We studied the interference resulting from the superposition of optical lattices, which are non-diffracting fields propagating in free space, and showed a Talbot self-imaging effect. These lattices are formed by spatially Fourier transforming a "quasi"-orbital angular momentum (OAM) state. We experimentally observed that although the Talbot images change, the Talbot length is insensitive to the topological charge of the "quasi"-OAM state. Our findings can be useful for laser-written photonic lattices.

The Talbot effect, also referred to as self-imaging, is a phenomenon characterized by the periodic repetition of planar field distributions in certain types of wave fields, such as acoustics [1,2], electrons [3], plasmons [4], x-ray [5,6], photons [7–9], and atomic [10]. The Talbot effect has found interesting applications in different areas. A nice review about this subject was published in [11]. In optics, it was proved that the Talbot effect is a consequence of the light diffraction after crossing a one-dimensional periodic structure with Talbot length expressed as $z_T = d^2/\lambda$. Here, $d$ and $\lambda$ are the period of the structure and the wavelength of the incident light, respectively.

Recently, the Talbot effect has been theoretically explored using orbital angular momentum (OAM) of entangled two photon states, showing that the Talbot length is insensitive to the topological charge (TC) [12], but to the best of our knowledge, this effect was not experimentally explored.

Non-diffracting beams or a finite number of plane waves have induced a great variety of two- or three-dimensional optical lattices in linear [13–20] and nonlinear media [21]. Therefore, in the context of non-diffractive optical fields, an optical lattice can be expressed by the superposition of $Q$ plane waves of equal amplitude, whose propagation vectors have a common projection $k_x$ respect to the $x$ axis. The transverse component modulus of the propagation vectors $k_T$ is also a constant given by the identity $k_{T}^2 = k^2 - k_x^2$, where $k = 2\pi/\lambda$ is the wave number. The projection of the propagation vectors of interfering waves to the $x$-plane form angles, respect to the $x$ axis, which are multiples of $2\pi/Q$. The spatial inverse Fourier transform of this field is precisely a "quasi"-OAM state [22], and this state can be approximately simulated by passing a Laguerre–Gaussian (LG) beam through a circular pinhole array [23]. This state is considered as a superposition of Gaussian beam spots radially dislocated from the center of the same amount with a certain azimuthal angle and a constant phase proportional to this angle [22].

In this paper, we explored the Talbot effect using a superposition of two optical lattices, which were generated by a superposition of two "quasi"-OAM states. We studied the Talbot effect by interfering "quasi"-OAM states with different moduli of the wave vectors and with different TC. Figure 1 illustrates the main idea of this paper. The first and the second column describe the intensity of the beam and its respective phase distribution. Figure 1(b) shows a set of pinholes superimposed with the beam, forming a "quasi"-OAM state. Figure 1(c) displays the superposition of two "quasi"-OAM states. The longitudinal propagation of the spatial spectrum of the field in Fig. 1(c) will present the Talbot effect. It is important to note that when extrapolating the number of pinholes to infinite in Fig. 1(b), a ring structure will be formed, and its spatial spectrum is the well-known Bessel beam, a non-diffracting beam [16].

Considering that the Gaussian spots in Fig. 1(c) are so small that they can be written as Dirac’s delta functions, the two interfering non-diffractive optical lattices field can be described as

$$f(x,y) = c \sum_{n=0}^{Q-1} \left\{ \exp[ip_1(n\Delta\theta)] \exp[i2\pi\rho_1(x\cos(n\Delta\theta) + y\sin(n\Delta\theta))] + \exp[ip_2(n\Delta\theta)] \exp[i2\pi\rho_2(x\cos(n\Delta\theta) + y\sin(n\Delta\theta))] \right\}, \quad (1)$$

where $\rho_{1,2} = k_{T_{1,2}}/2\pi$ are the spatial frequency and $\Delta\theta = 2\pi/Q$. $p_{1,2}$ are integer numbers and represent the TC.
The propagation can be easily described by

\[
 f(x, y, z) = \sum_{n=0}^{Q-1} \left\{ \exp(i\rho_1(n\Delta\theta)) \exp[i2\pi\rho_1(x \cos(n\Delta\theta) \\
 + y \sin(n\Delta\theta))] \exp \left[ iz\sqrt{k^2 - (2\pi\rho_1)^2} \right] \\
 + \exp(i\rho_2(n\Delta\theta)) \exp[i2\pi\rho_2(x \cos(n\Delta\theta) \\
 + y \sin(n\Delta\theta))] \exp \left[ iz\sqrt{k^2 - (2\pi\rho_2)^2} \right] \right\}. \tag{2}
\]

Considering the intensity pattern \(|f(x, y, z)|^2\), the Talbot effect is described by the phase of the interference term

\[
 \phi(x, y, z) = 2\pi x(\rho_1 \cos(n\Delta\theta) - \rho_2 \cos(n'\Delta\theta)) \\
 + 2\pi y(\rho_1 \sin(n\Delta\theta) - \rho_2 \sin(n'\Delta\theta)) + n\Delta\theta(\rho_1 - \rho_2) \\
 + z(\sqrt{k^2 - (2\pi\rho_1)^2} - \sqrt{k^2 - (2\pi\rho_2)^2}). \tag{3}
\]

A Talbot repetition occurs when \(\phi(x, y, z') - \phi(x, y, z) = 2m\pi\), where \(m\) is an integer number, resulting in

\[
 z - z' = z_T = \frac{2m\pi}{\sqrt{k^2 - (2\pi\rho_1)^2} - \sqrt{k^2 - (2\pi\rho_2)^2}}. \tag{4}
\]

To \(k \gg \rho_1\) and \(k \gg \rho_2\), it is not difficult to show that the Talbot length is

\[
 z_T = \frac{2m}{\lambda(\rho_2^2 - \rho_1^2)} \tag{5}
\]

where \(\lambda\) is the wavelength. It is important to point out that in Eq. (5), the TC and the number of plane waves \(Q\) do not influence the Talbot length.

Figure 2 shows the experimental setup. An \(\text{Ar}^+\) laser operating at 532 nm is expanded by two confocal lenses, \(L_1\) and \(L_2\), whose focal lengths are 1.65 mm and 300 mm, respectively. The expanded Gaussian beam illuminates a LETO reflective phase only spatial light modulator (SLM). The phase of the superposition of two optical lattices, Eq. (1), was encoded as the phase hologram [16]. The hologram was written on the SLM display. A Gaussian beam reflected in the SLM is Fourier transformed by the lens \(L_3\), of focal length 1000 mm, and a spatial filter (SF) is used to select the desired field, which is split according to Fig. 1(c). A lens \(L_4\), of focal length 200 mm, and confocal with \(L_3\), is used to image the optical lattices’ interference in a 16-bit charge-coupled device (CCD) camera, which is mounted in a translating stage.

Figure 3(a) presents the transversal pattern (parallel to the \(xy\) plane) of an optical lattice obtained from Eq. (2) for \(z = 0\). We extracted three slices, indicated by the red lines shown in Fig. 3(a), parallel to the \(xz\)-plane for \(y = -0.64\) mm, \(y = 0\), and \(y = 0.64\) mm. Talbot carpets are shown in Figs. 3(b)–3(d) with periodicity of \(z_T = 63.4\) mm. From Eq. (2), it is easy to see that these patterns change its shape by changing the TC, \(\rho_1\) and \(\rho_2\), but by Eq. (5), the periodicity \(z_T\) should not be changed.

Now we are going to experimentally confirm the last statement. Figures 4–6 illustrate the fact that Talbot length does not depend on the TC and \(Q\). Figure 4 shows the experimental results for \(Q = 3\), \(\rho_1 = 1\), \(\rho_2 = 2\), \(\lambda = 514\) nm, \(\rho_1 = (25/\pi)\) mm\(^{-1}\), and \(\rho_2 = (60/\pi)\) mm\(^{-1}\) for different \(z\) positions. It is possible to identify the Talbot length, which for this case is \(z_T = 5\) mm. Now, by keeping the same spatial frequencies \(\rho_1\) and \(\rho_2\) for different TC and \(Q\), Fig. 5 exhibits the same Talbot length as the previous figure. This fact corroborates with the theoretical model presented here through Eq. (5). However, it is important to notice that the optical lattices are different from each other, comparing Figs. 4 and 5.

Figure 6 presents a Talbot length of \(z_T = 2.6\) mm. Here \(\rho_2\) is the only different parameter from ones used to obtain the

![Fig. 1. Spectrum of optical lattices and diffraction of OAM states by a pinhole array: (a) OAM state, (b) its masking by a pinhole array, and (c) visualization of the spectrum of a Talbot optical lattice.](image)

![Fig. 2. Experimental setup. L1, L2, L3, and L4, lenses; BS, beam splitter; SF, spatial filter; SLM, spatial light modulator; CCD, charge coupled device.](image)
plots of Fig. 4. Now, not only are the 2-D optical lattices different but $z_T$, is as well, and the difference in the transversal pattern is just the size.

At this point, it is important to notice that by extrapolating the number of states $Q$ to infinity, Fig. 1(c) should represent the sum of two concentric rings, and for the spatial Fourier transformed field, we will obtain a Talbot effect along the propagation distance for two interfering Bessel beams [24]. However, playing with the TC and $Q$, we have a number of uncountable ways to obtain a controllable 3D optical lattice.

Our results can find application to record optical lattices in a photosensitive medium [25]. In fact, in recent years, the illumination with this type of optical structure has led to fascinating reconfigurable nonlinear photonic lattices [14,26,27].

In conclusion, we have designed a Talbot effect using interference of “quasi”-OAM states and experimentally showed that the Talbot length does not depend on the TC of these states. Remarkably, we can use the TC to control the shape of a periodic 3D pattern without changing the $z_T$. These results

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**Fig. 3.** (a) Transversal pattern for $z = 0$. (b)–(d) Talbot carpets along the red lines indicated in (a). We have used $Q = 3$, $p_1 = 1$, $p_2 = 2$, $\rho_1 = 25/\pi^2$ mm$^{-1}$, and $\rho_2 = 80/\pi^2$ mm$^{-1}$.

**Fig. 4.** Sequence of experimental images showing the Talbot effect: $Q = 3$, $p_1 = 1$, $p_2 = 2$, $\rho_1 = 25/\pi^2$ mm$^{-1}$, and $\rho_2 = 80/\pi^2$ mm$^{-1}$.

**Fig. 5.** Sequence of experimental images showing the Talbot effect: $Q = 4$, $p_1 = 1$, $p_2 = 1$, $\rho_1 = 25/\pi^2$ mm$^{-1}$, and $\rho_2 = 60/\pi^2$ mm$^{-1}$.

**Fig. 6.** Sequence of experimental images showing the Talbot effect: $Q = 3$, $p_1 = 1$, $p_2 = 2$, $\rho_1 = 25/\pi^2$ mm$^{-1}$, and $\rho_2 = 80/\pi^2$ mm$^{-1}$.
may be useful for engineering 3D structures for direct photopolymerization laser writing or to nonlinearly inscribe 3D photonic lattices in photosensitive material [28]. Here we have used Gaussian spots uniformly distributed around some radios and phases with a constant change between the spots, simulating a LG beam crossing a pinhole array. The periodicity only depends on the transversal spatial frequency; therefore, in a future work under way, we will engineer these states such that the number, the angular position, and the phase of the spots will produce desired periodic 3D structures in the Fourier transformed states.

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REFERENCES