Experimental generation of arbitrary abruptly autofusing Circular Airy Gaussian vortex vector beams

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Complex vector modes represent a general state of light nonseparable in their spatial and polarization degrees of freedom, which have inspired a wide variety of novel applications and phenomena, such as their unexpected propagation behaviour. For example, they can propagate describing periodic polarization transitions, changing from one vector beam to another. Here, we put forward a novel class of vector modes with the capability to experience an abruptly autofocusing behaviour. To achieve such beams, we encode the spatial degree of freedom in the Circular Airy Gaussian vortex (CAGV) beams. We demonstrate the experimental generation of arbitrary CAGV vector beams and evince some of their properties, such as a rotation of intermodal phase. We anticipate that the fascinating properties of theses modes will prompt the development of novel applications associated to their autofocusing behaviour and polarization distribution.

Complex vector light beams have drawn a significant amount of attentions in recent time, in part due to the many applications that have inspired, but also due to the novel concepts and phenomena that are giving rise to1,2. Such modes are generated as a non-separable superposition between the spatial and polarization degrees of freedom (DoF), in a mathematical form identical to that of entangled photons, from which they coined the term classically-entangled. Crucially, the unlimited freedom in the spatial DoF gives rise not only to exotic polarization and intensity distributions in the transverse plane, but also to intriguing propagation behaviours, such as periodic or non-periodic polarization transitions, self-healing, transverse acceleration or resilience against atmospheric turbulence3–10. Even though cylindrical vector modes, such as, Laguerre- or Bessel-Gaussian, have gained popularity over the years, in recent time the generation of vector beams in noncylindrical coordinates systems have become a topic of late9–12. For example, travelling Parabolic- or accelerating-Gaussian vector modes that upon propagation in free space, evolve from a pure vector state to a quasi scalar one9 or accelerate along a parabolic trajectory preserving their polarization structure10. Vector beams have already demonstrated their potential in a wide variety of research areas such as, optical tweezers, optical metrology, optical communications, among others1,13–20. Hence, along with the discovery of novel vector beams, other fascinating properties will be discovered, paving the path to other applications.

As such, in this manuscript, we propose and experimentally demonstrate a general class of vector modes, which we term Circular Airy Gaussian vortex vector (CAGVV) beams, that are generated from a non-separable superposition of the polarization and spatial DoF encoded in the set of orthogonal Circular Airy Gaussian Vortex (CAGV) beams. Even though CAGV modes are well-known due to their abrupt autofocusing dynamics along the propagation direction, which has encountered several applications21, most of the work has been carried out in the scalar regime, including Circular Airy Gaussian beams, CAGV, elliptical Airy beams, amongst others22–24. Despite that a similar class of vector beams has been reported in the past25, the authors only focused on the abrupt polarization transition. Here we not only propose the generation of arbitrary CAGVV modes but also analyze the phase dynamics that such modes of different topological charges undergo upon propagation. More precisely, their intermodal phase rotates upon propagation as a function of the topological charges constituting the CAGVV vector mode. We provide a mathematical expression for this intermodal phase shift and

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Figure 1. Polarization distribution (front panels), intensity profiles (middle panels) and transverse phase (back panels) of the modes (a) $U_1 \hat{e}_R$, (b) $U_{-1} \hat{e}_L$ and (c) $\Psi_{1,-1}$, respectively. In (d) we illustrate schematically the autofocusing effect such beams experience upon propagation. Here, orange and green ellipses represent right and left circular polarization, while black lines symbolize linear polarization. For this example, $a = 1$, $w = 0.1$, $r_0 = 1$, $v_1 = v_2 = 0$.

demonstrate it experimentally. Finally, a propagation-dependent transition from linear to elliptical polarization is evinced through the Stoke Parameter $S_3$, which we corroborate theoretically and experimentally. Due to these intriguing properties, we anticipate CAGV beams to be a practical and flexible tool, with applications in both, fundamental and applied research.

**Theoretical background**

In the cylindrical polar coordinates, CAGV beams are given by,

$$U_m(r, \phi) = \frac{1}{w} Ai \left( \frac{r_0 - r}{w} \right) e^{i \theta + \nu} e^{i m \phi} e^{i \nu r},$$

where $Ai(\cdot)$ is the Airy function, $w$ is a scaling factor, $a$ is a truncation parameter and $r_0$ is the beam radius in the initial plane. The parameter $\nu$ is the initial launch angle, which plays a key role in the parabolic trajectory the beam follows upon propagating, for $\nu > 0$ propagate outwards along a diverging parabolic trajectory, while for $\nu < 0$ they propagate inwards describing an abruptly autofocusing trajectory. Additionally, such CAGV beam features an azimuthally-varying phase of the form $\exp(i \nu r)$, where the index $m \in \mathbb{Z}$ is known as the topological charge, associated to an $m \hbar$ amount of orbital angular momentum (OAM) per photon, with $\hbar$ being the reduced Plank constant.

To generate the CAGVV modes we coaxially superimpose two orthogonal CAGV modes of different topological charges and orthogonal polarization state in a nonseparable weighted superposition. Such superposition can be mathematically written as,

$$\Psi_{m_1,m_2}(r, \phi) = \cos \theta U_{m_1}(r, \phi) \hat{e}_R + \sin \theta \exp(i \alpha) U_{m_2}(r, \phi) \hat{e}_L,$$

where $\hat{e}_R$ and $\hat{e}_L$ are unitary vectors representing the right- and left-handed circular polarization states, respectively. $U_{m_1}(r, \phi)$ and $U_{m_2}(r, \phi)$ represent the CAGV modes with topological charges $m_1$ and $m_2$, respectively, weighted by the parameter $\theta \in [0, \pi/2]$. Additionally, the inter-modal phase $\exp(i \alpha)$, with $\alpha \in [0, \pi]$, sets a phase delay between both polarization components. From now on, we will omit the explicit dependence of $(r, \phi)$, unless is necessary.

For the sake of clarity, such superposition is schematically shown in Fig. 1 for the specific case $\Psi_{1,-1}$, constituted by the superposition of the scalar modes $U_1 \hat{e}_R$ and $U_{-1} \hat{e}_L$, as shown in Fig. 1a,b, respectively. Here, their polarization distribution is shown in the front panels with the orange ellipses representing right-handed circular polarization and green left circular. The middle panels show their intensity profile and the back panels their respective phase distribution. For this specific example we selected $\theta = \pi/4$, $\alpha = 0$ and $z = 0$, the resulting vector mode features a transverse radial polarization distribution, as schematically shown in Fig. 1c.

Importantly, the intensity profile of CAGVV beams inherit the self-focusing property of CAGV modes and therefore also feature an abruptly intensity collapse as function of propagation, as schematically illustrated in Fig. 1d. In addition their intermodal phase undertakes a phase rotation $\Delta \phi$, which depends directly on the topological charge of both CAGV scalar components. Such phase rotation has been observed theoretically before and according to Dong Ye et al., it is not attributed to the Gouy phase optical vortices acquire upon propagation in free space. Crucially, it was demonstrated in the context of scalar modes that a coaxial superposition of Laguerre-Gaussian beams give rise to off-axis optical vortices, which upon propagation rotate about the beam axis due to the Gouy phase. Such rotation is proportional to the topological charges of the constituting beams, which for the specific case $p = 0$ reduces to.
will be given by, through the Stokes parameter $S_{1}=\frac{\cos \phi}{\sin \phi}$.

Such phase rotate an angle of Gouy phase $\Delta \phi = 0$ which is marked as yellow arrow.

The rotation of the intermodal phase can also be described by Eq. (3).

\[ \Delta \phi = \frac{|m_2|-|m_1|}{m_2 - m_1} \Delta \xi, \]

where $\Delta \xi = \arctan(z/z_R)$ and $z_R$ is the Rayleigh distance. We propose and demonstrate experimentally that even though the constituting scalar beams in CAGVV modes do not interfere since they have orthogonal polarization, the rotation of the intermodal phase can also be described by Eq. (3).

Results

We now conduct a detailed analysis of the propagation dynamics of the generated CAGVV beams, both experimentally and through numerical simulations. More specifically, we first compute the four Stokes parameters and from these reconstruct the transverse polarization distribution of CAGVV beams. From this we can also reconstruct the intermodal phase as $\alpha = \arctan(S_2/S_1)$ and monitor its rotation as function of propagation. Finally, through the Stokes parameter $S_3$ we can monitor the evolution of circular polarization as the mode propagates.

Such analysis is carried out for three different cases, namely, $|m_1| = |m_2|$, $|m_1| > |m_2|$ and $|m_1| < |m_2|$, at the planes given by $z = 0.0 \text{ mm}$, $z = 720.0 \text{ mm}$, and $z = 783.0 \text{ mm}$. All beams were generated using the specific parameters $\alpha = 0.4$, $\omega = 0.1$, $r_0=1$, $v_1 = v_2 = 0$, and $\theta = \pi/4$. Applying Eq. (3), we propose that the phase shift $\Delta \phi$ these mode will acquire upon propagation from $z = 0$ to the focusing plane $z = \infty$ will be given by,

\[ \Delta \phi = \frac{|m_2|-|m_1| \pi}{m_2 - m_1} \frac{1}{2}, \]

where we have used that $\Delta \xi = \arctan(z/z_R) = \pi/2$.

As a first example we present the cases with equal topological charges $|m_1| = |m_2|$, which is shown in Fig. 2 for the specific case $\Psi_{1,-1}$. Here, numerical simulations are shown in Fig. 2a while experimental results in Fig. 2b. The first row of each figure shows the polarization distribution overlapped with the intensity distribution. The second row shows the reconstructed Stokes parameter $S_3$ (left panel) and the intermodal phase (right panel). Note that upon propagation the intensity distribution undergoes an abrupt autofocusing effect, as expected. Notice also that the polarization distribution remains invariant, always featuring a radial distribution. In addition, the Stoke parameter $S_3$ also features no change. Finally, given that the absolute value of both topological charges is the same, the Gouy phase is in general $\Delta \phi = 0$ and therefore, no phase rotation will be observed.

We now present results regarding the cases with different topological charges $|m_1| > |m_2|$, using the specific case $\Psi_{1,0}$ shown in Fig. 3, numerical simulations in (a) and experimental results in (b), as an example. Again, the reconstructed polarization distribution overlapped with the intensity profiles are shown on the top panels.
of each figure, whereas the Stokes parameter $S_3$ and intermodal phase $\alpha = \arctan(S_2/S_1)$ on the left- and right-hand side, respectively, of bottom panel. Again, and as expected the intensity profile experiences an abrupt autofocusing propagation behaviour. Further, at the 0th this mode features a polarization distribution of a mixed linear polarization states, which upon propagation evolve to elliptical. This can be particularly observed from the Stokes parameter $S_3$, that precisely allows to quantify the amount of right- and left-circular polarization, that in the centre of the beam increases from 0 to 1. This transition can be explained as a transition from OAM to Spin Angular Momentum (SAM). In regards to the intermodal phase, the fact that $|m_1| \neq |m_2|$ causes, for this specific case a clockwise phase rotation $\Delta \phi = \pi/2$ as shown at the bottom of each figure. Noteworthy, this phase rotation is in accordance with Eq. (4).

We finally analyse the case of $|m_1| < |m_2|$, whereby and without the loss of generality, the specific case $\Psi_{1-2}$ is shown in Fig. 4. In a similar way to the previous cases, the transverse polarization distribution overlapped with the intensity profile are shown in Fig. 4a,b, numerical simulation and experimental results, respectively. Here again, an abrupt autofocusing behaviour in the intensity profile can be observed as the beam propagates. Additionally, their polarization distribution in the transverse plane also experience a transition from linear to elliptical. This behaviour can be quantified through the Stokes parameter $S_3$ on the bottom-left inset, where the intensity of each circular polarization component (left and right) increases as the beam propagates, in a similar way to the previous case. Finally, here also a phase rotation is observed originated from the inequality of $|m_1|$ and $|m_2|$, which in contrast to the previous case, it happens in an anticlockwise direction, as shown in the bottom-right inset of the same figure. For this specific example, a total phase rotation $\Delta \phi = -\pi/3$ can be observed, in accordance to Eq. (4).

Discussion

In this manuscript we introduced, theoretically and experimentally the Circular Airy Gaussian vortex vector modes, generated as a weighted superposition of Circular Airy Gaussian vortex beams. Such vector modes not only inherit the self-accelerating and autofocusing behaviour from their scalar regime, but also present a propagation dynamics of their transverse polarization distribution and intermodal phase rotation. To be more specific, their transverse polarization distribution evolves from linear to elliptical along the auto-focusing process, while the intermodal phase original angle allows to be under controlled following an invariant, clockwise and anticlockwise rotated trajectories. A possible explanation for this lies in the fact of a transfer from OAM to SAM, which can be directly observed via Stokes parameters. To corroborate this, we conduct a details analysis of the propagation dynamics of our generated CAGVV beams at various propagation distances and for three cases, namely $|m_1| = |m_2|$, $|m_1| > |m_2|$ and $|m_1| < |m_2|$. From this, we first reconstructed their transverse polarization distribution via Stokes polarimetry, where a polarization distribution of a mixed linear polarization states evolve to elliptical upon propagation. We further analysis the propagation dynamics of the intermodal phase that CAGVV modes experience upon propagation. From this we observed a propagation-invariant intermodal phase for the case $|m_1| \neq |m_2|$, a clockwise and anticlockwise phase rotation the cases $|m_1| > |m_2|$ and $|m_1| < |m_2|$, respectively. This findings allows us to provide a mathematical expression that related the rotation with both topological charges, which also fits well with previous studies applied to the scalar beams. We further quantified the observed experimental rotation through numerical simulations and demonstrated these results fit very well with the mathematical expression, evincing that indeed, the OAM not only directly affect the intermodal phase rotation, but also can be transferred to SAM upon propagation, see the intensity dynamics undergoes from zero to maximum in the transverse distribution of the Stoke parameter $S_3$. It is also worth mentioning that the dynamics of CAGVV can be adjust through the initial launch angle parameter $\nu$, which allows a wide variety of possibilities in the manipulation of propagation trajectories, as well as their polarization-variant structure.

In regards to the generation of complex vector beams, SLMs are perhaps one of the most versatile devices due to their high flexibility. In our technique, the SLM’s screen is digitally split into two sections and each encoded with an independent hologram, which enables a compact way to generate arbitrary vector modes. Another unsurpassed advantage of our setup is the high stability, which relies on the fact that both constituting scalar
beams travel the same optical path, experiencing exactly the same phase difference. Hence, our setup shows advantages not only in the wide variety of vector modes that can be generated, but also because it is highly robust against external perturbations.

In summary, complex vector modes inherit properties from the mode their spatial DoF encoded on, and give rise to many intriguing propagation characteristics. For example, accelerating-Gaussian vector modes propagate along a parabolic trajectory and feature propagation-invariant intensity and polarization distribution, the vector Bessel-Gauss beams shown in a non-diffracting way, maintaining the same intensity distribution while their polarization distribution undergoes a periodic transformation from one state to another. Nonetheless, our generated CAGVV beams present in this manuscript are completely different, not only in their initial complex amplitude but also in their propagation dynamics (which results from their intrinsic self-accelerating property), propagation behaviour, including the abrupt autofocusing of intensity, phase rotation, controllable propagation trajectory, amongst others. Particularly, the self-accelerating property of our generated CAGVV beams also give rise to a polarization dynamics, which demonstrated to be related with the topological charges of both constituting scalar mode. Finally, these novel vectorial states of light, are of paramount importance, which will pave the way towards the development of novel applications. For example, the CAGVV beams allows to offer a flexible tool for practical applications in a wide variety of fields, such as optical manipulation, optical tweezers, amongst others.

**Methods**

To generate CAGVV beams we implemented the experimental setup schematically depicted in Fig. 5. Here, a linear horizontally polarized laser beam (\( \lambda = 532 \text{ nm} \)) is expanded by lenses \( L_1 \) and \( L_2 \), and subsequently transformed into a diagonally polarized beam with the use of a half-wave plate (HWP\(_1\)) at 22.5°. Afterwards, a polarizing beam splitter (PBS) separates the beam into its horizontal (yellow color) and vertical (purple color) polarization components. With the help of mirrors \( (M_1 \) and \( M_2 \), both beams are directed to a spatial light modulator (SLM), which in conjunction with the PBS for a highly stable interferometer. The screen of SLM is digitally split into two sections (left and right), each of which is addressed with one independent hologram, which encodes the Fourier transformation of the constituting wave fields defined by Eq. (1). In combination with a lens \( L_3 \) (\( f = 300 \text{ mm} \)), two independent optical fields are generated in the focus plane. Due to the fact that SLMs only modulate horizontal polarization, HWP\(_2,3\) are used to properly modulate the polarization states of both beams, before and after hitting the SLM. Notice that each arm travels the same optical path, no extra phase difference is induced in the whole round trip. Finally, the two target optical fields exit the interferometer from the opposite side of the PBS, travelling along a common-path, generating in this way the desired vector beams in the linear polarization basis. To transform them from the linear to the circular polarization basis, a quarter-wave plate (QWP) at 45° is inserted along the path of the beam. Finally, a charged-coupled device (CCD: FL3-U3-120S3C-C with a resolution of 1.55 μm) placed in the focal plane of \( L_3 \), is mounted on a rail to record the intensity of the generated beams as a function of propagation. From such intensity measurements the polarization distribution of CAGVV modes are reconstructed, directly from the Stokes Parameters \( S_0, S_1, S_2, S_3 \), through the relations\(^{11}\),

\[
S_0 = I_H + I_V, \quad S_1 = 2I_H - S_0, \quad S_2 = 2I_D - S_0, \quad S_3 = 2I_K - S_0.
\]

Here, the required intensity projections, which represent the horizontal, vertical, diagonal and right-circular polarization components are represented by \( I_H, I_V, I_D \) and \( I_K \), respectively. Such intensities can be experimentally measured through a series of phase retarders inserted in front of the CCD camera. More specifically, we measure the \( I_H, I_V \) and \( I_D \) by passing the generated beam through a polarizer oriented at 0°, 90° and 45°, respectively, while \( I_K \) is measured by inserting a QWP at 45° with the polarizer at 90° (see\(^{11}\) for more details). As way of example, we show the experimental Stokes parameters in Fig. 6a, where the reconstructed polarization distribution overlapped with the intensity profile \( S_0 \) for the specific case \( \Psi_{1,-1} \) at the plane \( z = 0 \) is represented in Fig. 6b. It is also worth...
Figure 6. Experimental Stokes parameters $S_0, S_1, S_2$ and $S_3$ of the vector mode $\Psi_{1,\pm 1}$ are represented in (a), respectively, from which the polarization distribution can be reconstructed, as shown in (b), where the intensity profile is also shown.

noting that the same amount of right- and left- circular polarized components in this case results in the zero intensity distribution of the Stokes parameter $S_3$ (see right bottom panel in Fig. 6a), that is also the reason that the final reconstructed transverse polarization distribution features with radial linear polarized states (see Fig. 6b).

Data availability
All data regarding the work presented here is available upon reasonable request to the corresponding author.

Received: 12 September 2022; Accepted: 25 October 2022
Published online: 31 October 2022

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**Acknowledgements**
This work is supported by Science Foundation of Zhejiang Sci-Tech University (ZSTU) under Grant No. 22062025-Y, the National Natural Science Foundation of China (61975047) and Natural Science Foundation of Heilongjiang Province (LH2022A016).

**Author contributions**
B.Z. performed the experiments. X.B.H., B.Z. and C.R.G. analysed and interpreted the results. X.B.H. and C.R.G. wrote the manuscript. X.B.H., R.P.C. and C.R.G. supervised the project.

**Competing interests**
The authors declare no competing interests.

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