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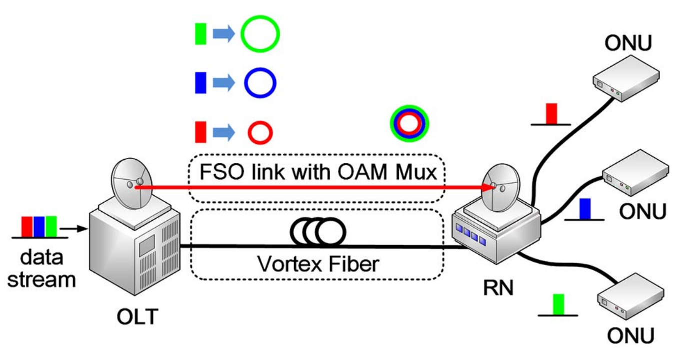

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A Novel PON Architecture Based on OAM Multiplexing for Efficient Bandwidth Utilization

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Abstract: In this paper, we propose and experimentally demonstrated a novel passive optical network access architecture based on orbital angular momentum (OAM) multiplexing. Multiple data channels are multiplexed by orthogonal OAM modes on the same wavelength to achieve efficient utilization of bandwidth resources. Twenty OAM modes, with each mode carrying 10-Gb/s on–off keying signal, are transmitted over 0.4-m free-space optics link. The bit error ratio (BER) performances of all data channels can be under a 3.8×10^{-3} enhanced forward error correction limit. The experimental results show the potentiality of the proposed architecture for providing user access with flexibility and bandwidth efficiency in future ultrahigh-capacity passive optical networks.

Index Terms: Free-space optical communication (FSO), multiplexing, orbital angular momentum (OAM).

1. Introduction

Rapidly increasing internet data traffic nowadays has aroused increasing demand for higher user access bandwidth. With limited bandwidth available for optical access network, an urgent problem to solve is developing advanced techniques for efficient utilization of bandwidth resources [1]. Various novel schemes concerning architecture, modulation format, signal processing and network protocol have been proposed to improve the performance of current passive optical networks [1], [2]. Recently, orbital angular momentum, with theoretically infinite orthogonal modes to improve spectral efficiency and transmission capacity, has attracted increasing research interest [3]–[5]. Backward compatible with existing multiplexing techniques such as time division multiplexing (TDM), wavelength division multiplexing (WDM), polarization division multiplexing (PDM), spatial division multiplexing (SDM), and mode division multiplexing (MDM), OAM multiplexing is capable of offering additional degree of freedom (DOF) for multiplexing. Allen first revealed the property of OAM carried by Laguerre-Gaussian (LG) beam in 1992 [6] and then, OAM was introduced to optical communication systems [7]. Many scheme and experiments utilizing OAM multiplexing based on FSO link [3]–[5], [7]–[11] and vortex fiber [12] have been reported.

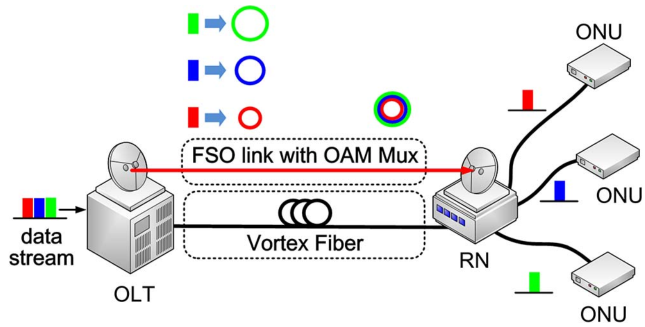

Fig. 1. Principle of novel PON architecture based on OAM multiplexing.

In this paper, we propose and experimentally demonstrate a novel PON access architecture based on OAM multiplexing. Multiple data channels are multiplexed by orthogonal OAM modes on same wavelength to achieve efficient utilization of bandwidth resources. 20 OAM modes with each mode carrying 10 Gbit/s OOK signal, are transmitted over 0.4 m FSO link. The bit error ratio (BER) performances of all data channels can be under 3.8×10^{-3} enhanced FEC limit. The experimental results show the potentiality of the proposed architecture for providing user access with flexibility and bandwidth efficiency in future ultra-high capacity passive optical networks.

2. Principle

The LG beam carrying OAM mode features helical phase front, which can be described by an azimuthal phase term: $e^{il\phi}$. The value l is known as topological charge which stands for different orthogonal eigen-states corresponding to different OAM modes and ϕ is the azimuthal phase. l must be an integer $(l = 0, \pm 1, \pm 2, \ldots)$ to satisfy the self-consistent condition. By employing reflective spatial light modulator (SLM) with pre-calculated hologram pattern, signal can be converted onto specific OAM mode to realize multiplexing or be converted back to fundamental Gaussian beam $(l = 0)$ to realize demultiplexing. Here, we propose to utilize orthogonal OAM modes multiplexing to realize PON access for multiple users.

Fig. 1 illustrates novel PON access architecture based on OAM multiplexing. The architecture consists of optical line terminal (OLT), remote node (RN) and optical network unit (ONU). It is worth noting that the link between OLT and RN can be FSO link or vortex fiber that supports OAM transmission. In OLT, the data from network is first modulated onto optical carrier. Depending on applications, OLT can either transmit multi-channel data for multiple user access or single channel data for multicasting. FSO link with OAM Mux/Demux is the major unique feature of the proposed architecture. Multi-channel signals are converted from fundamental Gaussian beam to LG beam with various OAM modes. Benefiting from the orthogonality of OAM modes, signal carried by different OAM modes will not interfere with each other. Meanwhile, multiplexing signals in the dimension of OAM significantly improves spectral efficiency thus enables efficient bandwidth utilization. After FSO transmission, OAM demultiplexing is done in remote node. Every OAM mode can be demultiplexed and detected independently by converting LG beam back to fundamental Gaussian beam while keeping other modes still in OAM mode. The converted beam is coupled into fiber again and sent to receiver in ONU. It should be noted that the architecture we propose is flexible and adaptive to various applications. For example, the architecture is basically suitable for user data delivery in access networks, both by wireless or wired link. For the former, FSO link can be useful while vortex fiber can be used for the latter [12]. Meanwhile, the architecture is also suitable for multicasting in which OAM modes can be utilized to carry different services for multicasting and demultiplexing can also be done at ONU.

Multiple OAM modes can be generated in various ways: A specially designed hologram pattern implemented to SLM [10], odd times reflection [4], [8], polarization multiplexing [4], [8] in free space and so on. In this paper, specially designed hologram pattern is implemented to

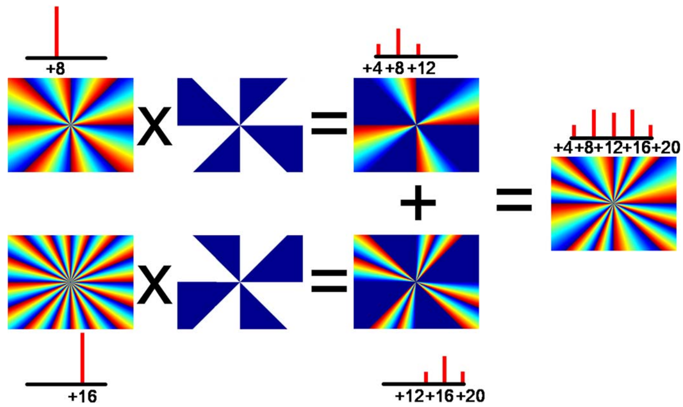

Fig. 2. Multiple OAM modes generation based on sliced phase pattern and angular mask.

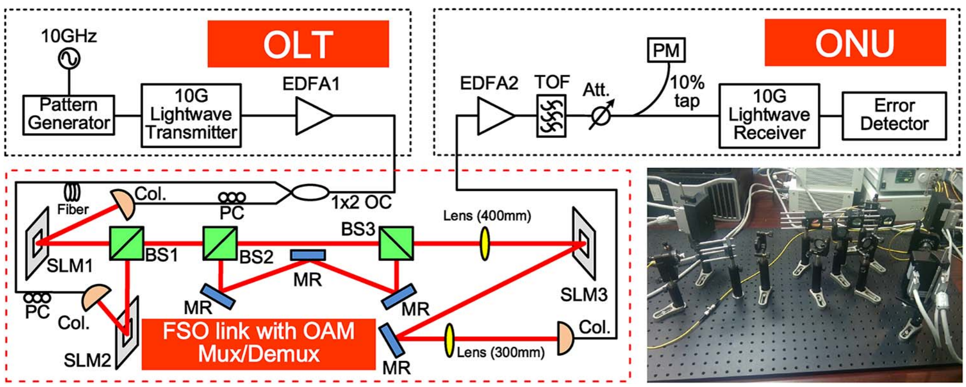

Fig. 3. Experimental setup of novel PON access architecture based on OAM multiplexing. EDFA: erbium-doped fiber amplifier, PC: polarization controller, SLM: spatial light modulator, Col.: collimator, BS: beam splitter, MR: mirror, TOF: tunable optical filter, Att.: attenuator, PM: power meter.

generate five OAM modes. In our experiment, one SLM is used to generate +4, +8, +12, +16, and +20 while another SLM is used to generate −6, −10, −14, −18, and −22. Fig. 2 shows the process of designing hologram pattern to generate OAM mode +4, +8, +12, +16, and +20 by one SLM simultaneously. First, we generate hologram pattern of +8 and angular mask with 4-fold rotational symmetry. Because of the angular diffraction principle, N-fold rotational symmetry angular mask will distribute energy from OAM mode l to $l + N$ and $l - N$ [13]. Therefore, part of the power on +8 will transfer to +4 and +12. In this way, we got the hologram pattern to generate 3 OAM modes: +4, +8, and +12. Meanwhile, we utilize similar principle to generate +12, +16, and +20. By superimposition of two hologram patterns, we obtain the sliced phase pattern to generate 5 modes. It should be noted that the angular mask is designed to be complementary to each other, which minimizes the interference between modes. With similar method, other 5 modes are generated by another SLM. Also, benefiting from the mirror image relationship of reflected LG beam with OAM mode, odd-time reflection can be utilized to generate the OAM modes with opposite charge sign [8]. In this way, we are able to generate 20 OAM modes with two SLMs, three beam splitters and three mirrors.

3. Experimental Setup

Experimental setup of novel PON access architecture based on OAM multiplexing is shown in Fig. 3. At OLT, microwave source with 10.665 GHz output is employed as the clock to the pattern generator. Then, the electrical signal with pattern length of $2^{31} - 1$ is modulated onto the optical carrier to generate a 10 Gbit/s optical OOK signal at 1550-nm by a 10 G lightwave transmitter (Agilent 83433 A). The following Erbium-doped fiber amplifier (EDFA1) is used to provide sufficient optical power up to 22 dBm coupled into FSO link. The optical signal is split into two branches via one 1 $\times$ 2 optical coupler (OC). The fiber length connected from OC to SLM1 and SLM2 is different to introduce deliberate delay between two branches. In this way, the information carried by beam incident onto SLM1 and SLM2 will not be the same. Polarization controllers (PC) are then used for both branches since the incident light must be horizontally polarized to ensure good performance of the reflective SLM1 and SLM2. The optical signal is incident on a liquid-crystal on silicon SLM (LCOS-SLM, HAMAMATSU, 792 $\times$ 600 pixels) with high-precision phase modulation characteristics. With collimators, optical signal is coupled from fiber to FSO link. Utilizing specially designed hologram pattern introduced in Fig. 2, fundamental Gaussian beam is converted to LG beam with five various OAM modes on both SLM1 and SLM2, respectively (+4, +8, +12, +16, and +20 for SLM1, −6, −10, −14, −18, and −22 for SLM2). Two LG beam, each carrying 5 OAM modes, are then combined by BS1 to realize 10 concentric OAM modes. It is worth noting that OAM modes generated by SLM2 will meet with additional reflection at BS1 compared with those OAM modes generated by SLM1. That is the reason why we implement hologram pattern generating −6 to −22 rather than +6 to +22. Therefore, after combining at BS1, the 10 concentric OAM modes are +4, +6, +8, +10, +12, +14, +16, +18, +20, and +22. After that, the beam is split into two optical paths by BS2. One path contains three additional mirrors to generate OAM modes with the opposite sign (−4, −6, −8, −10, −12, −14, −16, −18, −20, and −22) through mirror image relationship. Two optical paths are then combined by BS3. In this way, the data carried on each OAM mode is different from adjacent modes. After lens to adjust the beam size as well as collimation, SLM3 is employed to demultiplex and detect OAM mode. By just switching the hologram pattern on SLM3, the specific OAM mode with data needed is converted back to fundamental Gaussian mode. The FSO link between BS3 and SLM3 is 0.4 m. The beam then goes through another collimator and coupled into fiber again. Here, we employed an infra-red charge-coupled device (IR-CCD) camera for the convenience of adjustment and observing optical profile. At ONU, signal firstly goes through EDFA2 to compensate the loss during coupling and free-space propagation. A tunable optical filter is used to suppress unwanted components. Then the optical signal is input into a 10-G lightwave receiver Agilent 83434 A for direct detection. Finally, an error detector is employed to measure the BER performance. The inset of Fig. 3 is the photograph of FSO links in the experimental setup.

4. Experimental Results and Discussions

Fig. 4 is the optical intensity profile for detection of different OAM modes obtained by infra-red camera. Fig. 4(a)–(j) show the optical intensity profile of demultiplexing specific OAM mode (+4, +8, +10, +12, +16, +22, −6, −14, −18, and −20), respectively. We can all observe obvious round point in the center which indicates one of the OAM modes has been converted back to fundamental Gaussian mode. The multiple concentric rings can also be observed which represents other OAM modes are converted to corresponding values (e.g., when convert +4 to fundamental Gaussian mode, +8, +10, +12, and +16 will be converted to +4, +6, +8, and +12, respectively). However, the imbalance of power distribution on the OAM modes we generate can also be observed. For example, the Gaussian mode in the center after demultiplexing +4, +22, −6, and −20 is apparently smaller and darker. In fact, the main reasons for impurity of generated OAM modes are resolution limitation and imperfection of LCOS-SLM.

Fig. 5 shows eye diagrams of the 10 Gbit/s OOK signal carried by OAM mode +8 and −20. The eye diagram is observed under 50 ps/div. Here, we choose +8 and −20 OAM modes since they are just the best and worst channel, respectively. In Fig. 5(a), +8 is the OAM mode in the middle of original optical path (w/o mirrors) and the corresponding eye opening degree is good. In Fig. 5(b), −20 is the OAM mode by side of the reflection path (w/ odd mirrors) and the eye opening degree is over 3 dB worse than +8.

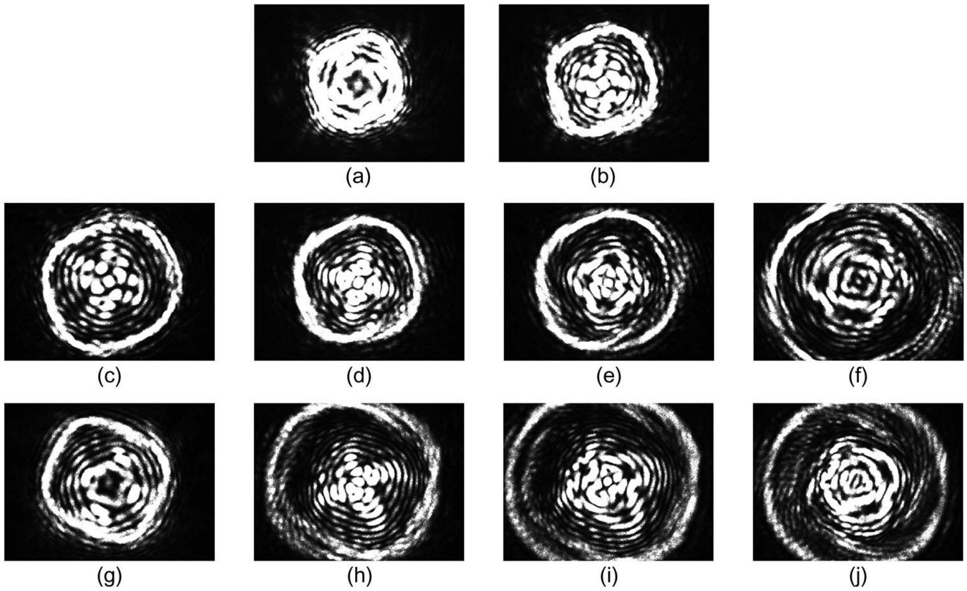

Fig. 4. Optical intensity profile (a) demux +4, (b) demux +8, (c) demux +10, (d) demux +12, (e) demux +16, (f) demux +22, (g) demux −6, (h) demux −14 (i) demux −18, and (j) demux −20.

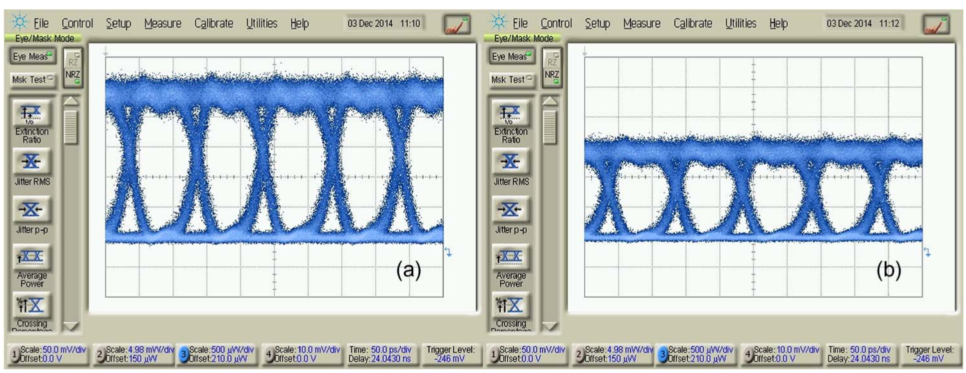

Fig. 5. Eye diagrams of optical OOK signal carried on (a) OAM mode +8 and (b) OAM mode −20.

Fig. 6 shows the BER versus received optical power of different OAM modes. We can find that the performance of OAM mode in original path shows better performance than corresponding mode in reflection path which is with same topological charge value but opposite sign. By comparing +8 and −8, we find the BER of OAM mode −8 is ~3 dB lower than OAM mode +8. However, within two groups of 10 modes in same path, the BER performance of OAM modes at two sides (e.g., +4, −6, −20, and +22) are ~3 dB lower than that in the middle. This result conforms to the imbalanced power distribution of the OAM mode generated by our hologram pattern. Considering these two factors, OAM modes −20 and +22 both show the worst performance. Optimized hologram pattern will achieve more balanced power distribution and channel performance.

5. Conclusion

In this paper, we propose and experimentally demonstrate a novel passive optical network access architecture based on orbital angular momentum multiplexing. Multiple data channels are multiplexed by orthogonal OAM modes on same wavelength to achieve efficient utilization of bandwidth resources. 20 OAM modes with each mode carrying 10 Gbit/s OOK signal are

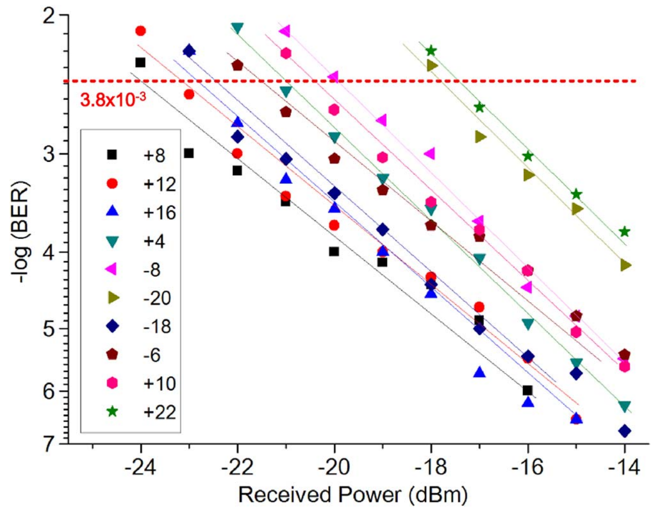

Fig. 6. BER versus received optical power of OAM modes.

transmitted over a 0.4 m FSO link. The BER performances of all data channels can be under 3.8×10^{-3} enhanced FEC limit. The experimental results show the potentiality of the proposed architecture for providing user access with flexibility and bandwidth efficiency in future ultra-high capacity passive optical networks.

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