Ultrafast topology shaping by a Rabi-oscillating vortex

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We realize a new kind of ultrafast swirling vortices, characterized by one or more inner phase singularity tubes which spiral around their axis of propagation. This is achieved by creating a quantum vortex in one component of a two-dimensional Rabi-oscillating field of polaritons, made of strongly-coupled excitons and photons. Coherent control and ultrafast imaging allow us to initiate and follow the dynamics of the oscillatory vorticity transfer between two condensates, much alike imaging a sub-picosecond precessing gyroscope. The dynamics in time and space of this highly structured photonic packet exhibits a peculiar phenomenology of conservation of angular momentum, through balance of the different subfields and creation of vortex-antivortex pairs. The vortex, or Rabi spiraling vortex state, represents a novel concept of topology shaping, a universal principle extendible to other platforms of coupled oscillators, from mechanical ones to different size and time ranges of electromagnetics, to be used, e.g., in radar or lidar systems, laser writing and free space communications. Ultrafast rotating vortex lattices represent a natural extension, that could be applied to drive or perturb atomic condensates or for other schemes of optical trapping, while the associated phase singularities can even be made to rotate superluminally in the transverse plane.

I. INTRODUCTION

Quantized vortices are typical of fields that can be described with a complex wavefunction, where the phase acquires a physical meaning, such as in superconductors [1], superfluids [2] and atomic Bose Einstein condensates (BECs) [3], in electron beams [4–6] as well as in linear and nonlinear optical fields [7–9], or in polaritons [10] made of composite photonic and atomic/electronic oscillations. Moreover, so-called optical “singular beams”, carrying angular momentum [11, 12], are possible solutions for free-space propagation, like Laguerre-Gauss (LG), Bessel and Airy beams with nonzero azimuthal number. Nowadays, angular quantization is pursued as an additional degree of freedom for information processing [13–15] with possibility for multiplexing [16–21]. This confers robustness to free-space communications [22, 23] and finds a variety of specialized applications, such as in femtochemistry to study new selection rules or to manipulate ionized states in photoionization processes [24, 25]. Quantized vortices are associated to a rotation around a centre, similarly to classical vortices, but since their wavefunction must reconnect with itself, its phase has to undergo an integer number of twists when looping around the vortex spatial core. This is called “phase winding”, or “topological charge”, and defines the (intrinsic) orbital angular momentum (iOAM), quantized in units of $2\pi$. The vortex core is a point-like phase singularity of null-density in which the wavevector diverges (being $k = \nabla \phi$). This zero-dimensional object becomes extended along one-direction if it is inside a 3D space or it is tracked in time, where it draw curves inside a multidimensional domain (for example of real space and time, but also in the reciprocal spaces of momentum and energy). These trajectories are called “vortex lines” and, being also quantized, “topological strings” [26, 27].

Interesting examples are given by the extended networks of vortex lines inside a 3D atomic BEC, whose configurations and reconnections give rise to different phase transitions [28–30], analogously to what happens with electrons/atoms vortices in superconductors. Closed loops are possible, known as “vortex rings” [31, 32], which can even become twisted to the extent of making vortex knots [33–36], as those induced in nonlinear optical media [37]. Recently, curved light beams [38] and standing or moving solenoidal beams [39], carrying or not a topological charge, have been proposed as the most advanced tools for optical tweezers [40–43], able to provide simultaneously trapping, levitation, rotation and even pulling force (tractor beams) [44]. All this rich phenomenology offers a lot of material to study topological complexity.

In this work, we realize experimentally a new platform to structure light in both space and time so as to carry simultaneously the three kinds of angular momentum of an optical beam [45]. Indeed, our states are circularly polarized, corresponding to spin angular momentum (SAM), they carry the topological charge of a vortex (iOAM) and are also, finally, swirling in time around their center-of-mass, corresponding to extrinsic orbital angular momentum (eOAM). The total angular momentum is conserved and the interactions between these various types give rise to a complex dynamics, even in

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absence of nonlinearities or interactions. Topologically, their structure is characterized by one or more spiral-ling inner vortex tubes which precess around the axis of propagation, like a gyroscope, on a sub-picosecond timescale. Polarization shaping (in time) of full Poincaré beam texttures (in space) is a further extension which we do not address here. The underlying dynamics is both of fundamental interest in singular optics and for possible applications, and represents an extension of the general result that a locally straight optical vortex line becomes helical when perturbed. Indeed, Nye and Berry [46, 47] showed that helical dislocations in 3D space can be ascribed to the superposition of straight vortex lines with, e.g., a tilted plane wave, and to their continuously varying relative phase, due to different wavevector directions. Here, we transpose this effect to the time domain by exploiting the beating of different frequencies. In summary, we propose and realise a concept of topology shaping, based on a universal mechanism rooted in the normal-mode splitting of coupled oscillators, and as such, is amenable to different platforms, from mechanical objects to bosonic force fields, and timescales, from over milli- to sub femto-seconds.

In our case, we make use of microcavity polaritons [48], a “quantum fluid platform” constituted of bosonic hybrid quasiparticles that result from the strong coupling of quantum well excitons with microcavity photons. The realisation of exciton polariton condensates in semiconductor microcavities [49, 50] has paved the way for a prolific series of studies into quantum hydrodynamics in two-dimensional systems [10, 51–56]. Microcavity polaritons are intriguing systems for the study of topological excitations in nonequilibrium interacting superfluids. These fluids can have strong nonlinear effects [57], peculiar nonparabolic dispersion [58, 59], a spinorial-degree leading to a possible spin-orbit coupling [60–62] or resonant vortex transmutations [63]. Full- and half-integer [64, 65] quantum vortices have recently attracted much interest and have been studied both under spontaneous [66, 67] and controlled generation [68], in metastable precessing configurations [69], as well as in pair-creation events [70, 71], vortex lattices, nonlinear splitting and branching dynamics [72] and pairwise interactions [73]. Also they have been proposed for sensitive gyroscopes [74] and information elaboration [75] schemes. Our study that combines all types of angular momentum in these fluids relies on a pulsed resonant excitation, with ultrafast tracking of their dynamics, in a regime where nonlinearities are kept negligible but that could be activated to enrich the phenomenology. However, already in their linear regime, polariton vortices are non-trivial, due to the coupling between two components—of photons and excitons—whose mixing also gives rise to composite vortices [76]. Their structure is transferred to the photons emitted by the system, which inherit these topological properties. While polaritons power the mechanism structuring light, this is detected through the external light field and is therefore ultimately a pure singular-optics effect. This is a convenient, effective and powerful way to shape light.

The key property of polaritons to structure light in such a complex fashion rely on the so-called Rabi oscillations [77, 78]. In the strong coupling regime of two oscillators—the photonic and excitonic fields—new normal modes of the system appear (see Fig. 1, top panel). These are known as the upper (UP) and lower polariton (LP) modes, which differ in energy by the Rabi splitting and with phase relationships such that the bare (photon and exciton) fields oscillate in-phase and with the rotating frame in the former case and in phase-opposition as well as against the rotating frame in the latter case. The simultaneous excitation of the two modes can be seen as a beating in time of their projection on the photon and

![FIG. 1. Polariton modes and Rabi oscillations. The top panel shows the photonic emission from the polariton device under off-resonant excitation, highlighting the energy–momentum dispersion of the two normal modes, the upper and lower polariton branches. The bottom panel shows an example of the Rabi oscillations in the photonic emission after resonant femtosecond pulse excitation. The modes splitting of 5.4 meV (at \( k = 0 \)) corresponds to a Rabi period of \( \approx 0.8 \) ps.](image-url)
exciton components (see Fig. 1, bottom panel). A complementary point of view is the cyclic transformation of photons into excitons and back (absorption/emission processes). Rabi oscillations are known since the first polariton studies, but their sub-picosecond imaging have only recently been achieved [77], and never before putting into evidence the rich interplay of desynchronization in space and time. We now associate the rich properties of the Rabi oscillating polaritons to the quantum vortex dynamics. While much work has been devoted to vortices by the polariton community, this is the first time to the best of our knowledge that their dynamics is considered together with their photon-exciton Rabi oscillations (only recently the vorticity transfer and dynamics in coherently coupled atomic BECs has been theoretically considered [79, 80]). Using double-pulse coherent control to induce ad-hoc phase-relationships between different space regions, we are able to shape a swirling vortex with a spiraling dynamics. Henceforth we will refer to such a new state as a *rarvote* (combining “Rabi” oscillations with “vortex”).

**II. EXPERIMENTAL SETUP**

The main features of our experiments consist in the ability 1) to generate a Rabi oscillating vortex, 2) to control coherently such a vortex and 3) to track in time with ultrafast precision its complex-valued field dynamics (i.e., both its intensity and phase). The coherent control is obtained by spatially overlapping a second retarded Gaussian pulse which triggers the non trivial dynamics described in the following. First, single or double optical vortices are generated externally to the sample, shaping a femtosecond Laguerre-Gauss $LG_{00}$ laser pulse into either $LG_{0\pm1}$ or $LG_{0\pm2}$ states by means of a patterned liquid crystal retarder (the so called $q$-plate, see [72, 81, 82]). Such femtosecond optical vortices represent the initial pulse (pulse $A$) directly generating the polariton fluid upon resonant photon-to-polariton conversion on the sample. The excitation laser is a 80 MHz train of 130 fs pulses with a 8 nm bandwidth properly tuned in order to resonantly excite both the LP and UP branches (with their central $k = 0$ states respectively located at 836.2 and 833.2 nm in our sample), which is mandatory to trigger Rabi oscillations. The modes splitting of 3 nm (5.4 meV) corresponds to a Rabi period of $T_R \sim 0.8$ ps. Once imprinted, the polariton vortices are left free to evolve. We operate in the intensity/density regime, weak enough in order not to perturb the vortex dynamics by the nonlinearities, and in a clean area of the sample so to avoid any unintentional effects from the disorder. The positional stability of the vortex is indeed observed in the dynamics (in absence of the second/displacing pulse), during the whole LP lifetime (whose decay time is $\tau_L \sim 10$ ps), with typical Rabi oscillations (quenching with the UP dephasing time $\tau_U \sim 2$ ps).

The second pulse, pulse $B$, is a $LG_{00}$ which can be obtained either before the $q$-plate shaper or even after it, upon accurate control of the phase-shaping degree and of the polarization states. Here we use co-polarized pulses $A$ and $B$ for simplicity and we decide to have them in the circular polarization, either $\sigma_+ \text{ or } \sigma_-$. Standard beam splitters (BS) and $\lambda/4$ plates are used to separate the beams, control the polarization and put them together before sending onto the sample. The relative power between the two pulses $P_B/P_A$ is set close to two, in order to have comparable top density for the associated polariton populations (at the time of the second pulse arrival). Such ratio is a tunable parameter to control the entity of the induced vortex displacement and following spiraling dynamics. The temporal delay $t_{AB}$ between the two pulses is controlled by the difference between the two arms lengths (excitation delay line). We point out that the overall delay between the two resonant pulses consists of two fundamental and conceptually different terms, with different time scales, $t_{AB} = \Phi_{AB} + \varphi_{AB}$. The former represents the coarse time delay, on the order of Rabi period (ps time scale), while the latter, the fine delay or relative phase, is of the order of the optical period (fs time scale). Their respective roles will be made clear in the following Sections.

Finally, the resonant condensate wavefunction is monitored collecting the photon leakage of the cavity and by the use of a time-resolved digital holography scheme [77]. Basically, the resonant emission is let interfere on an imaging camera with a time-delayed reference beam (detection delay line). The reference pulse is expanded by passing through a pinhole in order to make it wide and homogeneous. Hence, we apply digital Fourier-space filtering to retrieve both the amplitude and phase of the polariton wavefunction. Customized software allows us to monitor and adjust the dynamics in real-time during this operation. The polarization can be simply postselected on the detection side by using $\lambda/4$ or $\lambda/2$ plates and polarizing BS.

**III. RARTEXT DYNAMICS**

The spatial structures of pulses $A$ and $B$ are shown in the Fig. 2(a), in the case of the unitary rarortex experiments. Such maps are the initial polariton emission amplitude after independent excitation by one of the two states. We have a FWHM (full-width at full-maximum) of 30 $\mu$m for pulse $A$, the $LG_{01}$, and a FWHM (full-width at half-maximum) of 20 $\mu$m for pulse $B$, the $LG_{00}$ state. Typical dynamics after a sequence excitation by pulse $A$ and $B$ are shown in the following panels. Figure 2(c) represents a timespace chart of the fluid amplitude along a central crosscut, sampled with a $\delta t = 20$ fs timestep. Two Gaussian time envelopes are overlapped to the Rabi oscillations for clarity, in order to show the arrival time and time width of the two pulses. The chart makes evident the peculiar feature achieved by use of a
FIG. 2. Rartex experiment. (a) Polariton emission excited by independent resonant pulses, either the vortex $A$ or the plain Gaussian $B$. (b) Simplified scheme to represent the displacement of the vortex core position by a coherent overlap of the spatially Gaussian beam. The resulting state is asymmetrical, where new positions for both the maximum and the null (core) density are obtained at a radial distance set by the condition of totally constructive and destructive interference (i.e., a radial distance where the original beams have same intensity), respectively. (c) Timespace charts of the polariton amplitude along a central crosscut in the double pulse experiment, i.e., after the sequence of pulses $A$ and $B$. The superimposed time envelopes represent the time arrival and length of the two excitation pulses (delay $t_{AB} \approx 1$ ps). A desynchronization of Rabi oscillations along the diameter is evident in their bending after the arrival of pulse $B$. (d) Evolution of the polariton amplitude and phase. The snapshots are taken at times of $t = 1.20, 1.50, 1.58$ and $1.72$ ps. The phase singularity is tracked and marked as a yellow dot in the amplitude maps, and the red curve represents its trajectory along a timespan of two Rabi periods ($t = 1.2 \sim 2.8$ ps). See also the supplemental movie SM1.
double pulse with different topologies: the density unbalance along the crosscut, the filling of the empty core of the initial vortex by the second pulse, and, importantly, the desynchronization of the Rabi oscillations between different space locations.

The initial circular symmetric $LG_{01}$ vortex (Fig. 2(d), $t = 1.20 \text{ ps}$) is suddenly displaced aside upon arrival of pulse $B$ (see the panels at $t = 1.50 \text{ ps}$). Indeed the second pulse is a $LG_{00}$ with central top intensity and homogeneous phase, which coherently sums up to the previous polaritonic vortex field. The central phase singularity must be displaced to a new position of zero-density, with such a radius that the initially- and the newly-generated polariton populations balance themselves (see the simplified scheme of Fig. 2(b)). We briefly point out here that in the 2D case, the specific direction of initial displacement is set by the optical phase delay, or relative phase $\varphi_{AB}$, between the two pulses, i.e., the new azimuthal position is set by condition of destructive interferences (see following Sections).

Alongside, a new density maximum is obtained in the opposite azimuthal direction with respect to the core. Most interestingly, the obtained composite polariton fluid (which to an extent could be described in terms of displaced UP and LP vortices) is set into a very peculiar dynamics, with a rotation of the vortex core. Figure 2(d) also illustrates the amplitude and phase of the fluid at successive moments, where the phase singularity is at the boundary of a prevalently Gaussian-like distribution ($t = 1.58 \text{ ps}$), before coming back again closer to the inner region as in the last frame of Fig. 2(d) ($t = 1.72 \text{ ps}$). The induced trajectory is partially reported as a solid line in the amplitude maps, in the timespan of two Rabi periods ($t = 1.2 - 2.8 \text{ ps}$). It can be roughly described as spiralling with a looping time equal to the Rabi period $T_R = 0.8 \text{ ps}$ and radius damping given by the faster UP dephasing time $\tau_U \sim 2 \text{ ps}$. A similar effect, with opposite azimuthal direction and smaller radius, is obtained for the density center-of-mass, whose swirling represents the eOAM of the oscillating fluid. It is noteworthy to mention as well that the angular velocity, or the "swirling velocity" (rotation of the vortex around the center of the beam) is not constant, and actually varies a lot, mainly when the photon density is low (when most of the energy is in the exciton field)—see also supplemental movie SM1 and the following Section on the rartex modelization. During the first Rabi looping induced by the arrival of pulse $B$, the phase singularity is sweeping an elliptic curve with a mean radius of $20 \mu m$, that means it is moving at an average speed of $\sim 150 \mu m \text{ ps}^{-1}$, which is half the speed of light. It would be possible to expand the imprinting and the displacing beams, and to tune the relative power, in order to generate a rartex with superluminal movement ($> c$) of the phase singularity in the 2D device plane, and in the transverse plane for the emitted photonic component beam [83]. Such photonic emission could be used to drive another physical system [84] (e.g., an atomic BEC or optically trapped nanoparticles) and study their response to such a faster-than-light stimulus. It would be also interesting to devise the entity of angular momentum transfer [85] to an external system swept by our spiraling vortices.

The overall trajectory of the phase singularity can be observed as a $xyt$ vortex line, as shown in Fig. 3 in a $0.5 - 10 \text{ ps}$ time range. Here, we report such topological strings for two configurations, corresponding to counter-rotating initial vortices, i.e., with $l_A = +1$ and $l_A = -1$ winding. When starting with opposite winding (iOAM), also opposite spiraling directions are obtained (eOAM). This is an indication of the phase drive not only on the vortex initial displacement but on the entire desynchronization set by the interference between pulses $A$ and $B$ polaritons. The $xyt$ (2D plus time) rartex string topology is also imprinted in the emitted photonic beam, where it is directly mapped into the 3D $xyz$ structure, with $z$ the longitudinal direction of propagation. The spiraling-vortex tube represented in Fig. 3 would hence bear a 3D aspect ratio of approximately 75:1, having a longitudinal length of $3000 \mu m$ (i.e., along a duration of $10 \text{ ps}$) and a cross section with $40 \mu m$ size.

FIG. 3. Rartex topological strings in the $xyt$ domain. The two realizations (time range $t = 0.5 - 10 \text{ ps}$, step $\delta t = 0.02 \text{ ps}$) correspond to opposite $l = +1$ and $l = -1$ initial vortex charges, highlighting the resulting opposite spiraling effects.
IV. RARTEX MODELLISATION

The dynamics of the rartext can be captured by using two coupled-2D Schrödinger Equations \[\text{(c-2DSE)},\] most conveniently expressed in matrix form:

\[
\begin{equation}
 i\partial_t \begin{pmatrix} \psi_C \\ \psi_X \end{pmatrix} = \left( \begin{array}{cc} \frac{-\hbar \Sigma^2}{2m_C} & \frac{\Omega}{2} \\ \frac{\Omega}{2} & \frac{-\hbar \Sigma^2}{2m_X} \end{array} \right) \begin{pmatrix} \psi_C \\ \psi_X \end{pmatrix} + \mathbf{F},
\end{equation}
\]

where the photonic and excitonic fields \(\psi_{C,X}\), which initially give rise to two parabolic dispersions defined by their mass parameter \(m_{C,X}\), are now coupled via the Rabi coupling term \(\Omega\). The excitation scheme is simply added through the vector \(\mathbf{F} = (LG_{01} T_A + LG_{00} T_B, 0)^T\), acting only on the photonic component, where the Laguerre-Gauss pulse \(LG_{01}\) carries the vortex phase singularity and is followed by the second Gaussian pulse \(LG_{00}\). The functions \(T_{A,B} = e^{-(t-t_{A,B})^2/2\sigma^2}e^{-i\omega t}\) account for the pulse temporal dynamics, where the pulses are sent at a time \(t_{A,B}\), with a temporal spread \(\sigma\), and at an energy \(\omega L\). We first assume no decay terms in the c-2DSE, as we will see later that it mainly affects the amplitude of the vortex oscillation. One can see in Fig. 4(a) the basic vortex dynamics obtained from the numerical model. Here, the Laguerre-Gauss pulse is sent at an early time to generate the vortex, and the Gaussian pulse is sent at \(t_B \approx 4\) ps. While only the photonic field \(\psi_C\) is easily accessible experimentally, the theory allows us to study as well the excitonic component \(\psi_X\). We can also describe the system directly through its eigenstates, namely the polariton fields \(\psi_{U,L}\) by combining the bare fields \(\psi_{C,X}\), where no Rabi dynamics is present. The position of the vortex in these different field components is displayed as a function of time in the 3D panel of Fig 4, namely, in red (blue) for the photonic (excitonic) field and in green (purple) for the lower (upper) polariton field, respectively. After the first pulse, the vortex is perfectly centered into the beam and is motionless (in all fields). After the second pulse, the minimum of intensity no longer remains in the center of the beam, as shown on the density plots, which induces the vortex oscillations. Once projected on the 2D \(xy\) plane, the vortices in \(\psi_{C,X}\) describe perfect circles \((e,f)\), whereas in \(\psi_{U,L}\) they are simply shifted to a fixed position out of the center of the beam \((g,h)\). However, the \(\psi_{C,X}\) vortex in \(xyt\) is not perfectly helical, as the vortex angular velocity varies in time. The \(\psi_C\) and \(\psi_X\) vortices rotate around each other at the Rabi frequency similarly to a Newton’s cradle, one vortex slowing down while the other accelerates.

A complementary insight of the vortex dynamics can be obtained by looking at the OAM value for the different fields. The OAM is here conserved through the sum of the OAM of each sub-fields, which allows the OAM of the individual fields to vary. We thus have:

\[
\begin{equation}
\frac{d}{dt}(\langle \hat{L}\rangle_{\psi_C} + \langle \hat{L}\rangle_{\psi_X}) = \frac{d}{dt}(\langle \hat{L}\rangle_{\psi_U} + \langle \hat{L}\rangle_{\psi_L}) = 0,
\end{equation}
\]

where \(\langle \hat{L}\rangle_{\psi} = \langle \psi | \hat{L} | \psi \rangle\) is the expectation value of the operator \(\hat{L} = -i\hbar(x\partial_y - y\partial_x)\) acting on a field \(\psi\), the other components \(\hat{L}_x\) and \(\hat{L}_y\) being null as the system is 2D. The particle number is conserved in the same way:

\[
N_{\psi_C} + N_{\psi_X} = N_{\psi_U} + N_{\psi_L},
\]

and only varies when a pulse is applied, bringing more

![Fig. 4. Rartext modelization in absence of damping. The left panel (a) shows the xyt vortex lines for the different polariton fields (purple is the phase singularity in the upper polariton mode, green the lower, red the photon, blue the exciton). The initial condition set by pulse A consists in overlapped vortex cores between any of the fields. Upon arrival of pulse B the vortex cores are displaced in different positions. Afterwhile the upper and lower polariton vortices remain fixed in time, being these the normal modes, while the photon and exciton vortices start to rotate. Photonic density xyt maps are overlapped at selected time frames. (b) Fields total populations. (c) Total orbital angular momentum for the different fields. (d) Orbital angular momentum per particle, normalized in units of \(\hbar\). The color code of the different fields is the same of the previous panel (UP, LP, photon and exciton are plotted in purple, green, red and blue, respectively). The conserved quantity is plotted in orange (it corresponds to the total value as a sum of photon and exciton, or as UP and LP). (e-h) On the bottom panels the density maps at a given time frame appear, together with the vortex trajectory, for any of the four fields \(\psi_{C,X,UL}\) and \(\psi_U\) are the photon, exciton, lower and upper mode, respectively). The arrival time of the vortex and plain-Gaussian pulses is \(t_A = 1\) ps and \(t_B = 4\) ps, respectively. See also supplemental movie SM2.](Image 317x371 to 562x626)
FIG. 5. Rartex modelization with respect to different key parameters. (a) Energy-momentum dispersion for the bare (dashed) and polariton (solid lines) fields. The three colour ellipses highlight different energy tuning $\omega_L$ of the excitation laser pulses. (b) Distance $\Delta R$ between the splitted upper and lower vortex cores, upon changing time delay $t_{AB}$ between pulses $A$ and $B$. (i-iii) 2D+1 vortex lines for each of the bare and polariton subfields, in absence of damping ($\gamma_U = 0$) and for different laser tuning conditions ($\omega_L = -3.0$ and $3\text{meV}$, respectively). (iv-vi) Vortex lines for different time delays $t_{AB}$ between the two excitation pulses, corresponding to the same labels in panel (b). ($\alpha, \beta$) Simulations with realistic dissipation rate. The upper polariton decay ($\gamma_U = 0.2\text{ps}^{-1}$) results in the continuous damping of the circular trajectories for the photon and exciton vortex cores (spiraling red and blue lines). In (a) the system is initialized with a larger UP mode content so that the photon and exciton vortices start to rotate around the UP vortex core (purple line). Upon population reversal due to the faster UP decay, the vortices go on rotating around the LP core (green line) in the latter part of the dynamics. See also supplemental movie SM3.

particles in the system. The particle number and the total OAM computed for the different fields are displayed in Fig. 4(b, d). As expected $\langle \hat{L} \rangle$ and $N$ vary at the Rabi frequency for the bare fields, and remain constant in the polariton components. These two quantities can be combined to obtain the OAM per particle, defined as their ratio $l_{\psi} = \langle L \rangle_{\psi}/N_{\psi}$ and whose values for the different fields are plotted in Fig. 4(d). When the vortices are exactly in the center of the beam, that is before the second pulse, the OAM per particle is exactly quantized to one unit of $\hbar$. After the second pulse, the $\psi_{U,L}$ vortices do not oscillate but are displaced on the periphery of the beam, with a corresponding value of $l$ lower than 1. As mentioned by Pitaevskii and Stringari [86], for a vortex core displaced from the center of the beam, the OAM per particle takes a value lower than 1, the axial symmetry of the problem being lost. This quantity can thus be regarded as a measure of the vortex eccentricity. As the $\psi_{U,L}$ vortices are here symmetrically displaced, $l_{\psi_U}$ and $l_{\psi_L}$ thus share the same value. On the other hand, the $\psi_{C,X}$ vortices oscillate from the center to the periphery in circle, so that the variation range of $l_{\psi_{C,X}}$ remains constant.

We have identified two key parameters determining the position and the amplitude of vortex oscillations: the laser frequency of the pulses, and the time delay between them. We first focus on the effect of the laser frequency $\omega_L$. As shown in a previous study [77], the energy level at which the system is excited dramatically affects the polariton state, and consequently the Rabi oscillations in the bare fields. We have solved the c-2DSE for different laser frequencies, scanning different energy regions from the lower to the upper polariton energy, as shown in the sketch in Fig. 5(a). The $\psi_{C,X}$ vortices follow a simple dynamics. If the system is excited close to the LP energy, the $\psi_{C,X}$ vortices oscillate in circle around the $\psi_L$ vortex, whereas they oscillate around the $\psi_U$ vortex if the laser hits the UP energy level, as shown in Fig. 5(i,iii).
When the system is exactly excited resonantly between the UP and LP, the $\psi_{C,X}$ vortices follows a straight trajectory between the position of the $\psi_{U,L}$ vortices, see Fig. 5(ii). The time delay between the pulses is the parameter that most strongly affects the amplitude of oscillations. They intrinsically depend on the distance $\Delta R$ between the splitted $\psi_U$ and $\psi_L$ vortices. As shown in Fig. 5(b), this distance varies periodically (at the Rabi frequency) with the time delay $t_{AB}$ between the pulses. Examples involving different time delays are given in Fig. 5(i, iv-vi). The maximum oscillation amplitude is reached when the second pulse is sent in the so-called “Rabi-phase”. In the “anti Rabi-phase” configuration, the $\psi_{U,L}$ vortices converge to the same point in space, canceling the $\psi_{C,X}$ vortex oscillations.

The configurations previously presented in Fig. 5(i, vi) are stable as no decay sources have been introduced so far. The limiting factor is experimentally known to be the UP decay [77]. A term $\gamma_U$ accounting for the UP lifetime can be introduced in Eqs. 1, once written in the polariton basis by diagonalisation. It now reads:

$$\hat{H} = \begin{pmatrix} E_L & 0 \\ 0 & E_U - i\gamma_U \end{pmatrix}. \quad (4)$$

One can come back to the photon/exciton basis by applying $P$, the eigenvector matrix of the original Hamiltonian: $H = \hat{P} \hat{H} P^{-1}$. Figures 5(α, β) show the effect of the UP lifetime on the vortex dynamics when the system is excited close to the LP or the UP. In the first case (β), the amplitude of the oscillations for the $\psi_{C,X}$ vortices is simply damped, as the polaritons in the upper state vanish. A more interesting dynamics appears when the system is initially excited at the UP level (α). After the second pulse, the $\psi_{C,X}$ vortices start to oscillate around the $\psi_U$ one, similarly to the undamped case (iii), but as the UP population diminishes, this configuration becomes unstable and the $\psi_{C,X}$ vortices switch to rotate from clockwise to anticlockwise around the $\psi_L$ vortex with a decaying amplitude.

Similar dynamics are obtained upon reverting the time sequence of the two pulses (firstly setting a plain-Gaussian pulse $A$ and then seeding a vortex beam $B$), or by sending displaced vortex beams $A$ and $B$, and even using opposite OAM (i.e., vortex and anti-vortex) in the two pulses. Since the vortex motion is directly powered by the Rabi oscillations, we expect that the accurate control of these new topological strings could be achieved in the same way that we performed to control the quantum state (on the Bloch sphere) or the pseudospin (Poincaré sphere of polarization) in our previous experiments [77, 78]. The retarx scheme here enables an ultrafast topology shaping of the vortex state (on the equivalent OAM-Poincaré spheres [87], or even the shaping of vector beams on the spin-orbit hypersphere, if combined with the SAM degree of freedom [88, 89]).

V. PHASE CONTROL OF SPIRAL STRINGS

Coherent control hence allows us to rotate the whole $x,y,t$ topological strings around the $t$ axis by setting the relative phase delay $\varphi_{AB}$ between the two pulses. An example of this is shown in Fig. 6, left panel, where two vortex trajectories with the same winding are shown in the $0.5-6.0$ ps time range, for two slightly different values of phase delay. The entire $x,y,t$ topological surface described by the vortex strings when sweeping the relative phase $\varphi_{AB}$ can be drawn as illustrated in Fig. 6, right panel. It has been mapped at regular time intervals of $0.1$ ps, upon changing $\varphi_{AB}$ by successive $\sim \lambda/8$ steps (solid spheres). It is almost symmetric around the initial vortex position, and its radius breathes with the Rabi period. Here the detail of the spiraling vortex line during a single Rabi period ($2.0 - 2.8$ ps) is shown (blue tube, sampled every $20$ fs), as an example of how such a line is carved on the topological surface. It is straightforwardly observed that every encircling line that encompasses the topological surface produces a unitary

![Image](https://example.com/image6.png)

**FIG. 6.** Time-space vortex string and phase control. [left panel] The $x,y,t$ vortex trajectories (time range $t = 0.5-6.0$ ps) are shown for two different optical phase differences $\varphi_{AB}$ between pulse $A$ (vortex) and pulse $B$ (Gaussian). [right panel] A detail of the vortex line (blue tube) during a single Rabi period ($t = 2.0 - 2.8$ ps). The bottle-envelope represents the $x,y,t$ surface topology drawn by the different vortex lines when changing the optical phase delay between pulse $A$ and $B$. Its radius breathes with the Rabi oscillations. The topological bottle has been mapped (spheres) at $100$ fs time intervals, spanning $\varphi_{AB}$ in a $15\pi$ range by successive $\sim \lambda/8$ steps.
phase winding, for every value of $\varphi_{AB}$. If the phase delay between the two pulses is not controlled, and is randomly varying, the overall effect is to have an external 2D region that is never touched by the vortex core, an intermediate corona which is stochastically spanned by the flow vorticity, and an inner region of high flow intensity varying in direction pulse-by-pulse. The circular symmetry of the surface is a direct consequence of the symmetry of the initial vortex pulse $A$, of the Gaussian pulse $B$ and of their concentric alignment. This is also evident in the panels of Fig. 7, which report amplitude and phase of the polariton fluid at a fixed time into the dynamics ($t = 2.6 \text{ ps}$) but for different phase delays ($\varphi_{AB}$ spaced by $\pi/2$ intervals, which in other terms is $\lambda/4$ length delay differences). The displacement distance of the vortex from the centre at this time is always the same, but changing for the azimuthal direction according to the previous considerations, describing an almost perfect circle (black/white line). The rartex line in the virtual $xy\varphi_{AB}$ space assumes the helicoidal shape, as represented in Fig. 7, right panel.

### VI. DOUBLE RARTEX

A more complex experimental configuration involves a double vortex. Here, by means of a different $q$-plate carrying a double topological charge, we shape the photonic pulse into a modified $LG_{02}$ state [73]. Its $t = 2$ winding is translated into two unitary co-winding vortices, whose initial separation can be controlled by the tuning of the $q$-plate device. We exploit this effect to realize a polariton fluid with two spatially separated phase singularities, basically introducing an asymmetry factor in the initial state and in the following dynamics. Initially, the vortex cores are stably located in the inner region of the spot, split by about $12 \mu m$ along an oblique direction. This can be spotted in the maps of Fig. 8 reporting the amplitude and phase of the double vortex state at the time of $t = 2.0 \text{ ps}$ immediately before the arrival of the Gaussian pulse $B$. Upon overlap of pulse $B$, the vortices are moved further away in opposite directions, and reach a maximum distance of $\approx 40 \mu m$ (see panels corresponding to $t = 2.32 \text{ ps}$), starting a rotating movement. They reach a horizontal alignment ($t = 2.56 \text{ ps}$), before coming back to the central region after one Rabi period, top panels ($t = 2.80 \text{ ps}$). Their trajectories, extended into the next Rabi period ($t = 2.0 - 3.6 \text{ ps}$), are reported as solid lines. In summary, the two $xyt$ vortex lines are spiraling with respect to new equilibrium positions, as resumed by the rartex strings (right panel). We point out that the two strings have the same winding (iOAM), and consequently the same spiraling directions.

Coherent control of the optical phase delay between pulses $A$ and $B$ can be performed also for the double vortex, similarly to the previous case. Figure 9 (left panels) show the density at a fixed time of the previous dynamics ($t = 3.7 \text{ ps}$), but for different relative phase delays $\varphi_{AB}$ spaced by equal intervals of $\pi/4$ (corresponding to $\lambda/8$ steps in terms of space). They both describe the same circle (black/white line) when sweeping the phase delay, exchanging their positions when changing $\varphi_{AB}$ along a $\lambda/2$ length. Although the distribution of the polariton fluid and the positions of the vortex cores look as invariant through such a change, nevertheless, the two vortices can be distinguished by the continuity of their positions (true invariance is obtained upon integer $\lambda$ change). The topological surface in the $xyt$ space described by the double vortex strings is shown in Fig. 9 (mid panel), in the time range of one and half Rabi period ($t = 2.5 - 3.7 \text{ ps}$). It has been retrieved with the same procedure as in the case of the single vortex. Here the solid spheres represent the position of

![Image](image-url)
FIG. 8. Spiraling of a double quantum vortex. [Left and mid panels] Amplitude and phase maps of the polariton fluid, when starting with a double vortex and after arrival of the Gaussian pulse. The different frames correspond to time of $t = 2.0, 2.32, 2.56$ and 2.80 ps. The instantaneous phase singularities are tracked as yellow dots in the amplitude maps, and the solid lines represent the vortex trajectories integrated over two Rabi periods ($t = 2.0 - 3.6$ ps). [Right panel] Vortex lines plotted as $xyt$ curves (time range $t = 0.5 - 10$ ps, step $\delta t = 0.02$ ps). See also the supplemental movie SM4.

FIG. 9. Phase control of the double vortex strings. [Left] Polariton amplitude maps in the double vortex experiment. The snapshots are taken at $t = 3.7$ ps, and with four different phase delays $\varphi_{AB}$ spaced by $\pi/4$. The phase singularities have been marked with blue/red dots in the amplitude maps, and the black/white line is the fitting circle to the topological bottle. [Mid panel] The $xyt$ vortex lines of the two quantum vortices (blue and red tubes) during a one and half Rabi period (time range $t = 2.5 - 3.7$ ps). The topological bottle described by the vortex lines when sweeping the optical phase delay between the two pulses has been mapped (spheres) at 100 fs or 50 fs time intervals, spanning $\varphi_{AB}$ in a $15\pi$ range by successive $\lambda/8$ steps. [Right panels] Isotime vortex lines described when changing $\varphi_{AB}$ as explained before. The top and bottom panels correspond to $t = 3.7$ ps and $t = 2.6$ ps, respectively.

The two phase singularities, tracked at time intervals of $t = 0.1$ ps ($t = 0.05$ ps in the last part) and sweeping $\varphi_{AB}$ at $\lambda/8$ steps. The red and blue solid tubes are instead the vortex strings associated to a fixed phase delay (same of the previous Fig. 8, sampled with $\delta t = 0.02$ ps), climbing on the surface. Such a topological surface produces a self-twisting double bottle. It still appears to have a cylindrical symmetry, but in reality, two different topologies are observed, which can be revealed by plotting the isotime vortex strings in the virtual $xy\varphi_{AB}$ space. Indeed, when the distance between the two vortices is at a minimum, the trajectories become uncoupled, and each vortex follows a helix trajectory around different centers, as in Fig. 9 (right bottom panel, at $t = 2.6$ ps). This asymmetry is introduced as an anistropy factor given by the starting splitting of the two vortices, when compared to the displacement induced by pulse $B$. Hence, there is a nodal string of the topological bottle (intersection with fixed $t$ plane), where the double concentric cylinder undergoes a metamorphosis into two non-concentric and separated cylinders: the projection of such $xy\varphi_{AB}$ nodal string onto the $xy$ plane is a 8-shaped line (see also [83]). This example highlights the complexity of vortex strings and topological surfaces obtainable with polariton fluids when powered by the Rabi oscillations. Future directions to explore include...
FIG. 10. Moving Rabi vortex. (a) The $xy$ space maps of the polariton photonic amplitude at early time, at equidistant frames of $t = 1.80, 1.84, 1.88, 1.92$ and $1.96$ ps (bottom to top, respectively). Despite the propagation is to the right, the initial reshaping due to vortex rotation is such large that the packet seems moving slightly to the left, at such early times. (b) The polariton amplitude at later times, at equidistant frames of $t = 2, 4, 6, 8$ and $10$ ps, respectively. (c) Timespace chart of the polariton amplitude taken along the $x$ direction of movement, showing the Rabi oscillations and the spatial propagation. The launching momentum corresponds to a central $k = 1.9 \mu m^{-1}$ and the average group speed of the whole packet is $v_g = 1.3 \mu m$ ps$^{-1}$. (d) Vortex line plotted as $xyt$ curves (time range $t = 0.5 − 11$ ps, step $\delta t = 0.02$ ps). The trajectory is broken because in the $t = 1.82 − 1.94$ ps range two simultaneous vortices are seen (as represented in the left panels), the initial one pushed to the boundary (red curve, $0.50 − 1.94$ ps) and the replacing one drawn to the centre (blue curve, $1.82 − 11.0$ ps). The projection on the $xy$ plane illustrates the damped cycloid of the phase singularity during the vortex run. See supplemental movie SM5.

the implementation of such topology shaping to even more variegated beams, to realise, e.g., rotating vortex lattices or vortex-antivortex lattices (and observing, in the latter case, ultrafast cycles of pair-annihilation and -generation events).

VII. MOVING RARTEX

The peculiar dispersion of polariton fluids can be exploited to implement swirling beam and vortex dynamics, even in the case of a single-pulse experiment. Indeed the different effective masses of the LP and UP nor-
mal modes, result in their distinct group velocities \[59\], whereby a single wavepacket created at a finite in-plane wavevector \(k\), upon oblique incidence resonant fs-pulse excitation, can hence split into two fluids travelling at different speeds. As the initially coincident UP and LP vortex packets continuously drift apart, they trigger a rartex dynamics if carrying an iOAM. As a result, oscillating photonic and excitonic vortex states are seen once again, rotating both in their centre-of-mass and phase singularity, while moving.

The moving rartex experiment is shown in Fig. 10. There, the packet is launched by a femtosecond pulse at central in-plane wavevector of \(k = 1.9 \, \mu m^{-1}\), slightly above the inflection point of the LPB dispersion. We recall here that while the UP mode has a monotonically increasing group velocity \(\partial\omega / \partial k\) with the in-plane momentum \(k\), the LP presents a maximum velocity at the inflection point of the \(\omega(k)\) dispersion curve (see Fig. 1) \[58, 59\]. The first column shows the nontrivial dynamics of the rotating vortex during one of the initial Rabi oscillations. Panels of Fig. 10(a) correspond to isospaced time frames at 40 fs intervals, taken around the second minimum of the oscillating photonic amplitude (\(t \approx 2 \, ps\)). Here, the initial vortex core is suddenly displaced outside the density ring, and it is replaced by a cowinding vortex drawn from the outside. Their simultaneous presence is visible in the mid panels of Fig. 10(a). During the relevant time interval, the phase circulation along a closed ring still remains unitary because the excess vortex is compensated by an antivortex charge. Such splitting is ascribed to the initial effect of the UP and LP packets moving with differential speed, when they start to separate and the density of the UP is still larger (the secondary vortex is also seen at the two successive Rabi minima, but remaining at the boundary because of UP dephasing). Subsequently, the vortex packet therefore propagates preserving its shape, as shown in Fig. 10(b) (panels of the second column), which are taken at successive time delays of 2 ps. The full \(x_2y_2\) vortex line has been reported in Fig. 10(d). Here, apart from the initial splitting around 2 ps, the phase singularity is tracked as a continuous string in the following dynamics. Its structure consists in a translation movement plus a Rabi rotation, whose projection on the \(xy\) plane is basically a damped cycloid. The linear movement is associated to the whole vortex packet, with the core which would reside in its centre during movement (in absence of oscillations), while the Rabi-induced rotation periodically brings the core inside and outside the centre. Both the Rabi oscillations and the spatial propagation can be seen in Fig. 10(c), reporting the timespace chart of the photonic amplitude taken along the horizontal line of movement. The slope in such charts is associated to a vortex packet running at a group velocity \(v_g = 1.3 \, \mu m \, ps^{-1}\), in good agreement with the fitting of the LP mode dispersion \[58\] (which branch is the most contributing to the seen photonic density at long time).

The theoretical/numerical modelisation of the moving rartex is shown in Fig. 11. Here the Laguerre-Gauss profile is set in the photon field and imparted with a momentum \(k_x = 2 \, \mu m^{-1}\). This results in a moving vortex along the \(x\)-axis that Rabi oscillates. The radius of the vortex oscillations slowly increases as the beam propagates. As the UP and LP fields start to split, we observe the appearance of an other oscillating vortex core. As shown in Fig. 11(c-d) at \(t = 80 \, ps\), the beam contains two counter-rotating vortices. The same dynamics is observed in the exciton, but in this field, the vortices are oscillating in opposite directions with respect to the ones in the photonic field. After a long propagation time, the two polaritons are fully spatially separated, as seen in Fig. 11(e-f) at \(t = 300 \, ps\), at which point the system does not exhibit Rabi oscillations any more. We have not included the different decay rates and dephasing of the polaritons in order to observe the full dynamics. Such a picture is not possible to obtain with the current microcavity polariton samples. It is however useful to have it in mind to understand the full dynamics. An interesting result arises from the OAM \(\langle \hat{L} \rangle_\psi\), as shown in Fig. 11(g) for early times. Similarly to the two-pulse case, we see an oscillation of the OAM for the photonic and excitonic fields, but more surprisingly, this time the value of \(\langle \hat{L} \rangle_\psi\) increases with time. The OAM oscillation amplitude can be increased here by one order of magnitude with respect to the initial value, that depends on the beam’s density. The OAM is however still conserved through the sum of \(\langle \hat{L} \rangle_\psi_{\phi} \) and \(\langle \hat{L} \rangle_\psi_{\chi}\) (green curve). This result is at first surprising, but is not unphysical, since the UP and LP are slowing splitting in space, increasing at the same time the radius and the velocity of the vortex oscillations. The value of the OAM is expected to decrease as the UP and LP are separated, limiting the effect of the Rabi oscillations. This is what we see in Fig. 11(h), where the OAM was computed for a larger timescale. At large times, the OAM value converges to a single value, half of \(\langle \hat{L} \rangle_\psi_{\phi} \). This is a beautiful manifestation of the conservation of angular momentum in a system that has so many different degrees of freedom amongst which to be exchanged. We have seen that in the absence of overlap between the two wave functions (UP and LP here), the expectation value of \(\langle \hat{L} \rangle_\psi\) reduces to the sum of the expectation values of the sub-fields, which is steady and does not oscillate.

VIII. CONCLUSIONS

We have observed the dynamics of vortices in Rabi-oscillating fluids, here named “rartex”, which exhibit ultrafast spiraling effects due to the interplay of various types of angular momentum. The composite structure that results allows a vortex core to precess in the beam if their polaritonic vortex components are spatially separated. This dynamics can be triggered by sending a pulsed Laguerre-Gauss beam, that imprints the vortex
phase to the polaritons, and a second pulsed beam to displace the original vortex and couples its dynamics to that of the Rabi oscillations. Another method consists in taking advantage of the effective mass imbalance between the UP and LP modes, whose packets propagate with a different group velocity for a given imparted momentum. In both cases, the vortices of the polariton modes are spatially separated, and the vortices in the bare fields (excitons and photons) oscillate between them. This dynamics provides the basis for a new concept of topological shaping. The scheme is universal and can be extended, in principle, to many different platforms that involve fields of coupled oscillators. While the number of works on vortices in quantum fluids is enormous, such a vortex dynamics, that arises from the superposition of vortex states in polaritons, has not been observed in analogue systems so far, although synthetic gauge fields in cold-atom systems are going in this direction. Apart from the fundamental physical interest, these vortices could find applications in information processing (we have mentioned examples with multiplexing) or optical tweezers schemes. They could also be used as sensitive polariton gyroscope since they present a macroscopic and easily detectable response to small perturbations. Spiraling vortex lattices represent a straightforward extension to be used to trap or drive, e.g., atomic BECs. On demand, the rartex lattices can also be made superluminally rotating.

FIG. 11. Moving rartex modelization without damping. The top panels represent the density maps of both the photon (left, $\psi_C$) and exciton (right, $\psi_X$) components, at three different time frames of the vortex packet run ($t = 0$ ps, 80 ps and 300 ps). At later time the maps highlight the splitting of the initial vortices into the LP and UP normal mode packets, running at different speeds. The bottom panels present the OAM analysis for the running rartex. At short time the OAM oscillations grows as the LP and UP packets start to separate. At later times the OAM oscillations decrease because of the reduced space overlap between the two packets. In the realistic case the oscillations would quench in a shorter time range due to the fast UP dissipation. The OAM is conserved in the total field (green line). See also supplemental movie SM6.
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APPENDIX: SUPPLEMENTAL MOVIES

Movie S1 Experimental rartex dynamics as in Fig. 2. Photonic amplitude and phase in a 100 μm × 100 μm area, with 20 fs time step. The Gaussian beam B is arriving at around t = 1.6 ps The vortex core position is marked with a yellow dot in the amplitude map.

Movie S2 Computational rartex dynamics in absence of damping, as described in Fig. 4. The density map of the four subfields is shown during time. The vortex pulse A is arriving at t = 2 ps and the Gaussian pulse B is arriving at t = 6 ps. The four labels ψ_C,X,U,L indicate the cavity photon, the exciton, the upper mode and the lower mode subfields, respectively.

Movie S3 Simulated rartex dynamics associated to different parameters, and arranged in the same order as in Fig. 5. The 2D+t vortex lines for each subfield are shown (red, blue, purple and green line for the photon, the exciton, the upper and the lower mode, respectively). The xy photonic maps are shown too on the t = 0 and current time planes of each graph.

Movie S4 Experimental double rartex dynamics, as described in Fig. 8. Photonic amplitude and phase in a 120 μm × 120 μm area, with 20 fs time step. The vortex core positions are marked with yellow dots in the maps.

Movie S5 Experimental moving rartex dynamics as described in Fig. 10. The phase singularity is marked with a dot in the amplitude map.

Movie S6 Computational moving rartex dynamics in absence of damping, as described in Fig. 11. Both the photon and exciton components are shown, during the vortex packet propagation. The bottom panel shows the OAM oscillations, increasing with the initial packets’ separation and then lowering down due to decrease of the packets’ overlap at later times. The simulation allows also to appreciate the UP mode (leading vortex) and LP mode (trailing vortex) different group speed.

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