Terahertz for Next generation terabits per second Military Wireless, Aircraft and Space Communications

Wireless data traffic is experiencing an unprecedented growth in recent years. There is an expectation that everyone will be permanently connected to the Internet, no matter where they are. The internet protocol traffic is expected to grow beyond 130 exabytes per month by 2018. At the same time, the massive use of mobile connection is pushing the need for wide bandwidth delivered up to the end users in a wireless regime. People are expecting that more information of a higher quality is delivered immediately. The newer services are requiring higher and higher data volumes and transfer rates.

Among various data traffic, the video traffic is expected to be dominant. Some video traffic has already posed severe challenges to mobile networks,
including the forthcoming 5G mobile networks. For instance, it is expected that at least 10 Gbps traffic is needed for one virtual reality (VR) device. Moreover, full High Definition video is becoming increasingly important for mobile devices, and devices using Ultra High Definition (UHD) (4K and 8K) and 3-D rendering are also expected to become widely available in not so distant future.An uncompressed UHD video may reach 24 Gbps rate, and an uncompressed 3-D video with UHD can reach 100 Gbps.Ultimately, It is predicted that data rates will reach Terabit-per-second (Tbps) within the next five to ten years.

However, existing wireless technology is hard to support Tbps links. The state-of-the-art communication systems in ultra-wideband (UWB) or millimeter wave (mmWave) can only achieve

Gigabit-per-second (Gbps) rates. On the other hand, communications over the infrared (IR) or visible light (VLC), are restricted by several technical and safety limitations.

One way to achieve this is to move to higher frequencies for wireless links. Amongst others, the Terahertz (THz) band, 0.1–10 THz, stands out as one of the promising alternatives. Terahertz can provide hundredfold, increase in the frequency compared to the mmWave addressing spectrum scarcity and capacity limitation in current wireless systems. Terahertz wi-fi could in theory support data rates up to 100Gb/s within ranges of about 10m.

In February 2017, researchers from the Panasonic Corporation and National Institute of Information and Communications Technology (Hiroshima University), developed a THz transmitter data at a staggering rate of 100 Gbps over a single channel of 300 GHz. At this data rate, you can transfer a 0.1 terabit file before you can say the word 'it!'

The terahertz spectrum possibly can be the basis for the next "5G" network for cellphones. If cellphones on a current "4G" network can download data at 10 to 15 megabits per second, terahertz technology can potentially send data back and forth at terabits per second (or millions of megabits per second). Terabits per second shall enable super high-speed link to communication satellites, faster content download from servers to the mobile terminal, improved use in applications requiring real-time quality communication (like in orbit), and quick exchange of 3D videos in high definition.

In the past, the frequency spectrum ranging from 0.3 to 3THz (or 300 to 3000GHz) was spoken as infamous "Terahertz Gap" as it lies between traditional microwave and infrared domains but remained "untouchable" via either electronic or photonic means. The conventional "transit-time-limited" electronic devices can hardly operate even at its lowest frequency; the “band-gap-limited” photonic devices on the other hand can only operate beyond its highest frequency. However continuous progress is being made for Terahertz components and devices to overcome electronic/photonic barriers for realizing highly integrated Terahertz systems.

“Imaging, radar, spectroscopy, and communications systems that operate in the millimeter-wave (MMW) and sub-MMW bands of the electromagnetic spectrum have been difficult to develop because of technical challenges associated with generating, detecting, processing and radiating the high-frequency signals associated with these wavelengths. To control and manipulate radiation in this especially challenging portion of the RF spectrum, new electronic devices must be developed that can operate at frequencies above one Terahertz (THz), or one trillion cycles per second,” says DARPA.

The Researchers from the Tokyo Institute of Technology have already demonstrated 3Gb/s transmission at 542 GHz. At the heart of the team’s 1mm-square device is what is known as a resonant tunnelling diode, or RTD. During the 2008 Olympic Games in Beijing, scientists from Osaka University and NTT Corp. already demonstrated a 120 GHz data link across a distance of 1 km.

Terahertz Applications

Information showers: The inherently small communication range of THz cells (few meters radius maximum) and extremely high-rate (up to Tbps) cells can be used for deployment of THz access points (APs) in the areas with high human flow (e.g. gates to the metro station, public building entrances, shopping mall halls, etc.). With such a deployment strategy, each of the passing user is able to receive bulk data (up to several GBs), just while passing this AP. Such information showers can be used do seamlessly deliver software updates as well as other types of heavy traffic, such as high-quality video (e.g. a movie to watch in a train)

Mobile access: The applicability of THz communications to typical usage scenarios (e.g. indoor WLAN access) is limited due to considerable propagation losses. This could be addressed by trading the capacity of THz access points for coverage, primarily by reducing the utilized bandwidth and moving the entire communications from above 1 THz to the so-called "lower terahertz" carriers around 300GHz. As a result, it is possible to create reliable wireless links over tens of meters while retaining the capacity of tens of gigabits per second, which makes Wi-Fi-like THz access points (or even femto-cells for cellular access) become feasible.

Fiber-equivalent wireless links: The strategy for next generation wireless networks (5G and Beyond) envision the appearance of numerous high-rate small cells, operating in the mm Waves spectrum. The feasibility of multi-gigabit-per second wireless links in the lower THz band for the distances up to 1 km long have been recently experimentally validated.

Connectivity with miniature devices: The possibility to create micro-scale transceivers operating in the THz band allow networking of several micro- and nano-scale robots, capable to assist the society in many different areas, from environmental sensing to medicine .

Terahertz for Future Military and Space Communications

Terahertz wireless sensor networks shall also enable gigabit secure battlefield wireless sensor network and provide multi sensor fusion of wide range of imaging and non-imaging sensors. An ability to create highly directional beams with miniature size antenna arrays in conjunction with the high theoretical capacity of THz links results in a number of benefits for the security-sensitive usage, especially in military applications. THz ad hoc network can be formed in the battlefield to connect soldiers, armoured personnel carriers, tanks, etc. The limited transmission range and highly directional antennas makes eavesdropping extremely difficult.

In outer space, the transmission of THz is lossless, so we can achieve long-range secure Gigabit Aircraft to satellite Communication with very little power space. A single THz satellite communication link will support broadband data transfer rates far beyond (>20X) the limits of current microwave technology.

The easier pointing due to their wider beam width, it is suitable for the application in the GEO-GEO or LEO-GEO inter-satellite links, which can support the high-throughput (Gigabit) communication with high security as well as the ability to defeat the interference.

The increased bandwidth of terahertz shall also enable UWB Code Division Multiple Access (CDMA) communications schemes which provide high immunity to fading, large processing gain for combating jamming and low probability of detection and interception.

ISSCC: Panasonic develop 'A 105Gb/s 300GHz CMOS Transmitter'.

Hiroshima University, National Institute of Information and Communications Technology, and Panasonic Corporation announced the development of a terahertz (THz) transmitter capable of transmitting digital data at a rate exceeding 100 gigabits (= 0.1 terabit) per second over a single channel using the 300-GHz band. The research group has developed a transmitter that achieves a communication speed of 105 gigabits per second using the frequency range from 290 GHz to 315 GHz. At this data rate, the contents of an entire DVD can be transferred in a fraction of a second

“This year, we developed a transmitter with 10 times higher transmission power than the previous version’s,” said Hiroshima Professor Minoru Fujishima. “This made the per-channel data rate above 100Gbit/s at 300GHz possible. Terahertz could offer ultrahigh-speed links to satellites, and that could, in turn, significantly boost in-flight network connection speeds, for example.” Other possible applications include fast download from contents servers to mobile devices and ultrafast wireless links between base stations, he added.

“This year, they showed six times higher per-channel data rate, exceeding 100Gbit/s for the first time as an integrated-circuit-based transmitter,” said Panasonic, which worked with Hiroshima University and the Japanese National Institute of Information and Communications Technology to develop the transmitter. He pointed out that such links could beat optical fibres because that are made from glass where the speed of light is slower than in air or space, increasing data latency and barring them from systems that require ultra-fast responses. “Today, you must make a choice between high data rate fibre optics and minimum-latency microwave links. You can’t have them both,” said Fujishima. “But with terahertz wireless, we could have light-speed minimum-latency links supporting fibre-optic data rates.”

Panasonic points out that the range of frequencies used are currently unallocated, falling within the 275-450 GHz whose usage is to be discussed at the World Radiocommunication Conference (WRC) 2019 under the International Telecommunication Union Radiocommunication Section (ITU-R).

FUJITSU and NTT develop compact terahertz band receivers

FUJITSU has developed the world's first compact 300GHz receiver (which is part of the terahertz waveband in which attenuation during propagation of signals through the atmosphere is low) capable of wireless communications at tens of gigabits per second. They have developed an integrated module that combines receiver-amplifier chip and terahertz-band antenna with a low-loss connection within the cubic capacity at 0.75 of a centimeter, and that can be installed in mobile devices.

The use of this Fujitsu-developed technology will enable small devices to receive 4K or 8K HD video instantly, such as from a download kiosk with a multi-gigabit connection. It will also be possible to expand into such applications as split-second data transfers between mobile devices and split-second backup between mobile devices and servers.

They commonly used printed-circuit substrate to connect the antenna and the receiver-amplifier chip is ceramic, quartz, or Teflon. They replace the material with a low-loss polyimide, which can be micro-fabricated into printed circuit boards.

While polyimide as a material has a 10 percent higher loss than quartz, but since its processing accuracy is more than four times higher, the through-hole vias can be placed within several tens of microns of each other, halving the loss as compared to a connecting circuit on a quartz printed circuit. This allows the receiver to be highly sensitive which compensates the strong attenuation of terahertz waves when propagating through atmosphere.

NTT has also developed 300-GHz, a wireless-use IC for ultrahigh-speed short-distance wireless

communication system.

In the IC, a modulator and a power amplifier (which are required components of a transmission unit for wireless transmission) are monolithically integrated. High output power and low-loss wiring were achieved by multi-parallelization of the amplifier, and high data rate was achieved by a travelling-wave modulator. Moreover, by using low-loss and wideband waveguide-to-IC transition we designed, the deterioration of the characteristics due to packaging was negligible. By applying this module high-speed operation (i.e., 20 Gbit/s) was confirmed

Terahertz Multiplexers / Demultiplexers

Multiplexers / Demultiplexers are devices that are used to enable separate streams of data to travel through a single medium, by combining the signals through multiplexers at the transmitter end and separating them through demultiplexers at the receiver end, common examples are cable carrying multiple TV channels or fiber optic line carrying thousands of phone calls at the same time.

Researchers from Brown University have developed deices for multiplexing / demultiplexing terahertz waves. The multiplexer that Mittleman and his colleagues have been working on makes use of what's known as a leaky wave antenna. In this case, the antenna is made from two metal plates placed in parallel to form a waveguide. One of the plates has a small slit in it. As terahertz waves travel down the waveguide, some of the radiation leaks out of the slit. It turns out that terahertz waves leak out different angles depending on their frequency.

"That means if you put in 10 different frequencies between the plates — each of them potentially carrying a unique data stream — they'll come out at 10 different angles," Mittleman said. “Now you’ve separated them and that’s demultiplexing.” On the other end, a receiver could be tuned to accept radiation at a particular angle, thus receiving data from only one stream.

“We think it’s definitely a reasonable solution to meet the needs of a terahertz communication network,” said Nicholas Karl, a graduate student at Brown and the paper’s lead author. Karl led the experiments on the device with fellow graduate student Robert McKinney. Other authors on the study are Rajind Mendis, a research professor at Brown, and Yasuaki Monnai from Keio University in Tokyo.

The group plans to continue its work to refine the device. A research group from Osaka University is collaborating with Mittleman’s group to implement the device in a prototype terahertz network they’re building.

Tufts Researchers Build A Chip-Sized, High-Speed Terahertz Modulator

Tufts University engineers claim to have a breakthrough with their successful fabrication of an on-chip device that can perform gigahertz-rate amplitude modulation, and switching of broadband terahertz electromagnetic waves confined within a novel slot waveguide with tunable, two-dimensional electron gas.

“A prototype device is fabricated which shows THz intensity modulation of 96% at 0.25 THz carrier frequency with low insertion loss and device length as small as 100 microns. The demonstrated modulation cutoff frequency exceeds 14 GHz indicating potential for the high-speed modulation of terahertz waves. The entire device operates at room temperature with low drive voltage (<2 V) and zero DC power consumption,” the researchers wrote in a paper published in

Scientific Reports.

Previously-built THz modulators were capable of reaching speeds of only up to a few kilohertz (kHz). The Tufts University team claims to have experimental results showing gigahertz speed modulation of THz waves for the first time.

“This is a very promising device that can operate at terahertz frequencies, is miniaturized using mainstream semiconductor foundry, and is in the same form factor as current communication devices. It’s only one building block, but it could help to start filling the THz gap,” said Sameer Sonkusale, Ph.D., of Nano Lab, Department of Electrical and Computer Engineering, Tufts University, and the paper’s corresponding author, in a news release.

A well-known application for building fast and compact terahertz modulators is to achieve high data rate wireless communication, where an inherently high carrier frequency of THz wave will support much wider signal bandwidth compared to the radio frequency (RF) bands used today, according to the researchers. But wider applications abound, such as in material identification, imaging, wireless communications, chemical and biological sensing.

DARPA’s thrust in Terahertz

DARPA has made a series of strategic investments in terahertz electronics through its HiFIVE, SWIFT and TFAST programs. “To fully exploit the sub-MMW band will require monolithic microwave integrated circuits (MMICs) that can operate up to THz frequencies. And to make these THz MMICs (or “TMICs”) will require THz transistors with maximum oscillation frequencies (fmax) well above 1 THz.

The objective of the Terahertz (THz) Electronics program is to develop the critical device and integration technologies necessary to realize compact, high-performance electronic circuits that operate at center frequencies exceeding 1.0 THz.

Successes in the THz Electronics program could catalyze the development of revolutionary applications by enabling coherent THz processing techniques such as THz imaging systems; sub-MMW, ultra-wideband, ultra-high-capacity communication links; and sub-MMW, single-chip widely-tunable synthesizers for explosive detection spectroscopy.

The program is focused on two critical THz technical areas:

Terahertz Transistor Electronics

This part of the program has aggressively developed multi-THz Indium Phosphide-based transistors (heterojunction bipolar transistors, or HBTs, and High Electron Mobility Transistors, or HEMTs) and has demonstrated TMICs operating up to and above 1 THz. In addition, THz low-loss inter-element interconnect and integration technologies have been developed, enabling compact THz transmitter and receiver modules to demonstrate wireless communications at 220 GHz, 670 GHz, and 850 GHz – hundreds of times faster than your cell phone.

Terahertz High Power Amplifier Modules

This part of the program aims to develop compact, micromachined vacuum electronics devices to produce a significant increase of output power at frequencies beyond 1.0 THz and to radiate that energy at an antenna. Already, micromachined traveling wave tube amplifiers (TWTs) operating at 670 GHz and 850 GHz have been built and tested and have produced the highest linear output power available at these frequencies.

Northrop Grumman Corporation, under DARPA's Terahertz Electronics, has created a fastest solid-state amplifier integrated circuit ever measured, operating at a speed of one terahertz. The ten-stage common-source amplifier Terahertz Monolithic Integrated Circuit (TMIC) exhibits power gains several orders of magnitude beyond the current state of the art, using a super-scaled 25 nanometer gate-length. The Northrop Grumman TMIC showed a measured gain of nine decibels at 1.0 terahertz and 10 decibels at 1.03 terahertz.

Terahertz Photonics

"Scientists are turning to the development of photonic, rather than electronic, devices for THz communications because it is easier to achieve higher data rates using photonic components," said Nagatsuma of Osaka University. "In addition, photonics-based systems might be deployed in the future convergence of fibre optic and wireless communications networks," commented Nagatsuma. He believes that ultrawideband amplifiers and antennas are the most crucial components needed to make full use of the bandwidth. "Even for photonics-based systems, amplifiers are necessary to boost the output power in the transmitter and to increase the sensitivity in the receiver," he stressed.

"Therefore, over the past 10 years many developments have been made to prepare for the future convergence between fiber optic and mobile end users, in backhaul – point to point (P2P) – or fronthaul schemes," writes Guillaume Ducournau, Institute of Electronics, Microelectronics and Nanotechnology. "Both require very high frequency transceivers, and electronic/optic approaches are under investigation. In addition, the massive development of multilevel encoding combined with standard WDM (wavelength division multiplexing) and the context of coherent networks and core signal processing is now established. Thus, the quest for direct optical to radio transceivers has become very attractive and would enable direct bridges between optical data rates and mobile data delivery.

THz communication devices will require innovation in integration and packaging to be practical. Guillermo Carpintero of Universidad Carlos III de Madrid in Spain described how he and his co-workers are tackling this challenge and have developed integrated photonics-based sources of millimetre and THz waves during 40th International Conference on Infrared, Millimeter, and Terahertz Waves (IRMMW-THz).

“Although we tried to use available generic integration-platform building blocks, there is no building block for Bragg mirrors,” said Carpintero. As a result, the team developed the concept of integrated multimode interference reflector mirrors for mode-locked lasers. The optical spectrum of the optical heterodyne source based on the mode-locked photonic integrated circuit around 1,560 nm showed a carrier wave frequency of 90 GHz. The team has used this on-chip optical heterodyne source to perform broadband wireless data transmission.

“For nomadic usages, development of siliconbased photonics and/or CMOS might enable advanced integration and miniaturization, which is especially required for mass market applications, such as those embedded in mobile terminals,” writes Guillaume Ducournau.

THz Communications technologies

In the meantime, marvelous advances in hardware are making THz communications a reality. Currently, high-performance Silicon-Germanium (Si-Ge) based front-ends can generate signals up to 0.84 THz. Besides, the study on transceivers with Gallium-Nitride (GaN) based power amplifiers has demonstrated capabilities over 1 THz.

Many new compact, room temperature, terahertz sources are being developed. Teraphysics has developed miniature helical TWT for operation at 650 GHz under contracts from NASA Jet Propulsion Laboratory (JPL), the Defense Advanced Research Projects Agency (DARPA), the Army Research Office (ARO), and the Air Force Office of Scientific Research (AFOSR).

Photonic devices, such as Quantum Cascade Laser (QCL) sources, are also investigated for the THz band. Specifically, THz digital-to-analog (D/A) converters and analog-to-digital (A/D) converters have been designed using radio-frequency (RF) photonic technology.

Moreover, the magnet or voltage controlled THz phase shifters based on graphene/liquid crystal have been developed at room temperature for THz beamforming. In addition, novel nano-devices, e.g., compact graphene antennas, will be feasible for THz transmission in the near future. Undoubtedly, this ultra-broadband communication is just around the corner.

The significant decrease in the wavelength in terahertz enables packing a large number of antennas in a small area, which could provide more gains to establish reliable links. Thus, gains from multiple antennas should be explored to combat and compensate for such losses.

“We now have many enabling technologies thanks to the recent progress of semiconductor devices and integrated circuits operating at THz frequencies,” Nagatsuma of Osaka University told Nature Photonics. “In addition to the data rate, other expected advantages of THz communications over microwave communications are low power consumption and smaller transceiver size, particularly coming from a reduction in the antenna size,” he added.

InP Devices

To date, the terahertz band is mostly unused for a lack of suitable electronic components, which are commercially available only up to around 100 GHz.” In order to reach these high frequencies, both intrinsic and extrinsic parasitic capacitances need to be reduced, and semiconductor materials with high electron mobility need to be used. For this purpose, we developed a transfer-substrate Indium Phosphide (InP) Hetero-Bipolar Transistor technology. Besides high electron mobility, the InP material system offers a high breakdown field due to its large energy gap, enabling higher output power at THz frequencies than any other semiconductor material,” write Leibniz-Institute IHP Frankfurt. Capacitances are effectively reduced with the transfer-substrate approach.

“InP HBTs with an emitter size of 0.5 × 5 µm2 are defined by electron beam lithography, demonstrating an fmax of more than 450 GHz at a breakdown voltage of BVCEO = 4.5 V. Monolithically integrated circuits such as amplifiers, mixers, and oscillators operating in the frequency range from 100 GHz to over 300 GHz have been fabricated and tested.”

The cutoff frequency of ultra-high frequency transistors is increased with geometrical device scaling. The cooling of these transistors becomes ever more important as the power density increases with shrinking device dimensions. The heat can be efficiently extracted from the transistors with the integration of an electrically isolating diamond heat spreading layer, without having to compromise the high frequency performance. The thermal resistance of diamond-integrated InP HBT could be reduced by more than a factor of three compared to standard InP HBT, reaching a value below 1 K/mW. The RF output power of analog amplifier circuits operating at around 100 GHz could be doubled with the inclusion of the diamond heat sink.

System integration of integrated terahertz circuits requires a suitable mounting technology, foremost to connect the terahertz circuit to an antenna structure. The required mounting and connection technology needs to be sufficiently broadband, should not incur significant RF losses, must be reproducibly manufacturable from the initial electromagnetic design, and needs to be low cost. Classic bond wire connections are difficult to implement beyond 100 GHz due to manufacturing tolerances.

A flip-chip mounting technology based on gold-tin with 10 µm design rule was developed, including multilayer passive submount substrates with shielded transmission lines, which were manufactured in a process sequence similar to the InP DHBT process flow. Passive and active InP HBT circuits were mounted onto these submounts and measured. A bandwidth from DC to 450 GHz could be demonstrated. The insertion loss of the flip-chip transitions was less than 1 dB even at the highest frequencies.

Wafer-scale InP DHBT – SiGe BiCMOS hetero-integration process – SciFab

“Based on the transferred-substrate concept, we developed a wafer-scale 3D integration approach of InP DHBT technology onto Silicon Germanium Bipolar-CMOS (SiGe BiCMOS) wafers using face-to-face adhesive wafer bonding, subsequent InP substrate removal, and formation of vertical RF interconnects between the InP DHBT and SiGe BiCMOS subcircuits. In this complementary approach, we combine the advantages of both technologies: highly complex BiCMOS analog and digital circuits are augmented with the high bandwidth and output power of InP DHBT amplification and mixing stages. Signal sources including a BiCMOS VCO and InP mixing and power amplification stages operating at up to 330 GHz were demonstrated.”

Challenges

Nevertheless, there still exist many challenges in THz communications requiring innovative solutions, where the well-established technologies may be prohibited. Sensitive to atmospheric attenuation and molecular absorption, the THz signals experience an extremely severe path loss, which leads to a great limitation on communication distance. Meanwhile, the complex structures of THz devices pose extra constraints on the system, where conventional approaches, e.g., completely digital signal processing at baseband for each antenna, are no longer suitable.

THz Antenna

Due to the enormous path loss for long distance in space and tiny power capacity, the high gain antenna is preferred. The traditional reflector antenna used for THz band will bring some problems because of the extremely higher requirement of surface precision, although this kind of antenna has larger gain.

THz Signal Processing

The classical signal processing method cannot fully benefit from the properties of the THz band signal. The new channel models are required for the THz wave propagation. New coding schemes are needed to overcome the channel errors in the THz band. Different bandwidths and transmission distances of THz wave applications require various adaptable modulations.

Low-cost system architectures and communication schemes are needed, which should be adaptive and stable to the whole THz band.

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