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Robust Demultiplexing of Distinct Orbital Angular Momentum Infrared Vortex Beams Into Different Spatial Geometry Over a Broad Spectral Range

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ABSTRACT Multi-channel structured light with orbital angular momentum (OAM) can be applied in different applications. For example, OAM modulation and OAM multiplexing in fiber optics communications, high-dimensional quantum cryptography-based OAM states for transmitting secure information across free-space, and independent data streams through OAM beams multiplexed free-space optical links. Using a simple and efficient system consisting of a spiral phase element (SPE) and a multi-channel vortex filter (MVF), we have converted input Gaussian beams into multi-channel OAM-based vortex beams for infrared wavelengths. An SPE has been designed, which generates optical vortices with wavelength-dependent topological charge (including fractional values). The resulting complex fields are optically relayed on a binary MVF designed by modulo-2π phase addition of multiple fork gratings with topological charges 1, 2, and 3 and azimuthal orientations. In this way, the MVF generates beams with different OAM states for different carrier waves with different angles and maps them at desired locations in the detector plane. In this study, both 3×3, as well as a hexagonal configuration, were used. Furthermore, the experimentally obtained OAM spectrum qualitatively agrees with the results of numerical simulations, thus verifying our approach. The presented approach opens a new pathway for developing an efficient multi-channel OAM beams generator designed for a specific wavelength and illuminated by an input beam of different wavelengths over a broad spectral range.

INDEX TERMS Laser tuning, optics, optical vortices, optical filters.

I. INTRODUCTION

Vortex beams have numerous applications and have been widely reviewed [1]. Such beams with orbital angular momentum (OAM) have potential in increasing communications capacity [2]–[5] and revolutionize the field of free-space optical communication. However, many vortex beam generators experience limitations, such as low efficiency, complex configurations, and narrow bandwidths, particularly for transmission systems. The problems and substantial results connected to OAM beams and their concrete applications are reviewed and reported [6]–[9]. Specifically, vortex beams with infinite topological charge gain a new accuracy for multiplexing to enhance data capacity [2]–[4], and such beams induce a force for particle trapping [10]. However, single-channel vortex beams from conventional devices such as Q-plates, phase plates, and mode converters cannot overcome constraints in increasing data storage capacity

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and competency of optical trapping [11]–[14]. In such situations, multi-channel vortex beams are more desirable to achieve atomic physics, communications, and information technology requirements. The OAM optical vortex beams have unique spatial distribution, and their wavefront spirals around the optical axis during propagation. The independent structured beams with different OAM modes can be multiplexed, spatially propagated, and demultiplexed [15]–[17]. Usually, multi-channel OAM beams individually generated and coaxially multiplexed with multiple beam combiners lead to additional losses. A large number of optical elements, accurate alignment conditions, and intricate fabrication of optical elements together make optical schemes more complex and unsuitable for implementation in numerous applications. Therefore, we exclusively concentrated on a cost-effective and versatile optical method for generating multi-channel OAM beams with minimal inherent losses. Note that in the present work, the conversion of OAM beams based on spiral phase plates strongly depends on the wavelength of an input beam, whose OAM value changes with the wavelength. The commercial and dynamic tools were discussed for OAM mode formation and detection. All those studies were based on active devices such as spatial light modulators, liquid crystals, and digital mirror devices sensitive to laser threshold damage and not suitable for high power applications. These devices are relatively expensive and responding to specific polarization states because their dimensions and combinations can control the OAM beams into different configurations and dimensions, making the approach more expensive [18]–[20].

In this work, we presented a robust and flexible approach for OAM mode generation, detection, and demultiplexing with the combination of optical elements SPE and MVF that are fabricated with well-established manufacturing technologies. Without using a spatial light modulator (SLM) [20] and any other digital devices, optical vortex beams of different wavelengths (visible and infra-red range) are generated with the spiral phase element printed into the fused silica substrate using a lithography process. Further, the second element, MVF of two configurations, consist of OAM generators associated with unique linear phases, which map different OAM states to different transverse locations in the sensor plane in hexagonal and 3 × 3 square array configurations. The MVFs are synthesized with the superposition of several rotated fork-shaped gratings. The roles of these two structures (MVFs) are exciting and vital in OAM mode mapping at desired locations of different spatial geometries. The proposed MVFs are fabricated using a well-controlled and straightforward laser writing technique.

II. THEORETICAL ANALYSIS AND NUMERICAL MODELLING

The action of SPE substantially depends on the wavelength of laser radiation λ and is described by the function:

$$h_{SPE}(\varphi, \lambda) = \frac{\varphi\lambda}{2\pi(n(\lambda) - 1)}, \tag{1}$$

where φ is the azimuth angle, $n(\lambda)$ is the refractive index of the material in which the optical element is manufactured (for radiation with the wavelength λ). The relief height of a SPE made for laser radiation with the wavelength λ_0 is described by the following formula:

$$h_{max}(\lambda_0) = \frac{\lambda_0}{n(\lambda_0) - 1}, \tag{2}$$

when the optical element (2) is illuminated with laser radiation with an arbitrary wavelength λ, the field of the following type is formed [21]:

$$\tau_{SPE}(\varphi) \approx \exp\left(i\frac{\lambda_0}{\lambda}\varphi\right) = \exp(i\mu\varphi), \tag{3}$$

where $\mu = \lambda_0/\lambda$ corresponds to the generated vortex beam order, which can have fractional values [22], [23]. Recently, such beams have attracted the attention of researchers in connection with their promising use in multiplexed transmission of information [5], [24]–[26]. The value of μ can be measured using a multi-channel filter [27], [28] based on the correlation method [29]. We use in this work the multi-channel diffraction filter formed by a superposition of spiral phases with different topological charges and unique linear phases:

$$\tau_F(x, y) = \sum_{p=1}^{P} exp\left(-im_p\varphi\right) exp\left[i\left(\alpha_p x + \beta_p y\right)\right], \tag{4}$$

where P is the number of MVF channels (or diffractive orders) matched with angular harmonics of various orders m_p and $\left(\alpha_p, \beta_p\right)$ are the corresponding spatial carrier frequencies. **Figure 1** and **2** shows the synthesis of the phase of MVF matched with optical vortices of orders $m_p = [-3, -2, -1, 1, 2, 3]$ (hexagonal configuration) and $m_p = [-3, -2, -1, 0, 1, 2, 3]$ (3 × 3 square configurations), respectively.

Let us consider a beam with a wavelength λ incident on the SPE designed for a topological charge $m = 1$ for a wavelength λ_0, and the phase of SPE is given as $\Phi_{SPP} = m\varphi$. The ratio between the design wavelength and incident wavelength is given as $\mu = \lambda_0/\lambda$. The second element, MVF, consists of OAM generators associated with unique linear phases, which map different OAM states to different transverse locations in the sensor plane.

The design wavelength is $\lambda_0 = 1.5\ \mu m$ and the optical configuration is simulated for $\lambda = 0.5\ \mu m$, $0.6\ \mu m$, $0.75\ \mu m$, $1\ \mu m$, $1.5\ \mu m$, $2\ \mu m$ and $3\ \mu m$. In accordance with Equation (3), it corresponds to the generation of vortex beams with topological charges μ =3, 2.5, 2, 1.5, 1, 0.75 and 0.5. So, the parameter μ need not be an integer but also fractional.

It must be noted that such fractional charges have been investigated earlier, but the wavelength was constant, and the SPE phase was varied less than or greater than 2π [30], [31]. In this case, the wavelength is changed when the phase of SPE is maintained constant (0-2π) for a particular wavelength.

The resultant vortex beam with the topological charge μ incidents on the MVF. The simulation results for the MVF of the 3 × 3 configuration (**Figure 2**) are shown in **Figure 3**. This MVF is matched with vortices $m_p = -3, -2, -1, 0, 1, 2, 3$. Two diffraction orders have zero vortices to simplify the

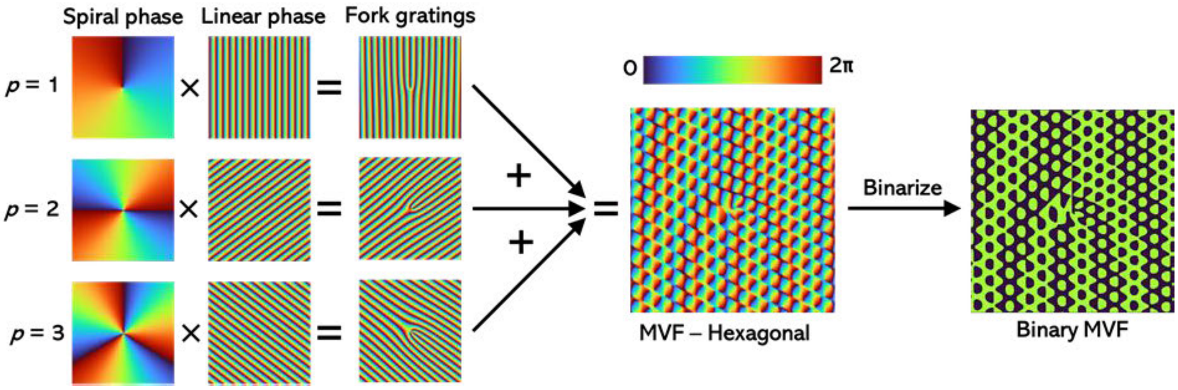


FIGURE 1. Synthesis of binary phase MVF using spiral and linear phases defined in Equation 4 in hexagonal configuration.

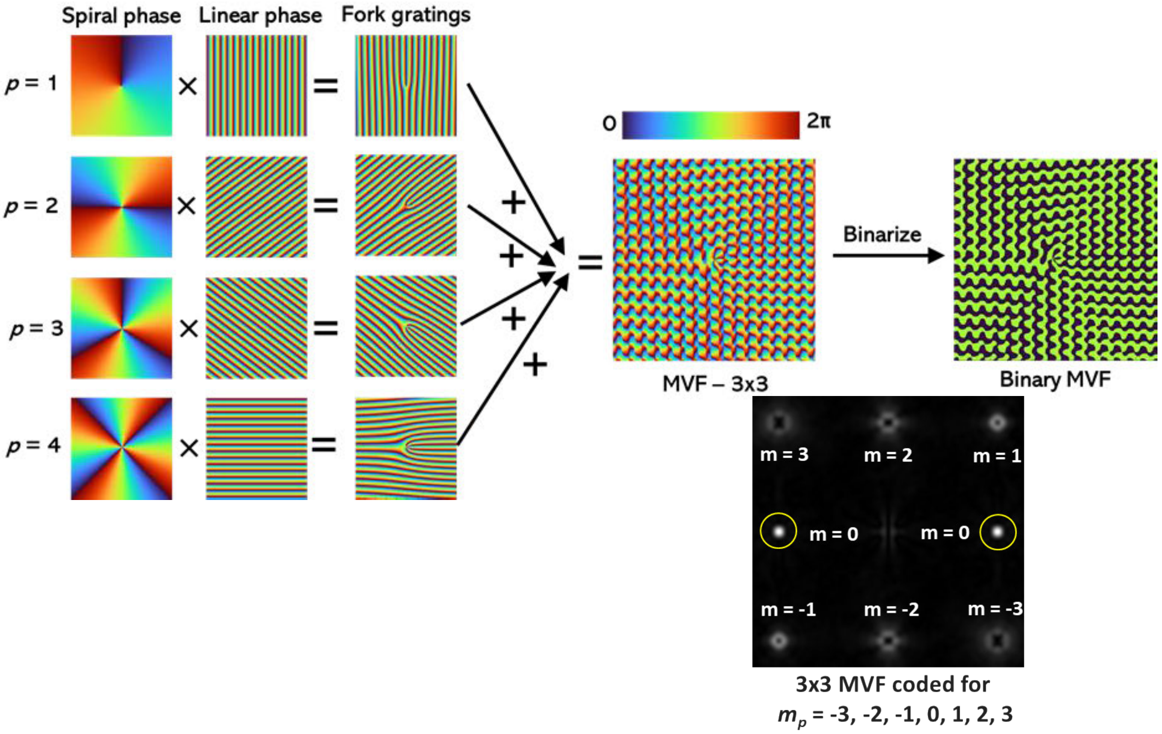


FIGURE 2. Synthesis of binary phase MVF using spiral and linear phases defined in Equation 4 in 3 × 3 configuration.

detection of fractional orders in the range (-1,1). The presence of correlation peaks simultaneously in two diffraction orders corresponds to the detection of an input vortex beam with a fractional topological charge [21], [26]. When a vortex beam is generated by the SPE coupled with vortices encoded in the MVF, we get a set off-axis vortex beams with the topological charges $\mu_p = \mu + m_p$. Thus, vortex beams with μ_p orders are generated simultaneously at different diffractive orders p (**Figure 3**). A situation when μ_p =0 corresponds to the generation of a non-vortex beam and a correlation peak is appeared in the focal plane, so the OAM state of the input beam can be detected. The MVF with hexagonal configuration will act analogously.

III. EXPERIMENTAL OBSERVATIONS

An experimental arrangement for measuring the values of the orbital angular momentum at different wavelengths by spatial filtering is shown in **Figure 4**. The wavelength is adjusted by tuning the NT-242 laser source to the appropriate wavelength. The elliptical light beam from the NT-242 laser source was expanded by the beam expander setup. The resulting beam is limited to a converging circular beam with an initial diameter of 8 mm relayed and guided through a 4f telescope configuration. Therefore, for recording high-quality images of the emerging orders, a sufficiently large distance is necessary to focus the entire field distribution on the camera sensor. As a result, long optical track length forms large focal spots in the camera plane. Note that we employed a camera sensor (InGaAs KB-Vita-Vs-320) that is sensitive for the wavelength range of 900-1700 nm, and the selected sensor has a pixel size of 30 μm. To record the images of intensity distributions for the wavelength range of 400-1000 nm, we used a CMOS sensor (CMOSIS-CMV4000), and it has large screen dimensions with a large screen of 11.3 mm ×11.3 mm with

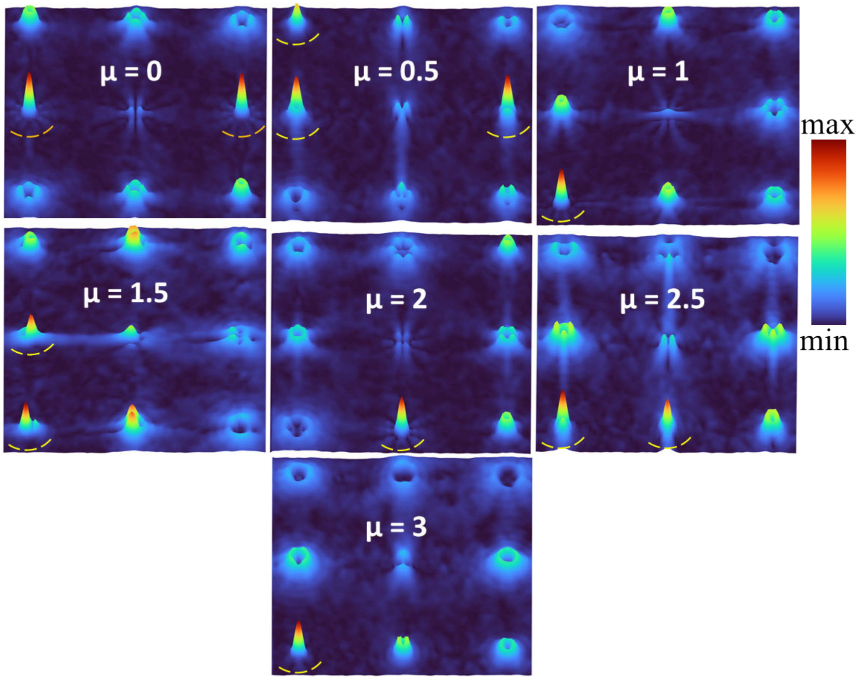


FIGURE 3. Simulation results of light diffraction from the MVF in 3 × 3 configuration.

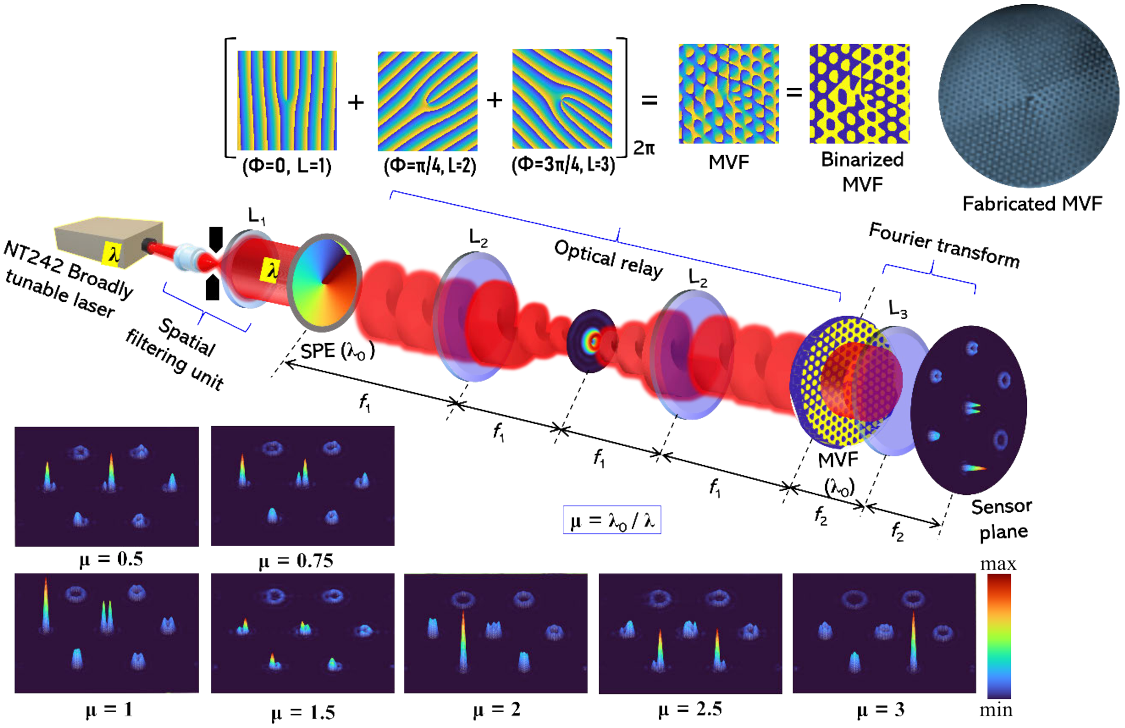
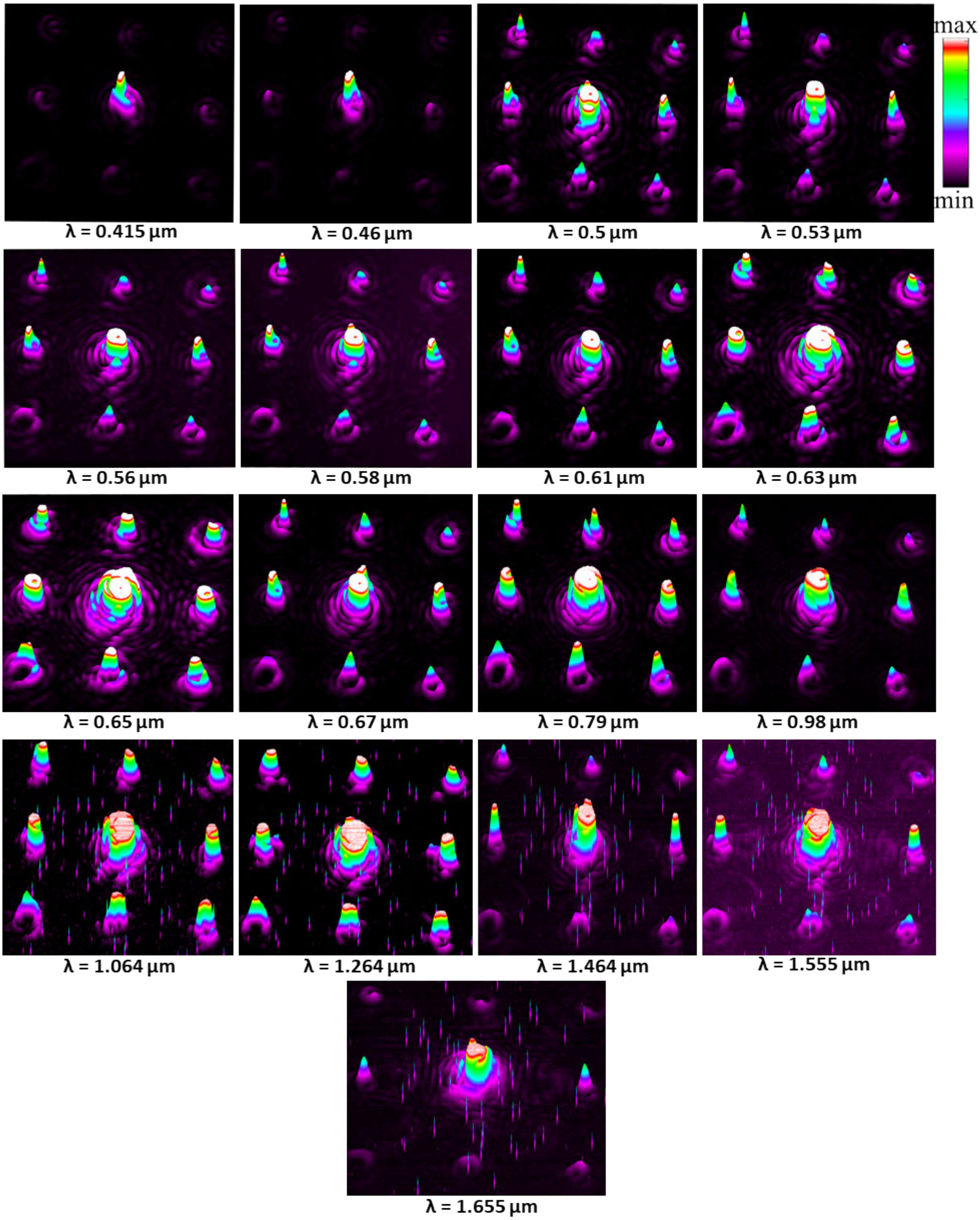


FIGURE 4. Composition of MVF with fork-gratings of different phases, and a photograph of fabricated MVF shown as a circle inset (top). Experimental arrangement for generating multi-channel vortex laser beams of different OAM orders (middle). The 3D intensity distributions generated by MVF for different wavelengths are shown in insets (bottom). The values of μ are calculated, and the integer value of OAM spectrum for wavelengths close to multiples of the base wavelength. The correlation peaks are observed in diffraction orders for specific wavelengths, not in diffraction orders for other wavelengths. For particular wavelengths, the correlation peaks are shifted from diffraction orders corresponds to fractional OAM values.

a pixel size of 5.5 μm. The sensor matrix records the image of the focal spots and their spatial decomposition at the focal distance.

We found that while changing the wavelength, the divergence of the laser beam changes due to the dispersion of the refractive index of quartz material in lenses used in the experimental arrangement. Therefore, this effect purely depends on the incident wavelength. Consequently, it is essential to control the beam size at the outlet of the beam expander, and it is achieved by inserting the spatial filter unit before the SPE.



λ = 0.415 μm

λ = 0.46 μm

λ = 0.5 μm

λ = 0.53 μm

λ = 0.56 μm

λ = 0.58 μm

λ = 0.61 μm

λ = 0.63 μm

λ = 0.65 μm

λ = 0.67 μm

λ = 0.79 μm

λ = 0.98 μm

λ = 1.064 μm

λ = 1.264 μm

λ = 1.464 μm

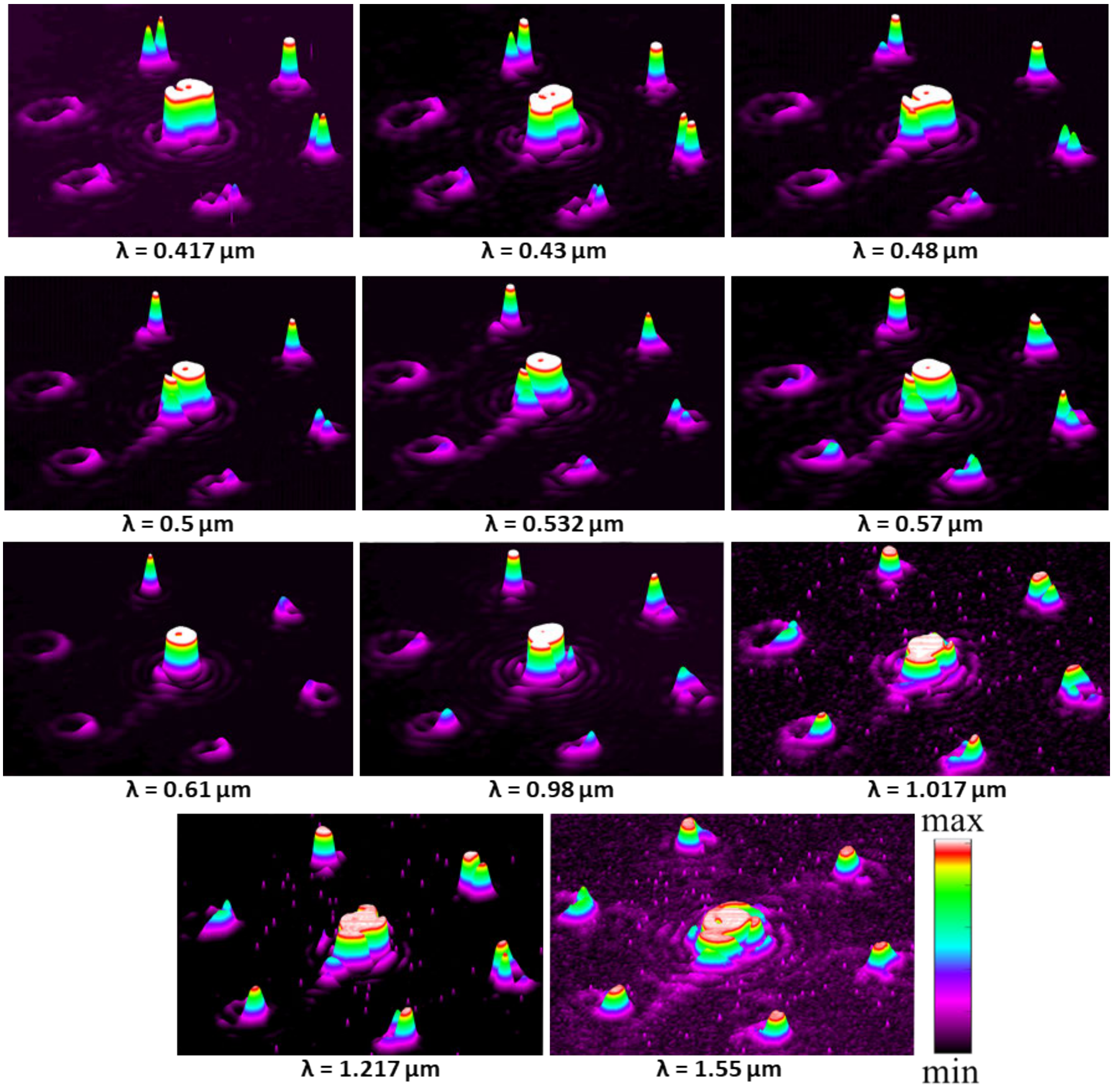
λ = 1.555 μm

λ = 1.655 μm

FIGURE 5. **Multi-channel OAM beams in square arrays: experimental intensity distributions of multi-channel vortex beams with different OAM states over a broad wavelength range.**

The SPE was formed in a Fused Silica Substrate in a Single-stage etching process using the grey-scale mask. Grey-scale lithography enables the fabrication of the phase plate (staircases etched around 360° turn of the diffractive surface) using a single photolithography step followed by reactive ion etching (RIE). 5-micron thick positive AZ4533 Photoresist has been used. The height of the phase jump on the microrelief profile was 2200 nm.

Here, both the SPE and the specially designed and manufactured multi-channel vortex filter (MVF), including the zero-order, are installed in the converging beam. The distance between the beam expander and the SPE is about 10 mm,



λ = 0.417 µm
λ = 0.43 µm
λ = 0.48 µm
λ = 0.5 µm
λ = 0.532 µm
λ = 0.57 µm
λ = 0.61 µm
λ = 0.98 µm
λ = 1.017 µm
λ = 1.217 µm
λ = 1.55 µm

FIGURE 6. Multi-channel OAM beams in hexagonal arrays: experimental intensity distributions of multi-channel vortex beams with different OAM states formed by the MVF over a broad spectral range.

and the light energy from the SPE is directed through a telescope and further incident on the MVF. A multi-channel vortex filter (MVF) has the same optical properties for a wide range of wavelengths. The circular laser recording method was chosen to produce the MVF pattern on the surface of 80 nm thick chromium coated quartz substrate is pre-applied by the RF-magnetron sputtering process. Subsequently, the chromium film was accurately exposed with a sharply focused laser beam in accordance with a given design topology. Under the action of high-intensity laser heating, the film was oxidized. Next, it was developed using a chemical developer based on a cerium sulfuric acid solution. The sensor array placed in the focal plane allows recording images of correlation maxima at different values of the orbital angular momentum in the corresponding diffraction orders. The intensity distributions obtained in the plane of the camera setup for different wavelengths are shown in **Figure 5**, 3 × 3 configuration.

Figure 6 illustrates intensity distributions of fractional vortex laser beams over a broad wavelength range. An analyzer (MVF) was used to determine the order, and a correlation peak indicates an initial beam with an order number corresponding to a given correlation peak. As seen in experimental results, the spiral phase plate in the wavelength range 0.5μm-1.55μm forms a first-order vortex laser beam. In the wavelength range of 0.4μm-0.5μm, the vortex laser beam has two orders of magnitude. At a wavelength (λ) above 1.55μm, the vortex laser beam has a fractional orbital angular momentum.

IV. CONCLUDING REMARKS

We have demonstrated robust demultiplexing of OAM beams of different values into different geometrical configurations over a broad wavelength range. We have experimentally established this approach that offers cost-effective OAM modes generation and mapping at desired locations and with desired geometry is achieved with the combination of simple and effective optical elements (SPE, MVFs) that can generate efficient outputs for input laser beams over a broad wavelength range. We consider that our approach is simple and easy to handle relatively in comparison to existing techniques. Our experimental results can lead to useful applications such as optical manipulation, optical tweezers, higher-order quantum entanglement, nonlinear optics, transmitting information in free-space optical communications, telecommunications, and fiber optics communications. The experimental multi-channel OAM beams generator demonstrated in the present work is similar to current practices like wavelength-division multiplexing and demultiplexing. Furthermore, adaptive optics can be used to correct wavefront distortions and scattering losses caused by atmospheric turbulence. However, optical vortex beams with OAM are resilient to atmospheric turbulence effects, and the selected infrared wavelengths precisely match the transmission window of space. Our approach paves a way to reduce the cost of the commercial OAM modes-based communication systems and projected a simple method for increasing the number of channels in the communication system over free-space or fiber link with minimal intermodal crosstalk. With the latest advancements in fabrication technologies, we believe that high-performance diffractive optical elements are also possible [32]. OAM multiplexing and demultiplexing based on metasurfaces are attractive research, but their maximum efficiency can be determined at a specific wavelength and frequency. For other input wavelengths, metasurfaces efficiency is relatively low or trivial, and in such cases, the approach presented in the current paperwork is highly desirable. Moreover, the precise alignment of such nanostructures to the centre of an input laser is a tedious task. We plan to investigate communication systems based on metasurfaces in our future works.

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