Demonstration of 8-Channel 32-Gbit/s QPSK Wireless Communications at 0.28-0.33 THz Using 2 Frequency, 2 Polarization, and 2 Mode Multiplexing

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Abstract: We experimentally demonstrate a 32-Gbit/s QPSK THz wireless communication link using 2 frequencies, 2 polarizations and 2 OAM modes at ~0.3 THz. By tuning the frequency of the data-carrying lasers and the interfering CW laser, the system can cover the 0.28-0.33 THz band.

1. Introduction

There is a growing interest in the 0.1-1 terahertz (THz) carrier-frequency range to increase the available bandwidth for communication systems [1-6]. The source and transmitter technologies at these frequencies often utilize stable and tunable optical components [1-6]. For example, beating two coherent laser lines in a photodiode can produce highly stable THz sources of fine and wide tunability, offering accurate data channel frequencies over a broad range [5, 6].

As is common in communication systems, the data capacity of THz systems can be increased by multiplexing and simultaneously transmitting multiple independent data channels [1, 3-5]. For example, both frequency-division-multiplexing (FDM) [1, 3] and polarization-division-multiplexing (PDM) [4, 5] have been utilized to increase the data rate by transmitting multiple data channels on different carrier frequencies and/or on two different orthogonal polarizations. Additionally, space-division-multiplexing (SDM) can be used as a multiplexing domain [7, 8], and SDM can complement and be compatible with FDM and PDM. Specifically, a subset of SDM is mode-division-multiplexing (MDM), in which each data channel is carried by a different beam having an orthogonal spatial mode [7, 8].

One type of modal set is orbital-angular momentum (OAM), which can be considered as a subset of the Laguerre Gaussian (LG) modes. A beam that carries OAM has: (a) a phasefront that "twists" in the azimuthal direction as it propagates, (b) the number of 2π phase shifts in the azimuthal direction being the OAM mode order ℓ, and (c) an intensity profile that has a ring-like doughnut profile [7, 8]. OAM-based communication systems have been demonstrated in the optical and millimeter-wave domains [9-12]. Previous reports for OAM beams in the THz regime include: (a) generating and detecting OAM beams [13-15], (b) encoding bits of information on different OAM values [16], and (c) multiplexing two OAM-based 4-Gbit/s quadrature-phase-shift-keyed (QPSK) data channels in the 0.3-THz region [17]. However, there has been little reported on combining OAM multiplexing (i.e., MDM) together with FDM or PDM for high-capacity, free-space THz links.

In this paper, we experimentally demonstrate 8-channel 32-Gbit/s wireless communications at 0.28-0.33 THz using two-frequency-, polarization-, and mode-multiplexing with each channel carrying a 2-Gbaud QPSK signal (4 bits/baud). THz FDM channels are generated by mixing optical FDM channels and a continuous wave (CW) laser at another wavelength in a positive-intrinsic-negative photodiode (PIN-PD) based THz emitter. We generate such THz FDM signals for each polarization and the data channels with different polarizations are then multiplexed by a THz polarization beam combiner (PBC). Spiral phase plates (SPPs) made of high density poly-ethylene (HDPE) are used to generate and detect THz-OAM beams. A 32-Gbit/s QPSK wireless communication link is demonstrated by multiplexing 2 frequencies (0.3 and 0.303 THz), 2 polarizations (transverse electric (TE) and transverse magnetic (TM) pol.), and 2 OAM modes (OAM +1 and +3). The SNR penalties for the 8-multiplexed channels compared with a single THz-Gaussian channel are from ~2 dB to ~7 dB. The multiplexed link is shown to perform over the 0.28-0.33 THz band by tuning the frequency difference between the data-carrying lasers and the CW laser.

2. Concept and experimental setup

The concept of a THz wireless link using FDM, PDM and OAM multiplexing is shown in Fig. 1. At the THz transmitter (Tx), the THz FDM channels are generated by mixing data-carrying lasers and a CW laser, functioning as a local oscillator (LO) with a frequency spacing $\Delta f = f_1, f_2$. In this case, the generated THz FDM channels (data 1,2 at the PIN-PD output) have the carrier frequencies of f_1 and f_2. The FDM channels (TE pol. with data 1,2) are then multiplexed with the other two FDM channels (TM pol. with data 3,4) with orthogonal polarizations in free space. Subsequently, the FDM and PDM channels carried by the one OAM ℓ_1 beam are multiplexed with the other group of FDM and PDM channels carried by the OAM beam with a different mode order ℓ_2 with little inherent crosstalk. Thus, data capacity can be increased 8-fold by multiplexing these 2 frequencies, 2 polarizations, and 2 OAM modes (data 1-4 on OAM ℓ_1 and data 5-8 on OAM ℓ_2).

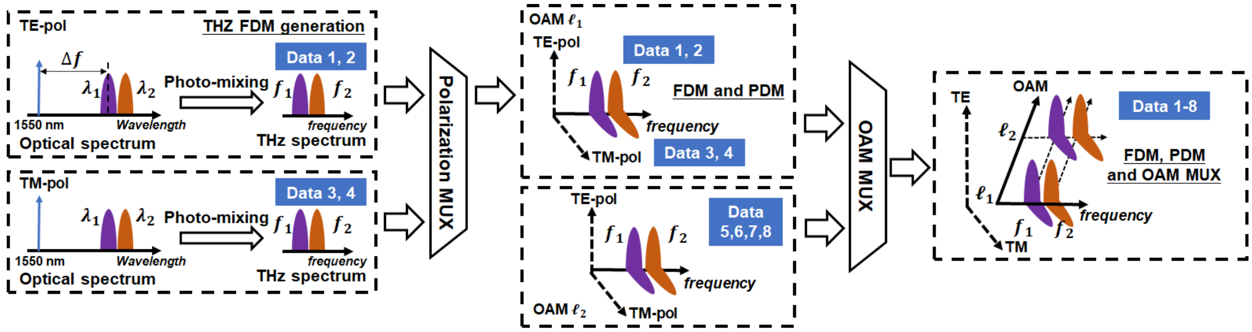

Figure 1. Concept diagram of using FDM, PDM and OAM multiplexing to increase the data capacity for THz communication systems.

Figure 2 shows the experimental setup. At Tx, laser 1 and 2 are modulated with a 2-Gbaud QPSK data signal, and the frequency offset between the two lasers is ~3.5 GHz. One of the lasers is delayed with a ~2-m fiber in order to decorrelate the signal. The frequency difference between the data channels and the CW laser (laser 3) is tuned from 0.28 THz to 0.33 THz. The optical power is subsequently split and mixed in 2 PIN-PDs to generate THz data channels with TE polarization. One of the THz transmitter is mechanically rotated by 90° to generate the orthogonal TM polarization, whose data has been decorrelated by another ~2-m fiber which preceded the PIN-PD of the TM transmitter. The THz FDM data channels on different polarizations are then multiplexed using a THz PBC. For OAM multiplexing, the FDM and PDM channels are firstly split to 2 paths, and in each path, the OAM modes are generated by using HDPE SPPs with $\ell = +1/+3$. Data channels with OAM +1 are delayed ~1m in the free space to decorrelate the data. The THz FDM, PDM and OAM-multiplexed beam is then transmitted over a 0.3-m distance. At the receiver (Rx), the multiplexed beam is firstly demultiplexed by using another SPP with an inverse OAM order ($\ell = -1/-3$). After the mode-demultiplexing, FDM channels on one of the polarizations are collected by the polarization-selective THz receiver. Both the FDM channels are subsequently amplified by a THz amplifier and down-converted to ~16-GHz intermedia frequency (IF) band by beating with a frequency multiplied radio frequency (RF) signal from the electrical LO in a THz electrical down converter. The IF signal is sampled by a digital oscilloscope and demodulated by offline postprocessing.

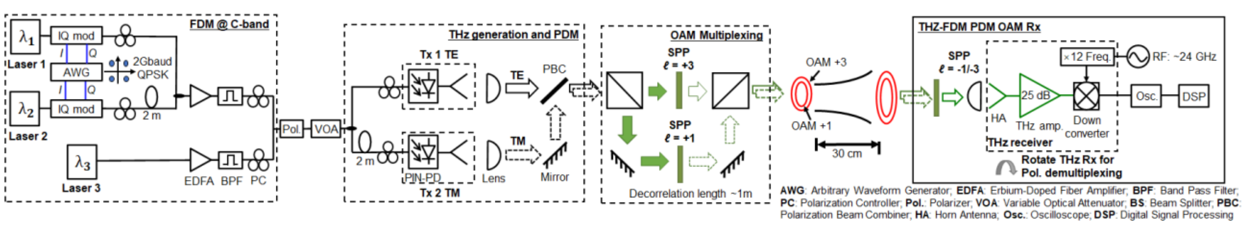

Figure 2. Experimental setup of an 8-channel 32-Gbit/s THz communication link using 2 frequencies (0.3 and 0.303 THz), 2 polarizations (TE and TM pol.) and 2 OAM modes (OAM +1 and +3) over a 0.3-m distance.

3. Experimental results and discussion

The generated OAM beams are characterized in a single channel using two CW lasers. Figure 3(a) shows the intensity profiles and interferogram (with a THz-Gaussian beam) for OAM +1 and OAM +3 on TE polarization at a frequency of 0.3 THz. The number of twists in the interferogram is the number of 2π phase changes of OAM modes ℓ.We also measure the mode spectrum of OAM +1 and OAM +3 for different polarizations and frequencies by changing the SPP for detection at Rx. As shown in Fig. 3(b), the power leaked to neighboring modes are ~-10 dB and ~-9 dB for OAM +1 and +3, respectively. The difference in OAM spectra between different measurements might be due to the imperfect alignment of the THz link.

Subsequently, we demonstrate a multiplexed link with 8 channels (frequency: 0.3 and 0.303 THz, polarization: TE and TM polarization, OAM modes: OAM +1 and +3). The normalized crosstalk between channels with different polarizations, frequencies and OAM modes is then characterized in the multiplexed link using CW light. As shown in Fig. 3(c), the received power of OAM +3 channels is ~2-4 dB less than the OAM +1 channels. This could be due to the larger divergence of the OAM +3. The results show that the channel crosstalk from different polarizations and OAM modes is <-14 dB. In addition, there is a fairly low power leakage (~-30 dB) from channels with different frequencies.

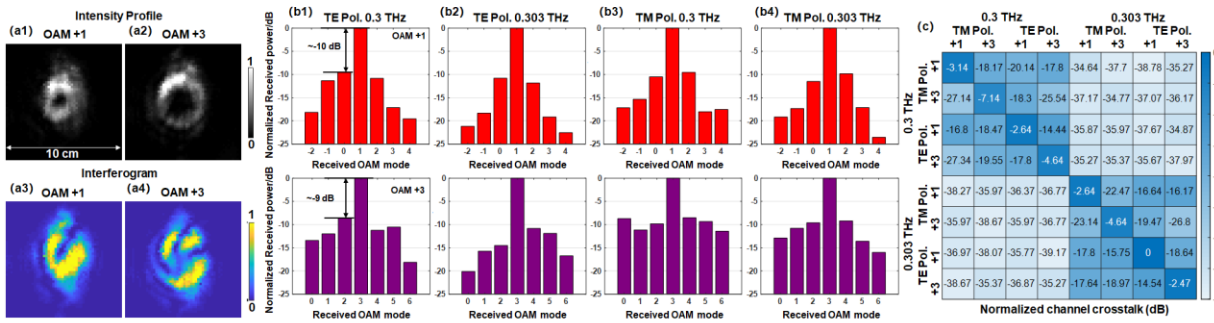

Figure 3. (a) Intensity profiles for (a1) OAM +1 and (a2) OAM +3. Interferogram with a THz-Gaussian beam for (a3) OAM +1 and (a4) OAM +3. (b) Mode spectrum for OAM +1 and OAM +3 with (b1) TE pol. 0.3 THz, (b2) TE pol. 0.303 THz, (b3) TM pol. 0.3 GHz, (b4) TM pol. 0.303 GHz, respectively. (c) Normalized channel crosstalk matrix for 8-multiplexed channels with 0.3 and 0.303 THz, TE and TM pol, and OAM +1 and +3.

Experimental results of the data transmission are shown in Fig. 4. Figures 4 (a1) and (a2) show the input optical spectrum and received electrical spectrum, respectively. The carrier frequency of the data channel can be calculated using the multiplication factor for the LO frequency, and the frequency $f = 12f_{\mathrm{LO}}.+f_{\mathrm{IF}}$. The 2 FDM channels have the carrier frequencies of 0.3 THz and 0.303 THz, respectively. The measured bit error rate (BER) performance is shown in Fig. 4 (b) and (c). The signal-to-noise ratio (SNR) is estimated from the measured data. Figure 4(b) shows the measured BER as a function of SNR in different scenarios for the channel with TE polarization, 0.3 THz, and OAM +3 as an example. In a link transmitting a single beam, the OAM +3 has a performance similar to that of the fundamental Gaussian beam. However, it is noticed that, compared with a Gaussian beam, OAM +3 has ~5 dB power loss due to its larger divergence. In FDM, PDM, and OAM multiplexed link, the crosstalk from other OAM modes and polarizations would induce ~5 dB and ~1 dB SNR penalties at the forward error correction (FEC) threshold, respectively. Moreover, there is nearly no SNR penalty that is further induced by different frequency channels. Figure 4(c) shows measured BER for all 8-multiplexed channels, and none of them exhibits an error floor that prevents from reaching FEC limit. The data channels carried by OAM +3 have ~3 dB more SNR penalty than channels carried by OAM +1. We also tune the frequency difference Δf between the data-carrying lasers and the CW laser. Figure 4(d) shows the measured error vector magnitude (EVM) for multiplexed channels generated with different Δf=0.28 THz or 0.33 THz. For data channels with EVM ~33%, the measure BER is ~1e-3 in the experiment. The results show all the channels can reach the FEC limit and indicate the frequency tunability of the multiplexed link with a ~50 GHz frequency range.

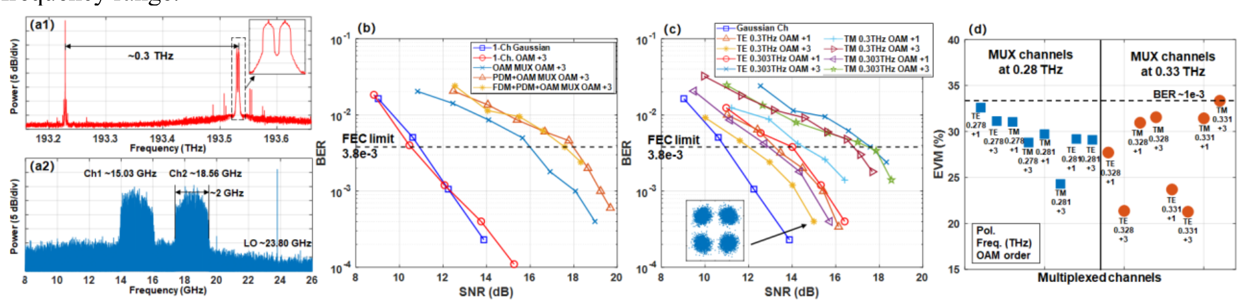

Figure 4. (a1) Measured input optical spectrum. (a2) Measured received IF spectrum for data channel at with TE pol., 0.3 THz, OAM +3. (b) Measured BER as a function of SNR in different scenarios. (c) Measured BER as a function of SNR for all 8-multiplexed channels. (d) Measured EVM for multiplexed channel at 0.28 THz and 0.33 THz.

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