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**5 authors**, including:


Andra Naresh Kumar Reddy
University of Latvia



Vijayakumar Anand
University of Tartu



Svetlana Nikolaevna Khonina
Russian Academy of Sciences



Saulius Juodkazis
Swinburne University of Technology

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# Simultaneous Detection of Modal Composition and Wavelength of OAM Fields Using a Hexagonal Vortex Filter

**Andra Naresh Kumar Reddy**[1,2], **Vijayakumar Anand**[3], **Vladimir V. Podlipnov**[4,5], **Svetlana Nikolaevna Khonina**[4,5], **and Saulius Juodkazis**[3,6]

[1]Hee Photonic Labs, Riga, LV-1002, Latvia
[2]Department of Physics of Complex Systems, Weizmann Institute of Science, Rehovot 7610001, Israel
[3]Optical Sciences Centre and ARC Training Centre in Surface Engineering for Advanced Materials (SEAM) School of Science, Computing and Engineering Technologies Swinburne University of Technology, Hawthorn, VIC 3122, Australia
[4]Samara National Research University, Samara 443086, Russia
[5]Image Processing Systems Institute — Branch of the Federal Scientific Research Centre "Crystallography and Photonics" of Russian Academy of Sciences, Samara 443001, Russia
[6]Tokyo Tech World Research Hub Initiative (WRHI), School of Materials and Chemical Technology Tokyo Institute of Technology, 2-12-1, Ookayama, Meguro-ku, Tokyo 152-8550, Japan

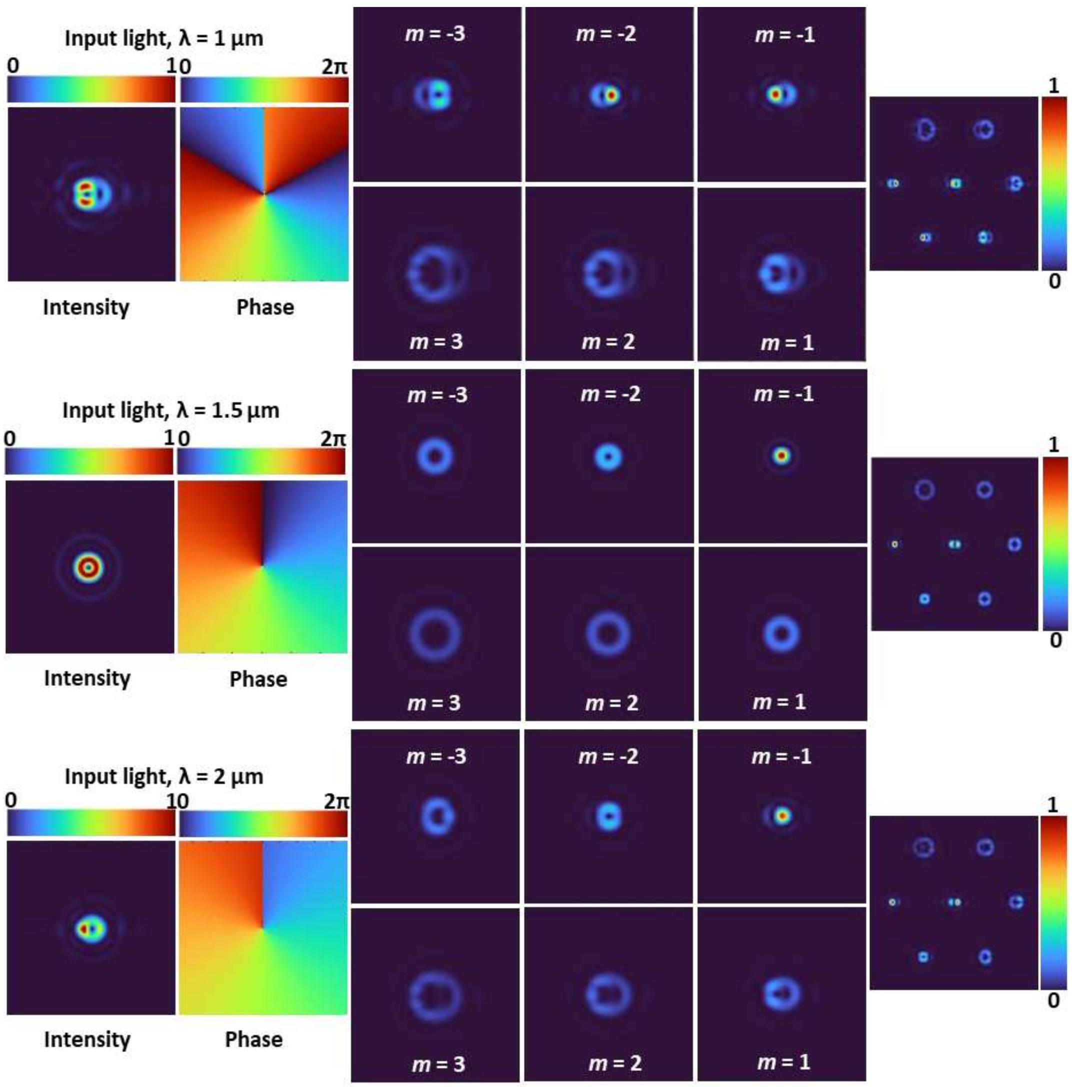
**Abstract**— The present study investigated the possibilities of transmitting information using different wavelengths (Near-IR) and different orbital angular momentum (OAM) modes simultaneously and applying modal decomposition using a passive hexagonal vortex filter (HVF) fabricated using a lithography procedure. The HVF was designed by a modulo-$2\pi$ phase addition of helical phases with three different orders (1, 2, and 3) with unique linear-phase functions in a hexagonal formation (0, $\pi/4$ and $-\pi/4$). When a light field composed of multiple OAM modes is incident on the HVF, they are spatially mapped to unique lateral locations in the detector plane. Any change in OAM mode will result in a variation in the intensity distribution at the different locations but no change in the lateral mapping locations. However, when there is a change in wavelength, the linear phase varies and maps the modes at different lateral locations from the center of the detector. In this way, it is possible to measure the modal composition of the light field and its wavelength simultaneously and independently. We believe that the proposed approach will introduce a new and efficient dimension — wavelength, for free-space optical communication (FSOC) applications resulting in enhancement of information bandwidth.

## 1. INTRODUCTION

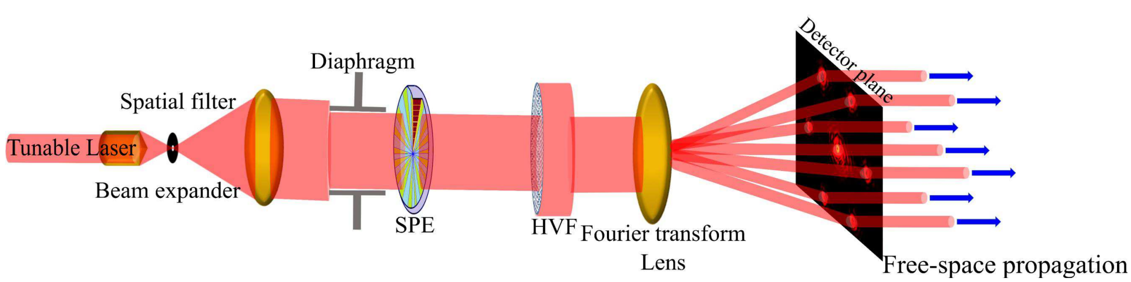
Light fields with orbital angular momentum (OAM) have numerous advantages in science and research applications. The propagation of vortex beams with integer and fractional OAM under different atmospheric conditions is essential for optical communication systems. Specifically, free-space optical communication (FSOC) is one of the oldest long-distance communication techniques developed over a century ago. FSOC is one of the potential techniques that can have long-range capability where physical connection by optical fibers is either expensive or not possible. While FSOC has not been successful commercially yet, mainly due to fog, there have been many continued attempts to realize its full potential for applications in the ground to space communications. In 2013, the Lunar Laser Communication Demonstration (LLCD) of NASA transmitted about 600 Mb/s from the orbit of the moon to earth. In recent years, there have been many studies on the application of light beams carrying OAM for optical communication applications with high bandwidth [1–4]. In most of the studies [4–8], an active device such as a spatial light modulator or digital mirror device has been used for mode multiplexing, and a fibre optic cable was used as the medium for guiding the modes to the receiver and therefore can support only a single wavelength. The above single wavelength limitation is not valid for FSOC. Furthermore, optical beams carrying OAM have a high tolerance to fog and atmospheric turbulence and therefore may be a solution by itself to the problems caused by fog.

In the present work, the light field composed of multiple OAM modes is effectively incident on the specially designed and fabricated hexagonal vortex filter (HVF). Thereby, the six different OAM modes were decomposed and mapped to unique locations in the detector plane. The intensity distribution at different lateral locations changes relatively with the change in the OAM mode. On the other hand, tuning the incident light wavelength causes variations in the linear phase of HVF that maps the OAM modes at different lateral locations in the detector plane.

The proposed approach is robust and efficient in OAM mode demultiplexing, leading to exciting observations such as transmitting the information with increased capacity using different wavelengths and different OAM modes simultaneously and independently. Further, we have a scope to demonstrate that the information-carrying vortex beams with varying modes of OAM transform




(a)




(b)

Figure 1: (a) Numerical calculation of intensity and phase of the light field distribution with multiple OAM modes of different wavelengths (near IR wavelengths) incident on the HVF consist of six OAM generators $m = -3, -2, -1, 1, 2,$ and 3, which are spatially demultiplexed in the hexagonal shape using modulo-$2\pi$ phase addition of helical phases and with unique linear-phase functions. (b) Schematic of proposed optical scheme for simultaneous detection of modal composition and wavelengths OAM fields. Further, the multi-channel OAM beam propagates in the free-space to transmit the information over a distance, SPE-spiral phase element and HVF-hexagonal vortex filter.

into the other form where the resulting light field passes through commercial VPP (vortices phase plate), which convert the beams into Gaussian beams. It is suitable for free-space propagation but Gaussian beams have a limited tolerance to atmospheric turbulence.

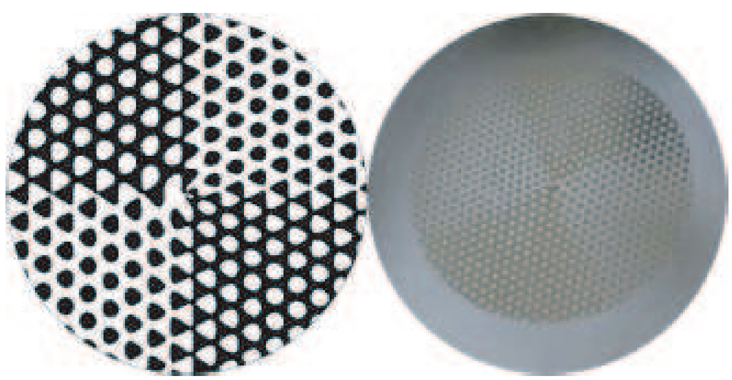
## 2. THEORY AND NUMERICAL SIMULATION

We design and employ a hexagonal vortex filter (HVF) based on the correlation method to analyze the resulting light field orbital angular momentum (OAM) modes. The hexagonal vortex diffraction filter is given as [9]:

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

where $p$ is the number of filter's channel (or diffractive orders) matched with angular harmonics of various orders $m_p$ and $(\alpha_p, \beta_p)$ are the corresponding spatial carrier frequencies. The HVF was designed by a modulo-$2\pi$ phase addition of helical phases with three different orders ($p = 1$, 2, and 3) with unique linear-phase functions in a hexagonal formation (0, $\pi/4$ and $-\pi/4$). The fabrication of the HVF is matched with optical vortices of orders $m_p = [-3, -2, -1, 1, 2, 3]$, and the corresponding numerical simulations are shown in Fig. 1. The HVF provides the effective formation of several diffraction orders of the same intensity, and the method of the carrier spatial frequency (Equation (1)) is universal. It allows us to choose arbitrary diffractive orders, in which spatial positions are determined by the given carrier spatial frequencies and give them an arbitrary weight ratio (energy distribution in the diffraction orders). Since the position of the $P$ diffraction order is determined by the values, so it will be completely arbitrary.

The precise execution of the following steps fabricated the proposed Hexagonal vortex filter (HVF). The standard lithography technology is used to fabricate the HVF mask. A quartz substrate of 80 nm thickness was directly used to create the proposed pattern with the chromium (Cr) hard-mask layer. With the lithography method, the proposed mask pattern was transferred into the chromium layer. Further, chromium masks were removed using etchants such as mixtures of perchloric acid and ceric ammonium nitrate after the whole process. A hexagonal vortex filter (HVF) has the same optical properties for a wide range of wavelengths. The HVF shown in Fig. 2 can be inserted in the proposed optical setup, as illustrated in Fig. 1, to generate light intensity distributions of multiple OAM modes spatially mapped at different locations in the detector plane.



(a) (b)

Figure 2: (a) Binary phase of the HVF embedded helical and linear phases. (b) Photograph of the fabricated HVF mask using lithography.

## 3. DISCUSSION

Let us consider a light field of multiple OAM modes of wavelength $\lambda$ incident on the HVF shown in Fig. 2 and the HVF binary phase synthesis using helical and linear phases described in Eq. (1). The HVF consists of OAM generators related to unique linear phases and maps different OAM modes to different lateral locations in the detector plane. The optical configuration shown in Fig. 1(b) is numerically simulated for $\lambda = 1\,\mu\text{m}$, $1.5\,\mu\text{m}$, $2\,\mu\text{m}$, and the corresponding results are presented in Fig. 1(a). We have chosen the IR wavelengths for the current investigation because they have a high atmospheric transmission window while building a free-space optical communication compared to visible wavelengths. The HVF consists of six OAM generators $m = -3, -2, -1, 1, 2$, and 3, which are spatially demultiplexed using modulo-$2\pi$ phase addition and then binarized. The light intensity outputs from the HVF at the six locations are shown in Fig. 1. The change in OAM mode results in a variation in the intensity distribution at the different locations but no change in the lateral mapping locations. However, if there is a change in the incident light field wavelength, the linear phase varies and maps the modes at different lateral locations from the center of the detector plane. Therefore, a simultaneous modal composition of light fields is achieved along with measuring the wavelengths independently. The OAM mode demultiplexing ability of the proposed optical scheme with broad near-IR wavelengths is helpful to achieve high purity, fog resilience and low crosstalk free-space optical communication. The current approach demonstrates the importance of OAM to act as a tool for tuning the degrees of freedom for the free-space optical communication system and the unique advantages of the HVF in OAM mode demultiplexing. The present study will be applicable for mid-IR and far-IR laser wavelengths.

## 4. CONCLUSION

We demonstrated a free-space OAM mode demultiplexing system with a hexagonal vortex filter in which OAM modes are spatially mapped to unique lateral locations. The change in OAM mode causes a change in intensity distributions at mapping locations, but their locations remain the same. The mapping locations change with wavelength. The present optical scheme has promising applications in developing a high capacity free-space communication system where the number of channels in OAM mode mapping and demultiplexing will be increased by changing the design of the vortex filter. For example, the vortex filter with modulo-$2\pi$ phase addition of helical phases with four different orders and unique linear phases can increase the number of channels, resulting in high information-carrying capacity.

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