Plastic Optical Fibres as Light Illuminators in Digital Fourier Transform Holography: Feasibility and Resolution Considerations

Paulo A. M. dos Santos and Ricardo M. Ribeiro

Abstract— **This paper describes the use of step (SI), double-step (DSI) and graded-index (GI) PMMA-based Plastic Optical Fibres (POFs) as the light illuminators for the Digital Fourier Transform Holography. The POFs can generate holograms with contrast and resolution comparable to the case of direct illumination by using red color lasers. DSI-POFs enabled the generation of better interferometric moiré patterns than of SI-POFs despite the same geometrical transversal size. The GI-POFs can produce fringes with better contrast and less noise holograms, thus providing enough visibility/resolution for possible applications as holographic profilometry and non-destructive tests.**

Keywords— Digital Fourier Transform Holography, Moiré Patterns, Plastic Optical Fibres, Profilometry.

I. INTRODUCTION

Digital holography (DH) is the method in which holograms are digitally recorded and stored by electronic image detectors as charged-coupled devices (CCDs). Henceforth, the generated holograms are numerically reconstructed by using proper algorithms running in a computer with enough memory and speed [1,2]. No chemical processing is need as in the classical analogue holography [3]. In the numerical reconstruction the intensity and phase distributions of the stored pattern are available from the digital process. The Digital Fourier Transform Holography (DFTH) is produced when the distance from the plane containing both the object and the reference light source is far from the hologram plane (the CCD sensor plane) that is, in the limit of Fraunhofer diffraction. In this case, specific algorithms generally based on the Huygens-Fresnel diffraction concepts, are used as a good approximation for this optical condition. Therefore, the Fast-Fourier Transform (FFT) algorithms can be used to perform the reconstruction of the holographic images. Some applications of digital holography are reviewed in [2,4].

Optical fibre holography (OFH) stands for a branch of holography in which the laser light is conducted by two optical fibres, one of them for the reference beam and the other for the object illumination. Even back to December 1974, many applications of OFH were already reported in holography, holographic interferometry and speckle metrology [5,6]. A survey in the literature pointed out some uses of glass fibres or bundles in holography [5-8]. Their main benefits are related to their immunity to EMI (Electromagnectic Interference), lighter weight, small volume and mechanical resiliency. The OFH may be suitable and useful when the working conditions involve space constraints to the experimental setup and for a proper optical operation. Therefore, the OFH allows operation in hostile environments and is also suitable for miniaturization of experimental setups due to reduced requirements for use of optical devices as mirrors, lenses, etc.

A further advantage of OFH is the easy and flexibility for detailed illumination of the object of interest, allowing an efficient surface analysis, for example in optical inspection with the application of interferometric techniques.

PMMA-based plastic optical fibre (POF) cables with the fibre itself and the polyethylene coating diameters of 1mm and 2.2mm, respectively, are the most manufactured and used around the world, especially for data communications [9,10]. Such POFs are useful in the visible spectrum. Their high optical attenuation is balanced by their sole use for short links up to about 500m without repetition, most commonly to ~100m [9,10]. Their flexibility allows for a tighter bend radius and therefore more compact deployment. Furthermore, in the practical viewpoint POFs require much less skill to perform terminations and optical interconnections when compared with silica fibres. POFs have been usually employed in communications, optical sensing, illumination and imaging, but seldom in holographic applications. However, to overcome some drawbacks of large (1mm or more) diameter silica fibres as the reduced flexibility and more difficult termination, it was already reported the use of POFs as dedicated image guide and for phase shifting digital holography purposes [11].

In this paper, we describe some advances relative to our previous work [12]. We report the application as well the comparative analysis of the most common types of PMMA-based POFs used on data-communications, i.e. the step (SI), double-step (DSI) and graded-index (GI). This kind of POFs convey red light from a laser to perform DFTH and Digital Interferometric Holography (DHI) by means of analysis of the moiré patterns. Some objects as dices, metal sheet and images from USAF were holographed using the POF-based OFH.

II. EXPERIMENTAL AND THEORETICAL BACKGROUND

In the present work a simple and well-controlled POF-DFTH experimental setup is proposed as is schematically shown in Figure 1. He-Ne laser (633 nm) was used as light source in the experiments (LASER). Alternatively, a Fabry-Perot laser diode (640 nm) was used only to check the possibility of obtain holograms with a less coherent light source. Indeed, similar holograms can be observed but it is not shown here. The optical beam is divided by the beam-splitter (BS) so that half of the

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power is directly (without lens) launched into each POF arms. The POF2 (~1m) convey the light so as to illuminate the object (OBJ) to be analysed. The POF1 (~1m) conducts the reference light that will be interfering with the light difracted by the OBJ. The interference pattern produced is captured by the CCD camera DMK 31BF03 model with 1024 x 768 pixels of 4.65μm x 4.65μm size from IMAGINGSOURCE Inc. The three types of POFs here employed are based on PMMA polymer and are commonly used in short range communications (< 500m range). The most usual POF have high numerical aperture (NA) and step-index (SI), high-NA-SI manufactured by Toray Industries (Japan). It presents NA = 0.46 and attenuation coefficient α < 150 dB/km. The second POF was the DSI (double-step index) or low-NA-DSI type presenting NA ~ 0.32 and α~150 dB/km, also manufactured by Toray Industries. The third POF was the GI-type (graded-index) manufactured by Optimedia (South Korea), presenting NA = 0.20-0.30 and α < 200 dB/km. Table I summarizes the relevant characteristics of the POFs used in the present work.

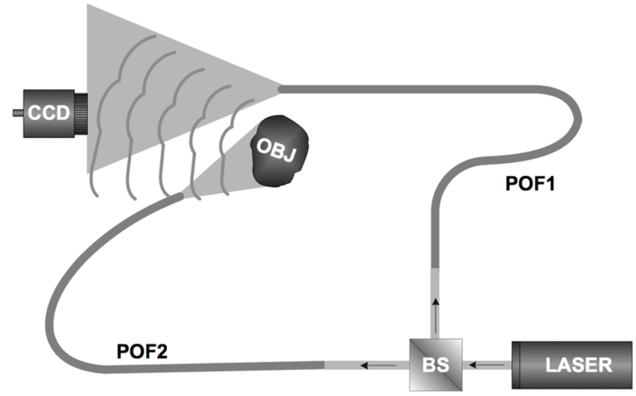


Fig. 1. The experimental setup used to carry out the POF-DFTH.

TABLE I. *OPTICAL PARAMETERS FOR EACH OF THE USED PMMA-POF TYPES.*

PMMA-based POF	NA	α (650 nm)
High-NA-SI (Toray PFU-CD1001-22-E1)	0.46	< 150 dB/km
Low-NA-DSI (Toray PMU-CD1002-22-E1)	~ 0.32	~ 150 dB/km
GI (Optimedia OMJ-Giga/FF-GI-SE100)	0.20-0.30	< 200 dB/km

A commercial POF-cleaver (Fiber Optic Cutting Block - Edmund Optics Inc.) with fresh blades was used to cleave the 2.2 mm SI, DSI and GI-POF cables here employed.

As previously mentioned, the holographic image reconstruction was accomplished with the use of an FFT algorithm. The reconstruction is based in the classical diffraction concept by Huygens-Fresnel equation, but approximated to the Fraunhofer limit [2]. This is the conceptual basis of DFTH method. Henceforth, the holographic reconstruction of the amplitude H(m,n) is numerically performed by Eq.(1)

$$H(m,n) = i\frac{|R|}{\lambda z}\left\{\sum_{k=0}^{N-1}\sum_{l=0}^{N-1} h(k,l)\exp\left[-i2\pi\left(\frac{km}{N}+\frac{ln}{N}\right)\right]\right\}, \quad (1)$$

that is the algorithm version of the present numerical reconstruction process. The image amplitude H(m,n) is calculated from (1), where R(x,y) is the plane of the reference wave, λ is the wavelength and z is the distance from the object to the recording plane. The CCD is the image recording sensor of N^2 pixels each one presenting $\Delta x \Delta y$ area. The recorded intensity pattern is discretized in intervals of $N\Delta x$ and $N\Delta y$, where (m,n) means the index that corresponds to address of each pixel of the discretized image. The reconstruction of the holographic images by using the POFs for illumination will be presented in Section 3.

III. Results and discussions

The top of Fig.2 shows the far-field images (spot-size) of the light exiting the SI, DSI and GI POFs, respectively, when measured at 4 cm distance. It is shown at the bottom the corresponding radial profile of the light intensity as generated by using the ImageJ public domain software.

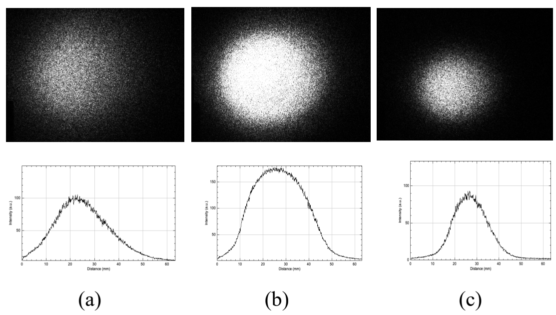
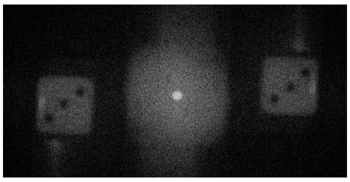


Fig. 2. Images and the radial scan trace of the spot-size measured in the far-field for the SI (a), DSI (b) and GI (c) PMMA-POFs.

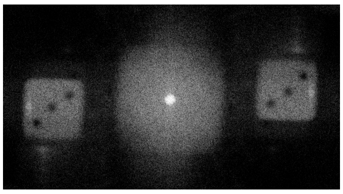
The SI, DSI and GI POFs present 25 mm, 31 mm and 18 mm beam-waist, respectively. It should be noted that the beam-waist of the DSI appears wider than that of the SI, the opposite of what was expected. In all three cases, the measured angular divergence was greater than the value theoretically calculated from the NA. The measured and theoretical angular divergence of the SI POF was the one that most agreed with each other, giving a difference of 7º more to the measured value. For the DSI-POF the difference was 24º and for the GI-POF ~ 11º, in both cases the measured value was more than the *double* of the theoretical value. It is believed that such increased spot-size values are due to the exactly way the (collimated) light is launched into each POF. POFs 1 and 2 of whatever type were all ~1m long. Therefore, the equilibrium mode distribution or EMD [9] had not yet been reached, that is, many modes and/or light contribution from the cladding will affect the output angular divergence of the fibres.

Fig.3 shows the image of the hologram of a simple dice captured by the using the three types of POFs. The GI fibre provides the better holographic image in Fig.3(c). The reason behind may be the lessen number of modes carried by the GI-POF as well the reduced NA provided by such fibre.

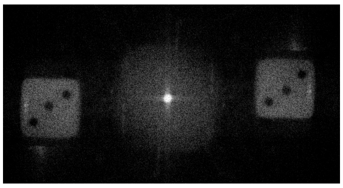
Fig.4(a) and 4(b) show the holographic image reconstructed for a flat metal sheet as an object, by using SI and DSI POFs. It is shown under the qualitative viewpoint that both images have very similar optical aspects.



(a)

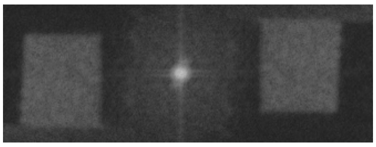


(b)

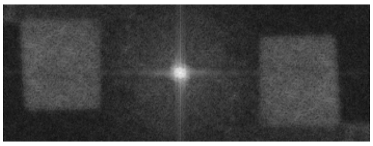


(c)

Fig. 3. Images of the digital hologram of a dice as achieved by the use of SI (a), DSI (b) and GI (c) PMMA-POFs.



(a)

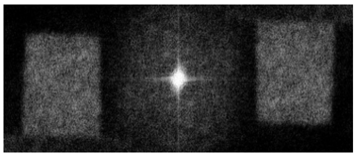


(b)

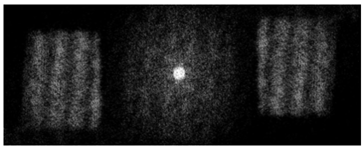
Fig. 4. Images of the digital hologram for a flat metal sheet as achieved by the use of SI (a) and DSI (b) PMMA-POFs.

Interferometric holograms captured by using the DSI-POF also for a flat metal sheet as object was shown in the images of Fig. 5. To produce this type of holograms, we have used a glass slide as a phase shifter. In this way, two holograms were produced in sequence, in which images are like those shown in Fig.5(a). Then a hologram is first taken before and a second one after the rotation of the glass slide [Fig.5(a)]. Then, the two holograms are added and the result reconstruted, which image will show the pattern of fringes superimposed, that is the generation of moiré-like fringe patterns in Fig.5(b).

Under the qualitative viewpoint (see Fig.5), the fringe pattern as generated by using the DSI-POFs presents a higher visibility degree when compared with the version generated with the SI-POFs (not shown here). A preliminary explanation may be due to the smaller numerical aperture of the DSI (~ 0.32) when compared with the SI (~ 0.46). As a result, the DSI presents ~ $(0.50/0.32)^2$ ~ 2.1 times lessen propagating modes than the SI-POFs. Single mode fibres (SMFs) carry only one mode. Then, it can avoid any modal noise that normally rises from multi-beam interference amongst spatial modes propagating in a multimode fibre. Consequently, the number of transversal modes in a fibre seems to determine the speckle noise that limits the visibility of interferometric patterns. Another possible explanation may be related to the light power level exiting each of the POF due the cleavage quality.



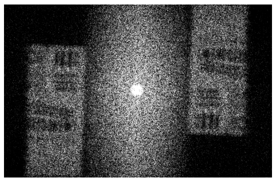
(a)



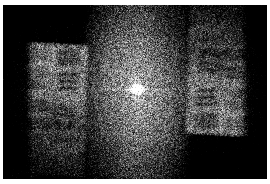
(b)

Fig. 5. Images of the digital interferometric holograms for a flat metal sheet as achieved by the use of DSI PMMA-POF. (a) shows the hologram before (and after) the insertion of a glass slide. (b) shows moiré fringes after superposition of both holograms.

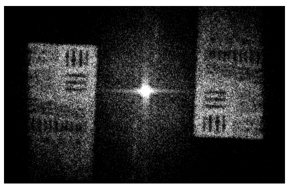
It is shown at the Fig.6 the holographic images by using the USAF 1951 3”x3” from EDMUND Optics Inc. resolution target as object.



(a)



(b)



(c)

Fig. 6. Images from the USAF 1951 target hologram as achieved by the use of SI (a), DSI (b) and GI (c) PMMA-POFs.

The element 6 of the group number -2 in the corner of the target corresponds 0.445 lines/mm (or 11.39 lines/pol) gives the resolution of the holographic images in Fig.6. All images in Fig.6(a), 6(b) and 6(c) are resolved, but is clear that the best result is obtained by using the GI PMMA-POFs as shown in Fig.6(c). This reinforce the previous comments made to the results presented in the Fig.3 where was pointed out that the reason of that may be the lessen number of modes carried by the GI-POF as well the reduced NA provided by such fibre.

IV. Conclusions

In conclusion, this paper demonstrates the experimental feasibility of the efficient use of 2.2-mm SI, DSI and GI-POF cables (fibre diameter of 1mm) as light conductor devices in: Fourier transform holography, image reconstrution and interferometric holography aplications. Depolarization measurements of both stretched ~1 m length of SI and DSI POFs were carried out and it have shown similar results, that is a complete loss of the initial launched linear polarization. Despite of depolarization, holograms were achieved. Given the measurement results, we can expect to obtain a better quality of holograms by using GI-POFs, which are able to provide optical beams with reduced NA and fewer number of spatial modes. We believe that due to the great advance experienced by digital holography in terms of scientific and industrial optical applications, our proposal could be interesting mainly in educational settings, development in laboratory, mechanical engineering, that is, fracture detection in materials surface, quality inspection in metallic structures, profilometry and non-destructive interferometric testing for general purposes.

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