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DEMULTIPLEXING OF OPTICAL BEAM WITH USING OF RAMAN-NATH ACOUSTO-OPTIC DIFFRACTION AND SINGULAR ACOUSTIC BEAM

I. SKAB[1], **M. KOSTYRKO**[1], **B. SULANOV**[3], **O. KRUPYCH**[1,2], **R. VLOKH**[1]

[1] Vlokh Institute of Physical Optics, 23 Dragomanov Str., 79005, Lviv, Ukraine, vlokh@ifo.lviv.ua
[2] Department of optoelectronics and information technologies of the Ivan Franko National University of Lviv, Generala Tarnavskogo Str. 107, Lviv, 79017, Ukraine
[3] Vacoms LLC, 1201 North Market Str., Suite 111, Wilmington, DE 19801

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Abstract. It has been shown that the acousto-optic Raman-Nath diffraction on the acoustic wave, which bears an acoustic vortex, is accompanied by the appearance of the diffraction maxima that bear an optical vortex. The charge of the vortices that appears as a result of the diffraction corresponds to the order of diffraction if the incident optical beam is the Gaussian beam and the charge of the acoustic vortex is equal to unity. When the incident optical vortex beam takes part in this process, the charge of the diffracted optical vortices is shifted on the charge value of the incident optical beam. As a result of the analysis, we obtained the relation for the charge of vortices of diffraction maxima. It has been found that the described effect can be used for controlled demultiplexing.

Keywords: demultiplexing, orbital angular momentum, optical vortex, acoustic vortex, Raman-Nath diffraction
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1. Introduction

Using composite (multi-charge or combined) vortex beams allows the data transmission rate to increase to hundreds of Gbit/s [1] and polarization multiplexing and demultiplexing to several Tbit/s [2]. In contrast, traditional data transmission methods using optical fibers in trunk lines provide bandwidth in the range of several Gbit/s. Recent studies have demonstrated the possibility of a record speed increase to 1.84 Pbit/s [3]. Such a speed was achieved in laboratory conditions using a 37-core fiber with a length of 7.9 km and 223 channels of wavelengths obtained from a single microcomb ring resonator, producing a stabilized dark-pulse Kerr frequency comb. It should be noted that progress in data transfer speed is practically annual. For example, in 2020, the record speed achieved was 44.2 Tbit/s [4]; in 2021, it was 319 Tbit/s. This progress is due to using both new optical elements and multiple wavelengths of optical radiation for data transmission. The next step in increasing data rates was using quantum properties of light, such as spin (SAM) and orbital angular momentum (OAM), which provide new possibilities for telecommunications. Thus, SAM is associated with orthogonal circular polarization of light and can acquire only two values, expressed in units of $\sigma = +1$ and $\sigma = -1$, while the value of OAM can, in principle, be infinite ($l = \pm 1, \pm 2 ...$). In this case, information can be transmitted by all OAM and SAM states, making it possible for photons to transfer an arbitrarily large amount of information distributed among their spin and orbital quantum states. These advantages of composite vortex beams have prompted research in the field of optical singular telecommunication in the last decade.

It should be noted that optical vortices, when propagating in the free space, are extremely stable and can be transmitted over gigantic distances without destruction. Thus, the authors of the paper [5] found that the vortex created by the M87 black hole covered a distance of 50 million light years without distortion. The experimentally confirmed data transmission distance through the atmosphere by a composite optical beam was 143 km [6], and through an optical fiber – it was 5 km [7]. In addition, high-speed data transmission by vortex beams is possible in the radio range of electromagnetic waves [8] and acoustic beams underwater [9]. One of the main problems of using OAM in telecommunication is the generation method of composite vortex beams and the method of their multiplexing/demultiplexing.

Up to now, many methods of generating beams that carry OAM have been proposed. These include generating vortices using computer-synthesized holograms, astigmatic optical elements, spiral plates, liquid crystal q-plates, anisotropic crystals, inhomogeneous fields, etc. [10-15]. Based on various combinations of commercially available liquid crystal q-plates with topological defect strength q=1/2 and 1 and phase-shifted half-wave elements, the addition/subtraction of OAM was proposed due to cascade conversion [16]. However, to ensure the spin-orbit conversion of the angular momentum, the input polarization can only be circular; that is, the SAM can be only two values ±1 from an infinite set of possible polarizations. To eliminate this shortcoming in work [17], the authors proposed to use so-called J-plates, which are glass substrates with a technologically applied nanoscale ornament with a topological defect. J-plates convert the full momentum of the pulse, i.e., both its spin and orbital components [18], and they can also transform orthogonal polarization states into states with different OAM values. In addition, as was recently demonstrated, with the help of a cascade scheme of *J*-plates, it is possible to generate beams with different separable and non-separable SAM and OAM states [19], which is necessary for demultiplexing. A certain disadvantage of *J*-plates is the complexity and cost of their manufacture, which requires high-technology electron beam lithography with the application of an atomic layer of TiO_2 and etching on a nano-scale. In the last few years, considerable attention has been devoted to searching for possibilities for generating composite vortex beams that bear the vortices of different charges, their modulation and demodulation, as well as multiplexing and demultiplexing. In particular, in the work [20], the possibility of forming and modulation-demodulation of optical vortex beams with different charges by a spatial light modulator with a loaded complex hologram was demonstrated. A liquid crystal spatial light modulator was used to form vector-vortex beams and a laser with applied concentric rings on the resonator mirror [21-23]. In our recent work [24], we have shown that a composite vortex beam can be generated using a dichroic liquid crystalline cell. The work [25] was devoted to the problem of generating optical vortex beams and their multiplexing and demultiplexing. The obtained results demonstrated uninterrupted transmission of information. However, the above generation, modulation, and multiplexing methods of composite vortex beams are mostly high-technological. In addition, they are passive, using pre-made optical elements that cannot change their parameters.

To our knowledge, acousto-optic (AO) diffraction had not been considered the method for vortex generation, despite the fact that the OAM can be transferred from an acoustical to an optical beam [26-28]. Moreover, the vortex beam preserves its intensity distribution and phase structure in the course of Bragg AO diffraction [29]. However, the AO diffraction in the

Bragg regime leads to only one diffraction maximum. Therefore in this work, we propose the simple method of generation and demultiplexing of the Gaussian beam into the beams with different vortex charges based on the AO Raman-Nath diffraction.

2. Results and discussion

The basic idea of increasing the data transmission speed is transforming Gaussian beams into multiple beams bearing different OAM and their demultiplexing. For this aim, in addition to the use of a polychromatic input beam, which has to be demultiplexed into channels at different wavelengths, each beam on these wavelengths has to be demultiplexed into the beams with different OAM that serves the individual channels of data transmission.

Let us consider the Raman-Nath AO diffraction in distilled water. The water is characterized by a high enough AO figure of merit (160×10^{-15} s^3/kg [30]) and a low acoustic wave (AW) velocity (1500 m/s [31]), thus representing an efficient AO material for the low-frequency range. At the frequency of 10 MHz, the acoustic wavelength for the longitudinal AW propagating in water is equal to $\Lambda = 148\,\mu\text{m}$. For the wavelength of optical radiations λ_0 = 632.8 nm, the diffraction angles of ±1 diffraction orders are equal to ±0.24 deg, of the ±2 orders – to ±0.49 deg, etc. If one uses a He-Ne laser, then λ_0 = 632.8 nm, and for Raman-Nath diffraction the thickness (L) of the cell over which the interaction takes place must satisfy the Klein-Cook condition: $L \ll \Lambda^2 n_0 / 2\pi\lambda_0 = 7.33\,\text{mm}$, where n_0=1.33 is the refractive index of water. However, ±1 and ±2 maxima will appear at the thicker AO cell, too (see, e.g. [32]).The acoustic vortex beam can be generated using a piezoelectric transducer with an acoustic spiral phase plate.

When the plane defect-free AW propagates in the AO cell along the z-axis it causes the change of refractive index:

$$n(z,t) = n_0 + \Delta n \sin(\Omega t - Kz), \tag{1}$$

where Δn is the elasto-optically induced change of refractive index, Ω is AW frequency, K - is AW wavevector and is t - time. The elasto-optically modulated optical phase can be written as

$$\Gamma = \frac{2\pi}{\lambda_0} n(z,t) L = \Gamma_0 + \Gamma_1 \sin(\Omega t - Kz), \tag{2}$$

where $\Gamma_0 = \frac{2\pi}{\lambda_0} n_0 L$ and $\Gamma_1 = \frac{2\pi}{\lambda_0} \Delta n L$. Then, if the optical wave propagates along the x-axis, its phase is modulated with the frequency of the AW, and the strength of the electric field can be written as:

$$E = E_0 e^{i(\omega t - \Gamma_0 - \Gamma_1 \sin(\Omega t - Kz))}, \tag{3}$$

where E_0 is the amplitude and ω is the frequency of the incident optical wave. In Eq. (3), we omit the optical wave wavevector to simplify further relations. Using the Jacobi–Anger expansion of exponentials of trigonometric functions [33]:

$$e^{-ia\sin\theta} = J_0(a) + 2\sum_{n=1}^{\infty} J_{2n}(a)\cos 2n\theta - 2i\sum_{n=1}^{\infty} J_{2n-1}(a)\sin[(2n-1)\theta], \tag{4}$$

where $J_0(a)$, $J_{2n}(a)$, and $J_{2n-1}(a)$ are the Bessel functions of the first kind of argument a and order 0, 2n, and 2n-1, respectively one can obtain the electric field of diffracted wave:

$$\begin{aligned}E &= E_0 J_0\left(\Gamma_1\right) e^{i(\omega t-\Gamma_0)} - E_0 J_1\left(\Gamma_1\right)\left(e^{i((\omega+\Omega)t-Kz-\Gamma_0)} - e^{i((\omega-\Omega)t+Kz-\Gamma_0)}\right) \\ &+ E_0 J_2\left(\Gamma_1\right)\left(e^{i((\omega+2\Omega)t-2Kz-\Gamma_0)} + e^{i((\omega-2\Omega)t+2Kz-\Gamma_0)}\right) - \ldots\end{aligned} \tag{5}$$

It is seen that the change of frequency and wavevector of the first and second diffracted orders are equal to Ω, K, and 2Ω, $2K$, respectively.

Then, let us suppose that the incident optical beam is the vortex beam with a topological charge l_{op}. This means that the exponent of Eq. (3) should contain an additional term that depends on the azimuthal angle φ around the direction of propagation of diffracted waves, i.e., the term $il_{op}\varphi$. It will affect all terms of Eq. (5), which has to be rewritten as:

$$\begin{aligned}E &= E_0 J_0\left(\Gamma_1\right) e^{i(\omega t-\Gamma_0+l_{op}\varphi)} \\ &- E_0 J_1\left(\Gamma_1\right)\left(e^{i((\omega+\Omega)t-Kz+l_{op}\varphi-\Gamma_0)} - e^{i((\omega-\Omega)t+Kz+l_{op}\varphi-\Gamma_0)}\right) \\ &+ E_0 J_2\left(\Gamma_1\right)\left(e^{i((\omega+2\Omega)t+l_{op}\varphi-2Kz-\Gamma_0)} + e^{i((\omega-2\Omega)t+l_{op}\varphi+2Kz-\Gamma_0)}\right) - \ldots\ .\end{aligned} \tag{6}$$

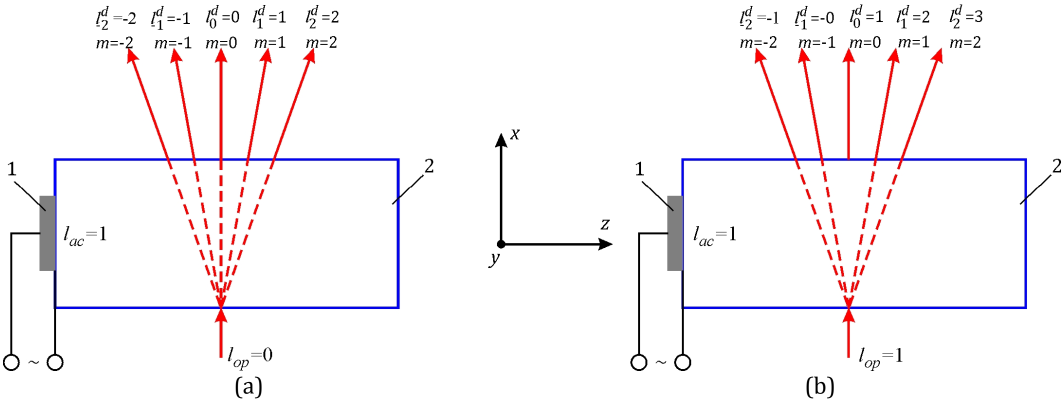
Hence, all maxima that appear due to Raman-Nath AO diffraction must bear optical vortices with the charge l_{op}. However, we aim to search for the conditions in which the different diffracted orders will bear vortices of the different topological charges. For this, suppose that the acoustic wave bears a vortex with the charge l_{ac} while the incident optical beam is Gaussian. In this case, Eq. (1) has the view:

$$n(z,t) = n_0 + \Delta n \sin(\Omega t - Kz + l_{ac}\varphi)\,. \tag{7}$$

Then Eq. (5) can be written as:

$$\begin{aligned}E &= E_0 J_0\left(\Gamma_1\right) e^{i(\omega t-\Gamma_0)} - E_0 J_1\left(\Gamma_1\right)\left(e^{i((\omega+\Omega)t-Kz+l_{ac}\varphi-\Gamma_0)} - e^{i((\omega-\Omega)t+Kz-l_{ac}\varphi-\Gamma_0)}\right) \\ &+ E_0 J_2\left(\Gamma_1\right)\left(e^{i((\omega+2\Omega)t-2Kz+2l_{ac}\varphi-\Gamma_0)} + e^{i((\omega-2\Omega)t+2Kz-2l_{ac}\varphi-\Gamma_0)}\right) - \ldots\ .\end{aligned} \tag{8}$$

As one can see, when $l_{ac} = 1$, the ±1 diffracted orders bear single-charged optical vortices with opposite signs, and ±2 diffracted orders bear optical double-charged vortices with opposite signs, etc. (see Fig. 1a). In contrast, the 0th-order maximum remains the Gaussian beam. This effect makes it possible to demultiplex Gaussian beams into beams that bear optical vortices with different OAM. Moreover, compared to computer-synthesized holograms, this demultiplexing can be controlled by the AW frequency and power. For example, by changing the frequency of AW, one can control the addressing of the vortex beams, while increasing the power can lead to increasing the number of diffracted maxima.



(a) (b)

Fig. 1. Schematic view of Raman-Nath AO diffraction on the AW that bears an acoustic vortex: (a) l_{ac}=1, l_{op}=0; (b) l_{ac}=1, l_{op}=1 (1 – piezoelectric transducer with an acoustic spiral phase plate, 2 – cuvette with distilled water).

Now let us analyze the situation when the incident optical beam bears an optical vortex with the OAM equal to l_{op} and AW bears acoustic vortex with the OAM equal to l_{ac}. Then the relation (8) can be written as:

$$\begin{aligned} E = {} & E_0 J_0\left(\Gamma_1\right) e^{i(\omega t-\Gamma_0+l_{op}\varphi)} \\ & -E_0 J_1\left(\Gamma_1\right)\left(e^{i((\omega+\Omega)t-Kz+(l_{op}+l_{ac})\varphi-\Gamma_0)}-e^{i((\omega-\Omega)t+Kz+(l_{op}-l_{ac})\varphi-\Gamma_0)}\right) \\ & +E_0 J_2\left(\Gamma_1\right)\left(e^{i((\omega+2\Omega)t-2Kz+(l_{op}+2l_{ac})\varphi-\Gamma_0)}+e^{i((\omega-2\Omega)t+2Kz+(l_{op}-2l_{ac})\varphi-\Gamma_0)}\right)-\ldots \quad , \end{aligned} \tag{9}$$

If the l_{op}=1, the 0th-order diffraction maximum will bear a single-charged optical vortex, the +1 diffraction order will bear a double-charged optical vortex, and the -1 diffraction maximum will be represented by the Gaussian beam (Fig. 1b). Thus, the charges of the diffracted optical beams should satisfy the relation $l_m^d = l_{op} + m l_{ac}$, where m is the order of diffraction maximum. It should be noted that the relation mentioned can be satisfied only under the condition of an existing nonzero projection of AW wavevector on the wavevectors of diffracted optical waves.

3. Conclusions

In the present work, it has been shown that in the course of AO Raman-Nath diffraction on the AW that bears acoustic vortex, the diffraction maxima are optical vortex beams. The charge of the vortices that appears as a result of the diffraction corresponds to the order of diffraction maxima if the incident optical beam is the Gaussian beam and the charge of the acoustic vortex is equal to unity. When the incident optical vortex beam takes part in this process, the charge of the diffracted optical vortices is shifted to the charge value of the incident optical beam. As a result of the analysis, we obtained the relation for the charge of vortices of diffraction maxima. Thus, using the AO Raman-Nath interaction, demultiplexing of beams by different OAM states can be achieved.

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Анотація*. Показано, що акустооптична дифракція Рамана-Ната на акустичній хвилі, яка переносить акустичний вихор, супроводжується появою дифракційних порядків, які переносять оптичні вихори. Заряд вихорів, що виникають в результаті дифракції,* *відповідає порядку дифракції, якщо падаючий оптичний промінь є гауссівським, а заряд акустичного вихору дорівнює одиниці. Коли в цьому процесі приймає участь падаючий оптичний вихровий пучок, заряд дифрагованих оптичних вихорів зміщується на значення заряду падаючого оптичного променя. У результаті аналізу отримано співвідношення для заряду вихорів дифракційних максимумів. Встановлено, що описаний ефект можна використовувати для керованого демультиплексування.*

Ключові слова*: демультиплексування, орбітальний кутовий момент, оптичний вихор, акустичний вихор, дифракція Рамана-Ната*