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Experimental opto-digital processing of multiple data via modulation, packaging and encryption

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Abstract

A new opto-digital protocol to handle multiple data in an efficient and secure way is proposed and experimentally demonstrated. In this method, the optical processor is a 2f system with a ground glass located in its input plane. The 2f system is placed in one arm of a Mach–Zehnder interferometer. The optically processed data are holographically stored and then filtered, theta modulated and multiplexed to obtain a single package containing all processed data. During the filtering procedure, the non-relevant information contained in the holograms is eliminated. Otherwise, these non-relevant data will introduce noise over the output plane affecting the retrieved objects. In this case, the theta modulation process performed with a grating allows recovering all data without superposition. In order to get the encrypted package a second random phase masks multiplies the package. The recovering procedure consists in multiplying the encrypted package by the complex conjugate of the random phase mask, an after a Fourier transform operation all data are retrieved. In this way, an authorized user recovers all data with a single operation, in the same plane and at the same time without noise or superposition. Experimental results demonstrate the validity and applicability of the proposal.

Keywords: image processing, optical packaging, theta modulation, encryption
PACS numbers: 42.30.-d, 42.30.Kq, 42.30.Va

(Some figures may appear in colour only in the online journal)

1. Introduction

The encoding of two or more inputs in a single one by optical or numerical means is called multiplexing. Multiplexing finds recent relevant use in optical projection tomography [1], extraction of the spatial modes excited in a multimode fiber [2], biosensing applications [3], dual-channel polarization holography [4], detection of ultrafast phenomena [5], to name a few. Other applications of multiplexing techniques regard the investigation of spatial angular multiplexing with digital holography in superresolution [6]. A scheme for the resolution enhancement of three-dimensional display, which uses multiplexed holographic optical element, was proposed [7]. The method adopts an angle-multiplexing technique of volume hologram with different angle of reference beams. Multiplexing also finds useful applications in a method based on incremental holographic multiplexing to create a refractive index ratchet distribution into a photorefractive crystal as an example for the generation principle of such complex multiperiodic lattices [8]. Spatial multiplexing is obtained by recording simultaneously more than one input on the same media. All the inputs are superimposed in one composite frame, and each of them can be independently reconstructed through a digital spatial filtering if the image bandwidth of

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each input is sufficiently low. Demultiplexing requires that each individual input be filtered out by performing the digital Fourier transform (FT) of the multiplexed inputs. The filtering in Fourier spectral domain is done by selecting a passband corresponding to the desired input. Then, the inverse FT on the filtered result is computed with the aim of obtaining a separate output for each of the multiplexed signals. The size of the object spectrum in the Fourier plane determines how many inputs can be efficiently multiplexed.

On the other hand, optical encryption of a single object or multiple data has achieved great development during the last decade [9–33]. The conventional encrypting methods employ double random phase encoding in a 4f and JTC architectures [9, 10], in the Fresnel domain or employing fractional Fourier transforms [11]. Some proposals include implementing a scheme by using a photorefractive crystal [12] or a digital holography technique [13, 14]. Some recent contributions allow overcoming some limitations of the optical encryption systems [15–17]. We find an opto-digital protocol to encrypt messages of any length, which is experimentally verified [15]. The technique employs the joint transform correlator (JTC) encrypting architecture. The procedure consists in encrypting separately each keyboard character, and after a multiplexing operation all encoded characters are combined into an encrypted keyboard. The keyboard is recovered using the encrypted keyboard and the security key. Finally, a selection-position key gives the right sequence to recover the message. In other contribution, the concept of container was introduced in the optical encryption field [16, 17]. The container is the corresponding quick response (QR) code of the information to be encrypted. The QR code is encrypted instead of the original information. After a right decrypting procedure, the decrypted QR is read and the original information can be retrieved without noise. The inclusion of this container avoids the inherent speckle noise present in the recovered data when using actual coherent encrypting systems.

In case of processing multiple data, multiplexing techniques also have been widely used for the optical encryption [18–29]. Recently, multiple-image encryption has received increasing attention in the field of information security using different approaches [18–23]. Many encryption schemes are based on phase retrieval algorithms in different domains [20, 21], meanwhile other include iterative Fourier transformations [22]. Moreover, Alfalou and Brosseau [23] pointed out that these techniques can be used for compression operations simultaneously.

Optical encryption techniques reinforce the security and applications when the multiplexing concept is included [24]. As pointed above, multiplexing allows storing multiple input data in a single package. Several multiplexing encryption methods were proposed using the mentioned JTC and the 4f architecture, for instance, in wavelength multiplexing [25] or in modifying the polarization state [26]. In all proposals, the encryption procedure is applied independently to every single data and then all encrypted images are stored in one package. In these conventional schemes, to recover only one input data without overlapping the key mask and/or encrypting optical parameters should be adequately selected [24–27]. In decryption procedures, the wavefront convey the information corresponding to all encrypted images. Therefore, the non-decrypted data represent background noise over recovered information affecting the decoded image quality. This serious drawback limits the amount of data to be securely managed by means of optical processors. The ideal method should enable to multiplex as much data as possible, and selectively and independently recover a single data of the multiplexed information free of background noise and superposition.

In recent works, solutions to the problems inherent to the multiplexing operation in a JTC and 4f architectures were found [28, 29]. The experimental multiplexing of encrypted movies using a JTC architecture was demonstrated [28]. This procedure is carried out using a Mach–Zehnder interferometer with the JTC encrypting architecture in one of its arms. The technique involves a filtering and a repositioning technique to decrypt movies without spatial superposition or background noise. Through this approach, three movies were encrypted using different security keys and then multiplexed. Each video is recovered employing their corresponding security key.

In other approach, the use of an inner spatial modulation of the speckles contained in each encrypted image before multiplexing is suggested. Thanks to the theta modulation, during recovering it is possible to introduce a filtering procedure to obtain each encrypted data individually. Accordingly, each encrypted data is recovered free of background noise and superposition when a unique key mask is employed [29]. According to this procedure, the theta modulation is applied on each encrypted data. As a consequence, the experimental implementation of this technique requires rotating the recording medium or the grating itself, which is difficult to implement in practical situations.

In this paper, we propose a new opto-digital alternative that uses the theta modulation technique to handle multiple data avoiding any experimental complexity. We employ a compact 2f optical system with a random phase mask in its input plane. The experimental setup is a Mach–Zehnder interferometer with the 2f system in one arm while the other arm provides the reference beam. Each processed data is stored in a CCD camera, filtered and theta modulated. Afterwards, a multiplexing procedure reduces the amount of handled information, and therefore making the whole process more efficient. Finally, a multiplication by a random phase mask provides security to the multiplexing. This proposed protocol takes advantage of optical systems and the digital processing for handling multiple data. The right retrieved procedure gives the whole data set simultaneously displayed and spatially separated. We present experimental results that make evident the advantages of the proposal.

2. General description of the method

The purpose of this contribution is presenting a procedure to manage multiple data in a simple, efficient and secure way without introducing significant changes or additional elements in the optical setup. For this purpose, every single data is processed optically and digitally. Afterwards, a multiplexing operation brings a single package containing all processed data. In order to protect the package, a random phase mask multiplies it. This second phase mask guarantees the generation of white noise over unauthorized retrievals. In the recovering process, the package is placed in contact with the complex conjugate of the random phase mask and after a Fourier transform operation all data are rightly retrieved.

2.1. Opto-digital processing of one object

We employ a compact optical processor consisting in a 2f system with a random phase mask in its input plane to optical store the data to be filtered, packed and encrypted (figure 1). The lens allows obtaining the Fourier spectrum of the input plane. The task of the random mask is spreads the information in the output plane of the processor, which is essential to our purpose.

In order to store the complex field contained in the optically processed data it is necessary to consider a holographic setup. Then, a Mach–Zehnder interferometer is implemented (figure 1). In the procedure, each input object to be processed $i_q(x_0, y_0)$ and a random phase mask $r(x_0, y_0)$ are in contact in the input plane of the optical processor, therefore the transmittance in the input plane is $f_q(x_0, y_0) = [i_q(x_0, y_0) \times r(x_0, y_0)] \otimes \delta(x_0, y_0)$ where $\delta()$ is the Dirac delta function and $\otimes$ represents the convolution. Each input is illuminated with a monochromatic plane wave, getting at the output plane the processed data,

$$F_q(u, v) = \Im\{i_q(x_0, y_0)\} \otimes \Im\{r(x_0, y_0)\} \tag{1}$$

where $\Im\{\}$ means the FT operation. In this case, (x_0, y_0) denoted the spatial coordinates, and (u, v) the Fourier domain coordinates.

For registering the information contained in equation (1), a beam splitter provides the reference plane wave that arrives at the output plane. The interferogram of the optically processed data is stored in the CCD camera is,

$$\begin{aligned} H_q(u, v) = {} & |F_q(u, v)|^2 + |W(u, v)|^2 \\ & + F_q(u, v)W^*(u, v) + F_q^*(u, v)W(u, v) \end{aligned} \tag{2}$$

where * means complex conjugate, $W(u, v) = \exp[-2\pi \mathrm{i}(\eta u + \gamma v)]$ represents the reference plane wave with $\eta = \cos\theta/\lambda$ and $\gamma = \cos\phi/\lambda$, $\cos\theta$ and $\cos\phi$ are the directional cosines and λ is the wavelength (see figure 1).

We want to retain only the relevant information contained in the interferogram. Therefore, we register separately the terms $|W(u, v)|^2$ and $|F_q(u, v)|^2$ by blocking the 2f arm and the reference arm, respectively. The procedure up to this point is experimentally developed and from now on, we perform digital operations. Subtracting these two last terms from equation (2) we obtain,

$$Q_q(u, v) = F_q(u, v)W^*(u, v) + F_q^*(u, v)W(u, v). \tag{3}$$

As we want to keep only one term, we proceed to perform the FT of equation (3) to get two spatially separated terms, and we filter the second term to obtain

$$n_q(x', y') = f_q(-x', -y') \otimes \delta(x' - \eta, y' - \gamma). \tag{4}$$

It is important to consider that we need to obtain the FT of the input plane information. This FT pattern is a speckle distribution which will be modulated in the next step of the procedure. Therefore, we apply an inverse FT to equation (4),

$$N_q(u, v) = F_q(-u, -v) \exp[-2\pi \mathrm{i}(\eta u + \gamma v)]. \tag{5}$$

The information contained in equation (5) represents the opto-digital processed data. This data contains the relevant information avoiding the background noise and preserving the information of the reference wave.

2.2. Modulation, packaging and encryption of the processed data

A multiplexing technique and an additional random phase mask are the appropriate tools to carry out our purpose of managing multiple data in an efficient and secure way. The main issue in multiplexing is the noise and the superposition of different information during recovering. In our scheme, the noise is associated to the non-relevant terms in the holographic recording. As we explained above, this noise is eliminated by implementing a digital filtering. Now, the next step is avoiding the superposition of the recovered data in the output plane. A strategy so far implemented in the multiple-encryption procedures to avoid this superposition is the well-known theta modulation method. The application of this protocol implies that each encrypted pattern must be modulated with a grating and then multiplexed [29]. It leads to a recovering process where each image is decrypted without any kind of overlapping.

In this new proposal, the theta modulation technique will be applied over each opto-digital processed data instead of each encrypted image like in the previous technique [29]. Due to the random phase mask inserted in the input plane of optical system, each processed data is a speckle pattern. Inserting a modulating process introduces an external tool that allows to spatially separating the different objects in the recovering plane.

The first step in the process is storing the hologram of each optically processed data (equation (2)). The recording of four holograms is schematized in figure 2. Each stored hologram is filtered to get the opto-digital processed data $N_q(u, v)$ (equation (5)). A crucial step is multiplied each processed object $N_q(u, v)$ by a grating $G_q(u, v)$ with a different orientation and pitch carefully selected to avoid the superposition of information during recovery. The grating can be expressed as $G_q(u, v) = \{\frac{1}{2}\cos[2\pi(l_q u + m_q v)]\}$; where l_q and m_q are the spatial frequencies of the grating.

Instead of managing each single data separately (equation (5)), we applied first a theta modulation and then a multiplexing procedure to obtain a single unit containing all processed data, this unit will be called package. If n represents the amount of processed objects, the resulting package is expressed as:

$$U(u, v) = \sum_{q=1}^{n} [N_q(u, v)G_q(u, v)]. \tag{6}$$

The package is ready to be sent directly to the user or manipulated to perform different processes. In this contribution we

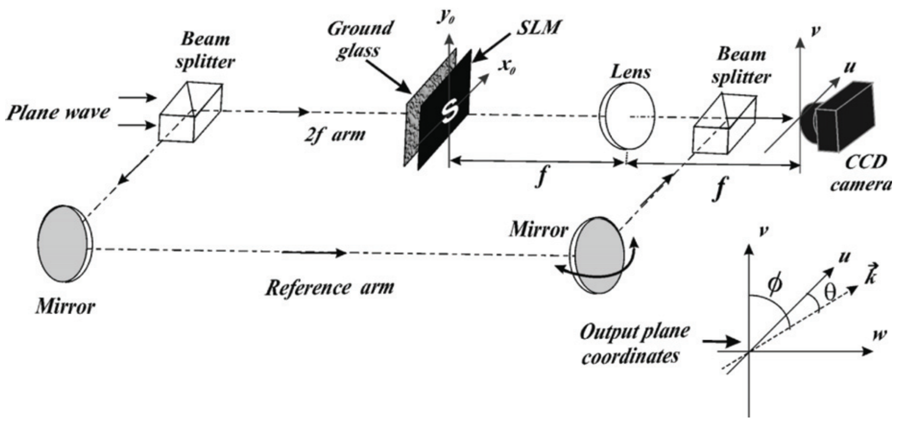

Figure 1. Mach–Zehnder interferometer for the optical processing (*SLM*: spatial light modulator, $\vec{k}$: propagation vector, f: the focal distance of the lens).

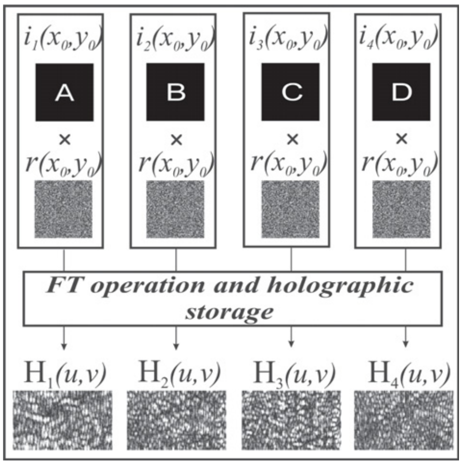

Figure 2. Diagram for the experimental recording of four holograms before filtering, modulation and encryption.

decided to protect the package using a key mask. Accordingly, the final step consists in a digital multiplication of $U(u, v)$ and $M(u, v)$:

$$P(u,v) = \sum_{q=1}^{n} [N_q(u,v)G_q(u,v)]M(u,v) \tag{7}$$

where $M(u, v) = \exp[2\pi \mathrm{i} d(u, v)]$ represents the random phase mask, which acts as the encrypting key while $d(u, v)$ is uniformly distributed on the interval $[0, 1]$. Then, the key mask satisfies the phase condition of independent white noise distributed in the region $[0, 2\pi]$. It is important to remark that the multiplication by the random phase mask allows obtaining an encrypted package (equation (7)). The modulation, packaging and encryption of the whole processed data are schematized in figure 4. Now, the encrypted package $P(u, v)$ is an information unit ready to be transmitted and received.

2.3. Recovering process

During retrieval, the encrypted package $P(u, v)$ given by equation (7) and the complex conjugate of the digital encoding key $M^*(u, v)$ can be sent to users in remote locations employing different channels to avoid intersection from intruders. The end user performs only a multiplication between $P(u, v)$ and $M^*(u, v)$ with a subsequent FT operation, to recover the hidden data in the corresponding chosen positions as following (figure 4):

$$\begin{aligned} k(x,y) &= \Im\left\{ \sum_{q=1}^{n} [N_q(u,v)G_q(u,v)]M(u,v)M^*(u,v) \right\} \\ &= \Im\left\{ \sum_{q=1}^{n} [F_q(-u,-v)\exp[-2\pi \mathrm{i}(\eta u + \gamma v)]G_q(u,v)] \right\}. \end{aligned} \tag{8}$$

Finally, all data are recovered without superposition,

$$\begin{aligned} k(x,y) = \sum_{q=1}^{n} [& f_q(x + l_q + \eta, y + m_q + \gamma) \\ & + f_q(x - l_q + \eta, y - m_q + \gamma)] \end{aligned} \tag{9}$$

where some constants are omitted. As can be seen in the expression of the recovering plane (equation (9)), the spatial position of each object in the output plane depends on the orientation of the wave plane, and the pitch and the orientation of the modulating grating (equation (9)). Therefore, the adequate selection of the grating's parameters and the carefully election of the wave plane orientation allows recovering all objects in the same plane without any kind of superposition. Figure 4 shows the different objects in different positions, according to the previous theta modulation acting on each original input. We can also confirm this fact when observing the modulation exhibited by speckles in $P(u, v)$, contained in figures 3 and 4.

The presence of two terms for every input object q in the output plane (equation (9)) is due to the theta modulation procedure. The data recovering is schematized in the block diagram of figure 4. It is important to take into account that all data are displayed in one step, in the same plane, and at the same time.

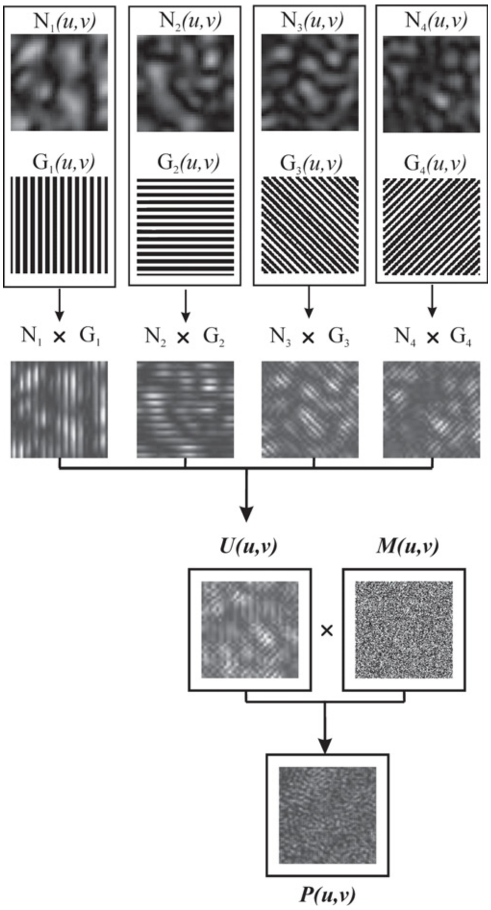

Figure 3. Graphical representation of the proposed protocol.

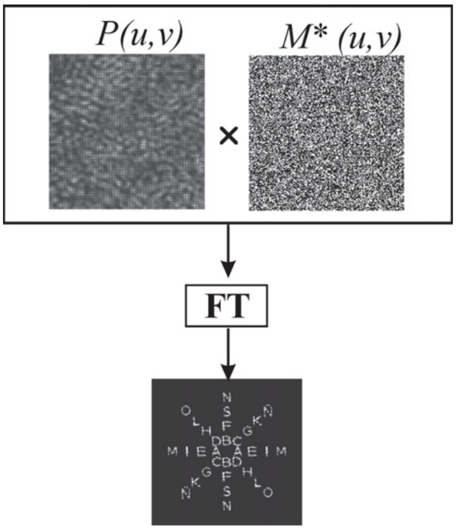

Figure 4. Diagram of the recovering process.

3. Experimental results

As mentioned in the previous sections, each optically processed data is holographically stored using the arrangement schematized in figure 1. We use a solid-state laser working at wavelength 532 nm and a lens of 200 mm focal length. Each input object of dimensions 3.2 mm × 3.2 mm is projected in a Holoeye LC2002 SLM working in amplitude mode with 800 × 600 pixels, pixel pitch 32 μm and fill factor 55%. A ground glass placed behind the SLM generates the input random mask. A CCD camera with 640 × 480 pixels and with 9.9 μm × 9.9 μm pixel size stores the holograms. In the digital step, according to the detailed description in sections 2.1 and 2.2, the stored and digitally processed data are multiplexed obtaining a single package. Finally, the package is protected employing a key mask.

Table 1. Angle and frequency parameters corresponding to the modulation given to each input object.

Input image	Angle (deg)	Frequency (ln mm^{-1})
A	0	420
B	90	420
C	45	560
D	135	560
E	0	980
F	90	980
G	45	1120
H	135	1120
I	0	1540
S	90	1540
K	45	1680
L	135	1680
M	0	2100
N	90	2100
Ñ	45	2240
O	135	2240

In the 2000 × 2000 pixels output plane, 16 objects in different positions are recovered thanks to the modulation procedure. The frequency range varies from 420 to 2240 lines mm^{-1} and the directions vary from 0° to 135° with respect to the horizontal axis. Table 1 shows a detailed description for each input object. In this way we guarantee no superposition between decrypted outputs.

Highlighting the differences with previous multiplexing methods [15, 18–21, 24–29] it is important to note that in the earlier proposals input data are individually encrypted prior to multiplexing, while in the present achievement data are first optically processed, modulated, and finally multiplexed in that order. Thus, we get a single package that is encrypted in one step by a random phase mask. On the other side, in our proposal the involved architecture, unlike all previous work, is a 2f scheme. Regarding in particular reference [29], the only overlapping aspect is the theta modulation technique. References [30, 35] although authors encrypt the multiplexed package, their setups do not use the 2f encrypting scheme.

In comparison with previous published material, we use a 2f architecture, while in [34] we find a fractional architecture and asymmetric keys are employed. Regarding [35], therein each entry is individually encrypted using a 4f setup prior to their multiplexing, while we encrypt optically with the 2f setup, then modulated individually and later multiplexed to build a package; finally this package is encrypted in a single step.

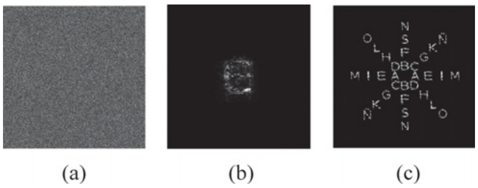

Figure 5. Experimental results when multiple inputs are processed. (a) Recovered data without employing the correct key. Recovering data using the right decrypting key: (b) but without including the theta modulation technique, and (c) applying the modulation procedure.

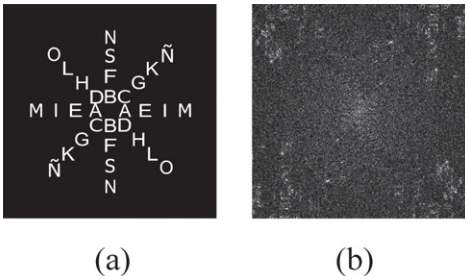

Figure 6. (a) Single input data and (b) recovered data when the correct key is employed.

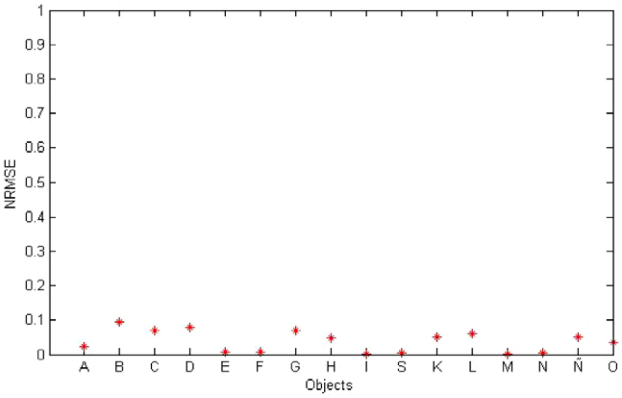

Figure 7. Curve showing the NRMSE comparing the output for each input object using our protocol with the respective output obtained using a non-multiplexing procedure.

The proposed opto-digital protocol provides the security of a conventional optical encrypting system without needing complex experimental arrangements. As expected, the retrieving of the input data is possible when the right key mask is employed. Therefore, the use of another key produces a noise result (see the result of figure 5(a)).

As can be confirmed by observing the result shown in figure 5(b), all data are recovered but spatially superposed when employing the correct key mask. This last result corresponds to the case when the procedure of section 2 is performed but omitting the theta modulation operation. The spatial overlapping avoids the right discrimination of each single recovered object. The signal of interest will be immersed in the overlapped information unless the theta modulation scheme is applied. We recall that the theta modulation allows positioning each recovered object in a determine coordinate in the output plane. This guarantees the non-overlapping among the recovered data. The potential of the proposal is evident from the result presented in figure 5(c), where all data are simultaneously recovered, besides being spatially separated.

At this point, it is key to observe that we use experimentally a coherent and analogical optical encrypting system. This implies a natural noise ever present in an experimental scheme over the recovered data as expected in any optical processing. The noise arises, not only from the physical limitations of the optical system, but also to the resolution limits, and the SLM and the CCD camera. Besides, we find dust and refraction index fluctuations in the air where the optical system is built for mention some causes. The same applies both for binary or gray-level images.

It is important to take into account that thanks to the multiplexing operation it is possible to process and recovered adequately multiple data [15]. In order to show the natural limitation of the optical systems all involved objects are processed as a unique input (figure 6(a)). This input image is selected in order to compare with the output result obtained with the proposed new protocol (figure 5(c)). This input is processed as described in section 2.1 and then encrypted with a key mask. Obviously, as we are dealing with a unique input, the modulation and multiplexing operations are not performed. During recovering, although the correct key is employed the original input is not correctly recovered as shown in figure 6(b). As we increase the number of input data, it results in the degradation of the recovered information. Although the information is properly decrypted, the original data cannot be adequately visualized. This last result reflects the importance of the multiplexing for handling efficiently multiple data in protocols that involve actual optical systems.

In order to evaluate the quality of the decrypted images when using our technique we present the curve of figure 7 where we plot the NRMSE corresponding to the comparison of each decrypted object from the multiplexed package with the same decrypted object used as a single entry on a regular encrypting architecture. We observe that the quality of the decrypted object is nearly the same for all inputs. Therefore it is reasonable to assume that our method does not introduce additional noise.

So far attacks were intended on single encrypted objects, but not on multiplexed packages. These attacks themselves deserve a new development line of research, which is beyond the scope of the present contribution.

Our method is a clear advance for enlarging the amount of collected data in a single package but also avoiding the problem caused by the information overlapping when retrieving. The methodology we propose is well suited for high-throughput applications, where large libraries of information have to be managed. In our case, a processing of the input data is carried out in an optical set up meanwhile the filtering, the theta modulation operation, the multiplexing, and the coding are digitally implemented.

4. Conclusions

In this contribution, a novel method for multiple-image managing by combination of modulation, packaging, and encryption has been proposed. Our opto-digital protocol increases the possibilities offered for processing multiple data including multiplexing operations avoiding superposition and noise during recovery, therefore the method is also effective for multiple-image encryption. To achieve this goal, a 2f scheme, a digital holography technique, along with a theta modulation procedure is employed. The theta modulation technique is the key element to avoid the overlapping of the recovered data. The digital implementation of the grating modulation technique simplifies the experimental setup. Another advantage of the proposed alternative appears in the retrieving procedure. An authorized user employs a simple digital procedure to recover all data in the same plane, at the same time and spatially separated. Additionally, the protocol guarantees a proper recovering while keeping all the security conditions. Experimental results demonstrate that the method is feasible and effective. This proposal can be implemented for applications in massive data managing systems including or not a security level.

We are aware that further research must be developed to find a threshold value to the maximum amount of recovered data without superposition. This threshold is directly related with the adequate combination of the rotations and frequencies of the modulating gratings that allows preserving the behavior of the grating, and an appropriate modulation over the speckle pattern.

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