High data-transfer density using 4-states optical vortices for deep space optical communication links

1st B. Paroli
Dipartimento di Fisica
Università degli Studi di Milano
Milan, Italy
bruno.paroli@unimi.it

2nd M. Siano
Dipartimento di Fisica
Università degli Studi di Milano
Milan, Italy
mirko.siano@unimi.it

3rd L. Cremonesi
Dipartimento di Fisica
Università degli Studi di Milano
Milan, Italy
llorenc.cremonesi@unimi.it

4th M. Potenza
Dipartimento di Fisica
Università degli Studi di Milano
Milan, Italy
marco.potenza@unimi.it

***Abstract*—Free space optical communications greatly benefit from radiation carrying orbital angular momentum because of the large number of topological charges that can be used to encode information at high density. In this work, we show how to realize an optical link by exploiting four mutually incoherent beams carrying different orbital angular momentum states. The four related channels are digitally modulated using On-Off keying techniques. The receiver is based on a local interferometer that allows recovering of the original information, with high efficiency, by exploiting only a small portion of the radiation wavefront. This technique can be applied for high data-transfer density in satellite network communications, when the radiation wavefront exceed the receiver size.**

***Index Terms*—optical vortices, optical communication, satellites**

I. INTRODUCTION

Radiation carrying Orbital Angular Momentum (OAM) formalized at the end of the twentieth century [1] opens important perspectives in the field of high-density optical communications thanks to the number of states that can be exploited to multiplex information channels in the same frequency band. There are currently many experiments that demonstrate how to multiplex and demultiplex information using orbital angular momentum both in fiber and in free space. These methods generally exploit the entire radiation wavefront or a considerable portion of it [2], [3]. However, such conditions cannot be achieved in practical long-distance communications, due to the natural divergence of the radiation, which makes the radiation wavefront larger than the receiver. Recently, we have shown experimentally how it is possible to multiplex and demultiplex information, by exploiting only a small portion of the radiation wavefront, by means of wavefront curvature [4] and local interferometry [5]. In the present work, we show for the first time the results of table-top experiments aimed at demonstrating the ability of multiplying, by a remarkable factor, the information transmitted in the same frequency band by overlapping four mutually incoherent OAM beams. Information transmitted using digital On-Off keying (OOK) modulation has been successfully received by exploiting a local interferometer. This method paves the way to important perspectives in high-density optical communications for applications in laser-link satellite networks or constellations. The paper is organized as follows: in section 2 we describe the experimental setup, in section 3 we show and discuss our results, and finally in section 4 we collect our conclusions.

II. EXPERIMENTAL SETUP

The experimental setup is shown in Fig. 1. Four independent information channels are generated through four independent He-Ne laser beams (radiation wavelength $\lambda = 632.8$ nm), each modulated by an acousto-optic modulator. The first diffraction orders produced by the modulators are selected through suitable diaphragms and sent to four corresponding Computer Generated Holograms (CGH) [6] printed in our laboratory onto high-resolution polyester film. The holograms correspond to four different OAM states with topological charge -2, +2, -4, +4, respectively. The first diffraction order from each hologram is then selected by additional diaphragms. The four optical vortices are then superimposed through independent beam splitters: a first beamsplitter overlaps the ± 4 states, a second beam splitter overlaps the ± 2 states and finally a third beam splitter overlaps the two pairs into a single composed beam. In this way, it is possible to make the beams collinear, by first acting separately on the beams ± 4 and ± 2, and finally overlapping the two pairs collinearly. The superimposed beams are spatially filtered to reduce noise and sent towards the local receiver using a pair of mirrors, as shown in Fig. 1.

The receiver is mainly composed by a beam splitter and a piezo-mirror as shown in Fig. 2. The beam splitter and the piezo-mirror are positioned at about 17 mm above the propagation axis of the transmitted beam. The portion of the radiation beam, impinging on the mirror, is deflected at right

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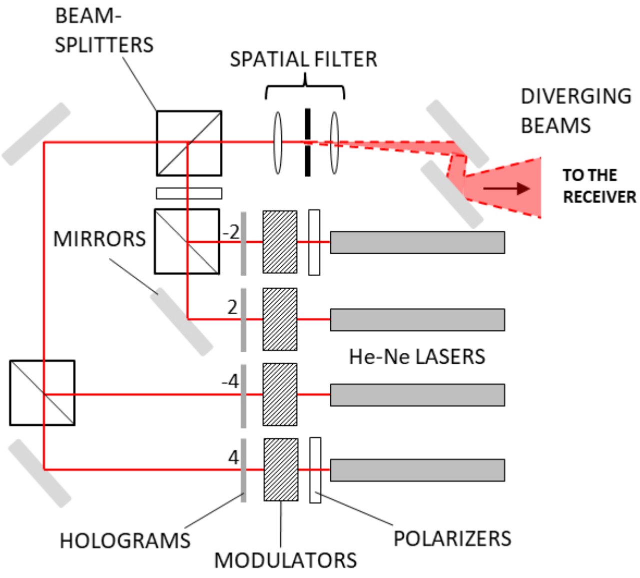

Fig. 1. Optical scheme of the transmitting system with the superposition of four OAM beams with charges ±2 and ±4. The polarizers are used to balance the intensities so that each beam has the same intensity at the receiver input ports. The diverging out beams propagate towards the receiver (shown in Fig. 2) positioned at a distance of about 70 cm from the transmitter. Numbers close to the holograms are the topological charges.

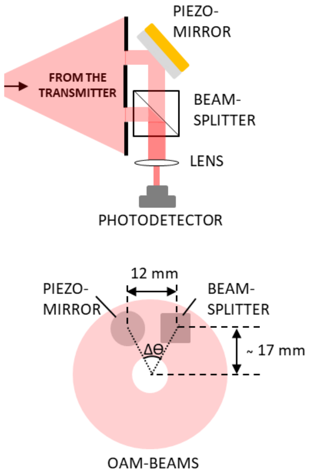

Fig. 2. Optical scheme of the receiving system. Top: Local interferometer used to separate the digital states of the superimposed OAM beams with charges ±2 and ±4. The piezo mirror is used to select the optimal working point of the interferometer as discussed in section 3. Bottom: Front view and geometry of the superimposed beams impinging on the interferometer with the relevant distances. The baseline between the input ports is $\approx$ 3 times smaller than the beam diameter (FWHM). For the same receiver size, the locality allows data to be received at a larger distance of about three times than receivers exploiting the entire wavefront.

angle towards the beam splitter that intercept a second portion of the transmitted beam, so that the two portions of the beam interfere in a detection plane, orthogonal to the propagation axis of the transmitted beam, at a distance of about 185 mm from the exit face of the beam splitter. A positive lens (60 mm focal length) is used to focus the interference pattern on a silicon photodetector (THORLABS PDA8A2). The voltage signal produced by the photodetector is proportional to the total intensity of the incident interference pattern and it is acquired through a digital oscilloscope (PICOSCOPE 4224A) to check the effectiveness of the proposed scheme to retrieve the original information from the four-fold composed beam.

III. RESULTS AN DISCUSSION

The transmitting and receiving systems have been used to verify the performances for high data transfer density by encoding the information in the OAM variable. The channels were independently modulated to generate a time-sequence of all 16 possible 4-bit digital combinations from $(a_1, a_2, a_3, a_4) = (0, 0, 0, 0)$ to $(a_1, a_2, a_3, a_4) = (1, 1, 1, 1)$, where a_1, a_2, a_3, a_4 are the bit values of the four digitally-modulated independent channels, corresponding to the topological charges $l_1 = -2$, $l_2 = 2$, $l_3 = -4$, $l_4 = 4$, respectively. The bit value "0" or "1" for each channel is obtained experimentally by applying a voltage signal with amplitude 0 V or 1.5 V, respectively, to the input control signal of the acousto-optic modulator, which interrupts or transmits the laser beam towards the corresponding hologram.

The experimental test consists in distinguishing as many combinations as possible through the corresponding different intensities produced by the interferometer, in order to maximize information density. The expected intensities are described by the hybrid intensity equation [7]

$$I_H(a_1, a_2, a_3, a_4) = 4I_0(r, z) \sum_{i=1}^{4} a_i \frac{\cos(l_i \Delta\theta + \Delta\phi) + 1}{2}, \tag{1}$$

where $I_0(r, z)$ is the intensity of the radiation at the detector coming from a single port of the interferometer and for each single OAM beam, r, z are the radial and axial coordinates, respectively, $\Delta\theta$ is the azimuthal angle between the piezo-mirror and the beam splitter (as shown in Fig. 2) and $\Delta\phi$ is the phase difference due to the different optical paths from the two interferometer ports to the detection point.

Equation 1 shows that in the case of four superimposed beams the maximum theoretical number of distinguishable intensity levels is 16, depending on the geometrical configuration and on the phase $\Delta\phi$. Since the geometrical configuration is fixed, we empirically change the phase $\Delta\phi$ (through the axial displacement of the piezo-mirror) in order to obtain a suitable separation of the voltage levels observed in real-time with the digital oscilloscope.

The experimental results are shown in Fig. 3. Notice here that the voltage levels, are all distinguishable within the noise ($\approx$ 1.2 mV peak-to-peak), except the two combinations (0,1,0,1) and (1,0,1,0) which are visibly superimposed.

To highlight the advantage obtained by our local interferometer exploiting OAM radiation, we repeat the experiment using only the interferometer port that illuminates the beam splitter so as not to be sensitive to the azimuthal phase $l_i \Delta\theta$

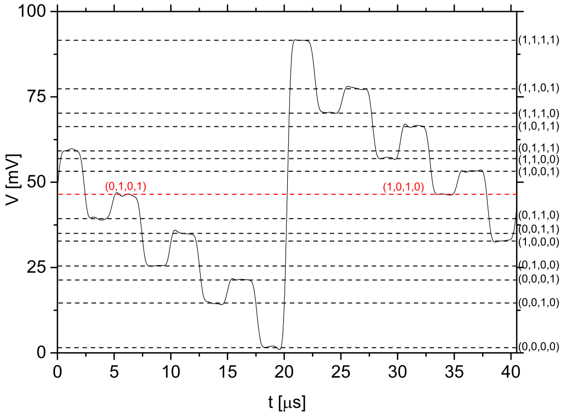

Fig. 3. Voltage signal of the interference intensity measured with the photodiode. The digital combinations, corresponding to the intensity levels (dashed lines), are shown on the right. Only the two combinations shown in red are indistinguishable.

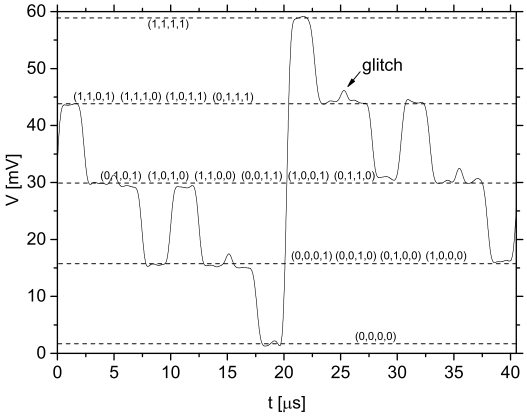

Fig. 4. Voltage signal of the intensity measured with the photodiode obtained by using a single port of the interferometer only. We show the intensity degeneracy (dashed lines) corresponding to the digital combinations. Notice the small glitch between two close degenerate levels due to the imperfect synchronism of the modulating digital signal transitions.

due to the orbital angular momentum of the radiation. The expected intensity values, for collinear and balanced mutually-incoherent beams and for a single port detection, are predicted by the following equation [7]

$$I(a_1, a_2, a_3, a_4) = I_0(r, z) \sum_{i=1}^{4} a_i. \tag{2}$$

Equation 2 shows that in the case of four superimposed beams the maximum number of distinguishable intensity levels decreases to 5, with respect to the previous case, in agreement with the experimental results shown in Fig. 4. Remarkably, as predicted by Eq. 2, the indistinguishable combinations, have the same multiplicity (i.e. the same number of bit ”1” in the combination), in excellent agreement with the experimental observations (see Fig. 4).

IV. CONCLUSIONS

In this work, we have demonstrated that it is possible to recover information, encoded through the digital modulation of four independent laser beams having different orbital angular momentum states, with an efficiency of 93.75% (where the efficiency is defined as the ratio between the actually distinct combinations and the total number of possible combinations). This efficiency decreases to 31.25 % when the proposed interferometric method is not used and is replaced by a standard single-port intensity measurement. The system is therefore able to multiply by a factor of 7.5 the amount of information that can be transferred in the same frequency band, compared to a single channel that uses the same modulation technique. Although in this experiment the modulation frequency is limited to 0.4 MHz, the method can be extended to significantly higher frequencies, even beyond tens of Gbit/s, for example by using state-of-the-art electro-optic modulators. The ability to recover information using only a small portion of the wavefront makes the method particularly suitable for high-density and long-distance communications in satellite networks. Although the method has been validated and demonstrated experimentally, different improvements should be considered for practical applications, such as: i) make the transmission system stable especially in inter-satellite scenarios where constant light beam alignment is needed, ii) reorganize digital information due to the degeneracy of a small fraction of the received states, iii) carry-out long time tests of the bit error rate to verify the performance of the communication system at high bit rate (tens of Gbps) and to evaluate the crosstalk between OAM states.

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