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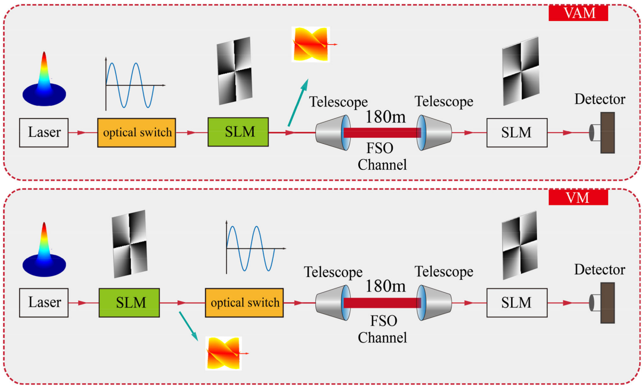

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Improve The Capacity Of Data Transmission In Orbital Angular Momentum Multiplexing By Adjusting Link Structure

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Abstract: Optical vortex is a structured beam with a spiral phase wavefront. Different orbital angular momentums (OAM) are orthogonal to each other and multiplexed together without crosstalk. Vortex optical communication (VOC) can obtain good bandwidth and channel number. In this paper, we creatively exchanged the order of the spatial light modulator (SLM) and the optical switch, the communication link from “Vortex after Modulation (VAM)” to “Vortex Modulation (VM)”, which constitutes a new link structure. Compared with the VAM communication link, the VM link has the advantages of higher transmission rate, better signal quality, lower signal error rate and so on. The results show that the VM link is 0.126 Gbit/s faster than the VAM on a single channel link, and 15.5 Gbit/s faster in 16-QAM 8 OAM beams multiplexing. The error rate of the received signal under the same conditions at the transmitting end has an improvement of 2∼4 orders of magnitude. The method is simple, convenient to implement, and has a significant improvement in transmission rate. It can provide a wide range of applications in vortex high-capacity communication.

Index Terms: Communication systems, optical vortices, OAM multiplexing, vortex modulation.

1. Introduction

Optical vortex is a special beam that carries OAM. Due to the unique structured spiral phase wavefront and "doughnut" shape intensity distribution, optical vortex has an important application prospect in optical manipulation, optical information processing, photonic computer, quantum communication, optical communications and other fields [1]–[7]. As vortex beam increases the new dimension of OAM on the basis of plane wave beside amplitude, phase, frequency and polarization [8], [9], the vortex beam can carry infinite orthogonal OAM states, which increases the number of channels and obtain higher channel capacity. Therefore, in recent years, orbital angular momentum communication has been one of the research hotspots in the field of optical communication [10], [11]. In theory, the OAM and other physical quantities are independent each

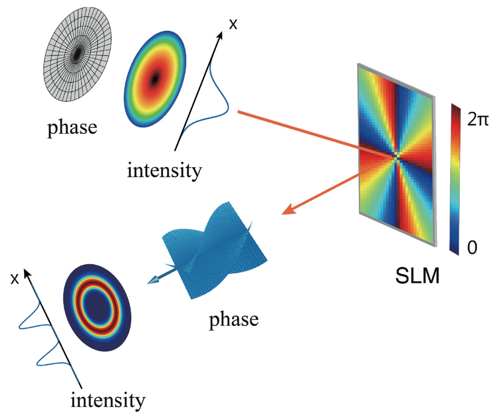

Fig. 1. Gaussian light is modulated into a vortex beam by a SLM, and the phase is spiral. The field strength is a hollow ring and the energy is concentrated on the ring.

other, so OAM communication technology can be seamlessly combined with traditional optical communication by integrating with existing WDM, PDM and other technologies [12].

With the increasing demand of communication market, the spectrum resources are becoming more and more precious [13]. How to improve efficiency is the difficulty of current research field of communication. In recent years, considerable researches have been done on improving the modulation rate, the number of OAM multiplexing, and the sensitivity of the detector. The performance of all aspects of VOC has been effectively improved, and the VOC technology has also been improved [14], [15]. A lot of work has been done to achieve higher transmission rate by increasing the number of channel multiplexing [16], [17], such as the 8-way OAMs multiplexing communication technology adopted by Jian Wang [18]–[22]. In the conventional structure of the OAM communication system, the number of channels is generally raised to increase the transmission rate. We have researched and improved the traditional link structure and increased the transmission rate by changing the link structure. Each link will have a rate increase during channel multiplexing, which can eventually improve the transmission rate of the entire communication link.

This paper focuses on a new link structure based on the traditional communication link, which exchanges the order of the modulator and SLM (where the SLM is only used to produce vortex beam). A unique link structure is constructed, which generates the vortex beam first and then modulates the signal. In addition, we discussed the performance of this link and compared it with VAM channel in transmission rate, bit error rate (BER) and spectrum width. These results show that this structure can improve the information transmission rate, reduce the BER and enhance the signal quality. Therefore, this structure has a good application value for increasing the transmission rate.

2. Methods

The vortex beam in this paper are generated using the SLM which has been loaded with a phase grayscale image produced by MATLAB numerical calculations. When Gaussian planar light is incident on the SLM, the SLM phase modulates the incident light at each pixel to form a vortex beam having a helical phase wavefront [23], as shown in Fig. 1. Its distribution of electric field intensity is a hollow ring, which carries the OAM.

The formula of the vortex beam is [24]:

$$A(x, y, z=0) = [(x - x_0) + i\,\mathrm{sign}(l)(y - y_0)]^{|l|} \exp[-(x^2 + y^2)/r_0{}^2] \tag{1}$$

This formula represents a vortex beam of order l complex amplitude distribution nested within the cross section of a Gaussian beam with a center at (x_0, y_0). Wherein, the sign of l m determines whether the vortex light is rotated clockwise or counterclockwise.

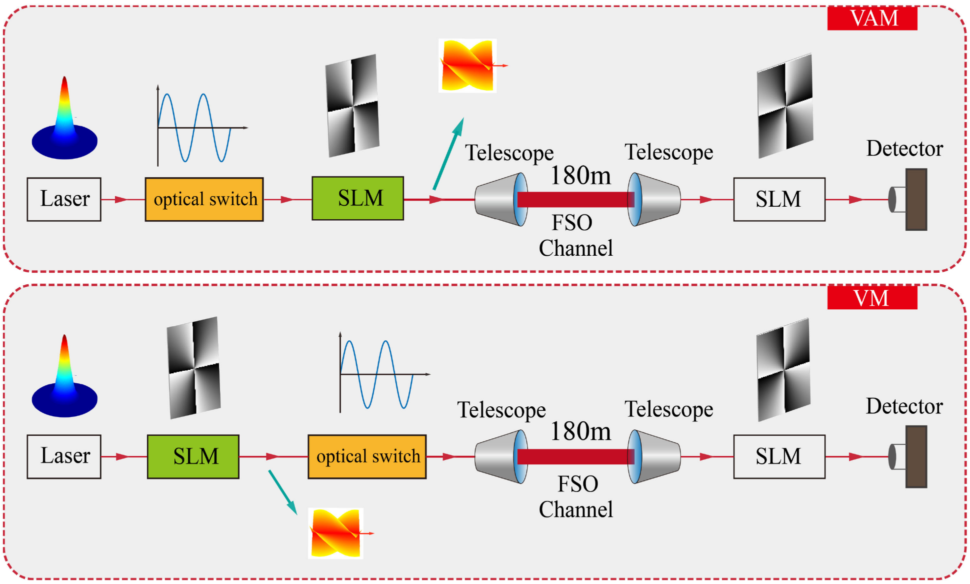

Fig. 2. Principle and explanation. In the previous method, the Gaussian beam is sent into the optical switch to modulate the signal, and then the SLM turns the Gaussian beam into a vortex beam. Then, the beam is converted into a parallel beam through the telescope system. Finally, the beam is received by the receiver and turned into a Gaussian beam by loading opposite phase SLM. In the new method, the vortex beam is generated first and then modulated by an optical switch. By changing the order of the two, the signal-to-noise ratio can be improved and the BER can be reduced.

In this paper, we creatively change the order between the optical switch and the SLM to produce a new method different from the traditional link structure. As shown in Fig. 2, we built a traditional structure communication link to form a VAM link, exchanging the order of the optical switch and the SLM to form a VM link. The optical switch in the link is a Mach-Zehnder modulator. It is particularly emphasized that in the VM link, because of the large vortex scale, we used a focusing lens to make the beam smaller before it was transmitted to the Mach-Zehnder modulator. In the study, we keep the bias voltage and Q point of the Mach-Zehnder modulator consistent. By passing the same signal through the two links at the same power, compared with the original VAM link, the signal quality and BER performance of the VM link are both improved. The discussion below is about the quantitative changes caused by changing the order of the optical switch and SLM.

2.1 Mach-Zehnder Modulator Influence On Link

When the beam passes through the Mach-Zehnder modulator, the Mach-Zehnder modulator adjusts the voltage of the two channels and changes the index of refraction to changes the optical path difference indirectly, so extinction can be achieved when the optical path difference of the two beams is π and when it is 0, the beam can pass. The transition of the electrical signal to the optical signal can be achieved by controlling the connection and disconnection of the beam by an electrical signal, which is the on-off keying modulation method. The principle diagram is shown in Fig. 3.

The equation describing the behavior of the Mach-Zehnder modulator is [25], [26]:

$$E_{\text{out}}(t) = E_{\text{in}}(t) \cdot \cos(\Delta\theta(t)) \cdot \exp(j \cdot \Delta\phi(t)) \tag{2}$$

where $\Delta\theta$ the phase is difference between the two branches and it is defined as:

$$\Delta\theta(t) = \frac{\pi}{2} \cdot (0.5 - ER \cdot (Modulation(t) - 0.5)) \tag{3}$$

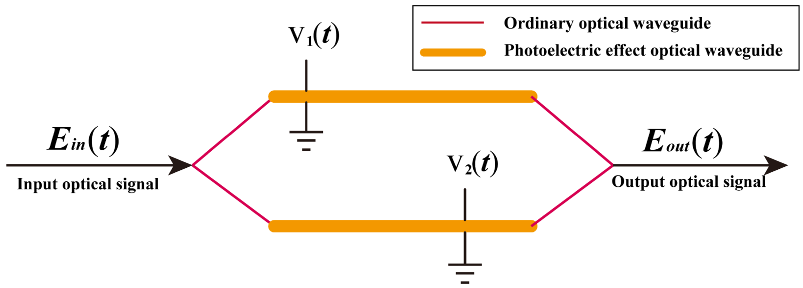

Fig. 3. Structure of Mach-Zehnder intensity modulator. $\nu_1(t)$ and $\nu_2(t)$ are the corresponding input electrical signals.

with:

$$ER = 1 - \frac{4}{\pi} \cdot \arctan\left(\frac{1}{\sqrt{\text{extract}}}\right) \tag{4}$$

The phase transition $\Delta\phi$ of the signal is defined as:

$$\Delta\phi(t) = SC \cdot \Delta\theta(t) \cdot (1 + SF)/(1 - SF) \tag{5}$$

Where the parameterSC is -1 if negative signal chirp is true, or 1 if negative signal chirp is false.extract is the extinction ratio,SF is the symmetry factor, and Modulation(t) is the electrical input signal. The electrical input signal is normalized between 0 and 1.

2.2 SLM Impact On The Links

As a core device for our system, the SLM can convert Gaussian beam into vortex beam and recover it into Gaussian beam, which has a dominated influence on generating vortex beam [27]. It not only changes the spin angular momentum (SAM) of the beam, but also the OAM [28]. The topological charge of the generated vortex beam satisfies a certain relationship with the phase pattern information loaded by SLM.

The liquid crystal material used in the SLM is a super-high-speed liquid crystal, which utilizes the birefringence effect and the twisting property of the liquid crystal. when the beam enters the dual-frequency liquid crystal SLM, the difference in indexes of refraction of the o-light and e-light result in the separation of o-light and e-light in the beam [29]. In the liquid crystal SLM, o-light and e-light hold different transmission rates. At the same time, when different voltages are applied at both ends of SLM, the liquid crystal molecules will deflect at different angles by using the distortion effect. Therefore, liquid crystal SLM can realize different phase modulation for each pixel.

When the upper gray phase image is loaded, the SLM will apply a voltage to each pixel of the liquid crystal panel in gray level. When an electric field is applied along the Z-axis, the relationship between the liquid crystal molecular turning and the applied voltage V is as follows [30], [31]:

$$\theta = \begin{cases} 0 & , (V \le V_c) \\ \frac{\pi}{2} - 2\arctan\left[\exp\left(-\frac{V - V_c}{V_0}\right)\right] & , (V > V_c) \end{cases} \tag{6}$$

In this formula, V_0 is the rated voltage of the modulation voltage and V_c is the threshold voltage. With the deflection of molecular orientation, the refractive index n_e along Z-axis also changes [32]:

$$\frac{1}{n_e^2(\theta)} = \frac{\cos^2\theta}{n_e^2} + \frac{\sin^2\theta}{n_o^2} \tag{7}$$

Here, the values of n_e and n_0 vary with the load voltage. The beam is incident on the SLM in the Z-axis direction, and the reflected beam will carry the information. The resulting optical field can be

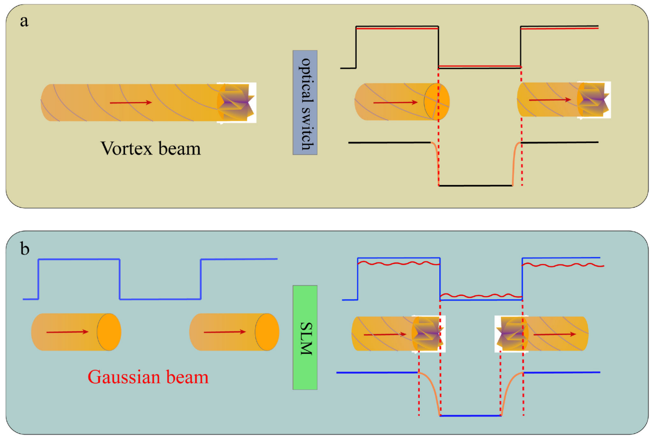

Fig. 4. This figure shows the difference between the signals encoded by the vortex beam in the VM and VAM links. 4(a) The signal encoded in the VM link. 4(b) The signal encoded in the VAM link.

represented by a Jones matrix as [33]:

$$J_1(x, y) = e^{j\varphi_1(x,y)} \cdot E_0(x, y) \cdot \begin{pmatrix} 1 \\ 0 \end{pmatrix} \quad (8)$$

Where $E_0(x, y)$ is the amplitude of the input field, and $\varphi_1(x, y)$ is the phase information loaded into the SLM pattern.

Because the SLM changes phase when the Gaussian beam passes through the spatial light modulator, the equiphase plane is distorted and becomes a jagged phase wave front at the front and back ends, so that the entire wavefront is no longer flat. In VM links, when the beam first passes through SLM, it becomes a vortex beam. Then, when it passes through the optical switch, the whole vortex beam is cut off and the wavefront is relatively flat. At this time, the 0, 1 signals in the vortex beam can be clearly distinguished, as shown in Fig. 4(a). In the VAM link, when the Gaussian beam first passes through the Mach-Zehnder modulator, it becomes a discontinuous beam of 0, 1 signals. When passing through the SLM, the SLM will delay the phase of the vortex beam, causing the wavefront jagged, as shown in Fig. 4(b). This jagged wavefront is exactly the 0, 1 partition of the modulated signal, which will cause power dispersion, and part of the power crosstalk from the signal 1 to 0. Finally, the power of the signal 1 is reduced, while the power of the signal 0 is increased, resulting in a decrease in the signal-to-noise ratio of the signal 1, which eventually leads to an increase in the bit error rate of the received signal at the receiving end. In the following, we compare the communication differences between VM link and VAM link in different communication systems.

3. Single Link Transmission Comparison

Based on the theory above, we have constructed three single channel links for a VM link, a VAM link, and a Gaussian beam communication link, respectively. The structure of VM link and VAM link are shown in Fig. 2, the OAM used is $l = +16$ [34]. The above communication links are all under the FSO channel and the transmission distance is 180 m, which uses the OOK modulation method. The signal is generated using pseudo-random bit sequence generator and converted into modulated electric signal by not-return-to-zero(NRZ) pulse generator. After that, the signal is loaded onto vortex beams utilizing Mach-Zehnder modulator. The Baud rate is $1.6*10^{10}$ b/s for single link communication system. In the test, the same signal is transmitted at different power, and information such as the BER and spectrum of the signals at different transmission power of the three links are obtained.

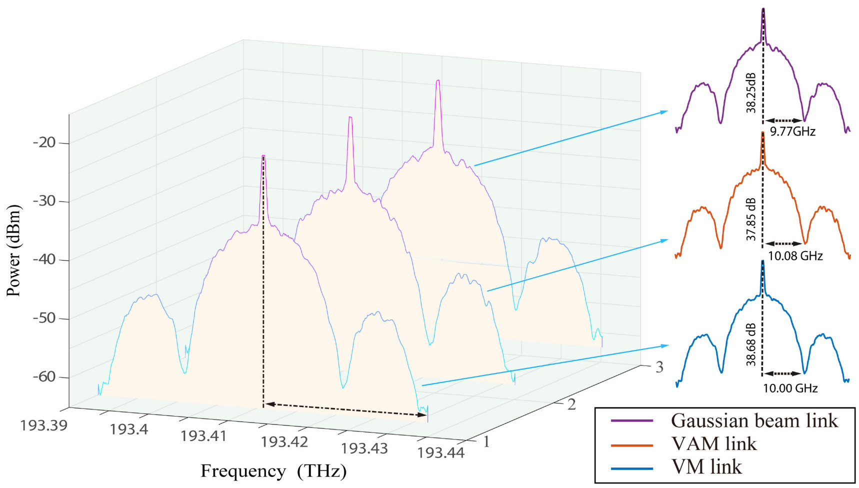

Fig. 5. Spectrum of the signal transmission. Comparisons of the bandwidth and power suppression sizes of Gaussian beam links, VM links, and VAM links.

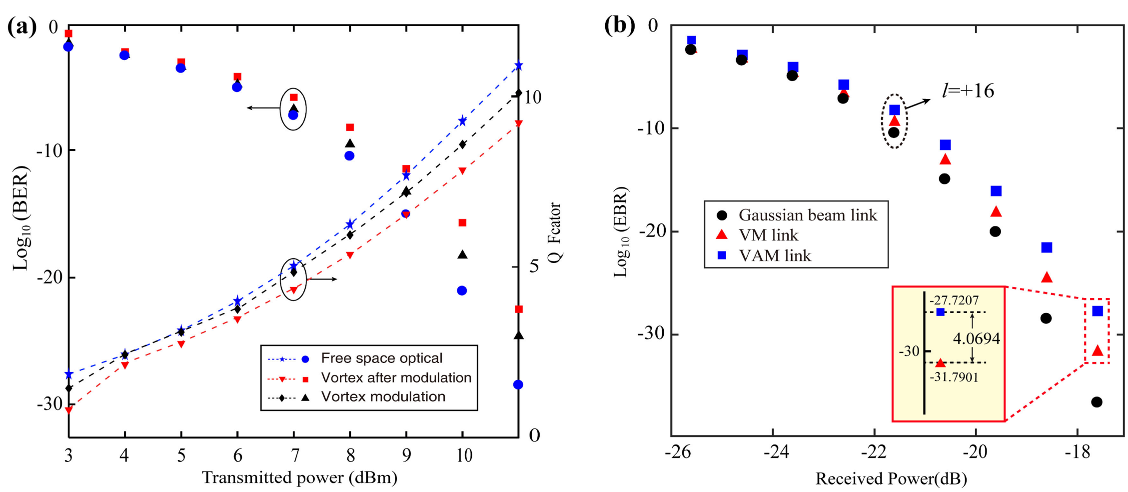

Fig. 6. (a) The comparison of transmission BER and the Q factor of different systems under the same transmission power. (b) The comparison of bit error rates of three links under different received powers.

Spectrum analyzer is applied in this communication link to observe the spectrum of the VM link, VAM link and Gaussian beam link. The results are shown in Fig. 5. All three channels use a communication band with a center frequency of 193.4 THz. The VAM link signal has 37.85 dB power suppression under the frequency offset of 10.08 GHz from the distance center. The VM link signal achieves 38.68 dB power suppression under the frequency offset of 10.00 GHz from the distance center. From the spectrum comparison, it can be found that VM link is superior to VAM link in both frequency bandwidth and power suppression.

After analyzing the data, the BER of the VAM, VM, FSO link can be obtained, and the signal noise ratio in VM is lower than that in VAM at different transmission power. The data results are shown in Fig. 6(a), 6(b). The BER is reduced by an average of 2∼4 orders of magnitude, which proves that the VM link we proposed has a bigger reduction on BER than VAM in VOC. From the Q factor of the signal measured in Fig. 6(a), it can be shown that the Q factor of the VM link signal is higher than that of the VAM link under different signal intensities. With the increase of transmission power, the Q factor of the three channels increases gradually. The higher the power, the greater the difference

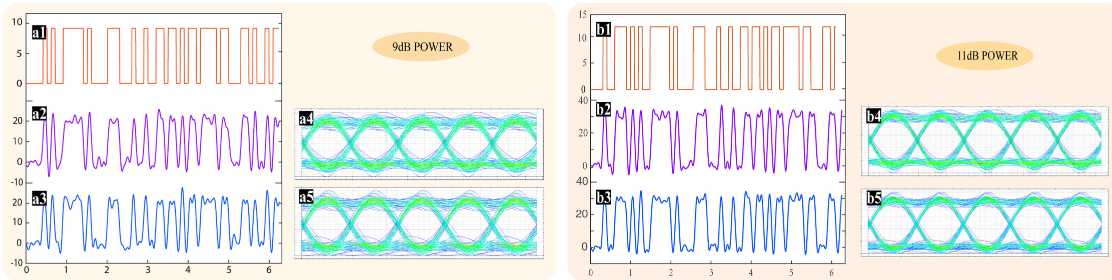

Fig. 7. Waveforms of transmitted signal and received signals and eye diagrams of received signals. a1∼a3, Waveforms of transmitted signal, received signal in VAM link and received signal in VM link, respectively. The transmission power is 9dB. a4∼a5, Eye diagrams of received signals in VAM link and VM link with transmission power at 9dB. b1∼b3, Waveforms of transmitted signal, received signal in VAM link and received signal in VM link, respectively. The transmission power is 11dB. b4∼b5, Eye diagrams of received signals in VAM link and VM link with transmission power at 11dB.

in Q factor. The data can further prove that the VM link has better transmission performance than the VAM link. In other words, while ensuring reception BER, the transmission distance of VM link is greater than VAM link.

Comparisons were made between different power and some of the data were listed below. When transmitting power is 9 dB and 11 dB, we load two different signals to VM and VAM links and observe the received waveform and eye diagram, as shown in Fig. 7(a), and Fig. 7(b). The figure compares the waveforms of the received signals and the eye diagrams of the VM and VAM links. At the same time, we conducted another study while ensuring that the three link signals have the same transmission power. The BER of the receiver remains consistent, the bit rate of each link is adjusted, and the transmission rate of each channel is compared. From the data in the Fig. 10(b), when $l = +16$ OAM, the transmission rate in single VM is 15.03 Gbit/s, which is 0.126 Gbit/s higher than VAM. VM links have higher transmission efficiency than VAM links.

4. 8 OAM Beams Multiplexing Transmission Comparison

After a validation in single channel communication, we try to further improve the transmission rate and apply this method to multi-transmit and multi-receive transmission systems. An 8 OAM beams multiplexed system consisting of 4+4 OAM polarization multiplexing was built. As shown in Fig. 8, in this system, beam is initially converted into a vortex beam with a topological charge of l through the SLM, and then the signal is loaded through the optical switch. At this time, the OAM beam of topological charge l will carry the signal.

We use eight different OAMs to carry signals simultaneously. Each signal combines them through the beam splitter (BS), and each two OAM beams are combined into one bundle. After two rounds of convergence, the four OAM beams finally become a bundle. They are then multiplexed together by using a polarization beam splitter (PBS), and transmitted into free space.

At the receiver, a beam multiplexed by 8 OAM beams is obtained. First, the polarization signals in the X and Y directions are decomposed by polarization demultiplexing. The separated X-direction signal contains four OAMs multiplexing (the same as the Y-direction). Use BS to split the beam into two, and after two splitters the beam will become four beams. Each beam contains four multiplexed topological chargesl_0,l_1,l_2, andl_3. The first beam passes through a SLM of phase image with a topological charge of $-l_0$, and the topological charge in this beam will be updated to $0,(l_1 - l_0)$, $(l_2 - l_0),(l_3 - l_0)$. The vortex beam with topological charge l_0 becomes Gaussian beam. The updated beam are focused through the lens, the topological charge of 0 become Gaussian beam which converge into a point, and the l non-zero vortex beam will be focused on a small ring. An opaque plate with small holes is placed in front of the beam path. The beam that is focused to a point passes, and the other beams that are focused into a small ring are blocked. The opaque plate

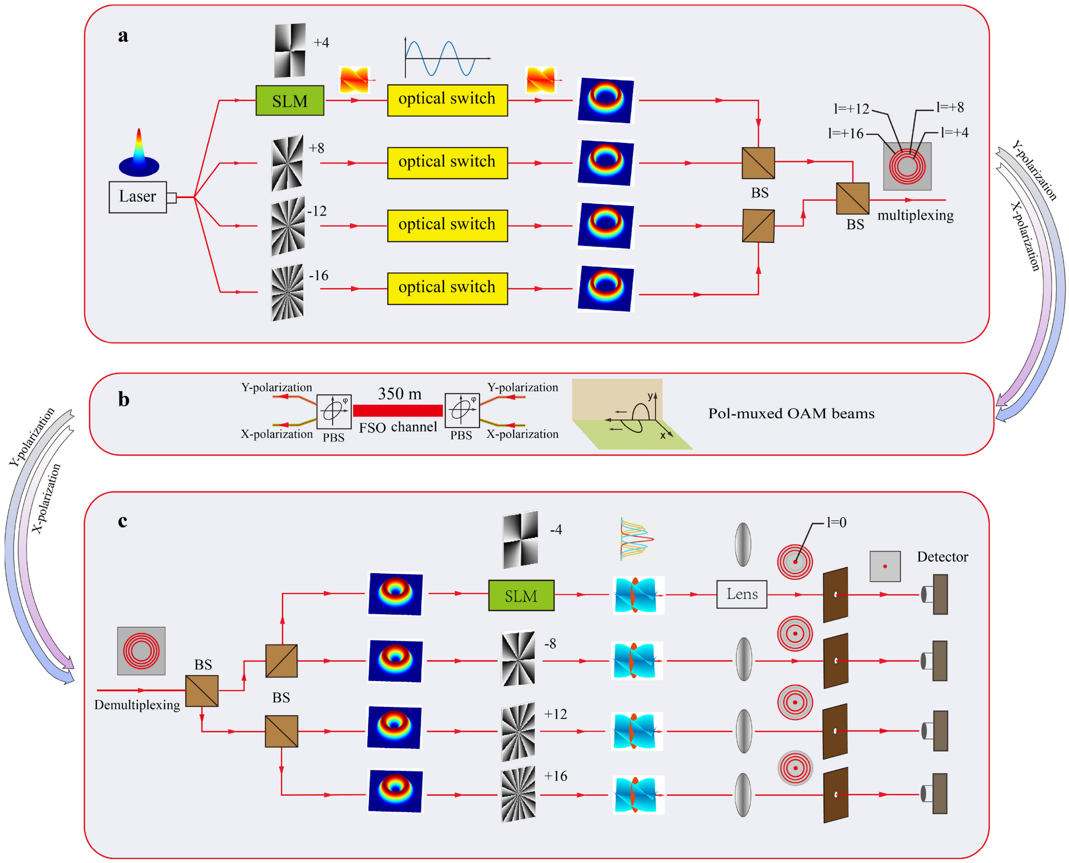

Fig. 8. Multiplexing and demultiplexing link structure. (a) Information is loaded onto the vortex beam and transmitted. Information of different OAMs is multiplexed in space. (b) Beams carrying OAM are transmitted in FSO channel and polarization multiplexing and demultiplexing are implemented. (c) Separation, filtering and detection of different OAMs for space multiplexed vortex beams.

with small holes acts as a filter, and finally only the beam of $l=l_0$ passes. In the same way for each channel, the mixed vortex is successfully separated. Finally, the vortex beam with only a single OAM is obtained [35]. The beam is subsequently inputted to the photodetector to convert the signal carried by the vortex beam into an electrical signal.

We use this 8-OAM-beams multiplexing system to perform normal communication transmission. The signal is transmitted in the FSO channel through 8 OAM beams multiplexing, and the signal is analyzed at the receiver [36]. Fig. 9.a$\sim$c shows different OAMs vortex optical transmission and multiplexed optical field diagrams in simulation and experiments [37]. In this research, for information transmission, when using VM and VAM links that both adopt 8 OAM beams multiplexing, it was found that the BER of the received signal in VM links is lower, and with the increase of transmission power, these differences reveal an increasing trend as shown in Fig. 9(d). At the same time, 8 OAM multiplexed signal constellations are presented. Measurements at the receiver show that the BER difference can reach 1.6 orders of magnitude, as shown in Fig. 10(a). The transmission rate of each channel of the VM link can reach 15.03 Gbit/s. When the transmitting end maintains the same transmitting power and the receiving end maintains the same BER, the single channel VM link achieves higher transmission rate than the single channel VAM link. For example, in Fig. 10(b) when the transmission power is fixed to 13 dB and the $\log_{10}(BER)$ is -9.84, the transmission rate of the single channel VM link is 0.121 GBit/s higher than the single channel VAM link. The ordinate in Fig. 10(b) Indicates the differences between the VM channel link and the VAM channel link in transmission rate.

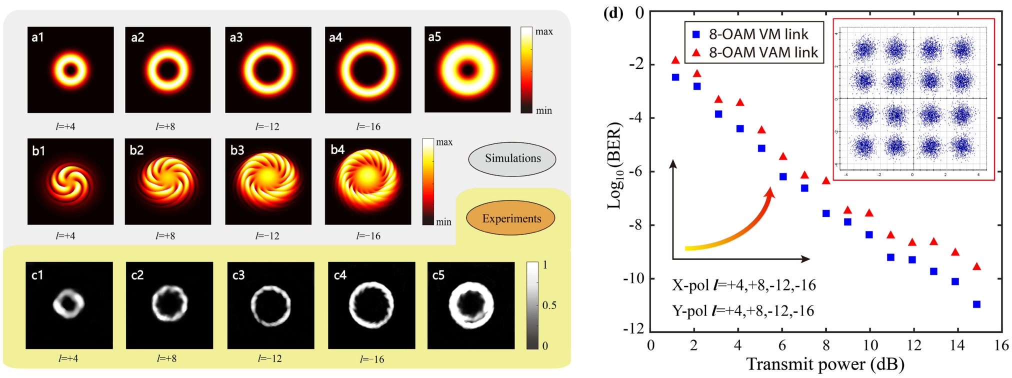

Fig. 9. Vortex optical field and comparison of transmission BER. a1∼a4, Simulated figures of single OAM optical field. a5, Simulated figure of OAM multiplexed optical field. b1∼b4, Interference patterns of different OAMs vortex optical and Gaussian optical fields. c1∼c4, Different OAMs optical field figures in the experiment. c5, The optical field after vortex optical OAM multiplexing in the experiment. d, Comparison in BER between VM and VAM link. With the increase of transmission power, the difference in BER becomes more conspicuous. The top right of this figure presents the constellation of the received signal in 16-QAM signal 8 OAM multiplexing communication.

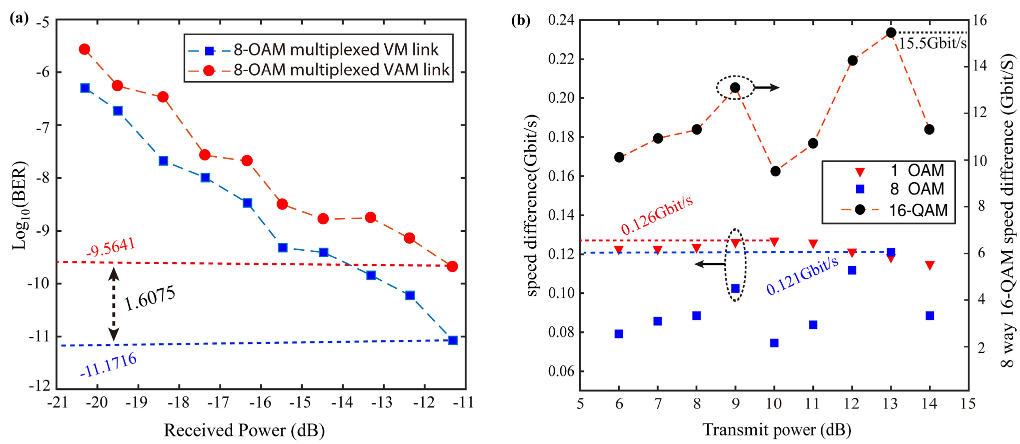

Fig. 10. (a) The BER comparison between the VM link and the VAM link in the case of 8 OAM beams multiplexing, the BER difference can be up to 1.6 orders of magnitude. (b) Comparison of transmission rate between 8 OAM beams multiplexing and 16-QAM 8 OAM beams multiplexing under single channel, the ordinate is the difference in transmission rate between the VM channel and the VAM channel.

When the 16-QAM signal is inputted, the difference between the VM and VAM transmission rate under a single link can be expanded to 1.936 Gbit/s. VM links can achieve 1.21 ($37.7 \times 4 \times 4 \times 2$) Tbit/s transmission rate in 8 OAM beams multiplexing. Compared with VAM modulation mode, the VM links have an advantage of 15.5 Gbit/s on the transmission rate. It can be found that in the 8 OAM beams multiplexing system, the VM link has a significant advantage on speed, which proves that our proposed structure can indeed improve the transmission rate. If this link structure is applied to a larger number of OAM multiplexing systems, then its speed advantage will be further revealed.

5. Discussion and Conclusion

A large number of studies have shown that in the transmission of high-efficiency OAM, modulation-coding and coding-modulation have different effects on information transmission. We compared both the "loading information after generating vortex beam" and "transferring the information directly into the Gaussian beam and then turning it into a vortex phase through the SLM". By studying comparatively, it is found that VM modulation mode is better than VAM modulation mode while using a single link transmission. The difference between the vortex of l=16 in the VM, VAM link and Gaussian beam in the FSO link were compared. It is found that the BER in the VM is 2$\sim$4 orders of magnitude lower than that in the VAM on average, and the spectral efficiency is 15.1 bitS^{-1}Hz^{-1}. When the 8 OAM beams (Data1 $\sim$ Data8, OAM1 $\sim$ OAM8) multiplexed link transmits the NRZ signal in OOK modulation mode, the transmission rate of single channel of the VM link can reach 15.03 Gbit/s. When transmitting a 16-QAM signal, the transmission rate of a channel can reach 150.8 (37.7 $\times$ 4) Gbit/s. The total transmission rate of the 8 OAM beams multiplexing can reach 1.21(37.7 $\times$ 4 $\times$ 4 $\times$ 2) Tbit/s, and the spectrum efficiency is 64.7 bits^{-1}Hz^{-1}.

While maintaining the same signal strength at the transmitting end, adjusting the transmission bit rates of each link and keeping the BER of the receiver constant, the transmission rate of VM and VAM channels are compared. The VM has a speed advantage over the VAM in different links and different modulation schemes. More specifically, the single channel modulation can achieve a speed advantage of up to 0.126 Gbit/s and as a result, when using 8 OAM beams multiplexing 16-QAM modulation, it can achieve a speed advantage of up to 15.5 Gbit/s.

In summary, when using the VOC system, we prefer to adopt the structure that first generates the vortex beam and then modulates the signal. The advantage of this link is that the transmission rate can be further improved and the BER can be reduced. This method is simple, convenient to implement, and can provide a wide range of applications in vortex high volume communication.

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