Long range millimeter wave wireless links enabled by traveling wave tubes and resonant tunnelling diodes

Claudio Paoloni[1*], Rupa Basu[1], Laxma R. Billa[1], Jeevan M. Rao[1], Rosa Letizia[1], Qiang Ni[2], Edward Wasige[3], Abdullah Al-Khalidi[3], Jue Wang[3], and Razvan Morariu[3]

[1] Engineering Department, Lancaster University, Lancaster, UK
[2] School of Computing and Communications, Lancaster University, Lancaster, UK
[3] High Frequency Electronics Group, School of Engineering, University of Glasgow, Glasgow, UK
[*]c.paoloni@lancaster.ac.uk

Abstract: High data rate wireless links are an affordable and easily deployable solution to replace or complement fiber. The wide frequency band available at millimetre waves above 100 GHz can support multigigabit per second data rate. However, the high attenuation due to rain and humidity poses a substantial obstacle to long range links. This paper describes a wireless system being developed for point to point links at D-band (DLINK), above 150 GHz, to enable a full fiber-on-air link with more than 1 km range and unprecedented data rate up to 45 Gb/s. The upper end of the D-band spectrum is used (151.5 -174.8 GHz) in full frequency division duplex transmission. The DLINK system consists of a transmitter using a directly modulated Resonant Tunnelling Diode (RTD) oscillator powered by novel traveling wave tubes (TWT). The performance and the small footprint of the front end will make the DLINK system highly competitive to the point to point links presently available in the market at frequencies below 100 GHz. The innovative approach and the design are oriented to large scale productions to satisfy the high data traffic demand of the new 5G infrastructure.

1. Introduction

A revolution in the distribution of internet beyond the fiber is needed to overcome the congestion of existing mobile networks, to enable massive IoT networks and new data-hungry applications such as virtual and augmented reality, real-time remote medicine, vehicle-to-vehicle (V2V) communications. Videos traffic is expected to increase five times in the next year and the traffic from personal computer will reduce to about 25% of the overall traffic by the 2021 [1]. This fast evolving scenario requires high densification of networks both for mobile and fixed access, with very high data rate backhaul and wireless links [2, 3]. Multi-gigabit per second (Gb/s) data rate wireless distribution is emerging as the most affordable solution to satisfy data demand and complement or replace fiber, that often has high deployment costs. The millimeter waves (mm-waves) portion of the spectrum offers wide frequency bands to support multi-Gb/s data rate. Presently, most of the available millimeter wave bands below 90 GHz are already used, such as Q-band, V-band and E-band. Point to point (PtP) links up to E-band (71-76 GHz, 81-86 GHz) are available in the market. Above 100 GHz more than 100 GHz of fragmented frequency bands are not exploited yet. This wide availability of frequencies can support tens of Gb/s. A number of solid state transmitters up to 400 GHz have been demonstrated, at laboratory or prototype level [4, 5].

The D-band (141 – 174.8 GHz), with available 28 GHz divided in three sub bands (141 - 148.5, 151.5 - 164 GHz and 167 - 174.8 GHz), is considered very promising to extend the actual links at higher frequency. The D-band has been already discussed by standardization and regulatory bodies, OFCOM, FCC (US), CEPT (Europe), ETSI [6] for paving the way for its commercial exploitation.

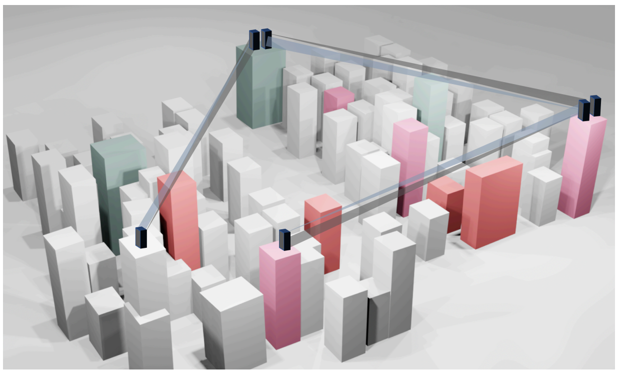


Fig. 1 *DLINK concept.*

This paper will describe the DLINK system being developed, the first D-band wireless link with unprecedented data rate up to 45 Gb/s, over 1 km distance, with 99.99% availability, up to ITU zone K (DLINK concept in Fig.1) [7]. The transmitter front end will be enabled by an innovative configuration by integrating for the first time Resonant Tunnelling Diodes (RTDs) with Traveling Wave Tubes (TWTs) to exploit their complementarity at millimeter waves.

Section 2 will discuss the challenge of transport of high data rate at D-band. Section 3 will discuss the topology and describe the key components of the new D-band Point to Point link. Section 4 will report on the D-band TWT and Section 5 on the Resonant Tunnelling Diode.

2. High data rate above 100 GHz

Above 100 GHz, the high atmosphere and rain attenuation together with the low transmission power of solid-state amplifiers, make arduous to build wireless links with adequate range and the availability (typically 99.99%) required by telecom operators for the quality of service. The availability is defined as the percentage time when a link is fully operational. In case of wireless network, it is the time that the signal to noise ratio (SNR) is sufficient to support the chosen modulation scheme. Usually, it is linked to a percentage of time with rain below a certain intensity producing defined attenuation. The sharp reduction of signal to noise ratio with distance permits very low modulation schemes, without adequate transmission power, limiting the potentiality of the available wide frequency bands. The use of high-order modulation schemes, e.g. 16QAM (QAM quadrature amplitude modulation) or higher, up to 256QAM, would provide data rate close to fiber link, but the required SNR has to be provided. For instance, below 100 GHz, E-band links could provide 10 Gb/s data rate with 2 GHz bandwidth in clear sky. However, in presence of rain or high humidity, typical of most of regions of operation, there is high risk of reduction of range or data rate.

In case of D-band, the total link losses, in line-of-sight, are about 160 dB, computed in case of operation in ITU zone K (42 mm/h rain) at the upper frequency (175 GHz), for 1 km distance. The link losses computed with the same parameters at 28 GHz are 130 dB, about 30 dB lower. This increase of losses has to be compensated by high gain stages (antenna or/and transmitter). At the increase of the frequency the antenna size reduces for the same gain, but at the increase of gain the footprint is relatively large. The transmission power by solid state amplifiers drops by about 20 dB per decade at the increase of frequency.

The calculation of the link budget is performed by the Friis equation, including the 9 dB of system losses (transitions, antenna losses, waveguides) and 17 dB of rain attenuation corresponding to 99.99% availability in ITU zone K. From the link budget calculation, a D-band PtP link for supporting 64QAM over 1 km needs about 40 dBm (10W) saturated transmission power, to apply at least 6 dB back-off. No solid-state power amplifier (PA) provides this level of transmission power. GaN PAs at 100 GHz reach 30 - 32 dBm. D-band InP technology PA could provide 14 -18 dBm [8].

The exploitation of the full potentiality of the millimeter wave spectrum above 100 GHz needs a breakthrough in transmission power.

3. D-band Point to Point

High data rate point to point links at millimeter waves are already widely used and available in the market for backhaul, fronthaul or emergency links. E-band frontends exploits the 10 GHz available at E-band (71- 76 GHz, 81 -86 GHz) with multi Gb/s data rate (1 - 10 Gb/s depending on range and environment condition). However, the large antenna footprint of actual commercial links (20 - 60 cm diameter) [9] prevents to aggregate them in large clusters when higher capacity is needed, due to potential site renting problems and the total footprint (e.g. 40 Gb/s needs not less than 7 - 8 front ends for a total, assuming 30 cm diameter antennas, of about 2 m^2). Higher capacity links are needed to overcome the difficulty of deployment of the fiber especially in urban environment.

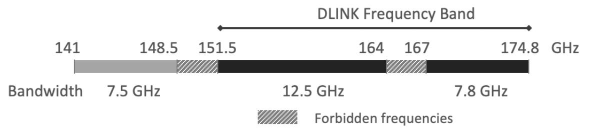
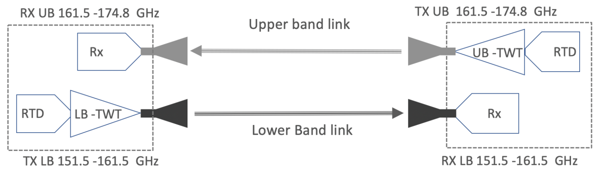
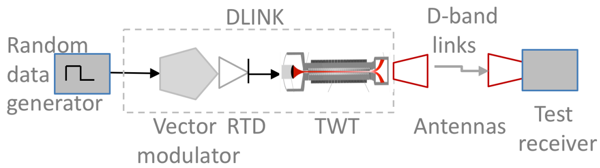


Fig.2 *D-band frequency allocation of DLINK system*



a)



b)

Fig.3 *DLINK system schematic a) Transmitter detail of the integration of the RTD and the TWT.*

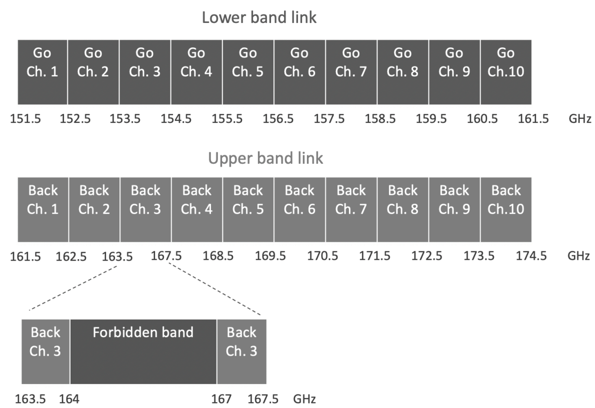


Fig.4 *FDD channel scheme.*

3.1 DLINK System

The DLINK wireless link aims to provide up to 45 Gb/s over 1 km. The link consists of two front ends operating in the region (151.5 - 174.8 GHz) of the D-band (Fig. 2). That band is split in two sub-bands. One front end will be built for transmission in the Upper Band with receiver in Lower Band, the second, for transmission in Lower Band with receiver in Upper Band (Fig.3). Each front end includes one vector modulator, one RTD, one TWT (Fig.3), and one receiver. The high power of the TWT permits to increase the SNR from the RTD transmitter (the latter provides about 1 dBm output power) to support high modulation scheme for long transmission distance, (e.g. 1 km range), with 99.99% availability. The direct carrier modulation avoids the use of upconverters with substantial circuit simplification.

3.2 DLINK Specifications

The specifications are set to achieve fiber data rate level wireless for more than 1 km, exploiting the two permitted sub-band above 150 GHz at D-band. DLINK link will be operated in FDD (Frequency Division Duplex) with 10 GHz wide Lower Band (LB) and 10 GHz wide Upper Band (UB), allocated in two sub-bands. The first sub-band (151.5 - 164 GHz), is 12.5 GHz wide. The first 10 GHz (151.5 - 161.5 GHz) of the Lower Band are used for the lower band link, the remaining 2.5 GHz are aggregated to the 7.5 GHz available in the upper band (167 - 174.8 GHz) to have 10 GHz return path. The 164 - 167 GHz is a forbidden band and is used as guard band. Finally, FDD works with two 10 GHz wide equivalent bands. The FDD modality was chosen for simplicity of implementation.

For the purpose of link modeling each band is split in ten 1-GHz channels. The channel allocation is shown in Fig. 4. Different channelization approaches can be considered for high flexible frequency allocation. Two novel TWTs, one working in 151.5 – 161.5 GHz band and one in 161.5 -174.8 GHz band will be designed and built. One TWT is used in the LB front end, the other in the HB front end. The transmission power achievable by the TWTs is about 10W saturated. This power will produce a Signal-to-Noise ratio to support 64QAM 5/6 modulation. Each channel can provide about 4.5 Gb/s, for an aggregated total 45 Gb/s data rate. It is notable that about 23 GHz difference between the minimum and maximum frequencies of the full band determines a significant difference of range for the same QAM (function of the SNR). Antennas with about 38 dBi gain will be used.

Table 1 shows the performance and the transmission range of the DLINK system for different modulation schemes and frequencies. The maximum link range is ruled by the highest frequency of the band (174.8 GHz) due to its highest attenuation. About 1 km is obtained at 64QAM. A reduction of the modulation scheme produces a substantial range improvement, but with lower data rate. It is notable the difference in range at the edge of the operation frequency band of about 14% (300 m) reduction at the high edge of the band. It is also notable that even a low modulation scheme provides about 15 Gb/s for more than 1.5 km. The comparison with a state of the art D-band solid state power amplifiers (assuming 16dBm) demonstrates the substantial range improvement obtained by using TWTs.

Table 1 Comparison of range for TWT and Solid State Power Amplifier as a function of modulation scheme and frequency

Link parameters: 38 dBi antenna gain, FDD 10 GHz + 10 GHz Bands, 1 GHz channel BW, 9 dB system losses, 6 dB back-off

			40 dBm TWT		16 dBm Solid State PA
Modulation scheme	Spectral efficiency (theoretical)	10 channels total data rate (real case)	Range at 151 GHz	Range at 175 GHz	Range at 175 GHz
64QAM 5/6	6 bit/s/Hz	45 Gb/s	1.2 km	1.05 km	0.35 km
16QAM 3/4	4 bit/s/Hz	30 Gb/s	1.6 km	1.3 km	0.53 km
QPSK 1/2	2 bit/s/Hz	15 Gb/s	1.9 km	1.6 km	0.73 km

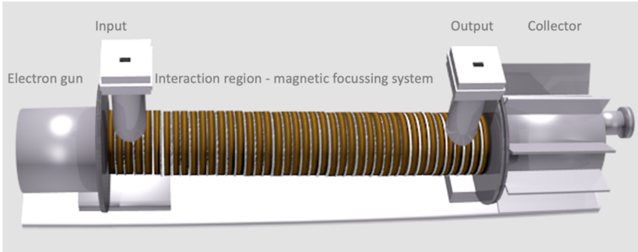
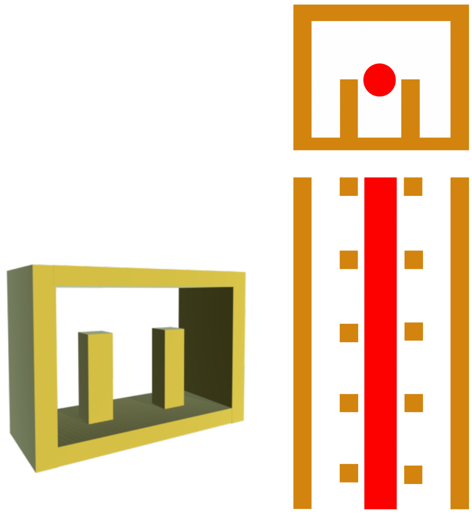


Fig.5 *Traveling wave tube.*

4. D-band Travelling Wave Tubes

Travelling Wave Tubes (TWTs) are wide band vacuum electronic amplifiers widely used in microwave communications. A TWT (Fig. 5) is made of an electron gun,



a *b*

Fig.6 *Schematic of the double corrugated waveguide a) 3D single cell, b) cross section and longitudinal section with the electron beam.*

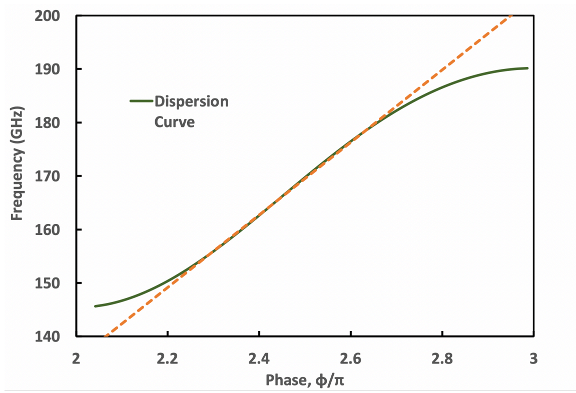


Fig.7 *Dispersion curve of the upper band TWT.*

a slow wave structure (SWS), a collector, a magnetic focusing system and vacuum RF windows to seal the flanges. The electron gun generates an electron beam with given current and voltage, confined by the magnetic system along the SWS. The SWS permits the transfer of energy from the beam to the input RF fields, by slowing down the field phase velocity close to the speed of the electrons. This mechanism permits to achieve multi-Watt power at millimetre waves making TWTs the only solution for high power amplification. Helix SWSs, typical of microwaves, have excellent performance, but are not feasible above 70 GHz due to the too small dimensions. Due to high cost and technology challenges, TWTs above 100 GHz are not available in the market and only a few prototypes have been built [10].
The DLINK system includes two TWTs, one for the upper link (164 - 174.8 GHz) and one for the lower link (151.5 - 164 GHz). A gain of about 35 dB and 10 W output power are the design specifications for both the TWTs. The difference in bandwidth will bring some variation in dimensions of the SWS. For economy, the same electron gun will be used. The design is oriented to low cost TWTs based on the double corrugated waveguide (DCW) used a slow wave structure. The DCW was already demonstrated relatively easy to build by conventional CNC machining up to 0.346 THz with good electrical performance [11, 12]. The topology is shown in Fig.6. It consists of two parallel rows of pillars to form the interaction channel where the beam travels and interacts with the RF fields.
The two TWTs were designed by the same procedure. In the following the design of the 161 - 174.8 GHz TWT will be described. The first step is the definition of the cold parameters, dispersion and interaction impedance, the second step is the design and simulation of the final TWT circuit.

4.1 Cold Parameter simulation

The cold parameters, dispersion and interaction impedance, define the interaction properties of a SWS over the operating frequency band. The first step is to dimension the single cell of the double corrugated waveguide (Fig. 6a) for wide band synchronism in the two band of operations of the TWT with a beam voltage of about 13.5 kV. CST-MWS [13] was used for the eigenmode simulations.
The dispersion curve for the upper band TWT is shown in Fig.7. It is notable the wide band of synchronism given by the overlap with the beam line for the 13.6 kV electron beam.
The interaction impedance is better than 1 Ω over the full band. This value assures the achievement of the TWT power specifications.

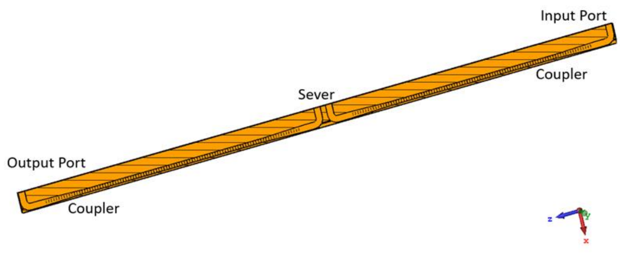
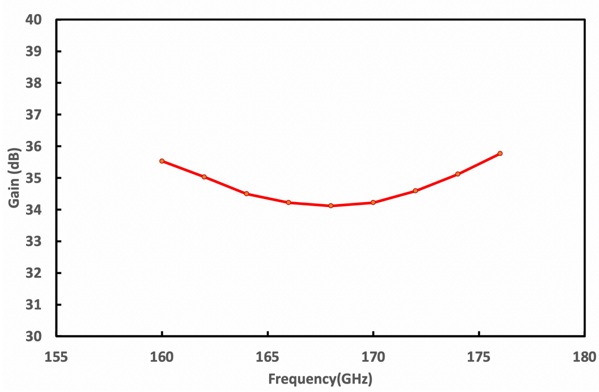
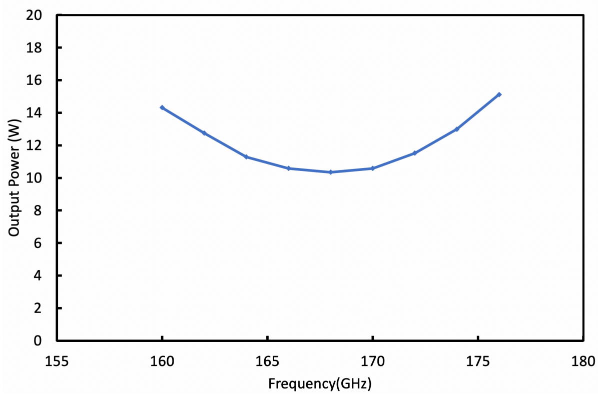


Fig.8 Simulation domain for TWTs large signal performance: two DCW sections separated by a sever.



(a)



(b)

Fig.9 (a) *Gain and* ***(b)*** *Output Power of Upper Band*

4.2 Large signal simulations

The second phase of the design is the large signal simulation of the TWT to get the output power over the frequency band to satisfy the system specifications. The particle in cell (PIC) simulations were performed by CST Particle Studio-MWS. The full TWT circuit was then simulated with two sections separated by a sever to achieve the system specifications. The purpose of the sever is to block backward wave signal that could ignite oscillations. The first section of the TWT circuit includes 65 DCW periods, the second section 70 periods to sightly increase the gain. The schematic of the computational domain use in PIC simulation is shown in Fig.8.
Gain and output power are shown in Fig.9. The TWT provides more than 10 W over the full bandwidth with about 35 dB gain.

5. Resonant Tunnelling Diodes

Resonant tunnelling diodes (RTDs) are the fastest electronic devices with demonstrated frequencies of up to 1.98 THz [14].

The InP-based RTD device typically consists of a narrow bandgap material ($In_{0.53}Ga_{0.47}As$ quantum well) sandwiched between two thin wide bandgap materials (AlAs barriers), making up the double barrier quantum well (DBQW) structure. The high frequency and RF output power capability of an RTD device can be estimated from epi-structure and the device *I-V* characteristic, which exhibits a negative differential resistance (NDR) region. The cut-off frequency

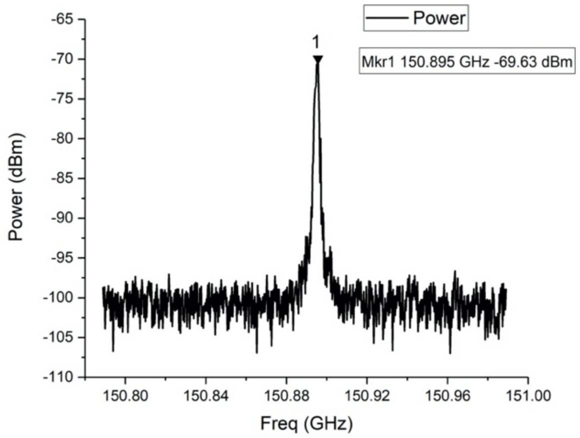


Fig. 10 *Measured spectrum of a D-band RTD oscillator.*

f_{max} is given by:

$$f_{\max} = \frac{G_n}{2\pi C_n}\sqrt{\frac{1}{R_S G_n} - 1} \qquad (1)$$

where C_n is the RTD self-capacitance, G_n is the absolute value of maximum negative differential conductance, and R_S is the contact resistance and the maximum power P_{max} is estimated by

$$P_{\max} \approx \frac{3}{16}\Delta V \Delta I\left(1 - \frac{f^2}{f_{\max}^2}\right) \qquad (2)$$

where ΔI and ΔV are the peak-to-valley current and voltage differences, respectively. State of the art RTD based transmitters include 2 mW, 15 Gbps at W-band using on-off

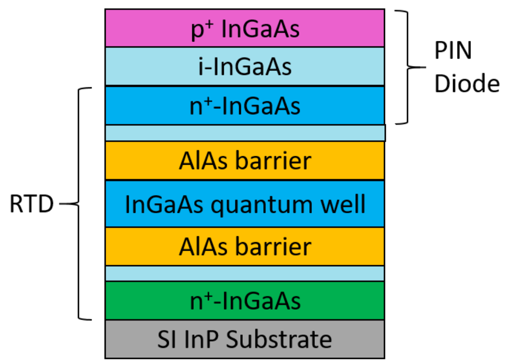


Fig. 11 *Resonant tunnel diode (RTD) and PIN diode.*

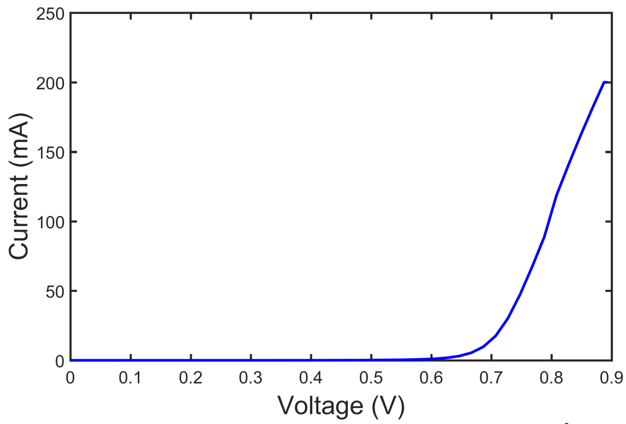


Fig. 12 *Measured I-V characteristics of 10x10 μm² PIN diode.*

keying (OOK) and amplitude shift keying (ASK) [15] and 1 mW with 110 GHz modulation bandwidth at 260 GHz [16, 17]. The fastest reported wireless data rates using RTD based transmitters include 34 Gbps at 500 GHz using single channel and 56 Gbps using dual channel links [18 - 20].

D-band RTD transmitters with integrated vector modulators (Fig.10) are being developed as TWT drivers. The transmitter design employs 2 RTDs in parallel with details as described in [15]. Fig. 10 shows the measured spectrum of one such oscillator for which the oscillation frequency was about 150 GHz with approximately -12 dBm power (the mixer loss is 57 dB from datasheet).

The use of a higher order modulation scheme such as quadrature amplitude modulation (QAM) is crucial to meeting the target data rates. To do this, very low-phase noise oscillators (< -90 dBc/Hz at 100 kHz offset and < -110 dBc/Hz at 1 MHz offset) are needed and are being developed. Low phase noise 28 GHz RTD transmitter with -95dBc/Hz@ 100 KHz and -114 dBc/Hz@1 MHz was demonstrated in [18]. Current approach is to scale up the design for operation in the D-band. A key advantage of this approach is the lack of a mixer and an amplifier from the transmitter, and this further enhances the low phase noise oscillator properties required for QAM.

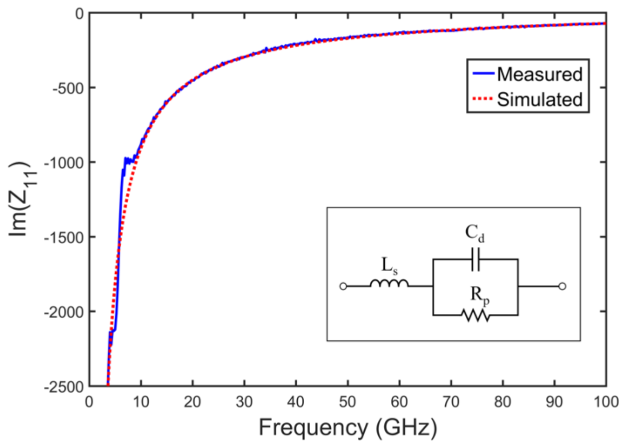


Fig. 13 *Measured vs Simulated imaginary part of device input impedance at 0 V. The inset shows the small-signal model of the device in OFF-state.*

At the heart of a vector modulator is a Lange coupler in a reflection topology with PIN diodes or FETs acting as switches on the coupled and direct ports [21]. Such a modulator which employs InP-based InGaAs PIN diodes [22] is being developed on this project at D-band.

The proposed PIN diode epi-layer structure was adapted from [23] and consists of a highly doped n^+ (1μm, $3x10^{19}cm^{-3}$) and p^+ (0.15μm, $1x10^{20}cm^{-3}$) layer separated by an undoped intrinsic semiconductor region i (1 μm, $5x10^{15}cm^{-3}$). The relatively large i-layer region was chosen in order to reduce the OFF-state capacitance and thus improve the insertion loss, together with a higher doping of the p^+/n^+ layers, which will reduce the ON-state resistance and thus improve isolation.

PIN diodes with 10x10 μm^2 active areas have been fabricated on the described structure for device characterization purposes. The devices exhibit a turn on voltage of around 0.6 V and a reverse breakdown voltage of -35 V. The On-state resistance R_{on} was determined from the device *I-V* characteristics (Fig. 12) to be 1.3 Ω at 0.8 V forward bias. The zero-bias device capacitance C_d was extracted from S-parameter measurements (Fig. 13) and is C_d = 18.2 fF. Using these parameters, the cut-off frequency (fc) of the 100 μm^2 area device can be estimated using $f_c=1/(2\pi R_{on}C_d)$ [23] to be 6.7 THz. It is estimated that this device in a shunt SPST switch configuration would provide around 26 dB isolation and a 0.73 dB insertion loss, based on the determined parameters at 150 GHz center frequency.

Since both RTDs and PIN diodes can be realised from the same InP-based material system, therefore through hetero-epitaxial integration (Fig.11) the monolithic integration of the modulator and transmitter is being implemented. Thus, the ultimate goal is the demonstration of an InP-based RTD/PIN diode technology as a low-cost wireless transmitter technology, and one which can be used to drive a TWT.

6. Conclusions

An innovative wireless system at D-band based on a Resonant Tunnel Diode oscillator, for generating high data rate signals, and novel Traveling Wave Tubes, to providing transmission power for long range links, was presented. The DLINK wireless system is expected to provide unprecedented performance with up to 45 Gb/s with a single transmitter to enabling high capacity links beyond 100 GHz for data transport in 5G and future 6G network architectures. The components of the DLINK system are in advanced development stage and are purposely designed to be affordable for an industry exploitation and wide deployment for future high capacity links

7. Acknowledgments

The DLINK - D-band Wireless Link with Fibre Data Rate project is funded by EPSRC grants EP/S009620/1 and EP/S009442/1.

8. References

[1] Cisco Visual Networking Index: Global Mobile Data Traffic Forecast Update, 2016–2021 White Paper, 2017

[2] J.Shi, L. Lv, Q. Ni, H. Pervaiz, C. Paoloni. "Modeling and Analysis of Point-to-Multipoint Millimeter-Wave Backhaul Networks", *IEEE Trans. on Wireless Communications*, Vol. 18, Issue 1, pp. 268 – 285, January 2019.

[3] Paoloni, C., et al. "Transmission Hub and Terminals for Point to Multipoint W-band TWEETHER System", *EUCNC 2018, Ljubljana, June 2018.*

[4] Nagatsuma, T., Ducournau G., and Renaud C.. "Advances in terahertz communications accelerated by photonics." *Nature Photonics* 10, no. 6, pp. 371-379, 2016.

[5] Dhillon, S. S., et al. "The 2017 terahertz science and technology roadmap." *Journal of Physics D: Applied Physics*, 50.4, pp. 043001, 2017.

[6] Lombardi, R. "Microwave and Millimetre-wave for 5G Transport." *ETSI White Paper* 25, February. 2018.

[7] C. Paoloni, R. Basu, L. Reddy Billa, J. Mahadev Rao, R. Letizia, Q. Ni, E. Wasige, A. Al-Khalidi and J. Wang, "Long range millimeter wave wireless links enabled by traveling wave tubes and resonant tunnelling diodes", *12th UK/Europe-China Workshop on Millimetre-Waves and Terahertz Technologies (UCMMT) 2019*, London, UK

[8] Merkle, T., et al. "Compact 110–170 GHz amplifier in 50 nm mHEMT technology with 25 dB gain." *European Microwave Integrated Circuit Conference (EuMIC2013)*, pp. 129-132, IEEE, 2013.

[9] https://e-band.com/products/e-link-eagle2/

[10] L. Wenqiang et al., "Development of D-band continuous-wave folded waveguide traveling-wave tube," *2015 IEEE International Vacuum Electronics Conference (IVEC)*, pp.1-3, IVEC.2015, China.

[11] M. Mineo and C. Paoloni, "Double Corrugation Rectangular Waveguide Slow-wave Structure for THz Vacuum Devices*", IEEE Trans. on Electron Devices,* pp.3169-3175, November 2010.

[12] Feng, J., Tang, Y., Gamzina, D., Li, X., Popovic, B., Gonzalez, M., Himes, L., Barchfeld, R., Li, H., Pan, P., Letizia, R., Paoloni, C., Luhmann Jr, N.C., "Fabrication of 0.346 THz BWO for Plasma Diagnostics", *IEEE Trans. on Electron Devices*, 8 p. March 2018.

[13] CST Studio Suite Help Document, CST Corp., Darmstadt, Germany. (2019). [Online]. Available: http://www.cst.com/.

[14] R. Izumi, S. Suzuki and M. Asada, "1.98 THz resonant-tunneling-diode oscillator with reduced conduction loss by thick antenna electrode." *42nd International Conference on Infrared, Millimeter, and Terahertz Waves (IRMMW-THz*), 2017.

[15] J. Wang, A. Al-Khalidi, L. Wang, R. Morariu, A. Ofiare and E. Wasige, "15-Gb/s 50-cm Wireless Link Using a High-Power Compact III–V 84-GHz Transmitter," *IEEE Trans. on Microwave Theory and Techniques,* vol. 66, no. 11, pp. 4698-4705, Nov. 2018.

[16] A. Al-Khalidi, J. Wang and E. Wasige, "Compact J-band Oscillators With lm RF output Power and Over 110 GHz Modulation Bandwidth," *43rd International Conference on Infrared, Millimeter, and Terahertz Waves (IRMMW-THz 2018)*, Nagoya, pp. 1-2, 2018.

[17] A. Al-Khalidi , K. Alharbi, J. Wang, R. Morariu . L. Wang, A. Khalid, J.M.L. Figueiredo and E. Wasige, "Resonant Tunnelling Diode Terahertz Sources with up to 1 mW Output Power in the J-Band", *IEEE Trans. on Terahertz Science and Technology*, 2020. (doi: 10.1109/TTHZ.2019.2959210)

[18] J. Wang, L. Wang, C. Li, B. Romeira, and E. Wasige, "28 GHz MMIC resonant tunnelling diode oscillator of around 1mW output power," *Electron. Lett*., vol. 49, no. 13, pp. 816–818, Jun. 2013.

[19] N. Oshima, K. Hashimoto, S. Suzuki, and M. Asada, "Wireless data transmission of 34 Gbit/s at a 500-GHz range using resonant tunnelling diode terahertz oscillator," *Electron. Lett*., vol. 52, no. 22, pp. 1897–1898, Oct. 2016.

[20] N. Oshima, K. Hashimoto, S. Suzuki and M. Asada, "Terahertz Wireless Data Transmission With Frequency and Polarization Division Multiplexing Using Resonant-Tunneling-Diode Oscillators," *IEEE Trans on Terahertz Science and Technology*, vol. 7, no. 5, pp. 593-598, Sept. 2017.

[21] A. E. Ashtiani, Sueng-Il Nam, A. d'Espona, S. Lucyszyn and I. D. Robertson, "Direct multilevel carrier modulation using millimeter-wave balanced vector modulators,", *IEEE Trans. on Microwave Theory and Techniques*, vol. 46, no. 12, pp. 2611-2619, Dec. 1998.

[22] V. Ziegler et al, "InP-based monolithic integrated PIN diode switches for mm-wave applications," *GaAs Mantech*, 1998.

[23] E. Alekseev, D. Pavlidis, D. Cui, "High- isolation W-band InP-based P-I-N Monolithic Integrated Switches", *1997 IEEE/Cornel Conference on Advanced Concepts in High-speed Semiconductor Devices and Circuits*, Aug. 4-6, 1997, Cornel University, USA.