Measuring both magnitude and sign of the orbital angular momentum of light in a Laguerre-Gaussian rotational-cavity system

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The orbital angular momentum (OAM) intrinsically carried by vortex beams has great application prospects due to its theoretically unbounded and orthogonal modes. Here, we propose a scheme to measure OAM including its magnitude and sign in a Laguerre-Gaussian (LG) rotational-cavity system, which consists of two input couplers and a rotating mirror. We show that since the effective cavity detuning in the traditional single LG cavity is only related to the magnitude of OAM, but not to its sign, only the magnitude of OAM can be measured based on the shift of the transmission spectrum of the probe field. In the double LG cavity, however, the effective cavity detuning varies with the magnitude and sign of OAM, which causes the spectral shift to be directional for different signs of OAM, thus we can simultaneously measure both of them, in which the measurable topological charge value can reach to ±50. Our scheme can not only measure a wide range of OAM, but also can distinguish its sign, which is a significant improvement for measuring OAM based on LG rotational-cavity system and can also expand its application prospects in the field of quantum sensing.

I. INTRODUCTION

Vortex beams, such as Laguerre-Gaussian (LG) beam, possess an azimuthal phase structure $e^{il\varphi}$, which can carry a well-defined orbital angular momentum (OAM) of $\hbar l$ per photon, with $\varphi$ and $l$ being its azimuthal angle and topological charge value [1][2]. This type of beams can be generated by diffracting a non-helical beam off a spiral phase plate [3][4] or off a computer-generated hologram [5][6]. Recently, the generation and detection of OAM-tunable vortex microlasers on the photonic chip were realized [7][8]. Due to their quantized OAM and their dynamic characteristics, these helically phased beams are widely used in many fields, such as quantum information technologies [9], optical communications [10][11], optical trapping [12], optical tweezers [13][14], and so on. Thus, it is of great importance to measure OAM of vortex beams (or its topological charge value) accurately, including both the magnitude and the sign.

To measure OAM of vortex beams, in general, we can analyze the related interference patterns directly, for example, the interference pattern between the spiral wave front and a flat wave front [15], or the interference pattern between a vortex beam and its mirror image [16]. With the use of a triangular aperture and an annular aperture, the measurement of the topological charge value with $l = \pm 7$ and $|l| = 9$ based on diffraction pattern were also reported [17][18]. Besides, the highest measurable value of the topological charge was raised to ±25 by using annular gratings [19]. Recently, based on optomechanically induced transparency (OMIT) [20][21], a quantum interference effect like electromagnetically induced transparency occurred in multilevel atoms [22], a wide range of OAM with the topological charge value ranging from 0 to 42 can be measured in theory with a LG rotational-cavity system [24], but this scheme cannot distinguish the sign of OAM.

In this paper, we propose a scheme to measure both magnitude and sign of OAM in a LG rational-cavity system. LG rational-cavity system was first proposed by Bhattacharya and Meystre to trap and cool the rotational motion of a mirror [24]. In this type of cavity optomechanical system, the intracavity radiation field can exchange linear as well as angular momentum with the mirror, which is the difference from the traditional cavity optomechanical system [25][26]. And later, many interesting physical effects have been also studied, such as the entanglement phenomenon based on LG rotational-cavity system [30][32], the ground-state cooling of rotating mirror in the unresolved sideband regime [33], and OMIT [28][34]. However, the measurement of OAM including the magnitude and the sign in LG rational-cavity system has not been reported, which will have wide applications in precision measurement, and will also expand the application prospects of LG rational-cavity system.

In our scheme, LG rational-cavity system consists of two input couplers and a rotating mirror. We show that the effective cavity detuning of our system varies with the magnitude and sign of OAM simultaneously, which is different from that of traditional single LG rational-cavity system [26][24]. In single LG rational-cavity system, the effective cavity detuning is only related to the magnitude of OAM but not to its sign, so with the shift of the OMIT window in Ref. [23], only the magnitude of OAM can be measured. In our system, however, both the magnitude and sign of OAM can be measured based on the spectral shift, in which the measurable topological charge value can reach to ±50. Besides, compared to single LG rational-cavity system, we observe an OMIT window similar to the Fano resonance, meanwhile we can
also realize a fully switchable light switch in our system.

This paper is organized as follows. In Sec. II we introduce our system model and derive the dynamical equation. In Sec. III we discuss in detail the transmission spectrum of the probe field in the double LG rotational cavity, and compare it with the case of single LG rotational cavity. In Sec. IV we propose our scheme to measure the magnitude and sign of OAM. Finally, we summarize our conclusions in Sec. V.

II. THEORETICAL MODEL

We consider a Laguerre-Gaussian (LG) rotational-cavity system shown in Fig. 1 which consists of two input couplers (IC1 and IC2) and a rotating mirror (RM). IC1 (IC2) and RM are all spiral phase elements, which can modify the azimuthal structure of laser beams [3, 4]. IC1 (IC2) is partially transparent and rigidly fixed, but RM is perfectly reflective and rotates about the cavity axis z (with angular equilibrium position φ0 = 0) on a support S. This support is assumed to be small enough so that its effects on cavity c2 can be neglected. The two input couplers and the rotating mirror are all spiral phase elements. Input fields injected to the system are Gaussian (G) fields with topological charge 0, and the charge on the LG beams at various points has been indicated.

FIG. 1. Arrangement for measuring the orbital angular momentum of light in the Laguerre-Gaussian (LG) rotational-cavity system, in which the two input couplers (IC1, IC2) are partially transparent and rigidly fixed, but the rotating mirror (RM) is perfectly reflective and rotates about the cavity axis z (with angular equilibrium position φ0 = 0) on a support S. This support is assumed to be small enough so that its effects on cavity c2 can be neglected. The two input couplers and the rotating mirror are all spiral phase elements. Input fields injected to the system are Gaussian (G) fields with topological charge 0, and the charge on the LG beams at various points has been indicated.

in which c1 (c2) and c2 (c1) are the bosonic annihilation (creation) operators of the two cavity modes, respectively, satisfying the commutation relation [c1, c2] = 1. ∆c1,c2 = ωc − ω1,2 and Ω = ωp − ω1 are the frequency detunings of the driving fields from the cavity resonance and the probe field. Lz and φ denote the angular momentum of RM about the cavity axis z and angular displacement with the commutation relation [Lz, φ] = −iℏ. g1,2 = cl1,2/L characterize the optorotational coupling between two LG cavity modes and RM [24, 30, 31], respectively, with c and L being the speed of light in vacuum and the length of the cavity. The last two terms describe the coupling between the input fields and the two cavity modes with amplitudes ϵ1,2 = √2κP1,2/ℏω1,2 and ϵp = √2κPp/ℏωp. P1,2,p is the corresponding powers of input fields.

Our scheme focuses on the mean response of the system to the probe field, so we consider the mean-value equations of the system, which can be obtained by deriving the Heisenberg equations of the system operators as well as adding the corresponding damping terms. By using the factorization assumption ⟨AB⟩ = ⟨A⟩⟨B⟩ [20], the mean value equations of the system operators can be
derived as follows,

\[
\frac{d c_1}{dt} = -[\kappa + i(\Delta c_1 + g_1 \langle \phi \rangle)] (c_1) + \epsilon_1 + \epsilon_p e^{-i\Omega t},
\]

\[
\frac{d c_2}{dt} = -[\kappa + i(\Delta c_2 - g_2 \langle \phi \rangle)] (c_2) + \epsilon_2,
\]

\[
\frac{d^2 \phi}{dt^2} = -\gamma_\phi \left( \frac{d \phi}{dt} \right) - \omega_\phi^2 \langle \phi \rangle
- \frac{\hbar}{T} \left( g_1 \langle c_1^\dagger \rangle (c_1) - g_2 \langle c_2^\dagger \rangle (c_2) \right),
\]

in which \( \gamma_\phi \) is the damping rate of RM.

The above mean value equations are nonlinear equations, but it can be solved by using the perturbation method due to the fact that the driving fields are much stronger than the probe field. By setting \( \langle O \rangle = O_s + \delta O \)\( (O = c_{1,2}, L_z, \phi) \), one can obtain the steady-state values of the corresponding dynamical variables as

\[
\phi_s = -g_1 \hbar |c_{1s}|^2 + g_2 \hbar |c_{2s}|^2 \quad I, L_{ss} = 0,
\]

\[
c_{1s} = \frac{\epsilon_1}{\kappa + i\Delta_1}, \quad c_{2s} = \frac{\epsilon_2}{\kappa + i\Delta_2},
\]

\[
\Delta_1 = \Delta c_1 + g_1 \phi_s
- \left( \Delta c_1 - \frac{g_1^2 \hbar |c_{1s}|^2}{I \omega_\phi^2} \right) + \frac{g_1 g_2 \hbar |c_{2s}|^2}{I \omega_\phi^2},
\]

\[
\Delta_2 = \Delta c_2 - g_2 \phi_s.
\]

in which \( \Delta_1 \) (\( \Delta_2 \)) represents the effective detuning of cavity \( c_1 \) (\( c_2 \)) from the driving fields. One can find that the effective detuning of cavity \( c_1 \) can be modulated effectively by cavity \( c_2 \). Besides, this modulation can be improved if we choose a cavity with higher cavity finesse and stronger driving power, as well as a mirror with smaller mass and size. Meanwhile, the resonantly driven cavity \( c_2 \) can also greatly enhance its modulation effect on cavity \( c_1 \).

Besides, the equations of the corresponding perturbation terms can be derived as follows,

\[
\frac{d \delta c_1}{dt} = -[\kappa + i\Delta_1] \delta c_1 - ig_1 \delta \phi (c_{1s} + \delta c_1) + \epsilon_1 e^{-i\Omega t},
\]

\[
\frac{d \delta c_2}{dt} = -[\kappa + i\Delta_2] \delta c_2 + ig_2 \delta \phi (c_{2s} + \delta c_2),
\]

\[
\frac{d^2 \delta \phi}{dt^2} = -\gamma_\phi \frac{d \delta \phi}{dt} - \omega_\phi^2 \delta \phi
- \frac{\hbar}{T} (c_{1s}^* \delta c_1 + \delta c_1^* c_{1s} + \delta c_1^* \delta c_1)
+ \frac{\hbar}{T} (c_{2s}^* \delta c_2 + \delta c_2^* c_{2s} + \delta c_2^* \delta c_2).
\]

The above equations of the perturbation terms can be solved by applying the ansatz, i.e., \( \delta O = O_s e^{-i\Omega t} + O_- e^{i\Omega t} \), then, one can get the solution of \( c_{1+} \), which corresponds to the response of the system to the probe field.

\[
c_{1+} = -i\epsilon_p [N_1 g_1^2 \hbar + 2N_2 \Delta_2 g_2^2 \hbar D_1(\Omega) + ID_2(\Omega)]
/2N_1 \Delta_1 g_1^2 \hbar + 2N_2 \Delta_2 g_2^2 \hbar D_3(\Omega) + ID_4(\Omega),
\]

with

\[
D_1(\Omega) = \frac{\Delta_1 + \Omega + ik}{\Delta_2^2 + (k - i\Omega)^2},
\]

\[
D_2(\Omega) = (\Delta_1 + \Omega + ik)(\Omega^2 - \omega_\phi^2 + i\gamma_\phi \Omega),
\]

\[
D_3(\Omega) = \frac{\Delta_2^2 + (k - i\Omega)^2}{\Delta_2^2 + (k - i\Omega)^2},
\]

\[
D_4(\Omega) = [\Delta_1^2 + (k - i\Omega)^2](\Omega^2 - \omega_\phi^2 + i\gamma_\phi \Omega).
\]

Then according to the standard input-output relation \[35\], i.e., \( c_{1\text{out}}(t) = c_{1\text{in}}(t) - \sqrt{2\kappa} c_1(t) \), with \( c_{1\text{in}} \) and \( c_{1\text{out}} \) being the input and output operators of cavity \( c_1 \), respectively, the expectation value of the output field can be written as \[20\, \[35\]

\[
\langle c_{1\text{out}} \rangle = \left( \frac{c_{1\text{out}}}{\sqrt{2\kappa}} - \sqrt{2\kappa} c_1 \right) e^{-i\omega_1 t}
+ \left( \frac{\epsilon_p}{\sqrt{2\kappa}} - \sqrt{2\kappa} c_1 \right) e^{-i\omega_p t} - \sqrt{2\kappa} c_1 - e^{-i(2\omega_1 - \omega_p) t},
\]

which clearly shows that in terms of the input probe amplitude, the transmission of probe field can be defined as

\[
T = \left| \frac{\epsilon_p/\sqrt{2\kappa} - \sqrt{2\kappa} c_1}{\epsilon_p/\sqrt{2\kappa}} \right|^2 = |1 - 2\kappa c_1/\epsilon_p|^2.
\]

### III. TRANSMISSION SPECTRUM OF THE PROBE FIELD IN THE DOUBLE LG ROTATIONAL CAVITY

In this section, we will study the response of double LG rotational cavity to the probe field, and compare it with the case of single LG rotational cavity. The parameters used in the numerical simulation of our paper are chosen from Refs. \[24\, \[30\, \[31\]. For RM, the radius \( R = 10 \mu m \), the mass \( M = 100 ng \), the angular frequency \( \omega_\phi = 2\pi \times 10 MHz \), and the mechanical quality factor \( Q_\phi = 2 \times 10^6 \). For cavity, the cavity length \( L = 5 mm \), the cavity finesse \( F = 5 \times 10^4 \), and cavity \( c_1 \) is driven with red-detuned driving (i.e., \( \Delta c_1 = \omega_\phi \), and the frequency \( \omega_1 \) of driving field is \( 2\pi c/\lambda_1 \) with wavelength \( \lambda_1 = 1064nm \)); meanwhile, cavity \( c_2 \) is driven resonantly with the effective detuning \( \Delta_2 = 0 \), which can be achieved by the use of electronic feedback. It is worth mentioning that the electronic feedback used in cavity \( c_2 \) is carried out routinely by many theoretical and experimental works \[23\, \[30\, \[31\, \[37\], which can set the net detuning of cavity independently of radiation pressure and can also avoid the occurrence of bistability. We would also point out
that cavity $c_1$ with red-detuned driving can exhibit bistability for strong enough driving field. However, the parameters used in our paper are chosen in the area of monostability.

At first, we analyze the transmission characteristics of probe field in single LG rotational cavity. As shown in Fig. 2, we plot the transmission spectrum of probe field in single LG rotational cavity as a function of the normalized detuning $(\Omega - \omega_\phi)/\omega_\phi$. For a fixed topological charge $l_1$ of LG light, one can observe from the curves of Fig. 2(a) that with the increase of the power $P_1$ of driving field, an OMIT window can occur in the transmission spectrum of probe field. Besides, for a fixed power of driving field, the OMIT window can also appear and its width becomes wider and wider when we increase the topological charge of LG light [see Fig. 2(b)]. Thus, based on the correlation between the window width and the topological charge, OAM can be measured in principle as shown in Ref. [23]. But, we would point out that only the magnitude of OAM can be measured via this method. This is due to the fact that the effective cavity detuning $\Delta_1$ of single LG rotational cavity is only related to the magnitude of OAM and not to its sign, which can be seen from Eq. (7) of our paper [this equation is simplified as $\Delta_1 = \Delta_{c_1} + 2I_0/h|c_{1a}|^2/(I_0^2L^2$ for single LG rotational cavity], and Eq. (4) of Ref. [23].

Now we study the transmission characteristics of probe field in the double LG rotational cavity. The transmission spectrum of probe field in the double LG rotational cavity is plotted as a function of the normalized detuning $(\Omega - \omega_\phi)/\omega_\phi$, as shown in Figs. 3(a) and 3(b). Here, it is worth pointing out that for the negative sign of OAM discussed below, the structure of cavity $c_1$ in our system model should change to that of Refs. [29,30]. From the curves of Fig. 3(a), one can see that for a weak driving field with power $P_1 = 0.1\mu W$, the Lorentzian-shaped transmission spectrum originally located at the resonance frequency $\Omega \approx \omega_\phi$ shifts obviously with the increase of the driving field of cavity $c_2$. What’s more, for different signs of OAM, the direction of the spectral shift is just opposite. Specifically, for the topological charge $l_1 = 50$, the transmission spectrum shifts to the right, but for $l_1 = -50$, it shifts to the left. Thus, this spectral shift can be served as a fully switchable light switch through adjusting the power of driving field, as shown in Fig. 3(c). Besides, one can find from the curves of Fig. 3(b) that for a stronger driving field with power $P_1 = 100\mu W$, a symmetrical OMIT window occurs in the resonance frequency $\Omega \approx \omega_\phi$, but this symmetry is broken once cavity $c_2$ is introduced, then an asymmetry window similar to the Fano resonance can be observed. Like the Lorentzian-shaped transmission spectrum [(see Fig. 3(a)], the asymmetric transparency window also has a strong correlation with the magnitude and sign of OAM simultaneously. This correlation can be understood based on the dependence of the effective detuning of cavity $c_1$ on the cavity $c_2$, i.e., the second term of Eq. (7), $g_1g_2\hbar|c_{2a}|^2/(I_0^2L^2)$. As shown in Fig. 3(d), we plot the normalized cavity detuning $(\Delta_1 - \omega_\phi)/\omega_\phi$ as a function of the driving power $P_2$. From Fig. 3(d), one can clearly see that the effective detuning of cavity $c_1$ strongly depends on the driving power of cavity $c_2$, in which different signs of OAM change in reverse with the increase of the driving field. Furthermore, one can also find that the value of the normalized cavity detuning is consistent with the position of the resonance valley of the transmission spectrum. The above shift of the transmission spectrum induced by cavity $c_2$ gives us the inspiration of measuring both the magnitude and sign of OAM simultaneously.

IV. MEASUREMENT OF THE MAGNITUDE AND SIGN OF ORBITAL ANGULAR MOMENTUM

In this section, we apply the spectral shift induced by cavity $c_2$ to measure the magnitude and sign of OAM.
simultaneously. As shown in Fig. 4(a), we plot the transmission spectrum of the probe field in the double LG rotational cavity as a function of the normalized detuning \((\Omega - \omega_p)/\omega_p\) for different driving powers \(P_2\) of cavity \(c_2\) \((P_2 = 0, 50\text{mW}, 100\text{mW})\), in which black curve and red curve represent \(l_1 = -50\), and magenta curve, blue curve and green curve represent \(l_1 = 50\). (c) Transmission of the probe field at resonance as a function of the driving power of cavity \(c_2\). (d) Normalized cavity detuning as a function of the driving power of cavity \(c_2\), in which the inset shows that due to the presence of optorotational coupling of cavity \(c_1\), the value of normalized cavity detuning is not zero. Parameters are: (a), (c) \(P_1 = 0.1\mu\text{W}, l_2 = 100\); (b), (d) \(P_1 = 100\text{mW}, l_2 = 100\); and other parameters are the same as in Fig. 3 except \(\Delta_2 = 0\).

Thus, based on the above analysis, compared with other schemes [17–19], our proposal can measure a wider range of OAM with the measurable topological charge value \(\pm 50\). Meanwhile, through measuring the position of the resonance valley in the double LG rotational cavity, our proposal can distinguish the sign of OAM compared to the case of single LG rotational cavity of Ref. [23]. Finally, we would point out that the sensitivity of our scheme can be improved when the effective detuning of cavity \(c_1\) is further modulated by cavity \(c_2\), which can be seen from Eq. (7). We believe that our scheme provides an effective and simple method for the measurement of OAM including magnitude and sign, and can work better with the rapid development of experimental technology.

V. CONCLUSIONS

In summary, we have investigated the transmission characteristics of the probe field in the double LG rota-
transmission cavity and showed that the effective cavity detuning depends on the magnitude and sign of OAM simultaneously, which is different from the case of single LG rotation cavity. Moreover, we found that the transmission spectrum of the probe field has a strong correlation with the magnitude and sign of OAM. Specifically, for different magnitudes of OAM, the transmission spectrum can show an obvious spectral shift, meanwhile, the spectral shift is directional for different signs of OAM. Thus, based on this feature, we propose a scheme to measure OAM including the magnitude and the sign, in which the measurable topological charge is up to ±50. This work provides an effective method to measure both magnitude and sign of OAM, and also expands the application prospects of the LG rotational-cavity system in quantum sensing.

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