Experimental Observation of a Photon Bouncing Ball

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An optical analogue of a quantum particle bouncing on a hard surface under the influence of gravity (a quantum bouncer) is experimentally demonstrated using a circularly curved optical waveguide. Spatially resolved tunneling optical microscopy measurements of multiple beam reflections at the waveguide edge clearly show the appearance of wave packet collapses and revivals (either integer and fractional), corresponding to the full quantum regime of the quantum bouncer.

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The motion of a quantum particle falling in a constant gravitational field, eventually reflected by a hard surface, is of great relevance in different areas of physics [1–11], mainly because of the possibility of observing quantum effects of gravity [10], testing the equivalence principle [9], and observing freely accelerating particles (Airy wave packets [4,12]). Experimental realizations of a quantum bouncer, i.e., of a quantum particle bouncing on a hard surface under the influence of gravity [1,2], have been reported using ultracold atoms [5–8] and neutrons [10]. Owing to the formation of a gravitational quantum well [1,2], the energy levels of the bouncing atoms or neutrons are quantized. Since the gravitational well is anharmonic, the quantum motion of an initially localized particle strongly deviates from the classical one at long observation times, and in the full quantum regime wave packet collapses and revivals should be observed as a result of quantum interference [13]. Unfortunately, the energy levels in a gravitational well are very closely spaced, making the classical limit ubiquitous in most practical cases and quantum interference effects hardly observable. Similarly, preparation of a quantum particle in a stationary Airy eigenstate, which is perceived as a freely accelerating particle [12] by a free-falling observer [4], remains to date out of a realistic realization in the quantum realm. Since these effects are in their essence a manifestation of the wave nature of matter and because of the similarity between quantum and classical interference [14], they can be observed as well for classical waves, such as optical or acoustical waves. Exploitation of the optical-mechanical analogy has enabled recently the first experimental demonstration of freely accelerating Airy wave packets for light [15], with interesting applications to optical micromanipulation [16]. Several optical analogues of quantum bouncers have been proposed as well [17–21]. Earlier experiments [17,18] showed light bouncing in inhomogeneous dielectric media and explained the observed light paths by the Hamiltonian analogy between classical mechanics and ray optics [18]. However, in such realizations the full wave regime, leading to beam collapses and revivals, was not accessible. Other proposals of photonic bouncers have been theoretically discussed both in the spatial [19,20] and temporal [21] domains. In the former case, a light beam is accelerated by an effective refractive index gradient produced, for instance, by carrier diffusion effects in photorefrative media [19] or by waveguide bending [20]. In the temporal domain, dispersive light waves in photonic crystal are trapped in a gravitylike potential created by accelerating solitons, and thus behave like a quantum bouncing ball [21].

In this Letter we report on the experimental demonstration of a photon bouncer (i.e., an optical analogue of a quantum bouncing ball) in the full wave regime, with a quantitative analysis of collapse and revival effects based on accurate scanning tunneling optical microscopy measurements.

Our optical analogue of the quantum bouncer is based on trapping of a light beam near the outer edge of a circularly curved wide channel waveguide of radius R and channel size a, as schematically shown in Fig. 1(a). A light beam injected near the outer edge of the waveguide undergoes a sequence of bounces due to total internal reflection, which mimics the motion of a quantum bouncing ball. As opposed to previous realizations of photon bouncers [17,18], in our experiment the beam is launched very close to the waveguide edge to enable the observation of wave packet collapses and revivals over propagation distances shorter than the perimeter πR of the semicircular waveguide. The trapping mechanism of light near the waveguide edge relies on the existence of Airy bound states similar to the whispering gallery waves found in spherical or toroidal microresonators [22]. In the curvilinear reference frame (u, v) shown in Fig. 1(a), which is related to the physical (x, z) frame by a conformal mapping [23], propagation of a monochromatic and scalar light beam at wavelength λ, localized near the outer boundary $u \sim 0$ of the waveguide

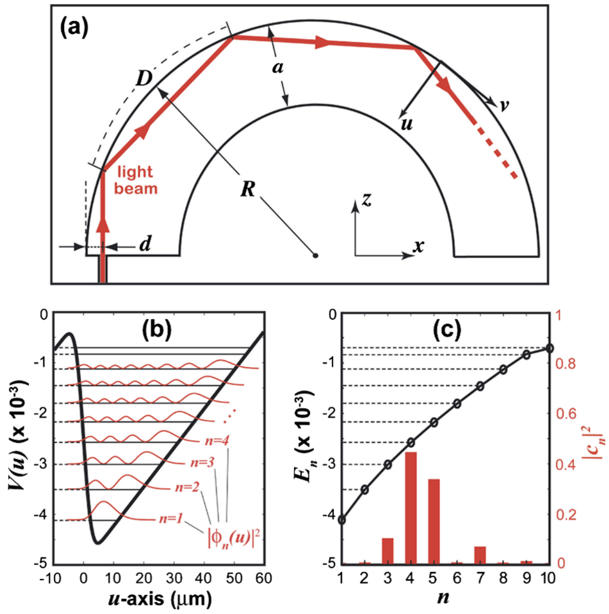

FIG. 1 (color online). (a) Schematic of the photonic structure designed to mimic a photon bouncing ball. (b) Effective one-dimensional potential well $V(u)$. Numerically computed energy eigenvalues E_n and corresponding eigenstates $\phi_n(u)$ of the well are also shown. (c) Wave packet spectrum $|c_n|^2$ for an initial Gaussian wave packet. Energy spectrum of the Hamiltonian $\mathcal{H}$ is also shown.

at a distance much smaller than R, is described by the following effective wave equation [20]:

$$i\lambda\!\!\!^{-} \frac{\partial \psi}{\partial v} = -\frac{\lambda\!\!\!^{-2}}{2n_s}\frac{\partial^2 \psi}{\partial u^2} + V(u)\psi \equiv \mathcal{H}\psi, \qquad (1)$$

where $\psi(u, v)$ is the complex electric field envelope, n_s is the substrate refractive index, $\lambda\!\!\!^{-} = \lambda/(2\pi)$ is the reduced wavelength, $V(u) = n_s - n(u) + n_s u/R$, and $n(u)$ is the effective refractive index profile of the straight channel waveguide. The analogy between our optical bouncer and the quantum bouncer [1,2] stems from the similarity between Eq. (1) and the Schrödinger equation of a nonrelativistic quantum particle of mass n_s in a potential $V(u)$, where the Planck constant h is replaced by the wavelength λ of photons and the temporal variable of the quantum problem is mapped into the curvilinear spatial propagation coordinate v. Note that, near $u = 0$, the potential $V(u)$ behaves like a gravitational well, in which the hard surface is provided by the outer waveguide edge whereas the gravitational potential is played by the fictitious transverse refractive index gradient perceived by light in the curved reference frame.

For the experiment, we manufactured a semicircular channel waveguide (radius of curvature $R = 19.8$ mm, channel size $a = 200$ μm) in a passive phosphate glass by the Ag-Na ion-exchange technique (see, for instance, Ref. [24]). The behavior of the effective one-dimensional potential well $V(u)$, estimated following a procedure similar to that detailed in [24], is depicted in Fig. 1(b). In the figure, the numerically computed (dimensionless) energy eigenvalues E_n and corresponding eigenstates $\phi_n(u)$ of the well [i.e., $\mathcal{H}\phi_n(u) = E_n\phi_n(u)$] are also shown. Note that the optical well exhibits a smooth profile at the edge of the waveguide, and a finite number (~10) of trapped modes exist owing to the finite refractive index difference between cladding and core waveguide regions. Nevertheless, provided that the low-order trapped modes are excited, our optical system closely mimics the problem of a particle bouncing on a perfectly reflecting surface under the influence of gravity, and each eigenstate $\phi_n(u)$ closely resembles the set of shifted Airy functions found in the quantum bouncer problem [2]. Wave packet excitation at the input plane $v = 0$ is accomplished by a narrow straight waveguide, which is displaced by $d \simeq 30$ μm from the outer edge of the wider circular waveguide [Fig. 1(a)]. The narrow waveguide is excited by bonding its input facet with the single-mode optical fiber of a fiber pigtailed laser diode operating at $\lambda = 980$ nm (see Fig. 2). The bonding system ensures an excellent long-term stability of the excitation setup, avoiding even small fluctuations of the coupled light mode that might be detrimental for an accurate and quantitative mapping of the light flow along the waveguide. The wave packet $\psi(u, 0)$ at the entrance plane, whose measured intensity profile is well fitted by a Gaussian function with a full width at $1/e^2$ of ~9.5 μm, excites a few eigenstates $\phi_n(u)$ of the optical well with an estimated spectrum $|c_n|^2$ centered at around $n_0 = 4$ as shown in Fig. 1(c), where $c_n = \int du \phi_n(u)\psi(u, 0)$. For the chosen values of R and d, the beam makes about $N = \pi R/D \sim 28$ classical bounces over the full curved waveguide path, where $D = 2R \arccos(1 - d/R) \sim 2.2$ mm is the curvilinear length between successive bounces calculated by a simple ray optics analysis [cf. Fig. 1(a)]. To study wave packet collapse and revival phenomena, let us expand the eigenvalues E_n at around $n = n_0$ up to second order; the propagated wave packet $\psi(u, v)$ at the arc length v is then given by

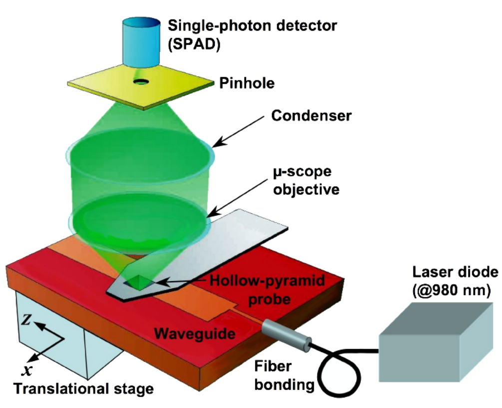

FIG. 2 (color online). Experimental setup for quantitative mapping of light flow along the photonic structure of Fig. 1(a) employing scanning tunneling optical microscopy.

$$\psi(u,v) = \exp\left(-i\frac{E_{n_0}v}{\lambda\!\!\!^{-}}\right)\sum_{l=0,\pm1,\ldots} c_{n_0+l}\phi_{n_0+l}(u) \times \exp[-2\pi i v(l/T_1 + l^2/T_2)], \quad (2)$$

where the spatial scales T_1 and T_2 are defined by

$$T_1 = 2\pi\lambda\!\!\!^{-}/(dE_n/dn)_{n_0}, \qquad T_2 = 4\pi\lambda\!\!\!^{-}/(d^2E_n/dn^2)_{n_0}. \quad (3)$$

For the spectrum shown in Fig. 1(c), at $\lambda = 980$ nm one obtains $T_1 \simeq 2.3$ mm and $T_2 \simeq 49$ mm; i.e., the two spatial scales are well separated. The beam evolution over the shortest spatial scale $\sim T_1$ reproduces the classical (ray optics) result. Here, the quadratic term in l entering in the exponent on the right-hand side of Eq. (2) can be neglected, and the wave packet undergoes a periodic motion with a spatial periodicity T_1 very close to the classical bouncing period $D \simeq 2.2$ mm predicted by the ray optics analysis (semiclassical regime). In this regime, $\psi(u,v) \simeq \psi_{\mathrm{cl}}(u,v)$, where $\psi_{\mathrm{cl}}(u,v)$ is the "classical" component of the wave packet [13] which is obtained by letting $T_2 \to \infty$ in Eq. (2). The time scale T_2 at the next order in the expansion is analogous to the quantum revival time scale of the quantum bouncer, and it is responsible for the appearance of collapsed and revival states for propagation distances in the spatial scale T_2 [2,13]. In particular, when v varies near $v \simeq T_2/2$, the quadratic phase term in Eq. (2) is close to $\pi l^2/2$, and one has $|\psi(u,v)|^2 \simeq |\psi_{\mathrm{cl}}(u, v - T_1/2)|^2$; i.e., the semiclassical wave dynamics is retrieved; however, the motion is out of phase as compared to the classical prediction by half a period. This corresponds to a fractional revival of the input wave packet. Similarly, at $v \simeq T_2$, one obtains $|\psi(u,v)|^2 \sim |\psi_{\mathrm{cl}}(u,v)|^2$; i.e., the classical bouncing motion is retrieved (first integer revival). Between subsequent revivals, a collapsed state, corresponding to a kind of "incoherent" superposition of the various wave packet components and leading to a fully delocalized field over a distance d from the waveguide boundary, is expected on the basis of general considerations [13]. The propagation distances at which the collapsed states occur depend on the precise shape of the input beam, and can be determined by direct numerical analysis of beam propagation.

A quantitative mapping of the light flow along the outer edge of the waveguide is accomplished by means of scanning tunneling optical microscopy imaging with a commercially available microscope setup employing a hollow-pyramid cantilevered tip (Fig. 2). The tip is brought to soft contact with the waveguide and converts the evanescent field at the upper surface of the sample into a propagating wave, which is then focused onto a pinhole for background rejection, followed by a single-photon avalanche detector. Such a technique has been previously demonstrated to be a reliable mean for high-spatial resolution measurement of intensity field distributions at the surface of evanescently coupled optical waveguides [25], and recently it led to the experimental demonstration of the optical Zeno effect [26].

Maps of light intensity distributions are then retrieved following the procedure detailed in [25], and analyzed to reconstruct the evolution of beam center of mass $\langle u\rangle = \int u|\psi(u,v)|^2 du$ versus curvilinear propagation distance v. Figures 3(a) and 3(b) respectively show the measured evolution of the beam center of mass and corresponding theoretical behavior obtained by a standard numerical analysis of Eq. (1) based on pseudospectral methods. The classical paraboliclike trajectory of the beam undergoing successive bounces, expected by a ray optics analysis (the classical limit of the quantum bouncer), is also depicted in the figures with a dotted line. An inspection of the data clearly reveals the appearance of wave packet collapses and revivals. At short propagation distances ($v \lesssim 10$ mm), the beam trajectory follows the classical (ray optics) path, and undergoes successive bounces like a ball bouncing on a hard surface under gravity. This is clearly shown in Fig. 4(a), where the detailed behavior of the light intensity map $|\psi(u,v)|^2$ for the first two bounces (near $v = 0$) is reported. At $v = v_1 \sim 14$ mm, a first collapse of the wave packet is clearly observed (Fig. 3). In this region, the light beam turns out to be fully delocalized over a distance d from the boundary, as shown in Fig. 4(b). At the longer propagation distance $v = v_2 \sim 22$ mm, i.e., close to $\sim T_2/2$, a first revival of the wave packet is observed [see Fig. 4(c)].

Note that the center of mass of the wave packet turns out to be out of phase as compared to the classical trajectory (see also Fig. 3), a clear signature that at $v \sim v_2$ a fractional revival is observed. This revival is followed by a second collapse, and then by the first integer revival [see

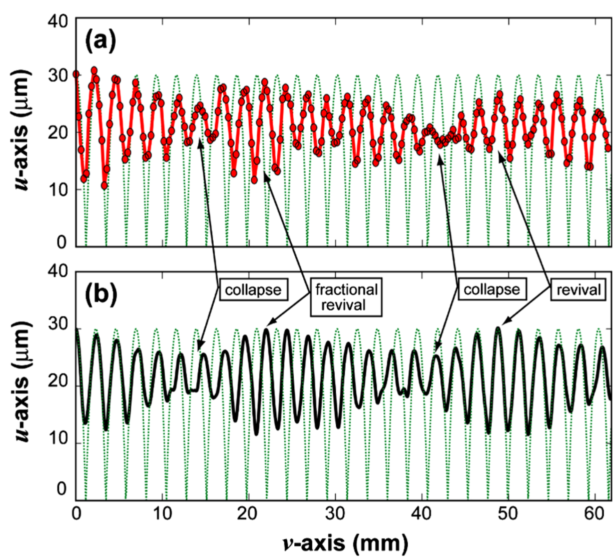

FIG. 3 (color online). (a) Experimental and (b) numerically computed beam center of mass of the photon bouncing ball versus the curvilinear propagation distance v. Classical trajectory (dotted line) is also shown for comparison.

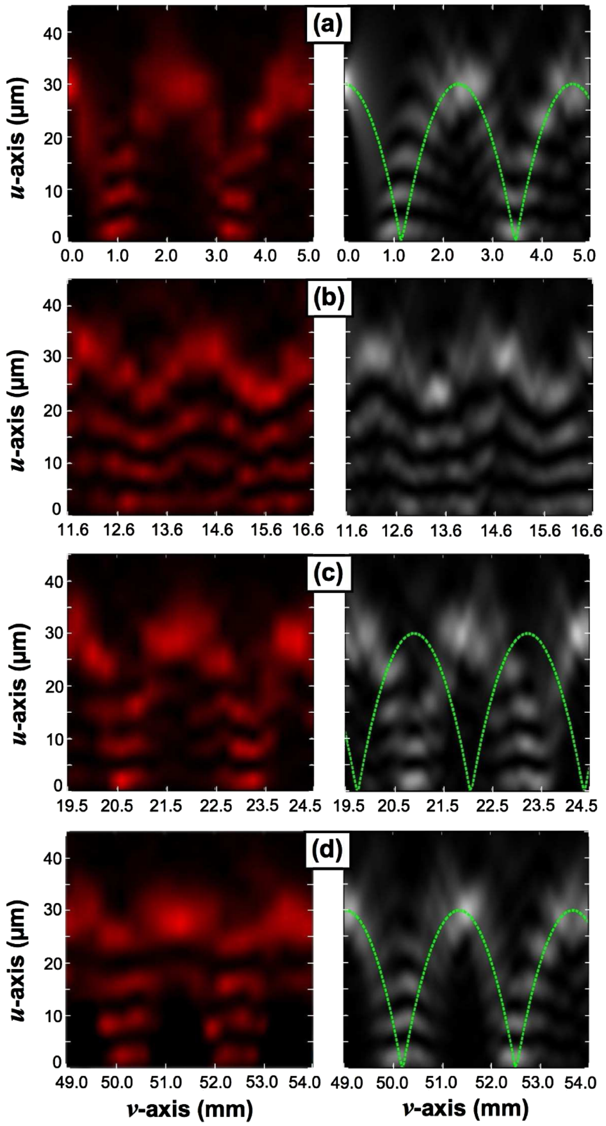

FIG. 4 (color online). Measured (left panels) and numerically computed (right panels) light intensity map $|\psi(u, v)|^2$ during (a) the first two bounces, (b) the first collapse, (c) the fractional revival, and (d) the first integer revival. The dashed line in (a), (c), and (d) is the classical trajectory.

Fig. 4(d)], which occurs at around $v \sim T_2$ according to theory.

In conclusion, an optical analogue of a quantum bouncer has been realized based on light propagation near the edge of a circularly curved optical waveguide. Quantitative mapping of light bouncing by scanning tunneling optical microscopy measurements enables the visualization of the transition from classical (ray optics) to full wave (beam collapse and revival) regimes, which is currently not accessible for matter quantum bouncers.

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