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THz Generation and Analysis with Electronic and Photonic Technologies

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With commercial 6G networks on target to launch in 2030, the race is on to harness radio technologies that can deliver lower latency, higher capacity and enhanced spectrum sharing. Specifications for 6G and most crucially, the optimal adoption of distributed radio access networks, push beyond 5G's gigahertz (GHz) technologies. One possibility to enable this leap in performance is stepping up to terahertz (THz) frequencies. THz science occupies the frequency range between microwave electronics and photonics. This area has attracted increasing interest during the past two decades and now targets the exciting opportunities that exist in sensing, imaging and data communications. Since the pioneering work to create a link between the electrical and optical/infrared regions nearly 100 years ago, the development of efficient, stable and compact THz sources and receivers is making THz science a practical reality.

6G mobile communications success will depend fundamentally on improved latency, higher data rates, better quality of service and expanded system capacity with THz waves central to realizing this ambition. With frequencies extending from 0.1 to 10 THz or wavelengths between 3 mm and 30 µm, THz occupies the spectral region between microwaves and optical waves. The prospect of large contiguous frequency bands providing extremely high data transfer rates in the Tbps range is making this a key research area for next-generation 6G wireless communications. Efforts to explore and unlock this frequency region require an interdisciplinary approach demanding close interaction between high frequency semiconductor technology for RF electronics and alternative approaches using photonic technologies. The THz region shows great promise for many application areas ranging from imaging to spectroscopy and sensing.[1]

There are multiple options for generating THz radiation. MMICs are an obvious candidate, but methods based on photonic technologies will also play a key role. The prospect of miniaturizing today's lab setups into photonic ICs means these approaches could become mainstream. In communications, the frequency range of 100 to 500 GHz remains an untapped region, but research in this area is attracting increasing interest because these high carrier frequencies are associated with the promise of unprecedented channel capacities. The challenges and opportunities are making THz the final frontier in the electromagnetic spectrum.

CLOSING THE "THZ GAP"

Figure 1 shows the so-called "THz gap" in the frequency spectrum of 0.1 to 10 THz. This chart shows conventional THz sources with solid lines and recently developed THz sources with ovals. The chart shows a visible power drop in this region.

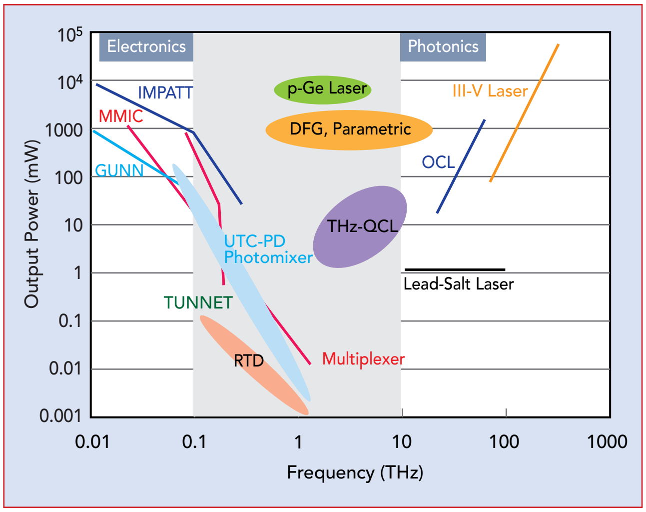

Fig. 1 **THz emission power as a function of frequency.**[2]

THz frequencies are too high for electronic devices because of excessive loss and limited carrier velocity. They are too low for photonic devices because of a lack of materials delivering a sufficiently small bandgap. Available power around the THz region is still much lower than in other spectral regions. A similar trend also occurs in signal detection where such a gap keeps this two-decade spectrum under-utilized in our spectrum-congested world.

There are three major approaches for generating THz radiation: classical electronics, direct THz generation with quantum cascade lasers and indirect generation optoelectronics. ***Figure 2*** shows sources for THz radiation on the borderline between electronics and photonics.

UP-CONVERSION: ELECTRONIC THZ GENERATION AND ANALYSIS

The "classic" approach has evolved tremendously. These components are very compact and can be operated at room temperature. The downside is that classical electronics cannot resolve bandwidth and efficiency limitations. Worse, electronic sources become inefficient at THz frequencies and provide only limited frequency tuning.

Fortunately, RF test and measurement equipment is available from vendors like Rohde & Schwarz to support 6G semiconductor, device and circuit characterization research in the mmWave and THz region. D-Band, with frequencies from 110 to 170 GHz, is seeing a strong research focus. Solutions supporting sub-THz and THz research include vector network analyzers (VNAs) for device characterization with frequency converters to 1.1 THz. External harmonic mixers extend frequency range support for signal and spectrum analyzers to D-Band and other frequency bands up to 500 GHz. Frequency multipliers extend signal generator frequency ranges to 170 GHz and beyond. Signal generation and analysis for the D-Band spectrum is possible with transmit (Tx) and receive (Rx) converters and antenna radiation performance measurements can be made using anechoic chambers. What follows investigates these test solutions in detail, outlining ways to generate and analyze THz waves for 6G research. We also describe the challenges presented by these bands.

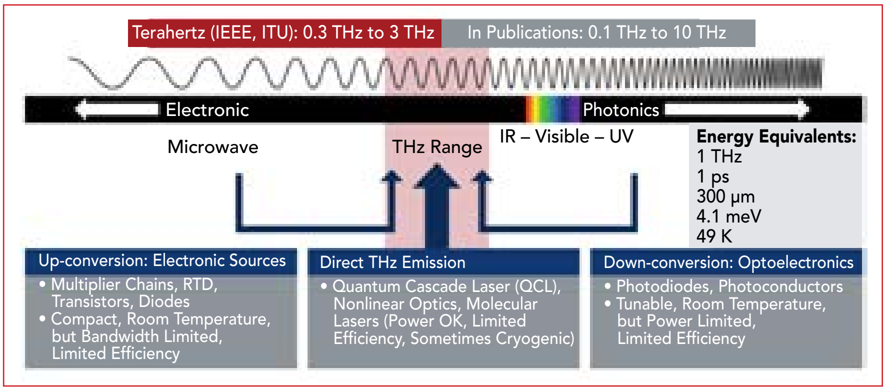

Fig. 2 **The three major approaches for THz radiation generation.**

VNA THZ MEASUREMENTS WITH METROLOGY-LEVEL ACCURACY

Measurements at frequencies up to 67 GHz are part of the standard repertoire of network analyzers. However, tests in the mmWave and THz ranges are significantly more demanding as they require external frequency converters. These frequency extenders up-convert stimulus signals and down-convert response signals to characterize devices operating at THz frequencies.

Characterizing active components in linear and nonlinear ranges requires a defined input power at the probe tip. Since on-wafer power calibration is not possible, the power at the waveguide output is calibrated by accounting for losses in additional waveguides, 1 mm cables and the probe tip. For power sweeps and compression point measurements, an integrated calibration routine in the R&S ZNA compensates for mmWave converter nonlinearities, providing maximum measurement dynamic range and reproducibility. The R&S ZNA uses system-integrated mmWave converters with metrology-level precision.[3] This allows active component measurements to be as convenient at high frequencies as they are at lower frequencies. ***Figure 3a*** shows a representative test setup with the R&S ZNA. ***Figure 3b*** shows that test setup modified for 330 GHz wafer-level measurements.

WIDEBAND SIGNAL GENERATION AND ANALYSIS IN D-BAND

D-Band, with the prospect of several GHz of bandwidth, has become one of the focus frequency bands for 6G research. ***Figure 4*** shows a typical signal generation and analysis setup supporting component and transceiver research in D-Band. The R&S FE170ST transmitter front-end up-converts the modulated signals from the R&S SMW200A vector signal generator to the 110 to 170 GHz frequency range. The R&S FE170SR receiver front-end down-converts the signals and transmits the intermediate frequency (IF) to the R&S FSW signal and spectrum analyzer.

ANTENNA RADIATION PERFORMANCE MEASUREMENTS IN D-BAND

5G pioneered the use of over-the-air (OTA) testing concepts for wireless communications in mmWave frequency bands. This was because large-scale and highly miniaturized antenna arrays are not easily accessible for conducted testing.[4] OTA antenna test concepts can be extended into D-Band and beyond for exploring THz communications and sensing. Future devices will incorporate even more highly integrated active antenna systems for ultra-massive MIMO and sensing applications. With 6G research focusing on frequencies above 100 GHz, advances in new wideband high gain antenna concepts and applied antenna measurement procedures are needed.

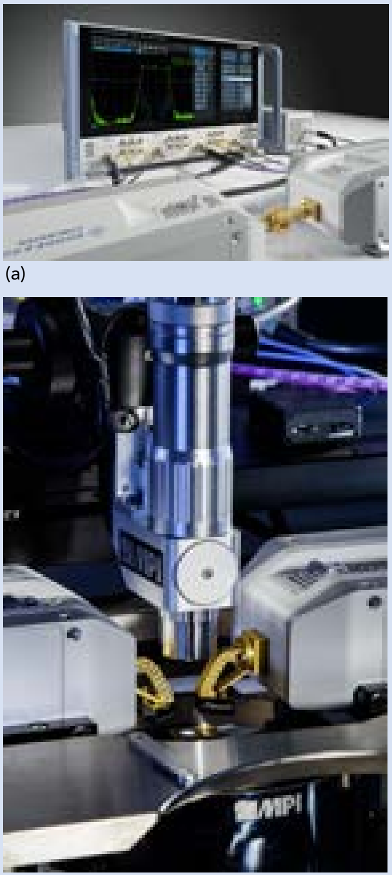

Fig. 3 **R&S ZNA vector network analyzer (a). R&S ZNA with MPI TS150-THZ integrated probe system for 330 GHz measurements (b).**

Fig. 4 **FE170ST and FE170SR D-Band signal generation and analysis test setup.**

Moving from legacy sub-6 GHz cellular services to 5G NR frequency range 2 (FR2) required a major technological leap. Since path loss increases with the square of frequency, higher gain antennas with electronic beam steering capabilities were introduced into user equipment and network infrastructure to ensure radio link performance. With the dramatic increase in IC complexity as a function of frequency, a majority of developments are now targeting a new incremental step at waveguide D-Band and G-Band (140 to 220 GHz). Rohde & Schwarz have developed a spherical scanning solution for measuring radiation performance in D-Band. The solution uses a new probe design with direct down-conversion that provides more than 50 dB dynamic range at 170 GHz. The R&S ATS1000 anechoic mobile spherical scanning range simplifies the test requirements because no mechanical modification or additional RF cabling is needed to measure the amplitude and phase-coherent response of a device under test (DUT) from 110 to 170 GHz.

EXAMPLE: OTA TESTING OF A D-BAND ANTENNA

Figure 5 shows a newly designed IMST D-Band lens-based leaky-wave-fed antenna evaluated in a system using spherical near-field scanning. The radiation pattern measurements were carried out in the R&S ATS1000, which includes a distributed axis positioner. The DUT could be used in 6G fronthaul point-to-multipoint scenarios. The simplified feed structure consists of an elliptical lens made of low permittivity ($\varepsilon r = 2.34$), low loss, high density polyethylene (HPDE) with 35 mm diameter ($20\ \lambda$ at 170 GHz). The feed consists of a $\lambda/2$ leaky wave air cavity, excited by a WR6 waveguide. The radiation pattern can be steered by displacing the feeder along the lens focal plane.

A DUT feeding assembly, shown below the lens antenna in Figure 5, is used to perform phase-coherent and time-stable measurements. This chain consists of a D-Band subharmonic mixer identical to the one used at the probe and a D-Band isolator that is attached to the WR6 split block of the DUT. Measurements are performed with the R&S ZNA43 four-port VNA where one port at the front feeds the IF signal to the DUT.

The block diagram in Figure 5 shows the measurement probe concept. An orthomode transducer is connected to a 20 dBi squared horn antenna with a 3 dB beamwidth of 16 degrees and a cross-polarization isolation of 25 dB over the complete D-Band frequency range. The assembly works reciprocally, transmitting or receiving two orthogonally-polarized fields when the DUT is set to Rx or Tx. Down-conversion or up-conversion occurs directly at the probe, removing RF cable loss. Both polarizations can be measured simultaneously.

The results in ***Figure 6*** reveal excellent agreement between the DUT full-wave simulations and the measurements. This confirms the accuracy of the measurement system and technique involving the new probe design. Phase-coherent data acquisition such as near-field-to-far-field (NF2FF) transformation can be successfully realized for passive antenna measurements. The untransformed measurement results in

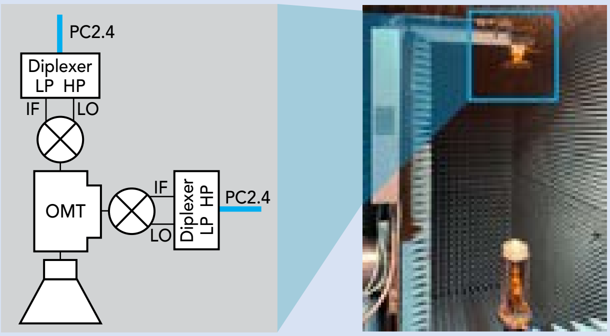

Fig. 5 **Block diagram and measurement setup of the spherical scanning system.**

red show that the main beam of the radiation pattern is already close to far-field asymptotic behavior.

The high efficiency D-Band lens antenna design realized gain greater than 30 dB over 42 percent bandwidth. Accurate characterization of this antenna was performed with a spherical scanning test system, capable of stable phase-coherent measurements, with direct frequency conversion at the DUT input and the test probe outputs.

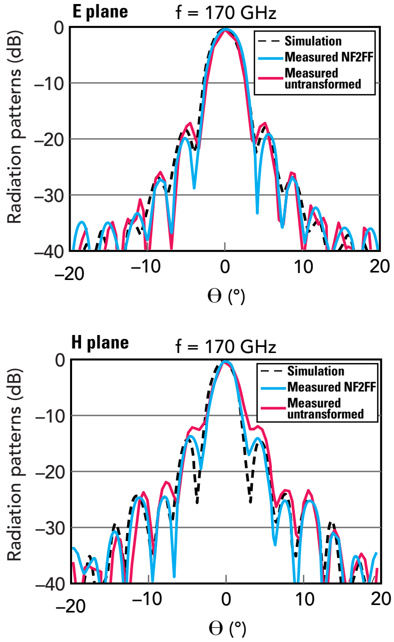

Fig. 6 **E-plane and H-plane directivity patterns.**

Phase coherence is a must to support the precise application of the near-field to far-field transformation algorithms that are essential for the accurate determination of radiation pattern nulls and sidelobe levels.

DIRECT THZ GENERATION WITH A QUANTUM CASCADE LASER

An alternative to electronic upconversion is direct THz generation. This approach uses a quantum cascade laser (QCL) and nonlinear optics (parametric optical processes). Reasonable power levels can already be reached with a QCL, but efficiency remains limited and often they must operate at cryogenic temperatures.

To meet these challenges, downconversion from the optical frequency regime using ultrafast photodiodes and photoconductors is another approach gaining interest. Down-conversion promises tunability over a broad range, operation at room temperature and the potential to reuse mature technologies developed for fiber-optic communications. The power envelope is being pushed, albeit with limitations in efficiency.

The generation of phase-coherent radiation in a laser is well-established and has led to applications combining optical communications with optical fiber technology. Central to success is allowing direct conversion of electrical current into coherent light. For optoelectronics, the direct bandgap III–V semiconductor materials GaAs and GaN are the most important.

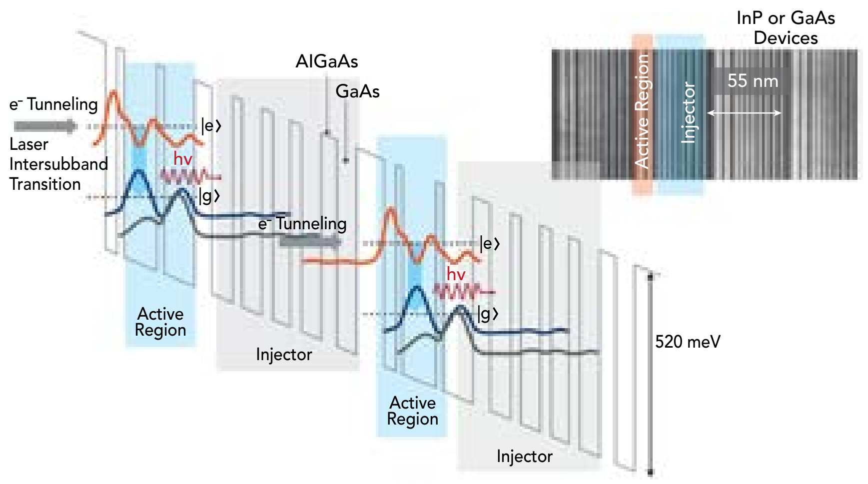

Fig. 7 **Lasing transition between inter-subbands engineered by semiconductor heterostructures in a QCL.**

Interband diode lasers are an inexpensive and efficient method for generating photons across the ultraviolet, visible light and IR frequency regions. However, THz photons have energies 100x to 1000x lower than visible photons and there are no materials with such a small bandgap and population inversion. To overcome these issues, laser emission is achieved in a QCL using inter-subband transitions in a periodic stack of semiconductor multiple-quantum-well heterostructures as depicted in ***Figure 7***.

Well depths can be engineered by controlling the layer depths during the fabrication process. The wavelength of the lasing transition is dependent on the physical structure of the device. So-called "electron wavefunction engineering" allows the generation of low energy THz photons not accessible with interband diode lasers. Multiple photons can be generated by a single electron, making the process extremely efficient. Tunneling from one well to the next is where the term "quantum cascade" originates. Light is emitted as electrons that "cascade" through multiple quantum wells forming a superlattice.

Successful operation of a QCL at THz frequencies was first demonstrated in 2002.[5] QCLs have quickly progressed in terms of frequency coverage, power output and operating temperature. By carefully designing the quantum wells, lasing has been achieved at wavelengths as short as 2.75 μm (109 THz) and as long as 161 μm (1.9 THz). Longer wavelength devices still require cryogenic cooling, but room temperature operation has been observed to at least 16 μm.

An approach using long wavelength THz QCL sources with intracavity nonlinear frequency mixing has made frequencies below 1 THz accessible. The journey towards a THz QCL that operates at room temperature has taken a step forward with the recent publication of a device that operates at -23°C. This temperature is within the reach of Peltier coolers.

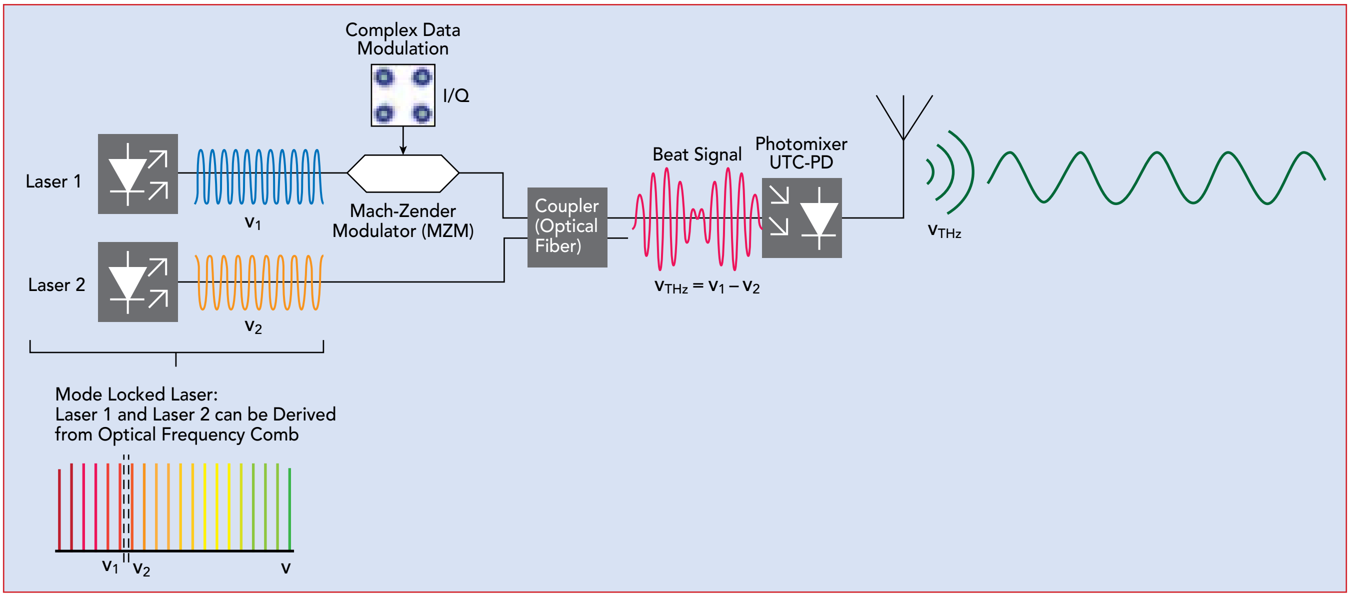

Fig. 8 **Photomixing process to generate THz radiation.**

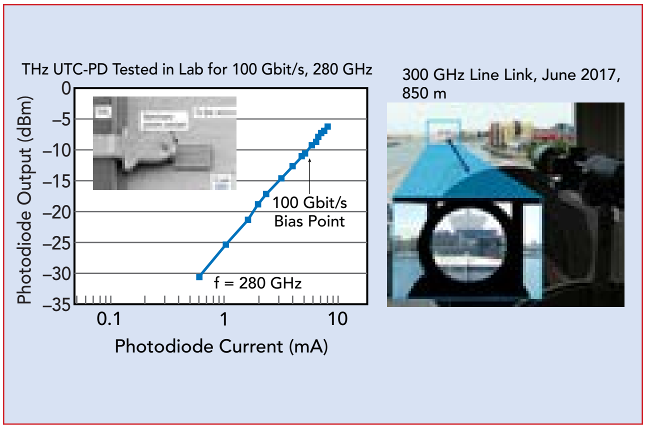

Fig. 9 **300 GHz data transmission in the lab (left) and an outdoor trial (right) (courtesy of Prof. G. Ducournau, IEMN, CNRS-Université de Lille).**

DOWN-CONVERSION PHOTONIC APPROACH: FROM OPTICAL TO THZ VIA PHOTOMIXING

The third approach is optoelectronic frequency domain THz generation, which uses a uni-traveling carrier photodiode or PIN photodiode as a photomixer. This indirect approach for continuous-wave THz generation has attracted strong interest. A photodiode can efficiently convert an optical signal into an electrical signal via a process where optical/infrared laser light generates free charge carriers in a semiconductor or organic crystal. The antenna structure surrounding the photomixer translates oscillating photocurrent into a THz wave, as depicted in the photomixing process in ***Figure 8***.

The photomixing process generates THz radiation at the beat frequency ($\nu_{THz} = \nu 1 - \nu 2$) of two slightly detuned single-mode lasers. One way to attain extreme frequency and phase stability is to derive both frequencies from an optical frequency comb. For data transmission, one of the lasers is modulated by a Mach-Zehnder modulator that consists of an interferometer that splits the beam into two arms. In one of the interferometer arms, the phase of the laser light is shifted relative to the other path by an electro-optic modulator resulting in a constructively or destructively modulated laser beam after the recombination of both beams. The beat signal impinges the photomixer uni-traveling carrier photodiode and the integrated antenna emits THz radiation.

State-of-the-art photomixers are based on either GaAs or InGaAs/InP and require laser wavelengths below the semiconductor bandgap (around 0.8 or 1.5 μm, respectively). By tuning the lasers, the beat note frequency can be varied over a broad spectral range, which translates directly into widely tunable THz radiation. This allows for use of the techniques developed to generate optical vector fields in optical communications, pushing these frequencies into the THz range. When adding frequencies, these techniques make it easier to implement multi-frequency communications. The combination also allows easy integration of these wireless links into fiber-optic infrastructure.

On-chip communications and future high speed inter-device communications will also require THz waveguides. These can be accomplished with topological valley photonic crystals exhibiting near-zero bending loss and zero back-scattering. Referencing both frequencies to the same frequency comb generator allows the transfer of the unique phase and frequency stability of optical combs in a broadband and tunable manner into the THz range. The receiver could be a Schottky diode or a setup symmetrical to the transmitter. This also holds promise for test and measurement instrumentation, since it can be scaled up to extend into the THz region range.

THZ WAVES FOR COMMUNICATIONS: 300 GHZ POINT-TO-POINT TRANSMISSION

THz data transmission trials with one Tx antenna and one Rx antenna have been performed in the lab and outdoors. Between 200 and 300 GHz, there is a transmission window with low atmospheric losses. In contrast to free-space optical links, mmWave or THz transmission is much less affected by adverse weather conditions such as rain and fog.

Figure 9 shows the successful trial results from the harbor of Dunkerque. This trial involved a 300 GHz, 850 m transmission link with an extremely focused beam. The responsivity of the device can be increased further with a metallic mirror below the diode mesa through wafer bonding. Further tests of 100 Gbps transmission in the terahertz window between 200 and 300 GHz have been demonstrated successfully.[6]

CONCLUSION

Continuous innovation in the field of test and measurement is a key enabler for making future 6G a reality. It will require intensive research in academia as well as innovative development in the industry. This research will continue to assist in the design of THz test and measurement products to provide solutions and expertise to pave the way for 6G, the next wireless communications standard. ■

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