Volume Phase Holographic Lenses for Efficient Planar Solar Track-Concentrators

M. A. Ferrara, G. Bianco, V. Striano and G. Coppola

Abstract Volume transmission phase holographic lenses were designed and recorded to obtain a simple, lightweight, compact and inexpensive planar solar concentrator. To avoid any mechanical movement, a passive solar tracking system is also proposed by using angular multiplexed holographic lenses. Furthermore, these solar concentrators have no overheating problems resulting from the absorption of infrared frequencies, because in this spectral region the proposed volume holographic lenses do not work. Finally, the realized samples were tested and a good efficiency was obtained.

Keywords Holographic lens · Solar concentration · Volume phase holographic optical elements

1 Introduction

Holographic PV concentrators were proposed for the first time in 80s [1–4], indeed holography as an optical technology presents many advantages respect to other concentrating optical systems (lenses or mirrors, for instance): it is much more versatile and cheaper than them. It can also eliminate the need for tracking, thus reducing the whole system complexity.

Among the different type of holograms, Volume Holographic Gratings (VHGs) show promise to enhanced performance in many applications respect to classical surface-relief grating technology [5–7]. A VHG is obtained inducing a periodical refractive index variation throughout the volume of an optically thick film [5, 6] and it can reach efficiency up to 100% for a selected wavelength. Furthermore, the hologram splits the solar spectrum so that the longer wavelength light can be separated to reduce unnecessary heating, while the shorter wavelengths spectra can

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be further divided into several bands to match the energy gaps of various solar cells [4, 8]. Thus, VHG allows obtaining high efficiency, controllable spectral response, and low scattering at the same time, and it is useful in many applications, such as Volume Holographic Optical Elements (V-HOEs) [9].

By implementing V-HOEs it is possible to develop holographic planar optics integrating the same functionalities of conventional concentrators (parabolic mirrors, Fresnel lens) reducing, in the meantime, cell volumes and costs. In addition, the versatility of holographic technology permits to cluster multiple holographic elements into the same panel, collecting solar rays with different incidence angles, although their efficiency could be lower if several holograms are multiplexed [10]. Such functionality can be exploited to develop the holographic passive solar tracker in order to increment the performance of single concentrators.

With this aim, we have been studied V-HOEs for controlling and directing the radiation of the sun with high potential for energy saving, taking into account all these important features.

2 Results and Discussions

V-HOEs have been recorded on a prototype of photopolymer sensitive to light at wavelength of 532 nm and deposited (thickness $\approx$ 30 μm) by the Doctor Blade method on a rigid support [11]. In order to obtain Volume Holographic Lens (VHL), a single lens was recorded with an in-line configuration by using a concave mirror with a focal length of 5 cm as object [12, 13]. The interference between a plane (reference) and a spherical (object) wavefronts allows to produce the desired refractive index modulation. The efficiencies of 40 VHLs were evaluated as the ratio between the power focused by the holographic lens and the power focused by a commercial Fresnel lens with the same focusing features. The mean value for the efficiency was 41.49% $\pm$ 1.35%. Additionally, each lens has been characterized at different angles of incidence, and an angular selectivity of about ± 8 was obtained.

Then, the passive solar tracking was realized by recording multiplexed holographic lenses. This structure allows directing the light in a given direction independently of the direction of the incoming light without any mechanical movement. In particular, a set of five lenses has been recorded on the same glass to focus the light on the same PV cell positioned close to the focus of the lenses system. The recording procedure was implemented for five angles: perpendicular illumination (0°), $\pm 15°$ and $\pm 30°$ illuminations. Holographic lenses at $\pm 15°$ and $\pm 30°$ were recorded by tilting of $\pm 15°$ and $\pm 30°$, respectively, the photosensitive substrate. A scheme of the realized multiplexed holographic solar concentrator is reported in Fig. 1.

The five multiplexed holographic lenses system has been characterized in terms of degree of concentration, expressed in number of "suns". This parameter is evaluated as the ratio between the intensity of the light harvested by the PV cell with and without the solar concentrator. Preliminary results show a degree of concentration for the proposed system on average of 3 suns over the angular range of $\pm 30°$.

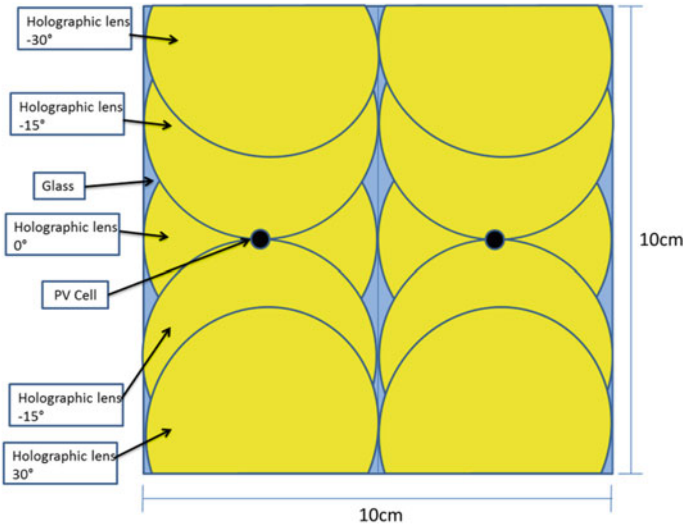

Fig. 1 Angular multiplex lenses recorded at five angles: 0°, ±15°, and ±30°

Finally, the passive solar tracking collection was experimentally characterized in real operative conditions. The generated voltage of the photovoltaic system was continuously monitored during a clear day (24 h) and results are reported in Fig. 1. The measurement was performed with the system tilted 30° backwards in order to be able to measure system performance at solar heights between −90° and 90°. During the day monitored, no mechanical movement of the concentrator configuration with five lenses was performed, thus a passive solar tracking was obtained in the periods of the day in which the sun fulfils the recorded angle of each lens, as can clearly be seen in Fig. 2.

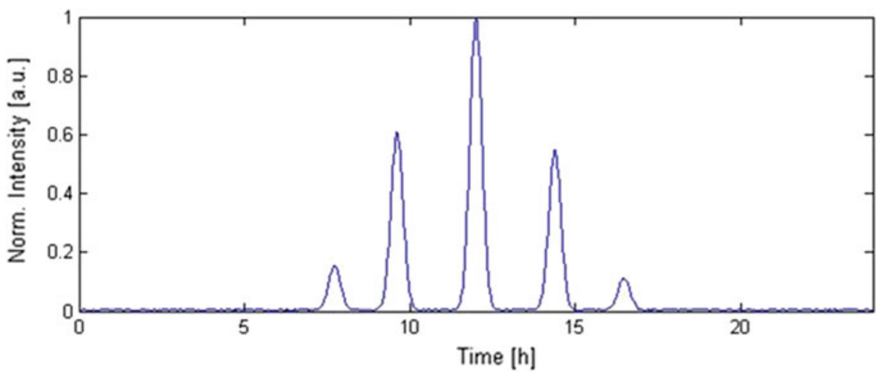

Fig. 2 24 h—measurement of the concentrated solar intensity in real operative condition

Moreover, an important feature of volume holographic lenses is that they show an optimal efficiency at wavelength for which they have been designed. Light nearly to the designed wavelength is still diffracted according to the grating equation but usually with lower efficiency. At wavelengths sufficiently far from the Bragg condition, light passes through the holographic element without being diffracted [14]. Thus, considering that our lenses are designed for a wavelength of 532 nm and that they well work in the range from 400 to 700 nm, while in the infrared region lenses do not work, thermal overheating of the photovoltaic cell is avoided.

3 Conclusion

In conclusion, in this work volume transmission phase holographic lenses were designed and realized to obtain a simple, lightweight, compact and low-cost planar solar concentrator. To avoid any mechanical movement, a passive solar tracking system was developed by using angular multiplexed holographic lenses. Moreover, our volume holographic lenses are not affected by thermal overheating due to the absorption of infrared frequencies, because in this spectral region they do not work. Our results show the possibility to realize solar concentrators for PV cells by using multiplexed VHL with a good efficiency and passive solar tracking.

References

1. Shakher C, Ramamurthy V (1987) Thick transmission phase holograms for photovoltaic concentrator applications. Sol Energy Mater 16:215–221
2. Bainier C, Hernandez C, Courjon D (1988) Solar concentrating systems using holographic lenses. Sol Wind Technol 5:395–404
3. Ludman JE, Riccobono J, Semenova IV, Reinhand NO, Tai W, Li X, Syphers G, Rallis E, Sliker G, Martín J (1997) The optimization of a holographic system for solar power generation. Sol Energy 60:1–9
4. Zhang YW, Ih CS, Yan HF, Chang MJ (1988) Photovoltaic concentrator using a holographic optical element. Appl Opt 27:3556–3560
5. Kogelnik H (1969) Coupled-wave theory of thick hologram gratings. Bell Syst Tech J 48:2909
6. Barden SC, Arns JA, Colburn WS (1998) Volume-phase holographic gratings and their potential for astronomical applications. In: Proceedings of SPIE optical astronomical instrumentation, vol 3355, p 866
7. Blanche PA, Gailly P, Habraken S, Jamar LC (2004) Volume phase holographic gratings: large size and high diffraction efficiency. Opt Eng 43:2603–2612
8. Zhang D, Gordon M, Russo JM, Vorndran S, Kostuk RK (2013) Spectrum-splitting photovoltaic system using transmission holographic lenses. J Photonics Energy 3:034597-1–034597-12
9. Tedesco JM, Owen H, Pallister DM, Morris MD (1993) Principles and spectroscopic applications of volume holographic optics. Anal Chem 65:441 A–449 A
10. Chemisana D, Collados MV, Quintanilla M, Atencia J (2013) Holographic lenses for building integrated concentrating photovoltaics. Appl Energy 110:227–235

11. Ferrara MA, Borbone F, Striano V, Coppola G (2013) Characterization of photopolymers as optical recording materials by means of digital holography microscopy. Proc. SPIE 8792:87920Z
12. Bianco G, Ferrara MA, Borbone F, Roviello A, Striano V, Coppola G (2015) Photopolymer-based volume holographic optical elements: design and possible applications. J Eur Opt Soc Rapid 10:15057
13. Bianco G, Ferrara MA, Borbone F, Roviello A, Pagliarulo V, Grilli S, Ferraro P, Striano V, Coppola G (2015) Multiplexed holographic lenses: realization and optical characterization. In: IET conference publications, Issue CP667. Fotonica AEIT 2015, Turin (Italy)
14. Baldry IK, Bland-Hawthorn J, Robertson JG (2004) Volume phase holographic gratings: polarization properties and diffraction efficiency. Publ Astron Soc Pac 116:403–414. https://doi.org/10.1086/383622