Terahertz Band Data Communications using Dielectric Rod Waveguide

Muhsin Ali[1*], Jonas Tebart[2], Alejandro Rivera-Lavado[1,3], Dmitri Lioubtchenko[4,5], Luis Enrique Garcia-Muñoz[1], Andreas Stöhr[2] and Guillermo Carpintero[1]

[1]Universidad Carlos III de Madrid, Avenida de la Universidad 30, 28911 Leganes, Madrid, Spain
[2]ZHO / Optoelectronics, University of Duisburg-Essen, Lotharstr. 55, 47057 Duisburg, Germany
[3]Yebes Observatory, Dirección General del Instituto Geográfico Nacional, Yebes, Spain
[4]KTH Royal Institute of Technology, Department of Micro and Nano Systems, Stockholm, Sweden
[5]Institute of High-Pressure Physics, CENTERA Laboratories, Warsaw, Poland
Author e-mail address: muali@ing.uc3m.es

Abstract: A terahertz data link is presented using dielectric rod waveguide (DRW) at 300 GHz and complex modulations for speeds up to 120 Gbps. Performance comparison with WR-3 rectangular waveguide validates the low-dispersion behaviour of DRW. © 2022 The Authors.

1. Introduction

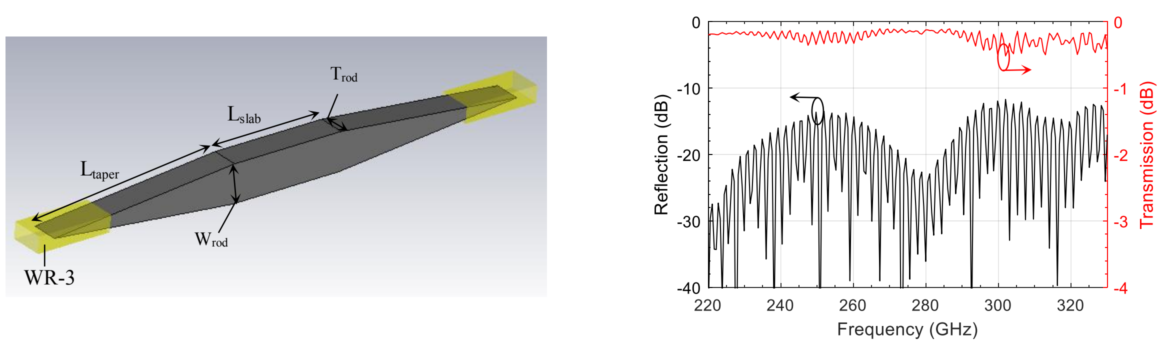
Terahertz (THz) frequencies (100 GHz – 10 THz) have received increased interest in recent years as the need to boost the capacity of communication systems continues to rise due to growing data traffic [1]. While the research on THz wireless communications is already ongoing, chip-scale data links are gaining attention [2, 3]. It involves routing or transport of large amounts of data in the order of Tbps between the chips, e.g. graphics processors, in a small area, providing ultra-fast interconnections. With the increasing number of chips and amount of data, the traditional interconnections reach their limits. Recently, Webber et al. [4] reported a photonic crystal based waveguide for 100 Gbps THz link, with a limited relative RF bandwidth.

In this paper, we report dielectric rod waveguide (DRW) technology providing broad frequency coverage, realising the low dispersion ultra-broadband interconnections for high-speed data communications. The performance of DRW is validated in a THz data link at 300 GHz using three different complex modulations, achieving peak bitrate of 80 Gbps with envelope detection (ED). The proposed system is scalable to different frequency bands.

2. Dielectric Rod Waveguide

The DRW is fabricated from a high-resistivity (> 10 kΩ) silicon (Si) wafer with a dielectric permittivity ε_r and loss tangent of 11.9 and 0.0001, respectively. The sketch and geometry of DRW used in this work are shown in Fig. 1(a). It consists of three sections. A rectangular slab, with length L_{slab}, width W_{rod}, thickness T_{rod}, through which the THz wave propagates and a matching taper with length L_{taper} on both sides of the slab. The purpose of this taper is to provide matching between the rod and hollow metallic waveguides to launch the wave into DRW.

One of the primary advantages of DRW is its ultra-broadband functionality. With a proper matching taper design, it can be coupled with different rectangular waveguides [5] while keeping the single mode operation. Fig. 1(b) shows the simulated S-parameters of DRW. One can notice that the transmission |S21| of more than -0.5 dB is maintained throughout the entire frequency band. While the reflections are better than -10 dB, indicating a good matching. Such performance makes it attractive for establishing communication links with wide signal bandwidth.



(a) (b)

Fig. 1. (a) Sketch of a DRW with matching tapers fed by WR-3 rectangular waveguides and (b) simulated reflection coefficient and transmission over WR-3 frequency band.

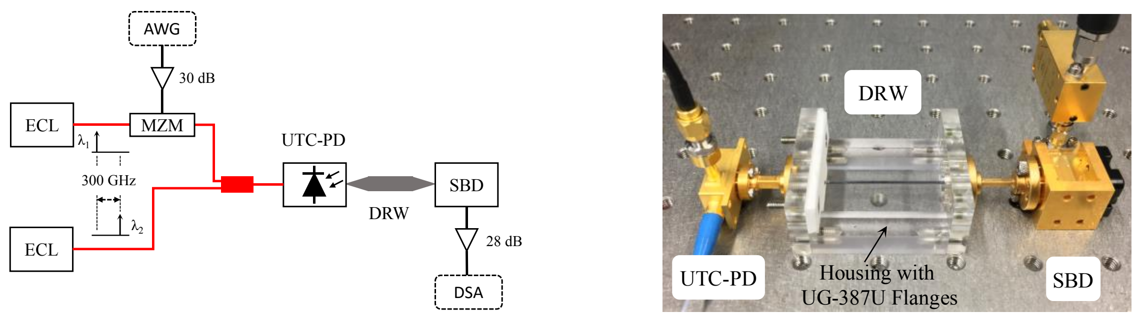
3. THz Communication Link

3.1 Experiment Description

The DRW is expected to support transmission of signals with ultra-wide bandwidth without distorting the phase information of the data signal. To validate this, we setup a photonics-enabled THz data link using the DRW with spectrally efficient complex modulation schemes and ED technique. The block diagram of the overall experimental setup is shown in Fig. 2(a). We utilise two free-running external cavity lasers to generate optical sub-carriers λ_1 and λ_2, whose frequency difference amounts to the carrier wave signal f_C of 300 GHz. Although the use of optical heterodyne results in a poor phase noise and spectral drift of f_C, the phase of complex-modulated signals at reception can still be detected [6]. The orthogonal frequency division multiplexing (OFDM) based I-Q data signal in the baseband (BB) is generated using a digital signal processing (DSP) routine. The number of sub-carriers in OFDM is 2048, with each modulated using QPSK, 16-QAM and 64-QAM signal format. The BB OFDM I-Q signal is generated using a 65 GSa/s arbitrary waveform generator (AWG) at an intermediate frequency (IF) of 10 GHz. The IF signal is amplified and fed into a Mach-Zehnder modulator (MZM) to modulate λ_1. The resulting signal is combined with λ_2, which functions as the optical local oscillator (LO) and amplified to reach a power level of 13 dBm. After passing through a polarisation controller, it is fed into a uni-traveling carrier photodiode (UTC-PD) to obtain the THz data signal. The UTC-PD has a WR-3 rectangular waveguide at the output. The spectral efficiencies for the transmitted single sideband THz signals are 1, 2 and 3 bits/s/Hz depending on the modulation format.

The DRW used for this work has dimensions of T_{rod} = 0.5 mm, W_{rod} = 1 mm, L_{taper} = 8 mm and L_{slab} = 45 mm, resulting in a rod waveguide length of 61 mm. In order to facilitate the mounting of the components, the DRW is assembled into a custom plug-and-play methacrylate housing featuring UG-387/U flanges.

The THz signal is transmitted over the rod waveguide and detected by a Schottky barrier diode detector (SBD), which works as an ED. Fig. 2(b) shows a photograph of the DRW assembly connected to the UTC-PD and SBD modules using a 20 mm long WR-3 waveguide section. In comparison to the heterodyne THz detectors, the use of ED leads to a simpler setup configuration as the RF LO is not needed to drive the mixer [7]. At the output of the SBD, the THz I-Q signal is down-converted to the IF, amplified and recorded by a 160 GSa/s digital signal analyser (DSA). A DSP routine is employed to demodulate the received signal and evaluate the link performance in terms of error vector magnitude (EVM) and bit error rate (BER).



(a) (b)

Fig. 2. (a) Schematic diagram of the experimental arrangement used for realising a THz data link at 300 GHz over a dielectric rod waveguide using complex modulation and (b) a photograph showing the DRW assembly mounted on a WR-3 band UTC photodiode and Schottky diode detector.

In order to establish a base line to compare the performance of DRW, we repeat the experiment by directly connecting the UTC-PD and the SBD in back-to-back using the WR-3 section, achieving a direct link. For both cases, the data bandwidth (baud rate) is varied from 2 to 20 GHz at each of the three modulation formats. Throughout the data experiments, the DC photocurrent I_{ph} of UTC-PD is fixed at a moderate value of 4.3 mA, providing -19 dBm output RF power.

3.2 Measurement Results

Fig. 3 includes the graphs plotting the measured EVM against the achieved data rates for OFDM-based QPSK, 16-QAM and 64-QAM. The peak bitrate achieved using the equipment available was up to 120 Gbps at 64-QAM. As can be seen, there is very little difference in the EVM values achieved for the DRW-based and direct links for all the modulation formats. This shows the low dispersion as well as low-loss capability of the proposed Si DRW which causes negligible phase distortion of propagating complex data signals. For the case of 16-QAM, the DRW link shows a slightly better EVM, which is attributed to the fluctuation in the optical power fed into the UTC-PD and a subsequent minor drop in I_{ph}. The EVM increases linearly with respect to the signal bandwidth (baud rate). The BER is also calculated from the recovered data for both data link cases. Fig. 4(a) shows the BER for 16-QAM-OFDM demodulated signal plotted against the bitrate. Again, the BER obtained for the DRW closely matches that of direct link. For less 40 Gbps, zero error transmission is achieved with DRW. If hard-decision and soft-decision forward error correction (HD-FEC), (SD-FEC) thresholds of 3.8 $\times 10^{-3}$ and 2×10^{-2} are considered, the error-free data rates of better than 60 Gbps and 80 Gbps, respectively, are achieved. The captured signal constellations are shown in Fig. 4(b).

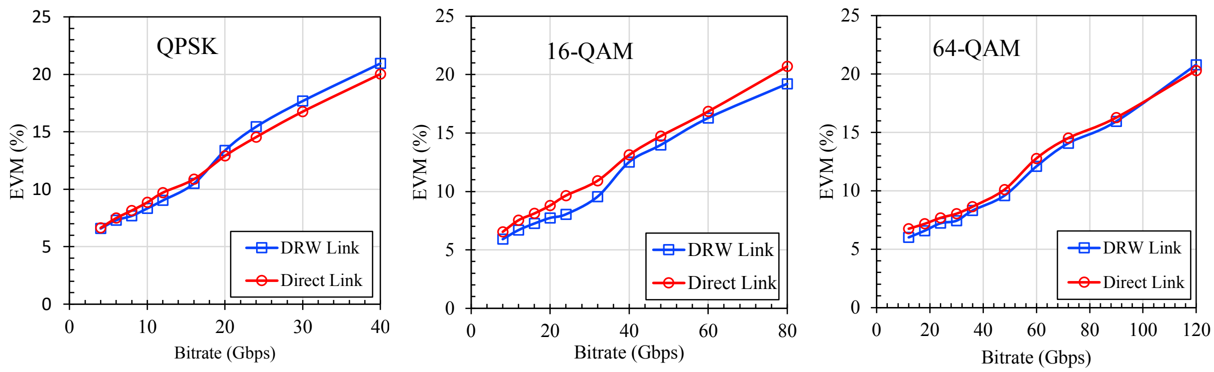
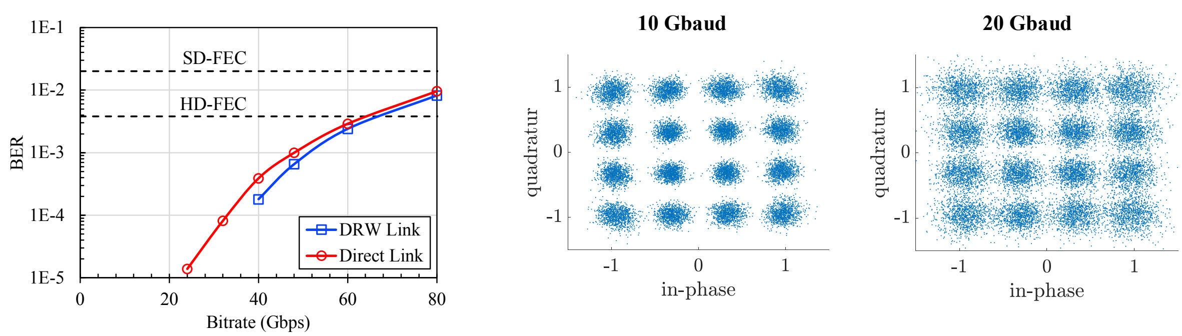


Fig. 3. Measured EVM for THz data transmission for the DRW-based and direct (back-to-back) links at different complex modulation formats of QPSK-OFDM, 16-QAM-OFDM and 64-QAM-OFDM.



(a) (b)

Fig. 4. BER versus the bitrate for 16-QAM-OFDM modulation format and (b) constellation diagrams for recovered symbols.

4. Conclusion

A THz data link was realised with a straight Si DRW and below FEC data rate of up 80 Gbps was achieved using complex modulations and direct detection. The link performance comparison against a WR-3 rectangular waveguide experimentally validated the low-dispersion capability of DRW in realising broadband interconnects. The integration of source/detector chips with DRW will result in compact transceivers for chip-scale networks.

Acknowledgment: We acknowledge funding from the European Union's Horizon 2020 through Research and Innovation Programme G.A No 862788 (TERAmeasure), under G.A No 871668 (TERAWAY, an initiative of the 5G Public Private Partnership) and MSCA G.A No 956857.

Reference

[1] T. Nagatsuma, G. Ducournau, and C. Renaud, “Advances in terahertz communications accelerated by photonics,” in *Nature Photon*ics 10, 371–379 (2016).
[2] S. Saxena, D. Manur, N. Mansoor, and A. Ganguly, “Scalable and energy efficient wireless inter chip interconnection fabrics using THz band antennas,” in *Journal of Parallel and Distributed Computing* 39, 148–160 (2020).
[3] S. Abadal, C. Han and J. M. Jornet, "Wave Propagation and Channel Modeling in Chip-Scale Wireless Communications: A Survey From Millimeter-Wave to Terahertz and Optics," in *IEEE Access* 8, 278-293 (2020).
[4] J. Webber et al., "Terahertz Band Communications with Topological Valley Photonic Crystal Waveguide," in *Journal of Lightwave Technology*, in press.
[5] A. A. Generalov, D. V. Lioubtchenko and A. V. Räisänen, "Dielectric rod waveguide antenna at 75 – 1100 GHz," in 7th European Conference on Antennas and Propagation (EuCAP), 2013, pp. 541-544.
[6] M. Freire Hermelo, P. T. Shih, M. Steeg, A. Ng’oma, and Andreas Stöhr, "Spectral efficient 64-QAM-OFDM terahertz communication link," in Opt. Express 25, 19360-19370 (2017).
[7] T. Nagatsuma, et al., "Terahertz wireless communications based on photonics technologies," in *Optics Express* 21, 23736-23747 (2013).