Experimental Demonstration of Free-Space sub-THz Communications Link Using Multiplexing of Beams Having Two Different LG Modal Indices

Amir Minoofar(1), Xinzhou Su(1), Huibin Zhou(1), Fatemeh Alishahi(1), Kai Pang(1), Kaiheng Zou(1), Runzhou Zhang(1), Shlomo Zach(2), Moshe Tur(2), Andreas F. Molisch(1), Hirofumi Sasaki(3), Doohwan Lee(3), and Alan E. Willner(1)

(1) Depart. of Electrical Engineering, University of Southern California, Los Angeles, CA 90089, USA minoofar@usc.edu
(2) School of Electrical Engineering, Tel Aviv University, Ramat Aviv 69978, Israel
(3) NTT Network Innovation Laboratories, NTT Corporation, Yokosuka 239-0847, Japan

Abstract *We experimentally demonstrate a free-space sub-THz communication link using multiplexing of beams carrying two different LG modal indices. Multiplexed $LG_{2,0}$ and $LG_{1,1}$ beams each carrying a 1-Gbaud QPSK data channel at 300 GHz carrier frequency are transmitted over 40 cm link distance.*

Introduction

There is growing interest in free-space communication links in the 0.1-1 THz carrier-wave frequency band due to: (a) the availability of more spectrum and thus potential for higher capacity as compared to millimeter waves, and (b) the availability of band, with a relatively low atmospheric absorption[1-3]. Moreover, photonic technologies can play an important role in such systems due to their ability to accurately generate and frequency tune THz signals by coherent mixing of two lasers[4-6].

As with many types of communication systems, there is motivation to further increase the capacity of these links by using space-division-multiplexing (SDM)[7]. In SDM, multiple independent data-carrying THz signals are simultaneously transmitted in the same frequency band to increase the aggregate capacity. One type of SDM is mode-division-multiplexing (MDM), in which each beam is spatially structured in amplitude and phase to propagate in one of multiple possible orthogonal modes[8,9]. Such orthogonal beams can be multiplexed, spatially co-propagate, and be demultiplexed with negligible inherent crosstalk. We note that this MDM approach is compatible with and orthogonal to other types of THz beam multiplexing, such as frequency- and polarization-division-multiplexing (FDM and PDM)[10-12].

An example of an orthogonal modal basis set comprises Laguerre Gaussian (LG) beams, which are characterized by two spatial indices: (1) azimuthal (ℓ): the number of 2π phasefront changes that occur in a central circle, and (2)

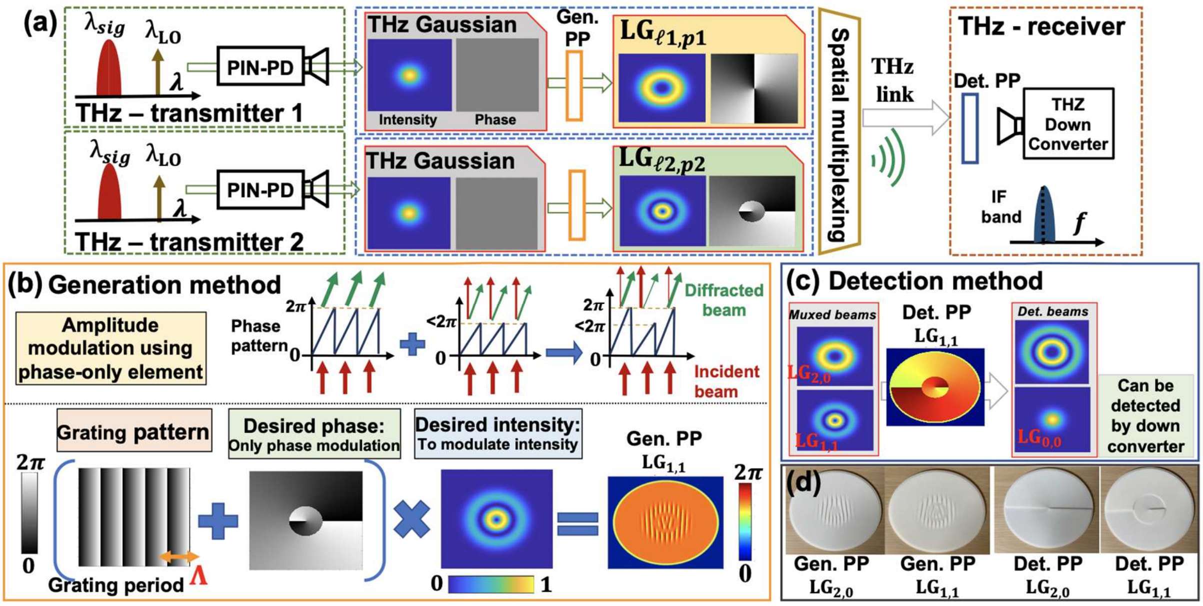

Fig. 1: (a) Concept of multiplexing THz beams having two different LG modes with different modal indices, including the THz Gaussian beam generation using PIN-PDs, (b) Generation method for complex amplitude modulation of LG beams, (c) Detection method of receiver phase patterns to convert it back into Gaussian beams, and (d) Fabricated phase patterns.

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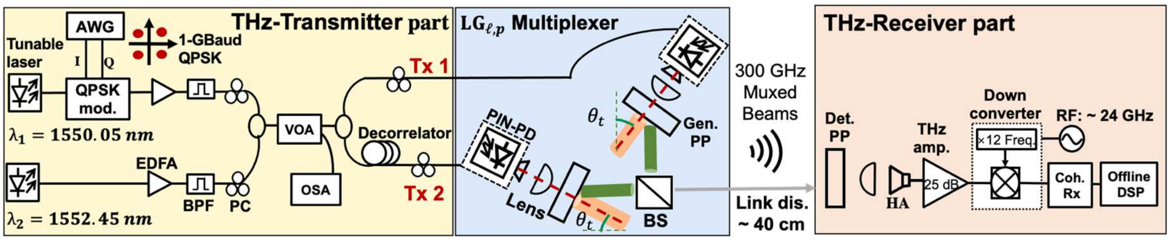

Fig. 2: Experimental setup of a THz MDM link using two beams with different LG modal indices ($LG_{2,0}$ and $LG_{1,1}$) for a 40 cm link propagation distance. AWG: arbitrary waveform generator, EDFA: Erbium-doped fiber amplifier, BPF: band pass filter, PC: polarization controller, Gen. PP and Det. PP: generation and detection phase pattern, VOA: variable optical attenuator, OSA: optical spectrum analyzer, BS: beam splitter, HA: horn antenna, and Coh. Rx.: coherent receiver

radial (p): related to the number of concentric intensity rings in the beam[13-14]. Recently, a subset of LG modes, known as orbital-angular-momentum (OAM) modes, have been demonstrated in such an MDM link[15]. However, that experiment, multiplexed modes that varied in only one spatial index, that being different ℓ modes but the same $p = 0$ mode. It might be a valuable goal to experimentally show that both modal indices can potentially be used for such THz MDM links, i.e., using a 2D set of modes rather than being limited to a 1D set of modes[13]. This could open up the possibility of a larger number of orthogonal modes and data channels in the multiplexed system.

In this paper, we experimentally demonstrate a free space sub-THz communications link using multiplexing of beams having two different LG modal indices carrying 4-Gbit/s quadrature-phase-shift-keyed (QPSK) data at 300 GHz. Two positive-intrinsic-negative photodiodes (PIN-PDs) with a broadband THz output spectrum were used for down-converting the optical data signal into the THz range. In each PIN-PD, two optical laser sources are mixed, wherein one of them is modulated with data signal (the two data streams are decorrelated). Then, the generated THz beams are converted to different LG modes using different phase patterns (PPs). For demonstration, a 4-Gbit/s data rate transmission over a 40 cm of free-space link is achieved with multiplexing two LG modes ($LG_{2,0}$ and $LG_{1,1}$), each carrying a 1-Gbaud QPSK signal. A bit-error-rate (BER) below the forward-error correction (FEC) threshold is obtained. Power penalty for multiplexed LG beams compared to single Gaussian transmission is ~6 dB. Crosstalk among these two modes is ~-16 and -14 dB.

Concept

Figure 1(a) illustrates the concept of multiplexing THz beams with different 2D modal indices. At the transmitter side, modulated data signal and a continuous wave (CW) laser source are mixed in a PIN-PD to generate a Gaussian THz beam. This beam with a flat phase profile is converted to an LG mode by passing through a PP. However, compared to OAM beams, which are commonly generated by spiral phase patterns (SPPs), here complex amplitude modulation is also required to achieve a $p \neq 0$ LG beam. To explain the technique, by varying the extent of phase shift over each grating period of a phase-only element, amplitude modulation can be achieved, shown in Fig. 1(b). Thus, a grating phase pattern with a grating period of 4.5 mm (corresponding to ~13° diffraction angle compared to unmodulated zeroth-order output beam for 300 GHz) is added to the desired phase. Subsequently, the amplitude of the desired beam can be used as an intensity masking to modulate the diffraction efficiency of the grating pattern[16,17]. Due to this approach, only the desired LG beam will be diffracted into the first order of diffraction while the undesired parts remain in other directions. After coaxial propagation through free space, the two LG beams are individually converted back to a Gaussian beam at the receiver by passing through the appropriate PP, Fig. 1(c), and then detected by a THz downconverter for data recovery in a coherent receiver.

Experiment

Figure 2 depicts the experimental setup in more details. Two tunable laser sources at λ_1 =1550.05 nm and λ_2 =1552.45 nm, corresponding to a 300 GHz frequency difference, are used. An arbitrary waveform generator (AWG) drives the IQ modulator to modulate λ_1 with a 1-Gbaud QPSK data signal. Then the modulated and CW laser are combined and then split, where one path is delayed to create the second uncorrelated data channel. A variable optical attenuator (VOA) and polarization controllers (PCs) are used to tune the power and adjust the polarization. Then the two PIN-PDs generate data modulated beam on a sub-THz carrier (300 GHz). A pair of lenses with diameters of ~5 (to collimate) and ~10 cm (to focus) is used at the transmitter and receiver sides, respectively. PPs, based on the explained

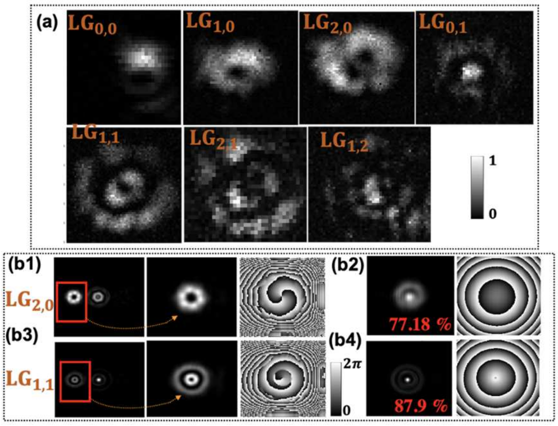

Fig. 3: (a) Experimental results for intensity profiles of $LG_{\ell,p}$ modes. (b1-3) Simulation results of intensity and phase profiles for generation and (b2-4) detection with resulting Gaussian purity for $LG_{2,0}$ and $LG_{1,1}$, respectively.

approach, are fabricated with a 3D-printing process using a photo-resin with a refractive index of 1.655 (Fig. 1(d)). After being mode-filtered by the appropriate PP which converts it to a Gaussian beam, the THz signal is received by a horn antenna (HA) and fed to a THz amplifier with a 25 dB gain. Radio frequency (RF) source at ~23.46 GHz is frequency multiplied by 12 and is mixed with the THz signal to down-convert it to ~18.4 GHz intermedia frequency (IF) band ($f_{300\ GHz} = 12f_{RF} + f_{IF}$). This IF data is captured by a digital oscilloscope and offline digital signal processing (DSP) used for data recovery.

Figure 3 (a) shows the intensity profiles obtained by scanning the down-converted THz beam at 52 cm distance from the PPs over a transverse range of 12 by 14 cm and 30×35 pixels for $LG_{1,2}$ and $LG_{2,1}$ modes and 12 by 12 cm with 50×50 pixels for other modes. As shown, for higher-order modes i) as expected the divergence increases with higher modal indices and ii) power loss during the generation is also higher, which makes it hard to observe outer rings for these modes compared to lower-order modes. Figure 3 (b1) and (b3) represents simulation results for the generation of $LG_{2,0}$ and $LG_{1,1}$ using the adopted approach, wherein desired LG beams have a spiral phase profile identical to their ℓ value at the designed diffraction angle. Figure 3 (b2) and (b4) shows the results of using the detection PPs at the same link distance of the experimental setup with their corresponding Gaussian purity values, which indicates 70-80% of power will go back to the Gaussian mode.

Experimental results for the 1-Gbaud QPSK data transmission are shown in Fig. 4. Figure 4(a) shows the input optical spectrum of the two laser sources, data and CW with a frequency difference of 300 GHz, used for mixing in the PIN-PD. Figure 4(b) shows the received electrical spectrum, which corresponds to the resulted IF frequency. The crosstalk matrix, measured when both lasers run CW, appears in Fig. 4(c). Results indicate that crosstalk among the two chosen modes is ~-16 - -14 dB. Moreover, a higher power loss and crosstalk for the $LG_{1,1}$ mode might be due to their lower mode purities during generation and detection[16]. Figure 4(d1) shows the BER performance of the multiplexing system for 5 different cases. Results demonstrate that both channels can perform below the FEC threshold (3.8e-3). Compared to transmission of sub-THz Gaussian beam with the added grating pattern, the power penalty for $LG_{2,0}$ and $LG_{1,1}$ is ~6 and ~6.5 dB, respectively. This penalty might be mitigated by using a material for PPs which has lower absorption loss at this frequency range. Moreover, two examples of constellation diagrams with their corresponding error vector magnitudes (EVMs) for receiving (i) a Gaussian beam and (ii) $LG_{2,0}$ when multiplexing 2 beams, are shown in Fig. 4 (d2) and Fig. 4 (d3), respectively.

Acknowledgements

Generous support from Vannevar Bush Faculty Fellowship sponsored by the Basic Research Office of the Assistant Secretary of Defense (ASD) for Research and Engineering (R&E) and funded by the Office of Naval Research (ONR) (N00014-16-1-2813); Defense Security Cooperation Agency (DSCA) (DSCA 4440646262); National Science Foundation (NSF) (ECCS-1509965); Airbus Institute for Engineering Research; Qualcomm Innovation Fellowship (QIF).

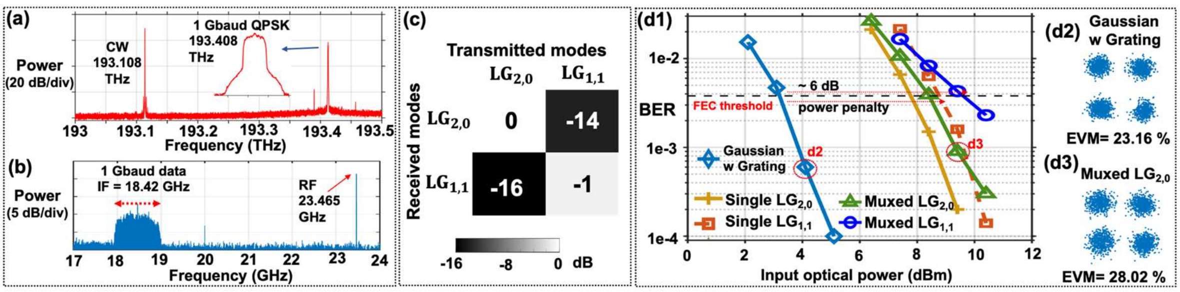

Fig. 4: (a) Input optical spectrum of data and CW source. (b) Received electrical spectrum of data and RF source. (c) Normalized channel crosstalk matrix in dB for $LG_{2,0}$ and $LG_{1,1}$. (d1) BER performance of the multiplexed 2 channels when input optical power of PIN-PD equals 10.4 dBm and (d2-3) Signal constellation diagrams at two different points with their EVM

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