Demonstration of 8-Mode 32-Gbit/s Millimeter-Wave Free-Space Communication Link using 4 Orbital-Angular-Momentum Modes on 2 Polarizations

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Abstract—**This paper reports an experimental demonstration of modal multiplexing using orbital angular momenta (OAM) in the millimeter-wave regime (28 GHz). Using 1 GBaud/s signals with 16-QAM modulation, a data rate of 32 Gbit/s is obtained by employing 4 different OAM modes (*l*= -3,-1,+1 and +3) on two orthogonal linear polarization states. Without any digital post-processing, the receiver can separate the different data streams since crosstalk among the OAM channels is low: measured to be better than -23dB with a 28 GHz narrowband carrier on a single polarization, and better than -16dB on both polarization states. The bit-error rate (BER) of 8 channels is measured, and found the raw BER is below 3.8×10^{-3}, thus allowing efficient use of forward error correction (FEC) codes.**

Keywords—Orbital angular monmentum; millimeter wave; modal multiplexing.

I. Introduction

Transmitting multiple overlapping spatial modes has the potential to increase the total link capacity, as well as the spectral efficiency in free-space communication systems [1,2]. In such a system, each mode carries an independent data stream and is orthogonal to (or at least linearly independent of) all other modes, such that efficient multiplexing and demultiplexing can be performed at the transmitter and receiver, respectively.

One approach for multi-mode communications that has received a fair amount of recent interest is the use of orbital-angular-momenta (OAM) [3]. OAM can be interpreted as a "corkscrew twist" of the phase front of a propagating wave. The wavefront phase of an OAM beam could change from 0 to $2\pi l$ azimuthally, in which l is known as the charge number of the OAM beam that can take any integer values; each OAM beam with $l\neq0$ has a doughnut-shaped intensity profile whose width increases with l. Note that OAM is distinct from the phase rotation of polarization (polarization can be interpreted as the "spin" of the photons, which is a different quantum number from OAM, and can take on only two values ±1/2). Each OAM beam with one charge number is theoretically orthogonal to (that is, distinguishable from) all other OAM beams with different charge values. The OAM beams have thus been suggested for modal multiplexing because their orthogonality enables multiple beams of different OAM charge numbers to be multiplexed together and subsequently demultiplexed with negligible crosstalk among them [4]. Each OAM beam can carry an independent data stream using the same carrier, and therefore the total information capacity equals the data rate of the single channel multiplied by the total number of OAM beams.

OAM has been demonstrated for different types of free-space communication systems, including: (a) optical [5]: Data transmission of 32 OAM channels (8 different OAM numbers, two polarization states in two groups of concentric ring) at wavelength of 1550nm (at frequency of 193.5THz). Each channel carried 100Gbit/s QPSK signal and a total capacity of 2.56 Tbit/s and a spectral efficiency of 95.6bit/s/Hz have been achieved; (b) radio frequency [6]: A Gaussian beam and another OAM beam have been used for communication at 2.4GHz carrier frequency. The transmitted signal bandwidth was 27MHz. However, only a single polarization was used, so that the total number of spatial streams was limited to 2.

Contributions: In this paper, we demonstrate a RF (mm-wave) links with OAM: an 8-mode, 32-Gbit/s millimeter-wave free-space communication link using 4 OAM modes on 2 polarizations. Each channel carries a 1Gbaud/s 16-QAM signal. A single carrier frequency is used at 28GHz (wavelength 1.07cm). Four different OAM beams of charge numbers l=-3,-1,+1, and +3 on two linear polarization states are used. We adapt the concept of *spiral phase plates*, previously used in optics, as a scalable method for creating OAM modes in the mm-wave regime. The spiral plates and lens made of high-density polyethylene (HDPE) are used to generate and demultiplex OAM beams. 50:50 beam splitters that work for both polarizations states are designed and used to multiplex multiple OAM beams. As this is a proof-of-principle experiment, the transmission distance is short - about 2.5 meters. At the receiver we demultiplex the OAM channels by using a spiral plate of inverse spiral surface. We demonstrate that crosstalk is low, allowing a decoding of the spatial streams *without* further processing by interference cancellers (BLAST-like structures) or maximum-likelihood detectors [7].

II. GENERATION OF MILLIMETER OAM BEAMS

The $l=0$ OAM mode is the basic mode emitted by standard mm-wave antennas (horn, lens, parabolic). Its intensity profile in the far field is Gaussian, with the maximum in the center of the beam. In contrast, higher-order OAM modes have a doughnut-like intensity profile and a spiral wavefront phase, see Fig. 1 for OAM beams of charge number $l=\pm1$ and $l=\pm3$. The doughnut-shaped intensity is related to the singularity of the phase at the center. For OAM beams with negative charge number, the phase (in a plane perpendicular to the beam propagation direction) grows clockwise, while for positive charge numbers the phase grows counterclockwise. The phase change in the angular direction is $\pm2\pi$ for $l=\pm1$, and $\pm6\pi$ for $l=\pm3$, respectively.

We adopt an approach to generate OAM beams by passing a regular Gaussian beam through a spiral phase plate [8] as illustrated in Fig. 2. The spiral surface induces different phase shifts in different parts of the input Gaussian beam. When the height difference of the spiral plate $\Delta h=l\lambda/(n-1)$, in which n is the refractive index of the plate material, λ is the wavelength of the millimeter wave and l is the OAM charge number, the transmitted beam becomes an OAM beam of charge number l [8]. Reversely, a spiral plate that has an inverse spiral surface can convert an OAM beam back into a Gaussian beam. The spiral plates we used to generate OAM beams are made of high density polyethylene (HDPE) which has refractive index of 1.51 at the frequency of 28GHz. Thus, to generate the $l=\pm1$ and $l=\pm3$ OAM beams the designed height differences are $\Delta h_1=\pm2.07$cm $\Delta h_3=6.21$cm, respectively. The diameter of the spiral plates in our experiment is 30 cm, which is larger than the aperture of the horn antenna we use to create the Gaussian beam (see below). We also designed a lens of focal length f=2m using HDPE to control the beam size of $l=\pm3$ to be similar to that $l=\pm1$ at the receiver. The spiral plates and lenses were fabricated by a precise Computer Numeric Control (CNC) machine process.

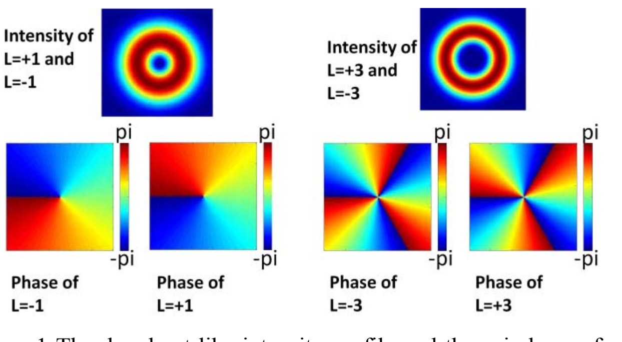


Figure 1 The doughnut-like intensity profile and the spiral wavefront phase of OAM beams of charge number $l=\pm1$ and $l=\pm3$.

Figures 3 shows the measured intensity of the Gaussian beam emitted from the antenna, intensity of the OAM beams after Gaussian beam passing through the spiral plates, and the interference patterns of the OAM beams and the Gaussian beams. The dual-polarization horn lens antennas used at transmitter and receiver have a diameter of 15cm. The image is recorded by a probe antenna with a small aperture diameter of 0.7 cm, whose output is recorded by an RF spectrum analyzer. The probe is attached to a two-dimensional (X-Y) linear translation stage with a scanning resolution of 1cm and a transversal coverage of 60 by 60cm. Fig 3a clearly confirms the ring-shaped intensity profile of the generated OAM beams. The spiral phases of the OAM beams were deduced from the interference patterns between each OAM beam and the Gaussian beam, combined via a beam splitter. The observed number of arms and their rotating directions shown in Fig. 3b fully meet the expectations.

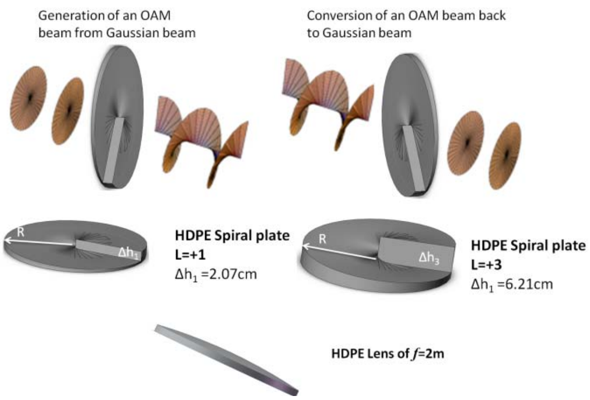
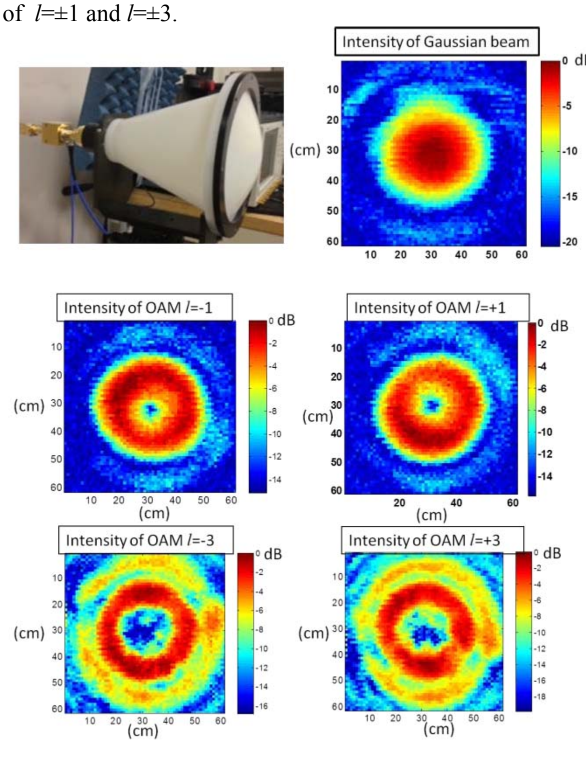
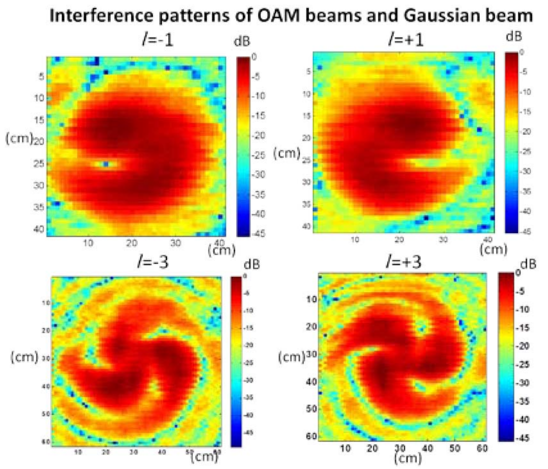


Figure 2 (Top) Illustration of the generation of an OAM beam from Gaussian beam by passing a spiral plate and the conversion of a OAM beam back to a Gaussian beam by passing through a inverse spiral plate.(Bottom) Dimensions of the spiral plates for OAM beams of $l=\pm1$ and $l=\pm3$.



(a)



(b)

Figure 3 (a) Measured intensity of Gaussian beam and 4 OAM beams of charge number l=±1 and l=±3, respectively. (b) Interference patters the Gaussian beam and OAM beams (l=±1 and l=±3, respectively) .

III. MULTIPLEXING AND DEMULTIPLEXING OAM BEAMS

After having demonstrated the generation of OAM beams, we now turn to the multiplexing and demultiplexing of the beams. Figure 4 shows a block diagram of our setup for multiplexing OAM beams, having 4 different charge numbers, on two orthogonal linear polarization states to a total of 8 independent beams. Since OAM and polarization are orthogonal domains of multiplexing, we can combine the two techniques to achieve higher transmission capacity, as well as higher spectral efficiency, since each of the 8 channels can carry an independent data stream.

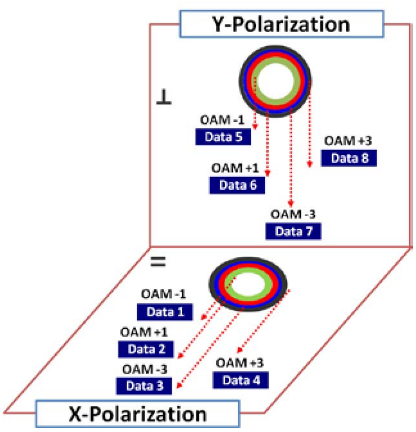


Figure 4. Concept of modal multiplexing by using 4 different OAM beams on two polarizations.

Before starting the detailed description of our multiplexing/demultiplexing method, Fig. 5, we note that each reflection, such as from a beamsplitter *inverts* the beam charge number. We start from 4 dual-polarization horn lens antennas with aperture diameter of 15 cm. For OAM l=+1 and l=-1 channels, the *same* spiral plates, capable of converting a Gaussian beam into an l=+1 one, are placed in front of the antennas to transform the Gaussian beams into OAM beams. A 50:50 beam splitter (BS1) that works for both polarizations is then used to coaxially combine the two l=+1 beams, transmitting the l=+1 unchanged and inverting, upon reflection, the other l=+1 one into an l=-1 beam. The same procedure is used for the generation of the l=±3 beams, using now the higher order spiral plates followed by lenses of focal length f=2m, whose roles are (i) to make the 4 OAM beams overlap; and (ii) to prevent the l=±3 beams from expanding into a too-large spot-size at the receiver. Then, a third beamsplitter, BS3, combines the l=±1 and l=±3 beams, thereby achieving the multiplexing of 8 OAM channels, comprising 4 different charge numbers and two polarizations. Figure 5 (b) shows the demultiplexing of one of the multiplexed OAM channels. By placing a spiral plate having an inverse spiral surface, we can convert one of the multiplexed OAM beams back into Gaussian beam while all other beams remain as OAM beams.

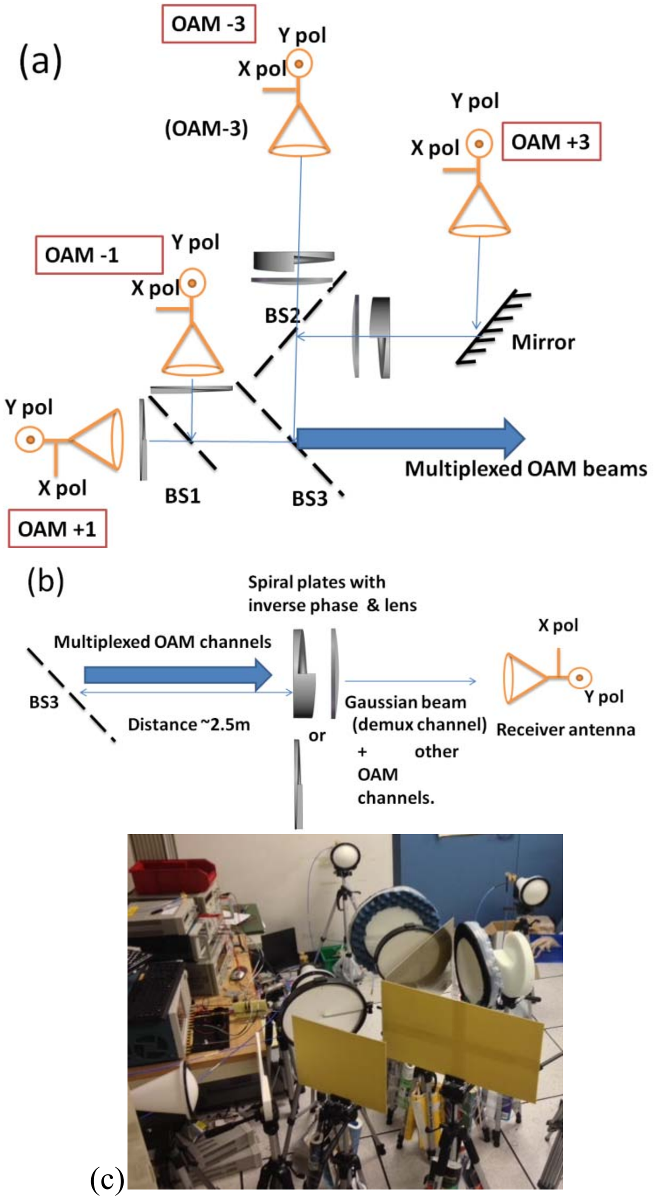


Figure 5 (a) Multiplexing of 8 OAM channels by using dual-polarization antennas, spiral plates, and designed 50:50 beam splitters

(b) Demultiplexing of one of the multiplexed OAM channel: Convert it back to Gaussian beam by using spiral plate and lens, and then use the antenna to receive the Gaussian beam for detection. (c) Photo of part of the the experiment setup, including antennas, spiral phase plate to generate OAM beams, beam splitters and lenses.

For example, when we demultiplex OAM channel l=+3, we use a spiral plate of spiral surface l=-3 which convert the original charge numbers [+1, -1, +3, -3] of the incoming beams into [-2, -4, 0, -6]. Only the beam of charge number l=0, which is of Gaussian shape, will be effectively coupled into the receiver antenna, since theoretically, the overlap integral of the gain profile (Gaussian-like) of the antenna and OAM beams of $l \neq 0$ is always zero. The aperture diameter of the spiral plates and lens used at the receiver is 45 cm, which can recover about 30%~40% of the OAM beam energy (remember that the OAM beam expands as it propagates).

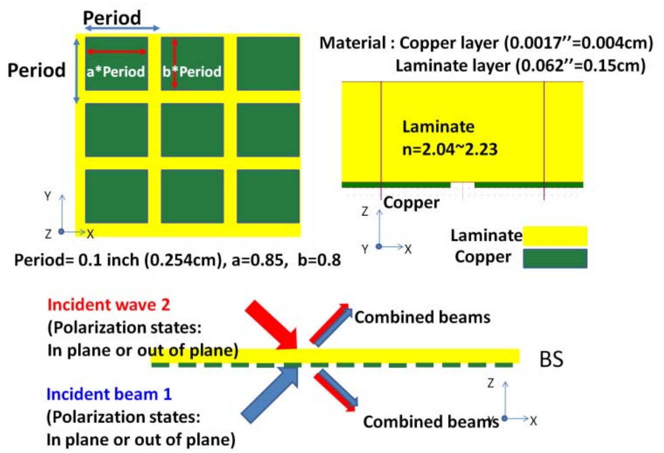


Figure 6. Design of 2D-perodic metal structure for dual-polarization 50:50 beam splitter at frequency of 28GHz to combine OAM beams. (Green: copper. Yellow: laminate).

Figure 6 shows our design of the polarization independent beam splitter. It is a periodic structure of metallic squares. The period is 0.254cm, which can be seen as sub-wavelength structure. The dimensions *a* and *b* of the metal square, which is copper covered by Tin-Lead solder, are chosen to make the whole structure 50% reflecting and 50% transmitting for both polarization states when the incident beam angle is 45 degrees. The design is based on simulation results using Finite-Difference-Time-Domain method (Rsoft-FDTD). The whole structure was fabricated by standard printed circuit board (PCB) process.

IV. Demonstration of 8-Mode 32-Gbit/s Link using 4 Orbital-Angular-Momentum Modes on 2 Polarizations

A. 16-QAM signal generation and detection

Figure 7 shows the block diagram of the setup used to generate and detect 1Gbaud/s 16-QAM signals for the demonstration of the 8 channel communication link. For the transmitter part, a 28GHz continuous-wave (CW) signal is first amplified by a 1-Watt amplifier (Amp1), and then split into two paths. Each of the resulting signals is used as the LO input of two IQ mixers. Two arbitrary waveform generators (Tektronix AWG 7102 and AWG 70002A), connected to the IF ports of the IQ mixers, are used to generate two independent pairs of I and Q waveforms, resulting in two independent 1Gbaud/s 16-QAM data streams. One 16-QAM signal is connected to one OAM channel of which the BER will be measured. The other 16-QAM signal is first amplified by another amplifier (Amp2) and then split into 8 paths. Seven of the outputs are connected to the other 7 channels and we manage to have all eight channels have the same output power at the antenna ports . When we test another channel, we switch the 16-QAM signal generated from IQ mixer 1, which is independent of the other 7 channels, to the channel to be tested. We also use cables of different lengths to decorrelate the signals from of the other 7 channels; in other words, due to the time delays, different symbols are applied to each of the interfering channels at any point in time.

For detection, we use an 80Gsample/s real-time oscilloscope (Agilent DSA-X 93204A), whose real time analog bandwidth of 32GHz is wide enough to faithfully capture the millimeter-wave waveform received by the antenna. Finally, the recorded signal (2×10^6 sampled points corresponding to 2×10^5 bits for 1Gbaud/s 16-QAM signal) is processed offline to recover the 16-QAM signal and calculate the BER. A variable attenuator is placed before the real-time oscilloscope to vary the signal-to-noise ratio (SNR).

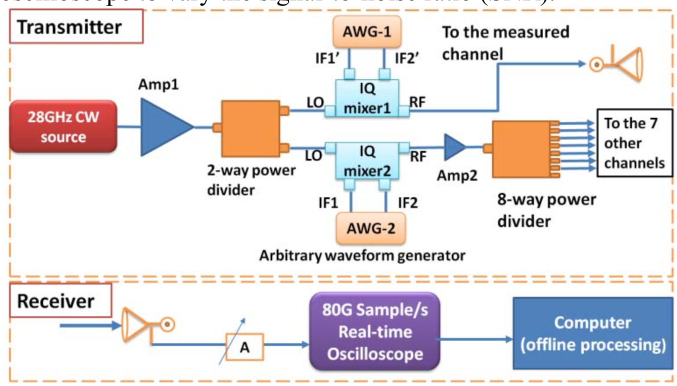


Figure 7 Transmitter and receiver of 1Gbaud/s 16-QAM signal of the 8 OAM channels communication link. Transmitter: CW (continuous-wave). Amp: amplifier. AWG: arbitrary waveform generator. Receiver: detection of 1Gbaud/s 16-QAM carried by 28GHz millimeter-wave by using 80GSample/s real-time oscilloscope followed by offline processing. A: tunable attenuator.

B. Crosstalk and Bit-error rate measurement of 8 OAM channels

We first characterize the crosstalk of the OAM channels by transmitting a 28GHz CW signal over the multiplexed OAM beams. By adjusting the positions of the spiral plate, lens, and receiver antenna, we could manage to obtain the lowest crosstalk from the other channels onto a particular channel of interest. It is expected that the power from the other channels would leak into the channel under detection, due to the imperfections of OAM generation, multiplexing and setup misalignment, which would essentially result in channel crosstalk when a specific channel is demultiplexed at the receiver. The crosstalk for a specific OAM channel l_1 can be measured by $P_{l\neq l1}$ /$P_{l=l1}$, where $P_{l\neq l1}$ is the received power of channel ℓ_1 when all modes except channel ℓ_1 are transmitted, and $P_{l=l1}$ is the received power of channel l_1 when only channel l_1 is transmitted.

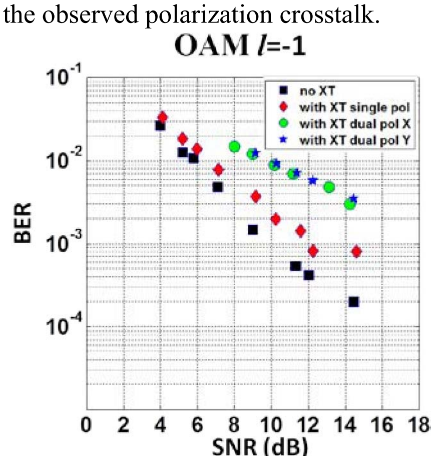
Crosstalk of the OAM channels measured at *f*=28GHz (CW)

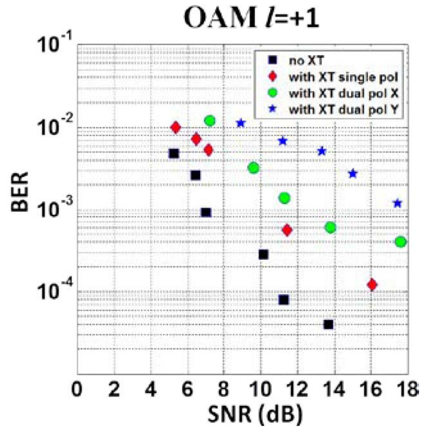
Pol \ OAM	*l*=-3	*l*=-1	*l*=+1	*l*=+3
Single-Pol	-25dB	-23dB	-25 dB	-26dB
Dual-Pol-X	-17dB	-16.5dB	-18.1dB	-19dB
Dual-Pol-Y	-18dB	-16.5dB	-16.5dB	-24dB

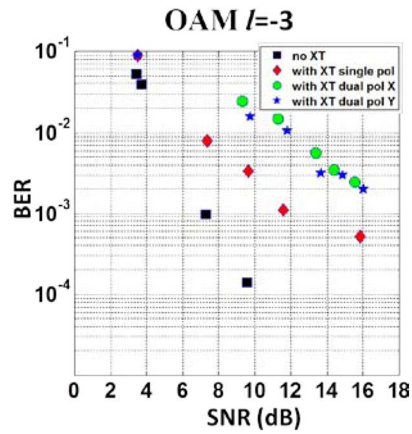
Table 1 Crosstalk of OAM channels measured at *f*=28GHz (CW). Single-pol: 4 channels of 4 different OAM numbers on the same polarization. Dual-pol: 8 channels of 4 different OAM numbers on both polarizations.

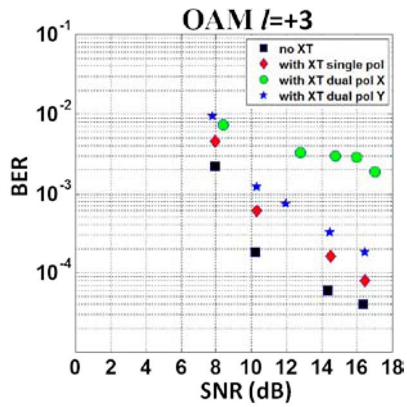
First we measure the crosstalk of the 4 OAM channels on the same polarization: as shown in the first row of Table1, we find values lower than -23dB. However, we have noticed that the crosstalk is frequency dependent. For example, the measured crosstalk is -19dB at 27.5GHz but -20dB at 28.5GHz. Since the transmitted signal is wideband, the expected crosstalk in the actual communication link is somewhat larger than the values shown in Table 1.

We further measure the crosstalk of the 8 channels when we turn on the other 4 channels on the other polarization. From Table 1 we can see the crosstalk values are much worse than the ones of the single polarization. We diagnose the cause of the polarization crosstalk by testing the antenna, beam splitter and spiral plates separately. The measured polarization extinction ratio of the antenna is about 30dB and the beam splitter doesn't introduce significant polarization crosstalk. It appears that the spiral plate is responsible for the polarization crosstalk and we conjecture that during the machining process, some stress-induced birefringence was induced in the plates, giving rise to the observed polarization crosstalk.









Figures 8. BER measurement of 1Gbaud/s 16-QAM signal on single OAM channel (no XT), 4 OAM channels of single polarization (with XT single pol) and 8 OAM channels of two polarizations (with XT X-pol , with XT Y-pol).

Figures 8 show the BER measurements of the 4 OAM channels of the single polarization states and 8 OAM channels of both polarization states, each channel carries 1Gbaud/s 16-QAM signal. The length of PRBS signal we used is 2^{15}-1. For each OAM charge number, we measured the BER when there is no crosstalk from other channels (black square, no XT), when there is crosstalk from other 3 OAM channels of the same polarization (red diamond, with XT single pol) and when there is crosstalk from the other 7 OAM channels on both polarizations (green dot and blue pentagram, with XT dual pol X and with XT dual pol Y). We see that the power penalty of each OAM state (*l*=-1,+1,-3 and +3) in the single-pol case is higher than that of either polarisation in the dual-pol case due to the fact that each channel in single-pol case experiences lower crosstalk from the other channels. We also observe that the OAM channel with higher crosstalk will consequently have worse BER performance, as expected. It is clear that each channel is able to achieve a raw BER below the 3.8×10^{-3} forward error correction (FEC) limit, which is a level that enables very low packet error rates to be achieved by the use of appropriate FEC codes (e.g., concatenated RS-Convolution code [9]). As an example, in Fig. 9 we show the constellations for OAM charge number *l*=3 when the SNR is 16 dB.

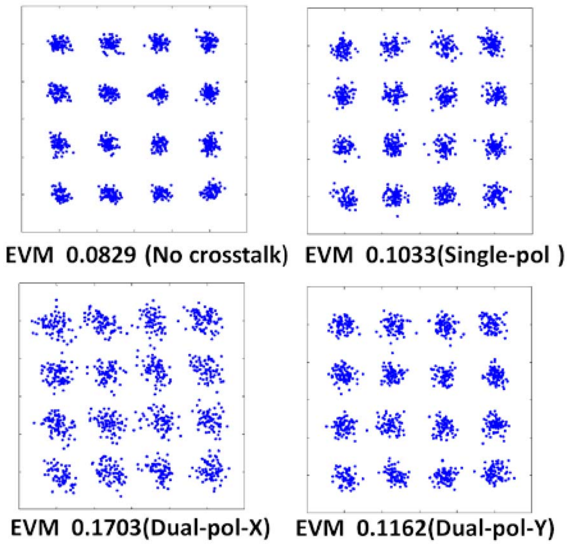


Figure 9. Constellation of OAM channel of charge number *l*=+3 when SNR is 16 dB, which corresponds to the fourth figure OAM *l*=+3 in Figs. 8.

V. SUMMARY

We have demonstrated modal-division multiplexing of an 8-mode, 32-Gbit/s millimeter-wave free-space communication link using 4 OAM modes on 2 polarizations. Each channel carries 1Gbaud/s 16-QAM signal riding over the same carrier frequency of 28GHz. Four different OAM beams of charge number *l*=-3,-1,+1, and +3 on two linear polarization states are used. Spiral phase plates and beam splitters have been used to create a scalable setup.

ACKNOWLEDGMENT

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