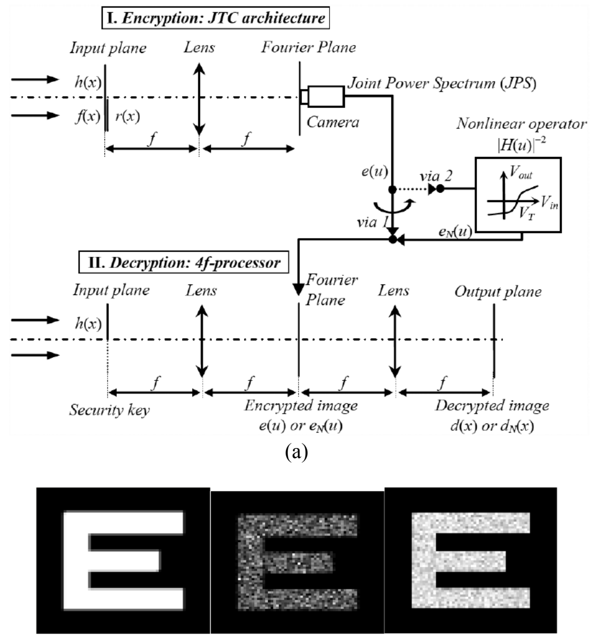
DOI: 10.1109/WIO.2016.7745591



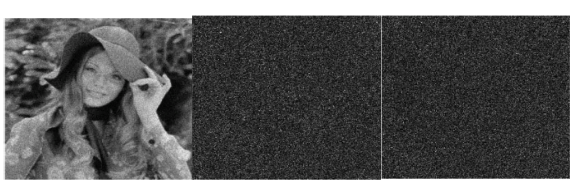
(b) (c) (d)

Fig. 1. (a) Optical setup. (b) Original image $f(x)$. Decrypted images for (c) linear JTC (via 1 in (a)); and (d) nonlinear JTC (via 2 in (a)).

it was originally proposed in [9]. Moreover, the introduction of this nonlinearity does not require to complicate the optical setup, therefore a conventional JTC suffices to implement the whole process. This nonlinearity also makes the system more resistant to chosen plaintext attacks (CPAs). We additionally explored the system resistance against this type of attack when a variety of probability density functions are used to generate the two RPMs of the encryption–decryption process [13]. The encryption system is asymmetric with respect to the random distributions used for the two RPMs, and the secret of the encrypted image is better protected when a non-uniform random distribution is used in the generation of RPM-II.

III. Extended Nonlinear Joint Transform Processor

The DRPE implemented with a JTC architecture has been extended from the Fourier domain to the Fresnel domain [14], the fractional Fourier domain [15-16] and the Gyrator domain [17-19]. In the nonlinear approaches [14,16,19], the nonlinear operations introduced in the JTC have become essential to correctly decrypt the input signal with satisfactory quality. Moreover, the extension to other domains has increased the security of the overall encryption-decryption system by introducing new parameters that must be adjusted prior to obtaining the hidden information.



(a) (b) (c)

Fig. 2. Decrypted images with the nonlinear Fresnel processor: (a) when the correct keys λ, z and the RPM $h(x)$ are used; (b) when the nonlinearity $\left|h_z(u)\right|^2$ is not introduced in the encrypted function and all the correct keys are used for decryption; and (d) using just an incorrect distance of propagation z=73mm, but the rest of keys are correct.

A. Fresnel domain

The nonlinear JTC-based encryption system in the Fresnel domain (FrD) can be applied by means of a lensless optical system [14], which minimizes the optical hardware requirements and is easier to implement. To do this, the input distributions described above are now modulated by two pure phase linear terms:

$$\begin{aligned} g(x) &= \exp\left\{\frac{i2\pi v_0\left(x-v_0\right)}{\lambda z}\right\} r(x) f(x) \\ c(x) &= \exp\left\{\frac{-i2\pi v_0\left(x+v_0\right)}{\lambda z}\right\} h(x) \end{aligned} . \qquad (3)$$

The linear phase terms are symmetrically introduced to ensure the complete overlapping of both Fresnel spectra at a distance of propagation z where the joint Fresnel power distribution ($\mathrm{JFPD}_z(u)$) is recorded. The encrypted function is now defined as the $\mathrm{JFPD}_z(u)$ divided by the nonlinear term $\left|h_z(u)\right|^2$ which is the Fresnel transform at the wavelength λ and the distance z. Both parameters have to be properly set for a satisfactory decryption (see Fig. 2a). Results shown in Figs. 2(b,c) prove that the introduced nonlinearity is essential to decrypt and retrieve the original image. When the nonlinearity is properly introduced, the other parameters (wavelength λ and propagation distance z) need to be correctly adjusted to avoid just noisy failed outputs (Figs. 2(b,c)). The cryptanalysis of the proposed system has proved that vulnerability to different attacks (CPA and known-plaintext attacks or KPA) of the JTC-based encryption system in the Fourier domain has been overcome by the proposed nonlinear scheme.

B. Fractional Fourier domain

A generalized formulation of the nonlinear JTC-based encryption systems using the fractional Fourier transform and its combination with a nonzero-order JTC were introduced with the purpose of improving the quality of the decrypted images and increasing the security of the processor [16]. The fractional order of the fractional Fourier transform, α, provides and additional parameter to further control the encryption and decryption stages. Robustness of the proposed encryption system to certain amount of degradation in the encrypted function has been tested with the presence of noise or partial occlusion of the encrypted distribution.

C. Gyrator domain

A fully-phase nonzero-order JTC architecture in the Gyrator domain has been designed with an improved resistance to brute force attacks, CPA, KPA and cyphertext-only attacks [19]. In this case the combination of two nonlinearities along with the rotation angle of the Gyrator transform improve the security of the encryption scheme.

IV. PHOTON-COUNTING MULTIFACTOR OPTICAL ENCRYPTION-AUTHENTICATION (MOEA)

Simultaneous encryption-authentication of multiple factors is a highly secure optical encryption method for demanding security systems (Fig. 3) [20]. Recent research in this field has demonstrated the potential of MOEA combined with nonlinear operations such as photon-counting imaging techniques for the secure surveillance of different items, with simultaneous verification of multiple factors, thus allowing a significant data compression with proved resistance against unauthorized attacks [21,1].

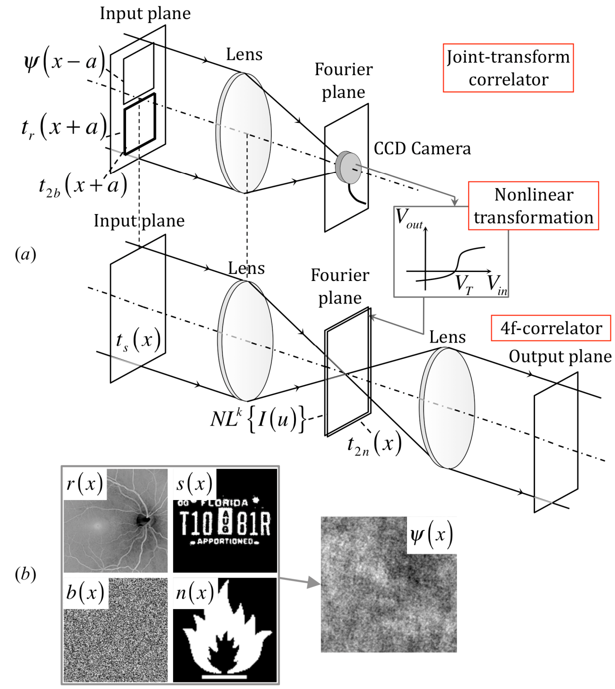


Fig. 3. (a) MOEA setup; (b) Four factors of different nature and MOEA complex-valued encrypted function.

V. CONCLUSIONS

Nonlinear modifications have been introduced in JTC-based encryption systems. As a result, the security of the encrypted image has improved and the system becomes more resistant to attacks without deleterious effects on the quality of the decrypted image. The extension to the Fresnel, fractional Fourier and Gyrator domains adds new parameters that require to be accurately set for satisfactory information decryption. The retrieval of the original image with extremely low level of noise in the decryption stage is possible thanks to the proposed nonlinear modification introduced in the joint power distribution. The recovered image shows higher quality than in other related systems that keep their joint power distribution unchanged. The nonlinear modifications do not increase the amount of data to transmit. In the case of photon-counting multifactor optical encryption-authentication, it even permits to significantly compress the information to transmit. All the described encryption-decryption systems are suitable for optoelectronic and/or digital implementation. Cryptanalysis shows the high resistance of the proposed encryption schemes against several types of attacks.

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