexposed. The silver halide grains in the light exposed region can get reduced to elemental silver in the presence of a developing agent (43). The development of the hologram results in the density variation of the recording medium. In the present case, further processing like bleaching and fixing are not done and the silver halide hologram thus developed is an amplitude hologram which appears to be dark (44). When the amplitude hologram is illuminated with a reference beam for reconstruction, the intensity of the diffracted light from it decreases by an amount depending on the darkness of the hologram. The visibility of the holographic image in this amplitude hologram only depends on the intensity variations of the reconstructing beam, as a whole appears with a reduction in the brightness and with reduced diffraction efficiency.

The schematic diagram for diffraction efficiency measurement of the HOE is shown in Fig. 6 (b). The same laser wavelength used for recording is allowed to fall on the HOE. Hologram of the pin hole has a property of focusing light. When light is incident on such a hologram, portion of light is focused and a portion is transmitted. As shown in Fig 6 (b), the focused light is along with the transmitted beam. The transmitted beam is cut off by using a mask with a small aperture (which allows the focusing beam to pass through it). The intensities of the incident beam and the beam at the focus are measured using a power meter. The diffraction efficiency (η_{DE}) is calculated (in percentage) using equation given below (3).

$$\eta_{DE} = \left(P_f / P_i \right) * 100 \qquad (1.17)$$

Where P_i and P_f be the intensities of incident beam and beam at the focus respectively.

7.1.2 Varaiation of Diffraction Efficiencies of In-line Silver Halide HOEs as a Function of Pin hole size:

The variation of diffraction efficiencies of the HOEs as a function of pin hole sizes ($d_{0.6}$, $d_{0.7}$, $d_{0.8}$, $d_{0.9}$ and d_1 are plotted in Fig.7. It is found that as the size of pin hole increases, more light rays are getting focused and hence the HOE d_1 (pin hole size 1 mm) has got the highest diffraction efficiency among the HOEs fabricated.

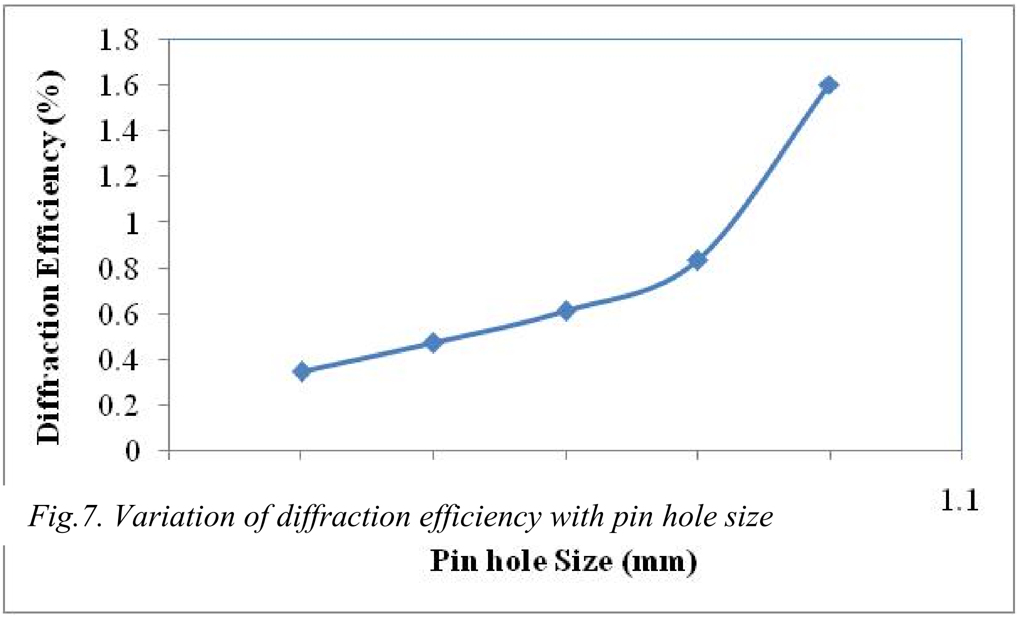

Fig.7. Variation of diffraction efficiency with pin hole size

From the Fig 2.3, it can be seen that all the HOEs possess very low diffraction efficiency of only less than 2 % .

7.1.3. Writing and Reading set up for Off- axis Silver Halide HOEs

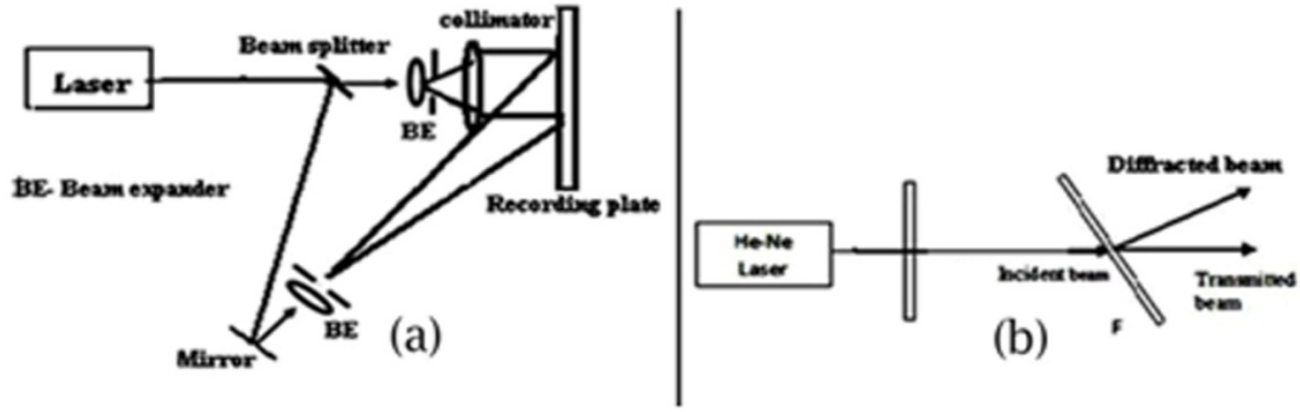

Fig.8(a) Transmission holographic optical element recording geometry and (b) Schematic representation for the diffraction efficiency measurement of holographic optical elements

The holograms fabricated in the in- line holographic geometry shows only low diffraction efficiencies. Thus, the recording geometry is shifted to off-axis configuration to improve the diffraction efficiencies.

The schematic representation of recording geometry of off- axis HOE and its reconstruction geometry are shown in Fig. 8 (a) and Fig 8 (b) respectively. The laser beam is split into two beams using a beam splitter and the beams are expanded using spatial frequency filters. The reference beam is made parallel using collimated lenses. The two beams are directed to the holographic film. The exposure time is controlled using a shutter placed in front of the laser.

The object beam is made to diverge from a point which is 10 cm away from the film. For recording HOE, the beam diameter of 1 cm is used and the inter beam angle between object and reference beams is kept at 27°. The samples are exposed to 80 $\mu J/cm^2$ energy.

The first order diffraction efficiency of HOE is found by allowing the laser beam to fall on the hologram placed at Bragg's angle (Fig 8 (b). The intensity of the focused beam is measured using a laser power meter placed at the focal point, in this case 10 cm from the hologram. The intensity of incident beam (P_i) and that of first order diffracted beam (P_1) are measured. The percentage of diffraction efficiency (DE) is calculated using equation (1.18) given below (3).

$$DE = \left(P_1 / P_i \right) * 100 \tag{1.18}$$

7.1.4 Diffraction Efficiencies of Off- axis Silver Halide HOEs as a function of beam ratio:

The first order DE of HOE for different beam ratio (ratio between object and reference beam) is measured with both direct and conjugate beams. Variation of diffraction efficiency of off-axis silver halide HOE with beam ratio is shown in Fig. 9. The highest DE is obtained when the HOE is recorded with a beam ratio of 1:3. For direct beam measurements, highest DE of 35% is obtained and for conjugate beam measurements ,highest DE of 33 % is obtained.

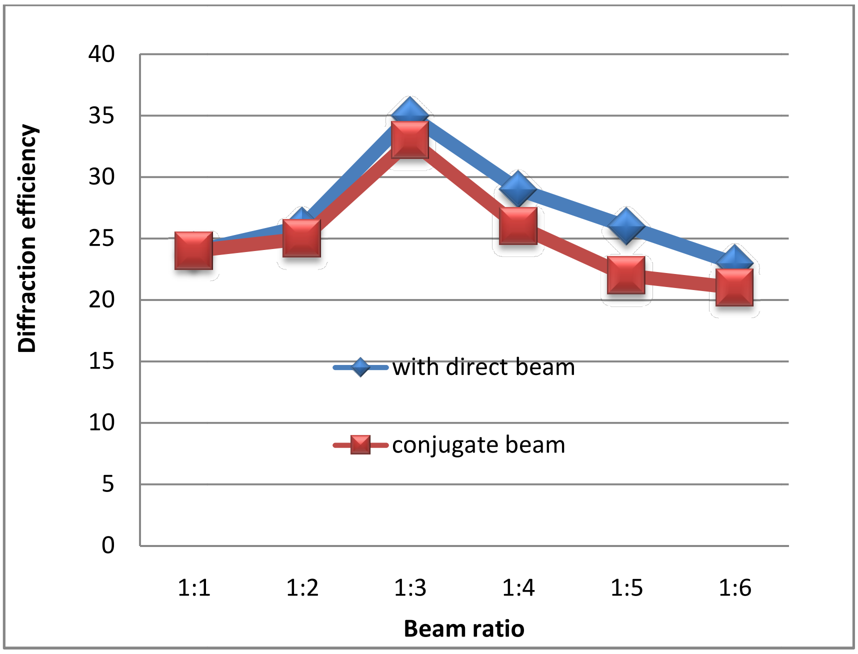

Fig.9. Variation of diffraction efficiency of off-axis silver halide HOE with beam ratio

7.1.5 Coupling of Silver Halide HOE with Solar Cell

The effect of coupling of HOE with a standard yellow sensitive Dye Sensitized Solar Cell (DSSC) of area 0.25 cm^2 is studied at Department of Physics, IIT Chennai. The DSSC (fabricated by IIT, Chennai) used titanium dioxide as photo-anode, N719 as sensitizing dye and tri- iodide/iodide redox couple as electrolyte. Simulations are made using Newport's ORIEL Class A solar simulator. The HOE is used to direct the light from the simulator to fall on DSSC. DSSC is initially placed at weakly illuminated region of the simulator and the efficiency measured at this position is 0.076. The HOE is placed vertically to the illuminating plane of simulator in such a way to make the yellow radiation falling on the DSSC and it is found that the efficiency of DSSC enhanced to 0.101(32.89 % enhancement).

7.2. Fabrication of a Red Sensitive Photopolymer for Holography:

A number of materials have been developed for holography and among them, photopolymer is highly versatile due to its unique properties such as rapid dry processing, low cost, high optical quality and resolution, low diffusivity, easy preparation techniques, transparency in the visible spectral region, high diffraction efficiency and angular selectivity (45). Even though, the photopolymer material has a significant role in the advancement of holography, its commercial availability is currently inadequate. The limited shelf life and storage life of commercial photopolymer restricts its extensive usage even if it claims very high diffraction efficiency. Hence, developing a photopolymer having enhanced shelf life and storage life with high diffraction efficiency is a major challenge in this area.

The present work describes the development of a new red sensitive photopolymer with enhanced shelf life and diffraction efficiency using gravity settling method .The basic mechanism for the hologram formation in the fabricated photopolymer is the radical polymerization, which is supposed to be the result of different physiochemical processes (46, 47). The first step is the initiation process, which involves the production of free radicals. The second step is the propagation by which the species propagate by combining with other monomer molecules forming a large polymer chain. The final step is the termination process by which the extinction of the polymerization takes place. After the polymerization process, the monomers are linked by covalent bonds and thus the distance between connected

monomers is shortened. Shrinkage occurs here creating a thickness change and refractive index modulation (46, 47).

7.2.1. Preparation of Red Sensitive Photopolymer:

Two types of photopolymer chemical composition are developed in our lab using gravity settling method. One set is designated as sample P_1 and the other set as sample P_2. The P_1 photopolymer material contains polyvinylalcohol (PVA) as binder, acrylamide (AA) as solid monomer, triethanolamine (TEA) as initiator and methylene blue as sensitizing dye. 0.375 molar AA, 0.223 molar TEA and 0.22 molar BAA are added to 10% transparent PVA solution. A uniform aqueous solution of .003 molar methylene blue dye in distilled water is prepared. Different concentrations of this dye solution are mixed with the above prepared solution and the sample with the optimum dye concentration is found. For sample P_2, 0.22 molar N, N'-methylene-bis-acrylamide (BAA) also is added to all the other ingredients of photopolymer P_1 as a monomer cross –linker. Cleaned glass slides of dimension 75mm X 25mm X 1.35 mm are used to cast films using gravity settling method. The films are fabricated in room temperature and dried for two weeks. The average thickness of the fabricated films are 200 microns (measured using Bruker's Dektak - TX Stylus thickness profilometer).

Suitability of a material to record holograms is determined by the diffracting property of the simple holograms written in the material. The simplest holographic recording geometry is two beam transmission grating geometry and hence simple transmission gratings are recorded in the fabricated photopolymer using two beam interferometry. Also, studies are done on a commercial grade photopolymer sample P_3, procured from M/s Light Logics Holography and Optics Pvt. Ltd.

7.2.2 Recording of First Order Transmission Holographic Gratings in Photopolymer:

Two beam interferometry shown in Fig.10 (a) is used to record transmission holographic gratings. The laser beam is split into two beams using a beam splitter. These beams are expanded using spatial frequency filters and made parallel using collimated lenses. The beam diameter is set to be 1 cm. The collimated beams are allowed to interfere inside the film. Path

lengths of two beams are made equal. First order diffraction gratings are recorded in the photopolymer film using He- Ne laser (632.8nm) by keeping the beam ratio at 1:1.

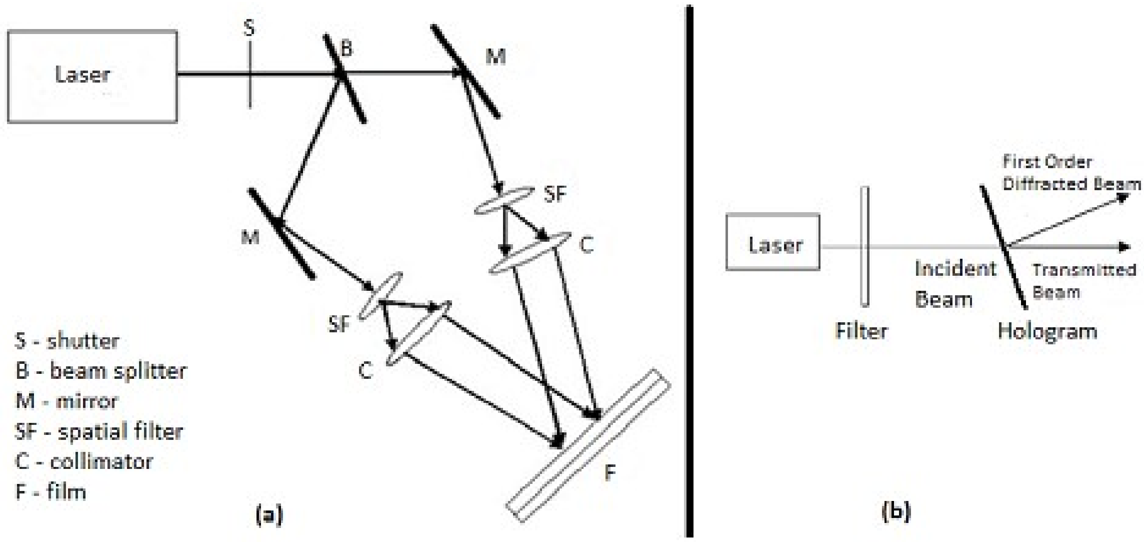

Fig 10 (a) : Two beam interferometry to record holographic gratings 3(b) :Diffraction efficiency measurements

7.2.3 Diffraction Efficiency (DE) Measurements:

The schematic representation of Diffraction efficiency measurements is shown in Fig. 10 (b). The laser beam is allowed to fall on the hologram placed at Bragg's angle. The diffracted beam is observed on the screen at Bragg angle and its intensity is measured using power meter. The intensity of incident beam (P_i) and that of the first order diffracted beam (P_1) are measured and the DE is calculated using equation (1.18) .

7.2.3.1 DE Measurements of Photopolymers with Varying Dye Concentrations:

First order diffraction gratings are recorded in the films at different exposure energies. DE measurements are carried out in the P_1 and P_2 samples. Holographic recording is done by keeping the beam ratio 1:1 and inter beam angle 30°.The variation of diffraction efficiencies with different exposure energies are shown in Fig. 3.2. The photopolymer films with the dye concentration of 4 X 10^{-5} M exhibit high diffraction efficiency in both (P_1 and P_2) samples. Those samples are designated as P_1' and P_2' photopolymers. The variation of diffraction efficiency with exposure energy for different dye concentrations for P_1 and P_2 samples are shown in Fig. 11 (a) and (b) respectively. The surface images of P_1' and P_2' photopolymers taken using 10 X microscopic objective are shown in Fig. 11 (c) and (d) respectively.

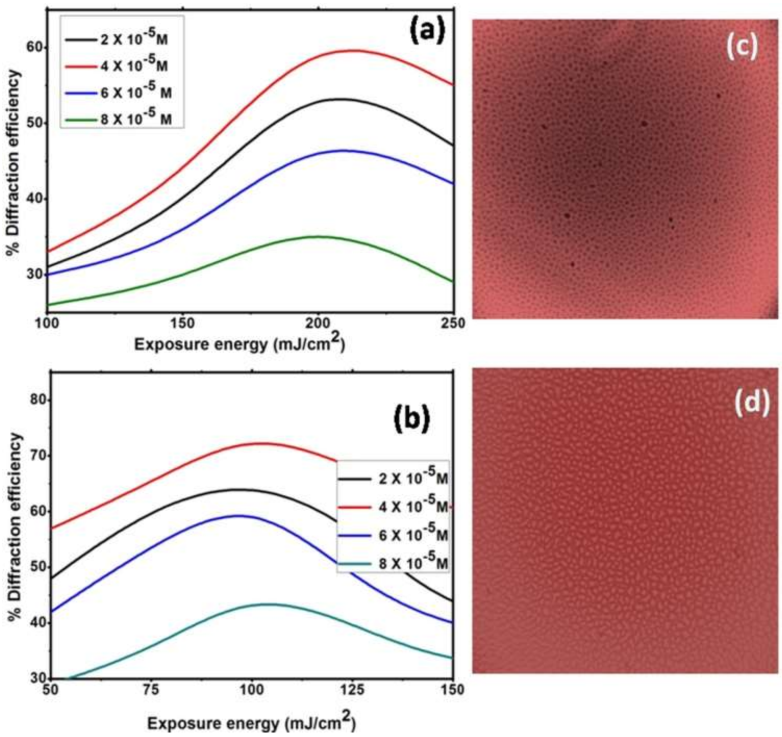

Fig. 11 (a, b): Variation of Diffraction efficiency with exposure energy for P_1 and P_2 photopolymers, Fig. 11 (c, d) surface images of of P_1' and P_2' photopolymers.

7.2.3.2 Optimization of Diffraction Efficiency in P_3 Photopolymer with Varying Exposure Energy

First Order diffraction gratings are recorded in the procured P_3 samples at different exposures with beam ratio 1:1 and interbeam angle 30°. Highest diffraction efficiency of 61 % at 225 mJ/cm^2 exposure is achieved and it is shown in Fig. 12.

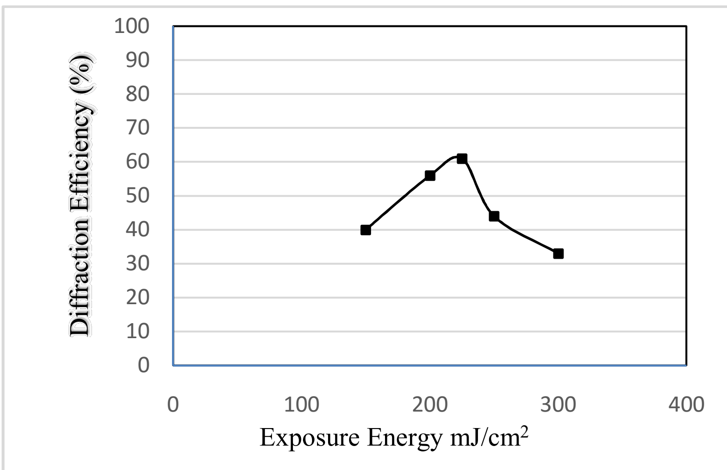

Fig .12 Optimization of exposure energy in P_3 photopolymer

7.2.3.3 Comparison of the Diffraction Efficiencies of P_1', P_2' and P_3 Photopolymer:

The fabricated photopolymer with cross linker (P_2') shows the highest DE compared to other photopolymer films. For the exposure energy of 100 mJ/cm^2, the sample P_2' shows the highest DE of about 70%, whereas the photopolymer without cross linker(P_1') shows the highest DE of about 60 % at an exposure energy of 200 mJ/ cm^2.The addition of cross linker not only increases the DE of the grating, but reduces the exposure energy needed to record the efficient grating also. The commercial grade photopolymer shows maximum DE of 61 % for an exposure of 225mJ/ cm^2.

The absorbance of both P_1' and P_2' photopolymer samples is found by Jasco V-550 UV – Vis spectrophotometer (Fig.13). No discrepancy is found in the wavelength of absorbance peak. The absorbance value of P_2' photopolymer is lesser than that of P_1' photopolymer. The respective absorbance peaks are that of methylene blue dye used for the fabrication of photopolymer. The bleaching of dye in the presence of photons is more for P_2' photopolymer.

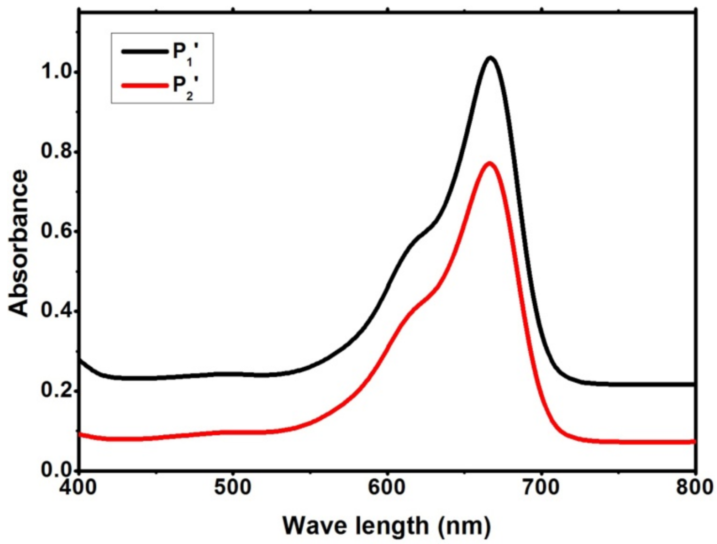

Fig. 13 Absorbance spectra of P_1' and P_2' photopolymer

7.2.4 Optimization of inter-beam angle used for recording and thickness of photopolymer samples:

P_2' photopolymer which shows the utmost diffraction efficiency and more light sensitivity is taken for further studies. In order to optimize the inter-beam angle (angle

between object and reference beams) of recording geometry, first order diffraction gratings are recorded in P_2' photopolymer having a thickness 200 μm at different inter-beam angles by keeping the exposure energy at 100 mJ/cm^2 and the beam ratio at 1:1. The uppermost diffraction efficiency of 80.80 % is achieved at an inter-beam angle of 27.5˚ [Fig. 14 (a)].

Various P_2' photopolymer samples are again fabricated using gravity settling method by varying the thickness of the samples and holographic diffraction gratings are recorded on those samples by keeping the inter-beam angle at 27.5˚, exposure energy at 100 mJ/cm^2 and beam ratio at 1:1. . The utmost diffraction efficiency is shown by the 200 μm thick P_2' photopolymer film. [Fig.14 (b)].

The absorption spectra of unexposed and laser exposed P_2' photopolymer film is shown in Fig. 14 (d). No noticeable shift in the wave length region of absorbance is occurred in P_2' photopolymer by recording holograms.

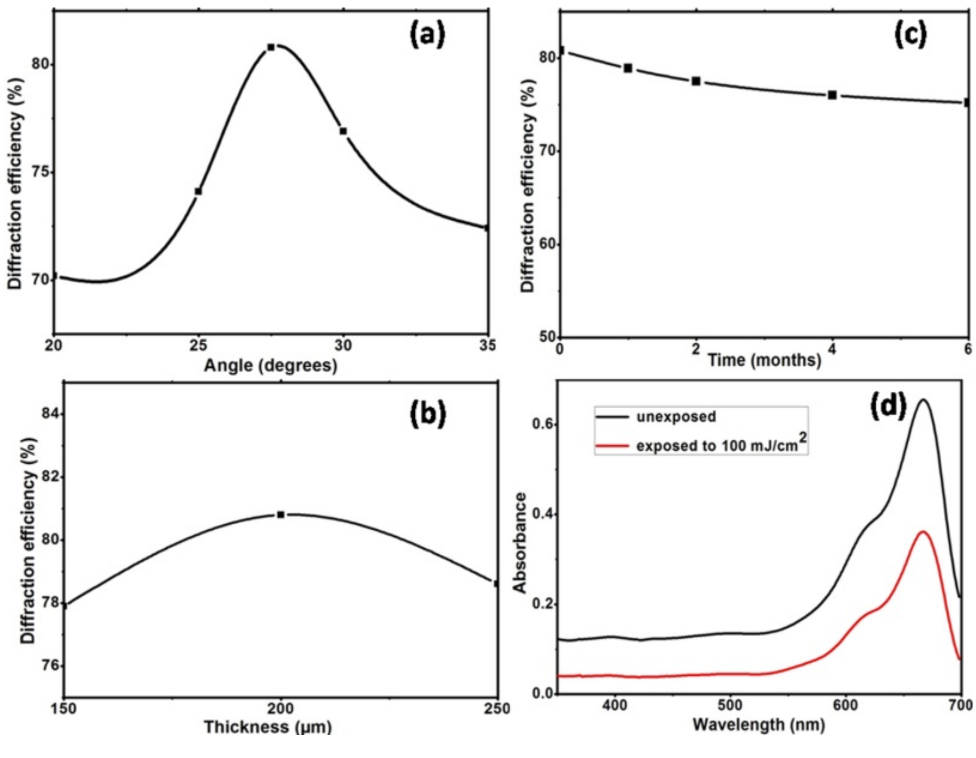

Fig 14 (a) Variation of diffraction efficiency (DE) of P_2' photopolymer as a function of inter-beam angle, (b) Variation of DE of P_2' photopolymer as a function of thickness, (c) Variation of DE of P_2' photopolymer as a function of time (ageing of sample) and (d) Absorbance spectra of unexposed and laser exposed P_2' photopolymer.

7.2.5 Shelf life Studies of Red Sensitive Photopolymers:

Shelf life is the length of time a material may be stored without deterioration; the length of time it remains suitable for use. One has to specify the shelf life while commercializing the material. It is most influenced by several factors such as exposure to light, mechanical stress, and contamination by things such as dust and scratches. So, in order to find the shelf life, we should store the samples safely to prevent the contamination.

To study the shelf life of the film, gratings are recorded on the film on each day after the film preparation and the diffraction efficiency is determined. It gives the idea that how long the material can be utilized. The shelf life of P_1', P_2' and P_3 photopolymer is studied for 4 months (Table.3) by recording holographic diffraction grating each day after the fabrication of photopolymer films and reading its diffraction efficiency. The shelf life of P_2' photopolymer material is studied for 6 months and it shows a brilliant stability as shown in Fig 14 (C).

Samples	DE after 1 month of polymer fabrication	DE after 4 months of polymer fabrication	Exposure Energy (mJ/cm^2)
P_1	45- 52 %	20 - 25 %	200
P_2	65 -81%	65-75%	100
P_3	18-25%	3-5 %	225

Table 3: Comparison of Photopolymers under study

7.2.6 . Storage life studies of P_2' Photopolymer:

In dye doped films, the diffraction efficiency can be reduced or remained unaltered on storage. How stable the information remains over time is determined by finding the storage life of the samples. For a recording medium, storage life is also an important parameter like other holographic parameters and a long storage life is required for practical applications. Storage life is defined as the property of film on ageing of the samples. It gives the idea that how long the material can hold (store) the recorded grating. The storage life of the grating is determined by measuring the diffraction efficiency of gratings after each day of grating formation. The storage life of P_2' photopolymer film is studied for six months and the material shows a wonderful stability in the storage life (Fig. 15).

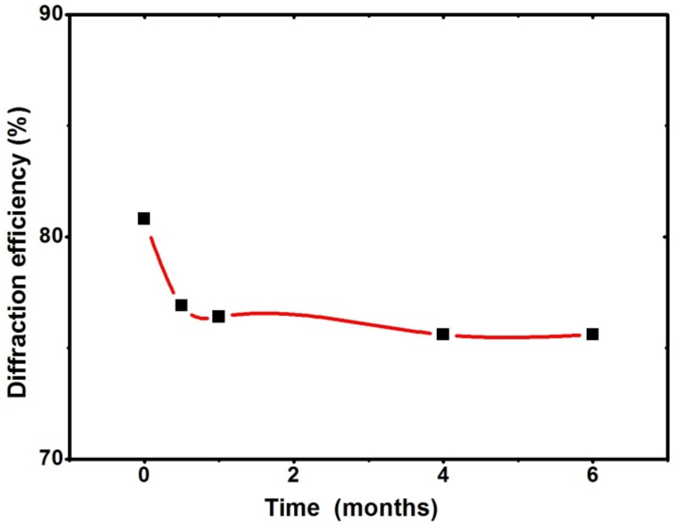

Fig . 15 Variation of DE of the holographic grating recorded in P_2' photopolymer as a function of time

Hence, P_2' photopolymer which is better in terms of DE, shelf life and storage life is exploited to fabricate holographic lens to use as a coupler for solar cells.

7.2.7 Coupling of Photopolymer grating with DSSC:

The grating recorded in the 200 micron thick P_2' photopolymer with 80.80% diffraction efficiency is coupled with a Dye Sensitized Solar Cell (DSSC) of area 0.20 cm^2 fabricated in our laboratory. DSSC consists of N719 sensitizer, mesoporous nanocrystalline titanium dioxide (TiO2) as photoanode, platinum coated fluorine doped tin oxide (FTO) as counter electrode and tri-iodide/iodide redox couple as electrolyte. Simulations are done using Newport's Class 3A solar simulator (model 67005).

DSSC is then coupled with HGE by placing HGE in between the simulator and DSSC in such a way to make the diffracted light from HGE reach DSSC. Simulations are done under various low and identical illuminance conditions for both HGE and DSSC. Since the absorption band of N719 dye comes within the blue to green wave length range of visible spectrum, mostly the diffracted blue/green components are allowed to fall on DSSC. The results obtained before and after coupling are compared [Table.4]. The illuminance is measured using the digital lux meter (LX 101A). The enhancement in power conversion efficiency of DSSC after coupling it with the HGE under various illuminance is also calculated [Table.4].

P_{in}	Coupling	V_{OC}	J_{SC}	FF	η (%)	% increment in η
500	Before coupling	0.4663	0.2045	44.65	1.49	153.69
	After coupling	0.5531	0.5230	37.38	3.78	
1000	Before coupling	0.5173	0.3960	43.42	1.56	145.51
	After coupling	0.5788	0.7822	48.29	3.83	
2500	Before coupling	.6089	0.9915	43.42	1.83	96.72
	After coupling	.6348	1.479	54.76	3.60	
5000	Before coupling	0.6404	2.210	53.58	2.65	52.45
	After coupling	0.6549	3.071	57.39	4.04	
10000	Before coupling	0.6662	4.665	53.76	2.92	48.63
	After coupling	0.7062	5.991	58.57	4.34	

Table.4: Characterization of DSSC before and after coupling with photopolymer grating.

7.3. Holographic Lens recorded in the Red Sensitive Photopolymer:

A Holographic lens is recorded in the fabricated red sensitive photopolymer material and it is coupled with a solar cell to increase the power conversion efficiency of solar cell.

7.3.1 Recording Geometry and Diffraction Efficiency Measurements of Holographic Lens:

A holographic lens is recorded in the P_2' photopolymer using an off- axis transmission geometry (Fig.16 a). The holographic lens is created by recording the interference pattern (Fig. 16.b) obtained by the superposition of a plane reference beam and spherical object beam.

The laser beam from a He- Ne laser of wavelength 632.8 nm and power 30 mW is split into two beams using a beam splitter (with beam ratio 1:4) and the beams are expanded using spatial frequency filters. The reference beam is made parallel and the object beam is made to diverge from a point. In the present case, this point of divergence is set at a distance of 10 cm from the photopolymer film. The path lengths of the two beams are made equal and the beams are directed to the holographic film. The diameter of both beams is set to 1 cm at the recording film by using suitable apertures and the inter beam angle (angle between object and reference beam) is kept at 30°.

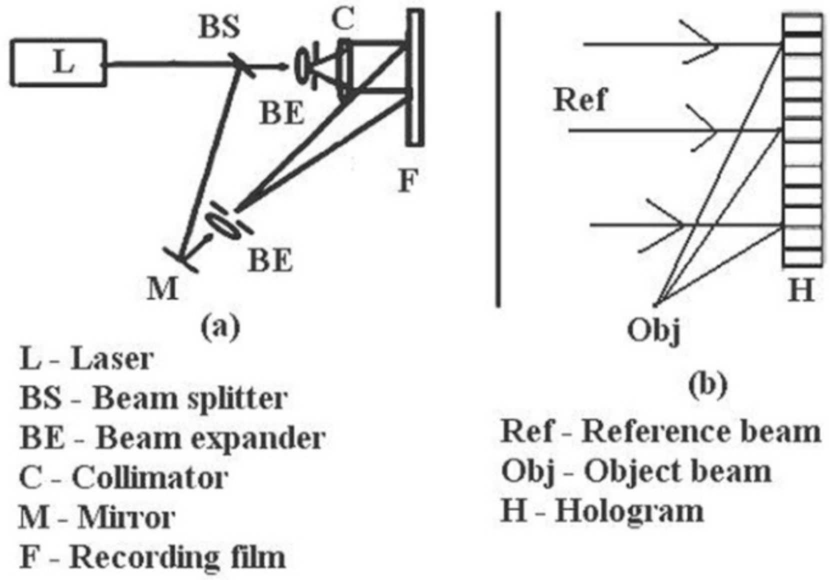

Fig. 16(a) Recording geometry for transmission holographic concentrator (b) Interference pattern formed in transmission holographic concentrator

The diffraction efficiency measurement of the holographic element is done as per the schematic diagram, Fig. (8 (b)) described above and the diffraction efficiency is calculated (in percentage) using equation (1.18) shown above.

The variation of first order diffraction efficiency of the optical concentrator with exposure energy is studied by varying the exposure energy from 150 mJ/cm^2 to 300 mJ/cm^2. It is found that the diffraction efficiency increases (up to 50%) with the increase in exposure energy up to 250 mJ/cm^2. The further enhancement of exposure energy causes depreciation in the diffraction efficiency of the holographic element as shown (Fig. 17*)*

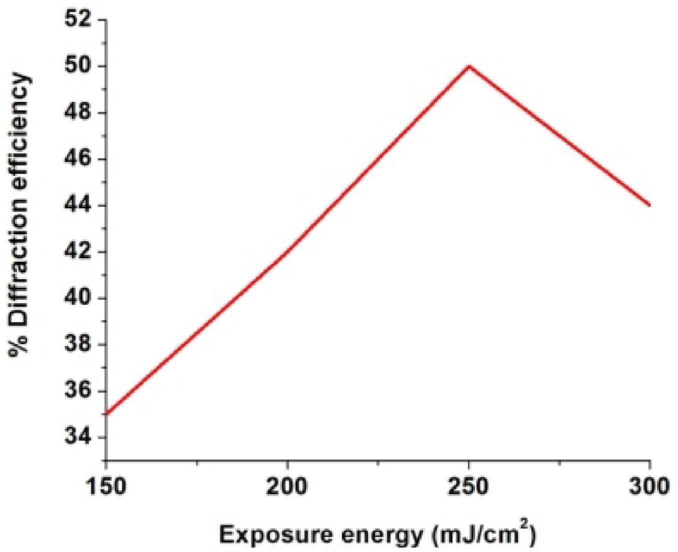

Fig. 17 Variation of first order diffraction efficiency of photopolymer holographic Lens with exposure energy

7.3.2 Coupling of window hologram concentrator with solar cells:

The holographic element so made can be attached to window panes or facades of a building to utilize the incident solar energy. This holographic optical concentrator can split the incident light in to its constituent wavelengths and focus the components at different points in a line (Fig. 18). Since different wavelengths are spatially separated by using holographic optical concentrator, one can place different solar cells optimized for those wavelengths along the corresponding focal points in the line of focus to enhance the energy conversion efficiency of the entire solar module. Each wavelength can be made to incident on respective solar cells for which they are matched in terms of photon energies. The unwanted wavelengths like far infrared components are filtered away from the solar module. An array of solar cells can also be arranged to account for the diurnal and seasonal variation in the angle of incidence of solar radiation.

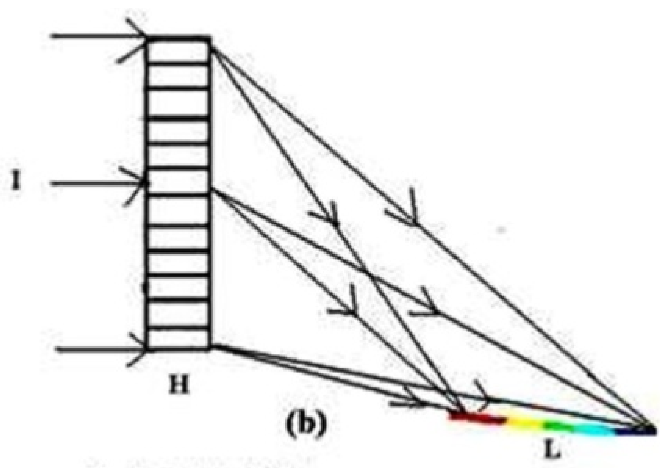

Fig. 18 Spectral splitting and focusing of incident light by holographic concentrator

The effect of coupling of holographic concentrator with a photovoltaic cell is studied at Department of Physics, IIT Chennai using Newport's ORIEL Class A solar simulator. The solar cell used for simulations is a standard yellow sensitive Dye Sensitized Solar Cell (DSSC) of area 0.25 cm^2. The DSSC (fabricated by IIT, Chennai) encompassed titanium dioxide photoanode, platinum counter electrode, N719 sensitizing dye and tri-iodide/iodide redox couple electrolyte. The concentrator hologram is employed to guide the light from the solar simulator to fall on DSSC. DSSC is positioned at feebly illuminated region of the simulator at the start and the efficiency measured at that position is 0.076. The concentrator is then kept vertically at an angle to the illuminating plane of simulator in such a way to make the yellow radiation falling on DSSC and it is found that the efficiency of DSSC enhanced to 0.111 (46.05 % increment).

The effect of coupling of the holographic optical element which is positioned vertically to the illuminating plane (as a roof top concentrator) of solar simulator is also studied at Amritha Viswavidyapeetom, Kerala. The DSSC of area 0.20 cm^2 fabricated in our lab consists of mesoporous nanocrystalline titanium dioxide (TiO_2) as photoanode, platinum coated fluorine doped tin oxide (FTO) as counter electrode, N719 as sensitizing dye and tri-iodide/iodide redox couple as electrolyte. Simulations are made using Newport's Class 3A solar simulator (model 67005). DSSC is placed at various low illuminance zones of the simulator and the efficiency at these positions is calculated. Then the coupling is done by placing the holographic element in between the simulator and DSSC in such a way to make the diffracted light falling on DSSC. The efficiency after coupling is also calculated. The holographic

element and the DSSC are kept at different positions having the same illuminance value. The illuminance at different positions is measured using the digital Lux meter (LX 101A).

(P in) (lux)	Coupling	VOC (volts)	JSC	Fill Factor	η (%)	% increment in η
500	Before coupling	0.569	0.117	62.1	1.446	69.16
	After coupling	0.609	0.242	89.1	4.591	
2500	Before coupling	0.649	0.740	74.2	2.494	21.93
	After coupling	0.659	0.840	78.5	3.041	
10000	Before coupling	0.684	2.410	78	2.250	18.31
	After coupling	0.690	2.815	78.3	2.662	

Table: 5: Couupling of Holographic lens with Dye Sensitized Solar Cell and the percentage increment in the efficiency of DSSC.

The main parameters of the solar cell performance are short circuit current density (J_{SC}) in mA/cm^2, open circuit voltage (V_{OC} in Volts), fill factor (FF) in percentage and energy conversion efficiency (η) (48). These parameters can be obtained by analyzing I-V curves. The relationship is given by

$$\eta = \frac{V_{oc} J_{sc} FF}{P_{in}} \qquad \text{-----------------} \qquad (1.19)$$

Where, Pin is the illuminance of light incident on the surface of test cell.

7.4 Fabrication of a Green Sensitive Photopolymer for Holography

The holographic material can potentially store data at a density of one terabit per cubic centimeter of the recording material (49). Hence, recording material has its own significance in holography. The sensitivity of the recording material to lower wavelength regime will lead to the further increment in the amount of data that can be stored and retrieved holographically (22). Hence, green sensitive holographic recording materials are beneficial than the widely used red sensitive materials in the data storage point of view.

7.4.1 Materials Chosen for the Fabrication of Green Sensitive Photopolymer :

Two types of photopolymer chemical composition are developed in our lab using gravity settling method. One set is designated as sample GP_1 and the other set as sample GP_2. The GP_1 photopolymer material contains polyvinylalcohol (PVA) as binder, acrylamide (AA) as solid monomer, triethanolamine (TEA) as initiator and erythozine B as sensitizing dye. 0.375 molar AA and 0.25 molar TEA are added to 10% transparent PVA solution. A uniform aqueous solution of .001 molar erythrosine B dye in distilled water is prepared. Different concentrations of this dye solution are mixed with the above prepared solution and the sample with the optimum dye concentration is found. For sample GP_2, 0.22 molar N, N'-methylene-bis-acrylamide (BAA) also is added to all the other ingredients of photopolymer GP_1 as a monomer cross –linker. Cleaned glass slides of dimension 75mm X 25mm X 1.35 mm are used to cast films using gravity settling method. The films are fabricated in room temperature and dried for two weeks.

Photopolymer film casting, recording of grating and diffraction efficiency (DE) measurements are done in the same way as explained in section 5.1, 5.2..1 and 5.2.2 respectively. Recording is done using a green laser.

7.4.2 Gratings recorded in Gp_1 Photopolymer and their DE Measurements:

Holographic diffraction gratings are recorded on various GP_1 photopolymer samples with an average film thickness of 200 µm and with different dye concentrations ($P_{1.1}$ with $7.0499 x 10^{-6}$ M dye concentration, $P_{1.2}$ with 2.0855×10^{-5} M and $P_{1.3}$ with 2.7615×10^{-5}M dye concentration)at various exposure energies ranging from 50mJ/cm^2 to 250mJ/cm^{2}with an increment of 50 mJ/cm^2.Recording is performed by keeping the beam ratio at 1:1; inter beam

angle at 30^0, and beam area at $1cm^2$. The diffraction efficiency measurements are carried out for the samples at various exposure energies and it is plotted in Fig. 19.

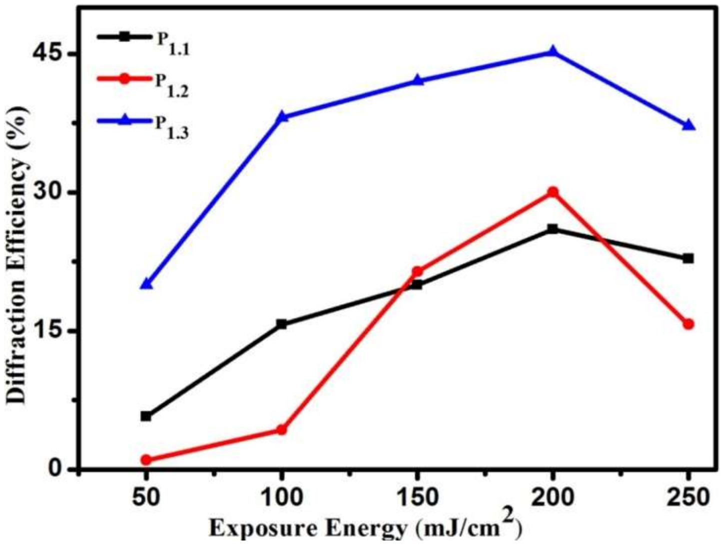

Fig.19 :The variation of diffraction efficiencies with exposure time for the three sets of GP_1 samples

The maximum value of diffraction efficiency obtained for three samples increases systematically with doping concentration. All these samples show their maximum diffraction efficiency at exposure energy of 200 mJ/cm^2. Highest diffraction efficiency of 45.16 % is shown by the sample $P_{1.3}$.

7.4.3 Gratings recorded in GP_2 photopolymer and their DE measurements:

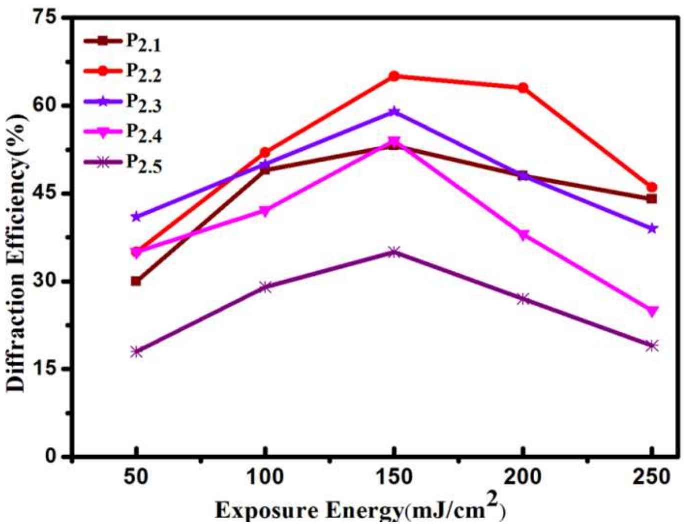

Fig.20: The variation of diffraction efficiencies of gratings with different exposure energies P_2 ($P_{2.1}$, $P_{2.2}$, $P_{2.3}$, $P_{2.4}$ and $P_{2.5}$) samples.

Several 200 μm thick GP_2 photopolymer samples of different dye concentrations namely 7.0499×10^{-6} M , 1.400×10^{-5} M, 2.0855×10^{-5} M, 2.7615×10^{-5} M and 3.4283×10^{-5} M (designated as $P_{2.1}$, $P_{2.2}$, $P_{2.3}$, $P_{2.4}$ and $P_{2.5}$) are selected for grating fabrication. The variation of diffraction efficiencies with different exposure energies (ranging from 50 mJ/cm^2 to 250 mJ/cm^2) for those gratings is shown in Fig.20.

Among the five samples chosen, the sample $P_{2.2}$(with dye concentration 1.400×10^{-5} M) shows the highest diffraction efficiency of 65 % at an exposure energy of 150 mJ/cm^2.Interestingly for all the samples fabricated with BMA cross-linker, the highest diffraction efficiency is shown by the gratings recorded with an exposure energy of 150 mJ/cm^2. This $P_{2.2}$ sample is taken for further studies.

7.4.4. Optimization of Various Parameters in $P_{2.2}$ Photopolymer:

7.4.4.1 Optimization of thickness in $P_{2.2}$ photopolymer:

To study the effect of thickness on the diffraction efficiency of gratings, four films of $P_{2.2}$ with different thickness namely 150 μm, 200 μm, 250 μm and 300 μm are fabricated. Holographic diffraction gratings are written on these samples at different exposure energies ranging from 100-250 mJ/cm^2 by keeping the beam ratio at 1:1and the inter beam angle at 30^0.The variation of diffraction efficiencies with different exposure energies for sample $P_{2.2}$ is shown in Fig.21.The photopolymer sample with thickness 200 μm shows the highest diffraction efficiency and so the 200 μm thick sample is selected for further studies.

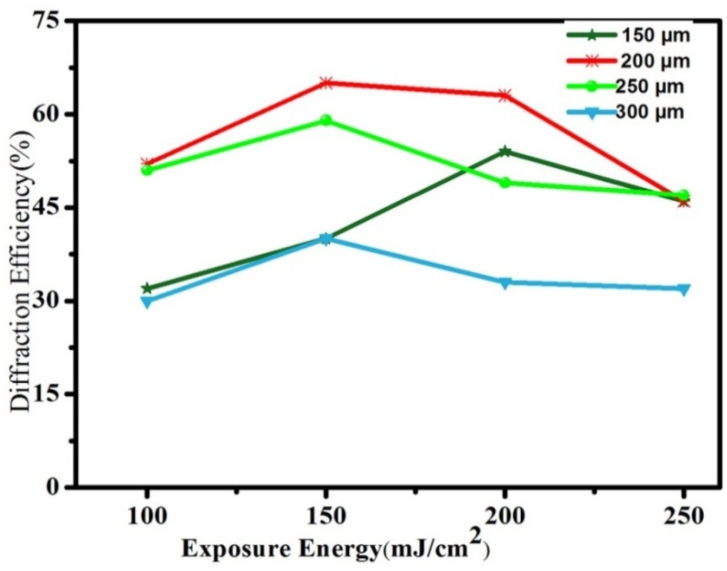

Fig.21: Variation of Diffraction efficiency with exposure energy for various $P_{2.2}$ sample with varying thickness.

7.4.4.2. Optimization of exposure energy in $P_{2.2}$ photopolymer:

To find the optimum laser exposure energy for writing a transmission holographic grating ,six gratings are recorded on 200 µm thick $P_{2.2}$ sample with different laser exposure energy by keeping inter beam angle at 30° and beam ratio 1:1. The highest diffraction efficiency 67% is obtained for the exposure energy of 175mJ/cm^2 (Fig. 22). Further increment in the exposure energy leads to the deprivation of diffraction efficiency. Thus175 mJ/cm^2 is selected as the optimum laser exposure for sample $P_{2.2}$.

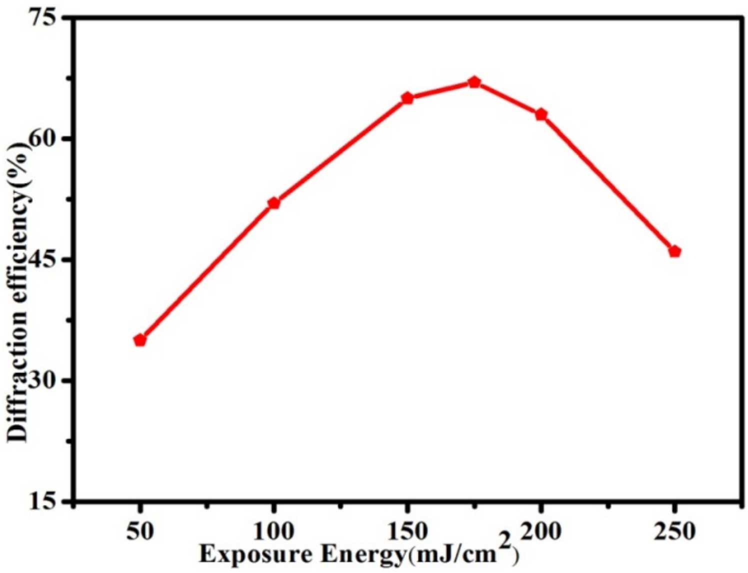

Fig.*22: Variation of diffraction efficiency with exposure energy for $GP_{2.2}$ sample.*

7.4.4.3. Optimization of beam ratio in $P_{2.2}$ photopolymer :

To optimize the beam ratio for recording the grating, the holographic gratings are recorded on the $P_{2.2}$ samples of thickness 200 µm by keeping the exposure energy at 175 mJ/cm^2 and inter beam angle at 30^0 and by varying the ratio between reference and object beam as1:1, 1:2, 1:3, 1:4 and 1:5. The maximum diffraction efficiency of 67% is obtained when the beam ratio is at 1:1 (Fig 23).

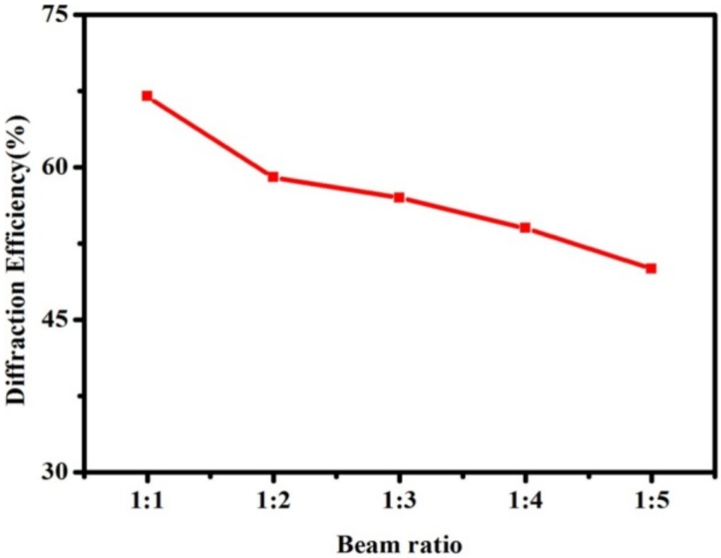

Fig.23: Variation of diffraction efficiency with various beam ratio for $P_{2.2}$ sample.

7.4.4.4. Optimization of inter-beam angle in $P_{2.2}$ photopolymer:

To optimize the angle between the reference and object beam for the recording of transmission holographic grating, different transmission diffraction gratings are recorded in 200µm thick $P_{2.2}$ photopolymer samples for different inter beam angle ranging from 20^0 to 30^0. Here, the exposure energy given is 175mJ/cm^2 and the beam ratio given is 1:1. The maximum diffraction efficiency of 70 % is obtained for an inter-beam angle of 25°(Fig.24).

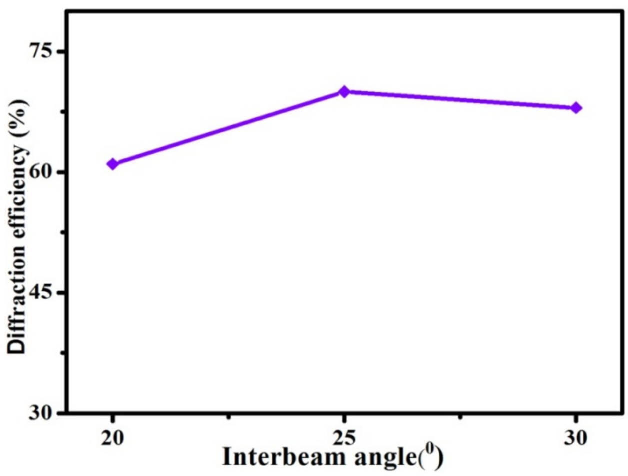

Fig.24: Optimization of inter beam angle in $P_{2.2}$ sample.

7.5. Holograms recorded in commercial grade green sensitive photopolymer:

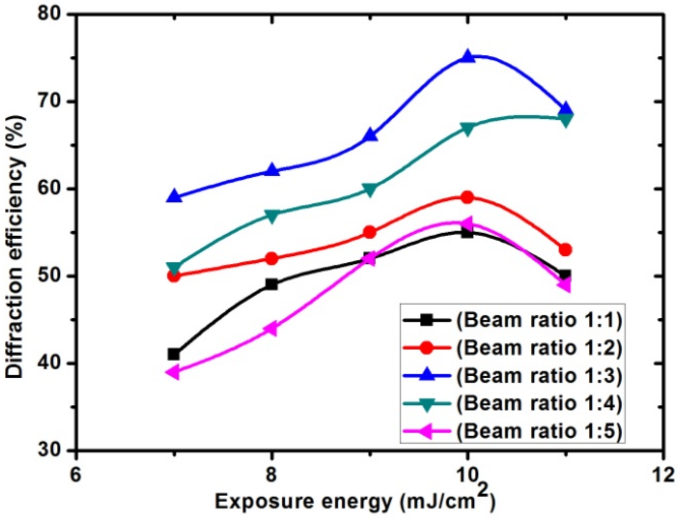

Fig. 25. The variation of diffraction efficiency of holographic lenses (recorded using green wave length) with laser exposure energy.

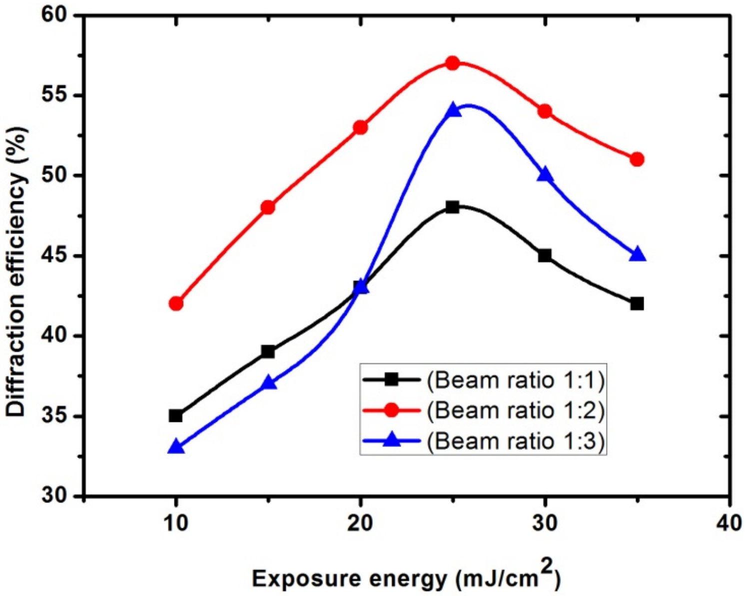

Fig. 26 The variation of diffraction efficiency of holographic lenses (recorded using red wave length) with laser exposure energy.

A new generation blue-green sensitive photopolymer plates called " Poly Light Holo Plates" which is a technical outcome of the collaboration between M/s Light Logics Holography and Optics Pvt. Ltd (India) and M/s Polygrama Inc. (USA) are procured and transmission holographic optical elements (lenses) are recorded in it. It is found that the recording plates are also sensitive to red wave length region. Hence several holographic lenses are recorded (using transmission recording geometry as shown in Fig.8 (a)) in those procured plates using green and red lasers. The recording is done by keeping the inter beam angle at 30^o. The area of both interfering beams is set to 1 cm^2 at the region of interference and the power of both beams is set to 0.5 mW at the interfering region. The diffraction efficiency measurements are done using the technology shown by Fig. 8(b).

The exposure energy is varied from 7 mJ/cm^2 to 11 mJ/cm^2 and holographic lenses are recorded using green wave length with different beam ratio (ratio between object and reference beam) ranging from 1:1 to 1:5. The variation of diffraction efficiency of holographic lenses versus laser exposure energy for the recording (for different beam ratio) is plotted in Fig. (25). The highest diffraction efficiency of 75 % is obtained for an inter-beam ratio (ratio between reference and object beams) of 1:3 and an exposure energy of 10 mJ/cm^2.

Several holographic lenses are again recorded using red wave length by varying the exposure energy from 10 to 30 mJ/cm^2 and with different beam ratio (ratio between object and reference beam) ranging from 1:1 to 1:3. The variation of diffraction efficiency of holographic lenses versus laser exposure energy for the recording (for different beam ratio) is plotted in Fig. (26). The highest diffraction efficiency of 57 % is obtained for an inter-beam ratio (ratio between reference and object beams) of 1:2 and an exposure energy of 25 mJ/cm^2.

8. Summary of the project work:

Transmission in-line amplitude and off-axis HOEs are recorded in PFG 01 silver halide recording material successfully. The amplitude in-line HOE has got a low DE of less than 2 % and fabricated off-axis HOE has got the higher diffraction efficiency of 35 % . When this off-axis HOE is coupled to a dye sensitized solar cell vertically to the plane of illuminance, a power conversion efficiency enhancement of 32.89 % is found and this result shows the possibility of using HOEs in a window pane to focus incident solar light on to solar cells.

A new research grade red sensitive photopolymer is fabricated in our laboratory. The influence of adding a cross-linker to this material is investigated and found that the addition of cross linker increases the diffraction efficiency and stability of the recording material. Also, the addition of cross linker reduces the exposure energy needed to record efficient holograms. A comparison of the fabricated polymer with a commercial grade photopolymer is also done. It is found the fabricated photopolymer is better in terms of diffraction efficiency, storage life and shelf life of the material.

A transmission holographic grating element with more than 80 % diffraction efficiency and 6 months storage life is recorded in the 200 micron thick photopolymer material with 6 months shelf life. The photopolymer gating is coupled with a dye sensitized solar cell and improvement in the power conversion efficiency of the cell is studied for various illuminance conditions. Efficiency enhancement is observed in all cases with the maximum value of about 154 % for the lowest illuminance of 500 lux. A transmission holographic concentrator isthen recorded in the fabricated red sensitive photopolymer material successfully using off-axis geometry. This fabricated holographic element is also coupled to a dye sensitized solar cell vertically to the illuminance plane and an efficiency enhancement of 46.05 % is found.

Photopolymer Holographic Lens is then coupled with a standard DSSC of 0.2 cm^2 area by keeping the element horizontally to the illuminance plane of the solar simulator also. Simulations are done under various illuminance conditions. Improvement in efficiency of DSSC is found in all cases with the maximum enhancement for low illuminance value. This result shows the possibility of using holographic element to enhance the output of solar cells when even when they work in less illuminance/irradiance conditions.

A novel green sensitive photopolymer is fabricated and characterized. Transmission diffraction gratings are recorded in two kinds of photopolymers; photopolymer GP_1 (without cross linker) and photopolymer GP_2 (with cross linker).The highest diffraction efficiency of 45.16% is obtained for the GP_1 category photopolymer, $P_{1.3}$ (with 2.7615×10^{-5}M dye concentration) at an exposure energy of 200 mJ/cm^2. The highest diffraction efficiency is obtained for the $P_{2.2}$ Photopolymer (having 1.400×10^{-5} M dye concentration) among GP_2 type photopolymers. Among the fabricated green sensitive photopolymers, holographic transmission gratings recorded in the 200µm thick photopolymer $P_{2.2}$ shows 70 % first order diffraction efficiency at an exposure energy of energy175mJ/cm^2, inter- beam angle of 25°and beam ratio of 1:1. It is apparent from the results that the influence of monomer cross- linker in

the photopolymer matrix increases the diffraction efficiency and sensitivity of the green sensitive photopolymer similarly as in the case of red sensitive photopolymer material.

Several holographic lenses are recorded in commercial grade photopolymer, Poly Light Holo Plates, that are sensitive to red and blue-green wavelengths. The sensitivity of recording plates is more in the blue-green wavelength region as less exposure energy is needed to record efficient holograms using green laser. Holographic lenses having diffraction efficiency of 75% are obtained if the recording is done at green exposure energy of 10 mJ/cm^2. When the recording plates are exposed to red wave length, diffraction efficiency is reduced to 57 % . Also, the red exposure energy needed to record 57 % efficient holograms is 25 mJ/cm^2.

Thus, the fabricated green sensitive photopolymer is close to commercial grade green sensitive photopolymer in terms of diffraction efficiency. But the sensitivity of commercial photopolymer is very high seeing that only 11 mJ/cm^2 exposure energy is needed to fabricate 70 % efficient holograms in commercial grade green sensitive photopolymer where as 200 mJ/cm^2 exposure energy is needed to fabricate 70 % efficient holograms in the fabricated green sensitive photopolymer.

9. Contributions made towards increasing the state of knowledge in the subject :

The petroleum sources are going to be over in the near future and we have an urgent need to effectively tap other sources of energy. Also, the emissions created by conventional energy-use are very high and there is a big requirement of clean alternate energy sources. The present project envisaged the development of high efficiency Holographic elements and the use of these in conjunction with solar cells to facilitate the creation of high yielding solar modules. The proposed system will be breakthrough advancement towards green and sustainable energy.

Two categories of photopolymer materials; one which is sensitive to red wavelength and the other to blue/green wavelength are fabricated in our lab using gravity settling method. Holograms recorded in the red sensitive photopolymer recording material accomplished better diffraction efficiency, shelf life and storage life and hence its suitability for commercialization is recognized. Suitability of using photopolymer holograms for energy conversion efficiency

in Dye Sensitized Solar Cells is exposed. Influence of cross-linker in a photopolymer to achieve stability is realized. Possibility of using holographic lens in window panes of a house is also recognized. The holographic optical elements can be used either in roof tops or in window panes to collect and guide more sunlight towards solar cell without sun tracking.

10. Outcome of the Project

Innovations/Technology developed :

a. Fabricated indigenously one red sensitive photopolymer material with enhanced shelf life and storage life of about 6 months and diffraction efficiency of about 81% for holographic applications. The fabricated material is compared with a commercial grade red sensitive photopolymer and the fabricated one is found better in terms of life and diffraction efficiency.

b. Several holographic optical elements like holographic gratings and lenses are recorded on the fabricated photopolymer successfully and those holographic elements are exploited to use in conjunction with Dye Sensitized Solar Cells to enhance the power conversion efficiency of solar cells.

c. Photopolymer based holographic gratings are employed for the efficiency enhancement of solar cells under low illuminance conditions for the first time. The maximum efficiency enhancement of about 154% is obtained for the lowest illuminance of 500 lux.

d. A green sensitive photopolymer material also is fabricated indigenously for holographic Applications.

e. Coupled silver halide based holographic lenses also with Dye Sensitized solar cell to increase the power conversion efficiency of solar cells particularly under low illuminance conditions and efficiency enhancement is achieved.

f. Placed silver halide and photopolymer holographic lenses vertically (as a window pane of buildings) and horizontally (roof top solar concentrator) to solar radiation and enhancement in power conversion efficiency of Dye Sensitized Solar Cell is realized in both cases. The possibility of using holographic elements in window panes for the efficiency enhancement of solar cells is also realized.

I l Journal Papers:

1. " Window Photopolymer Hologram for Solar Applications", A.B. Sreebha, S. Karpagam, P.T. Ajith Kumar, V.P. Mahadevan Pillai. IEEE Xpolre, 06 October 2016.

2. "Development of a Window Holographic Lens to Utilize Solar Energy", Advances in Optical Science and Engineering. vol 166. Springer, 2015.

Papers to be communicated soon

1. "Photopolymer based holographic thick grating elements for efficiency enhancement of dye sensitized solar cells under low illuminance",A.B. Sreebha,[a1] S. Suresh,[1] S. Karpagam,[1] V.P. Mahadevan Pillai[1]

2. "Influence of cross-linker and the effect of temperature on a red sensitive photopolymer holographic recording material", A.B. Sreebha, V.P. Mahadevan Pillai.

ll Papers presented in internatinal and national conference papers :

1. "Simple method to create zone plates using inline holography ", A.B. Sreebha, P.T. Ajith Kumar V.P. Mahadevan Pillai (International Conference on recent trends in Engineering and Material Sciences –ICEMS 2016, March 17-12, Jaipur National University, Jaipur)

2. "Photopolymer material for solar holography",A.B. Sreebha, P.T. Ajith Kumar V.P. Mahadevan Pillai ("International Conference on Energy, Functional materials and Nanotechnology" (ICEFN-2016, March 27-29, 2016, Kumaun University, Nainital)

3. “Window photopolymer hologram for Solar applications”, A.B. Sreebha, S. Karpagam, P.T. Ajith Kumar V.P. Mahadevan Pillai (International Conference on Energy Efficient Technologies ICEETS 2016, April 7-8 2016, St. Xavier’s College, Nagercoil)

4. “Development of a Window Holographic Lens to Utilize Solar Energy”, Authors : Sreebha A.B. and V.P. Mahadevan Pillai.(1st International Conference on Optoelectronics and Applied Optics, IEM OPTRONIX 2014, IEM Kolkata. November 17-18, 2014).

5. “Holographic Transmission Gratings in photopolymer for efficiency enhancement in solar cells under various photometric conditions” , A.B. Sreebha, S. Suresh, V.P. Mahadevan Pillai (National Seminar on Photonics and its Applications, University of Kerala, December 9 -11, 2015).

6. “ Highly efficient red sensitive photopolymer with enhanced shelf life for holographic applications”, A.B Sreebha, S.Karpagam, V.P. Mahadevan Pillai (National Laser Symposium, Sri Venkateswara University, Tirupathy, December 3-6, 2014)

7. “Development of a photopolymer material for holography and fabrication of holographic optical elements in the material ”, A.B Sreebha, S.Karpagam, V.P. Mahadevan Pillai.(Indian Science Congress, University of Mumbai, January 3-7, 2015).

8. ”Development of a photopolymer window as a Holographic Optical Element for solar energy concentration”, A.B Sreebha, S. Karpagam, V.P. Mahadevan Pillai (Keral Science Congress, Alappuzha , January 27 -30, 2015).

11. Future Scope:

- The diffraction efficiency of the holographic elements can further be improved by increasing the pH of the recording medium.

- Sensitivity of the photopolymer materials can be improved by incorporating by different electron donors.
- The refractive index measurements for different exposure can be studied. The storage life and shelf life of the holograms can further be enhanced by sealing the film with epoxy resin.
- The environmental stability is an important factor when the holographic element is going to be utilized for solar applications. So, the effect on temperature and humidity on the film properties has to be studied.

12. References:

1) "*Holography rides the wave front",* Jeff Hecht. New Scientist 4 Feb 1988

2)"*Holography: A Practical Approach"*, Gerhard K. Ackermann, Jürgen Eichler

3) "*Optical holography- Principle, techniques and applications*" ,P Hariharan. Cambridge University Press (1987)

4*) "Holography, 1948-1971*"Nobel Lecture, Dennis Gabor December 11, 1971, Imperial Colleges of Science and Technology, London.

5) "*Thermodynamic holography*", Bo-Bo Wei,Zhan-Feng Jiang, Ren-Bao Liu Scientific Reports 5, Article number: 15077 (2015)

6*) "Electron tomography and holography in materials science "* Paul A. Midgley, Rafal E. Dunin-Borkowski[2] *Nature Materials* 8, 271 - 280 (2009)

7) *"Direct Depth- and Lateral- Imaging of Nanoscale Magnets Generated by Ion Impact"* Falk Röder, Gregor Hlawacek, Sebastian Wintz, René Hübner, Lothar Bischoff, Hannes Lichte, Kay Potzger, Jürgen Lindner, Jürgen FassbenderRantej Bali, Scientific Reports 5, Article no: 16786 (2015)

8) "*In-line three-dimensional holography of nanocrystalline objects at atomic resolution*", F.-R. Chen, D. Van Dyck & C. Kisielowski, Nature Communications 7, Article number:10603 Published18 February 2016

9) "*Wide-field computational imaging of pathology slides using lens-free on-chip microscopy"*, Alon Greenbaum, Yibo Zhang, Alborz Feizi, Ping-Luen Chung, Wei Luo, Science Translational Medicine 17 Dec 2014:, Vol. 6, Issue 267.

10) "*Point-of-care and point-of-procedure optical imaging technologies for primary care and global health"*, Stephen A. Boppart and Rebecca Richards-Kortum, Science Translational Medicine 10 Sep 2014, Vol. 6, Issue 253.

11)" *Optical imaging techniques for point-of-care diagnostics",* Hongying Zhu, Serhan O. Isikman, Onur Mudanyali, Alon Greenbaum and Aydogan Ozcan , ***Lab Chip***, 2013,**13**,

12) *"Holographic measurements of inhomogeneous cloud mixing at the centimeter scale",* Matthew J. Beals, Jacob P. Fugal, Raymo*nd A. Shaw, Science 02 Oct 2015, Vol. 350, Issue 6256, pp. 87-90*

13) "Holographic Vortex Liquids and Superfluid Turbulence", Paul M Chesler, Hong Liu, Allan Adams, Science 26, July 2013.

14) "*Theory of Holography*" www.springer.com/cda/content.

15) "*Holography Principles:Technical Report"* No. DCSE/TR-2006-08
December 2006 by Martin Janda, Ivo Hanák, and Václav Skala

16)"Holography technique and practice" by Matt Lehmann

17) *" Holographic methods in the studies of thin film stress, vibration analysis and pattern recognition*" , Ph.D Thesis by Dr P.T Ajith Kumar, CUSAT 1991.

18) "*Azobenzene- Containing Materials for hologram"*, Haifeng Yu and Takaomi Kobayashi. Chapter 5 , Holograms Recording Materials and applications, published by InTech.

19) "*Light Sensitive Media- composites for recording volume holograms based on porous glass and polymer",* O.V. Andreeva, O.V. Bandyuk. Chapter 3, Holograms Recording Materials and applications, published by InTech.

20) "*Volume Transmission Hologram Gratings —Basic Properties, Energy Channelizing ,Effect of Ambient Temperature and Humidity"*, O.V. Andreeva, Yu.L. Korzinin and B.G. Manukhin,, Chapter 2 in Holograms - Recording Materials and Applications (2013).

21) L. Carretero, S. Blaya, R. Mallavia, R. F. Madrigal, A. Fimia, J. Mod. Opt., 45, 2345 (1998).

22) "*Fabrication and Characterization of Dye Sensitized Polymer Films For Holographic Applications",* Ph.D Thesis by Beena Mary John, CUSAT January 2008.

23) "*Holographic data storage*", H. Coufal, D. Psaltis, G. T . Sincerbox (Springer) (2000)

24) "*Basics of Holography",* P. Hariharan, Cambridge University Press.

25) V.Weiss, A.A.Friesem, J.Opt.Soc.Am.A.,11 , 2004 (1994)

26) "*Silver-halide recording materials for holography and their processing*", Hans I. Bjelkhagen (1995).

27. S.Kumar, K.Singh, J.Opt.(India) 19,108 (1990)

28. I.Banyasz, Opt.Commn., 267, 356 (2006)

29) "*CROP Photopolymers for hologram recording",* SPIE's International Technical Group Newsletter, 11,1 December (2000)

30) “*Holographic applications based on photopolymer materials*”, Nam Kim International workshop on Photonics and applications, Hanoi,Vietnam, 190-200. (2004).

31) “*Holographic Data Storage”*, H. J. Coufal, D. Psaltis and G. T. Sincerbox Springer, New York (2000).

32) ‘*A new metal ion doped panchromatic photopolymer for holographic applications’*, V Pramitha, Ph. D Thesis in Optics, Applied Optics Division, Department of Physics, Cochin University of Science and Technology, Cochin - 682 022, Kerala (2010).

33)”*Photochemistry, History and Commercial Applications of Hexaarylbiimidazoles”,* Rolf Dessauer 1st edition Elsevier (2006)

34) www.jirkacech.com/public/Thesis/node11.html : Hologram Classifications

35)” *Introduction to Optical Metrology”*, Rajpal S. Sirohi

36) http://www.holo.com/old/holo/book/book5.html “*Practical Holography*”.

37) http://silver.neep.wisc.edu/~lakes/EMA611HoloTranRefl.html “*Holography comparison: transmission and reflection holograms”* by Rod Lakes

38). light.ece.illinois.edu/ECE460/PDF/Holography.pdf

39) “*Reconstructed wavefronts and communication theory”,* E. Leith and J. Upatnieks JOSA, 52, 1123-112 (1962).

40) “*Wavefront Reconstruction with Continuous-Tone Objects*”, E. N. Leith and J. Upatnieks JOSA, 53, 1377 (1963).

41) ocw.mit.edu/courses/media-arts-and-sciences/mas-450.../ch10offaxisluholos.pdf

42)” *Holographic Optical Elements*” , D.H Close “Optical Engineering Vol 14, 1975.

43) “*Silver-Halide Recording Materials for Holography and their processing”*, H. I. Bjelkhagen Bjelkhajen, 1993. New York.

44) “Silver Halide Materials”, Dinesh Padiyar, http://www.holographyforum.org/data/pdf/aa-Collection.../grains-dinesh.pdf.

45*)” CROP Photopolymers for hologram recording”,* SPIE’s International Technical Group Newsletter, 11,1 December (2000)

46) V. Weiss and E. Millul, Appl. Surf. Sci. 106, 293 (1996).

47) S. Blaya, L. Carretero, R. Mallavia, A. Fimia and R. F. Madrigal, Appl. Opt. 38, 955 (1999).

48) Jun-Ho Yum, Etienne Baranoff, Sophie Wenger, Md. K. Nazeeruddin and Michael Grätzel, Energy Environ. Sci.**, 842-857, 2010.**

49) *“The Complete Book of Holograms How They Work and How to Make Them”,* Joseph E .Kasper And Steven A. Feller.,Dover Publications ,INC Mineola ,New York.