Photonics, Fiber and THz Wireless Communication

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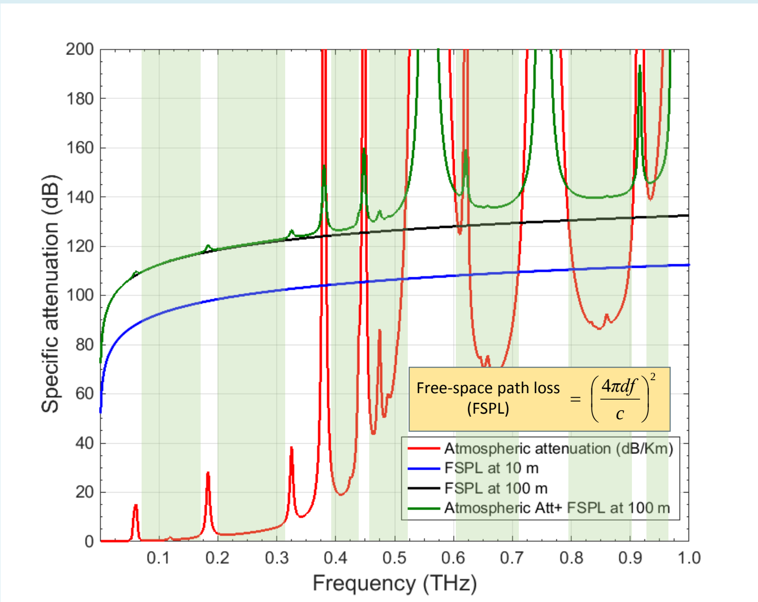
Introduction

There is a continuous increase in wireless traffic data driven by the increasing range of image-rich services and applications for mobile devices. Edholm has predicted that the evolution of data rates via wireless system is doubling every 18 months [1]. For example, according to the latest report from Cisco' s visual networking index [2], global mobile data traffic increased from 2.1 exabytes/month (2.1 billion Gigabytes/month) in 2014 up to 3.7 exabytes/month in 2015. The continued exponential increase is dependent on user needs for higher data rates for potential applications such as HDTV, high quality video conference, 3D displays, and instant downloads of large amount of data. Wireless communication networks are facing major challenges in accommodating this increase in data traffic demands. Telecommunication and wireless engineers are working hard to find solutions to counter the data speed limitations in wireless networks. For any communication link the data speed limit is based on the Shannon theorem where the upper bound of the information rate of data that can be communicated with low rate of errors at a certain average signal power is limited by the channel bandwidth. Therefore, there are two possible approaches which are always considered. The first is to increase the spectral efficiency of the signal, this means increasing the number of transmitted data bits per second for the same equipped bandwidth. For a given bit error rate this approach requires higher signal to noise ratio and hence higher transmitted power, a major concern for battery operated devices. The second approach is to use ultra-high bandwidths available beyond 20 GHz.

The electromagnetic spectrum is stacked with small bandwidth channels for all radio, television, cellular radio, Wi-Fi, radar and other users. This means that new spectrum in the lower frequency bands is not available. Currently, Wi-Fi is the most widely used wireless public network. It is currently accessed by nearly all mobile devices due to its licence-free spectrum, low implementation cost for indoor/outdoor schemes and ease of access. However this is limited to the assigned bandwidth. For example, Wi-Fi capacity based on IEEE standard 802.11n/ac can provide speed of up to 100 Mbit/s for 40 MHz bandwidth at 2.4 GHz or 433 Mbit/s for 80 MHz bandwidth in the 5 GHz frequency band. Furthermore, wider spectral bands have also been allocated at millimetre waves (mm-waves) (i.e. frequency band 30 GHz- 100 GHz) with a total bandwidth of less than 7 GHz such as in 60 GHz, 70 GHz, and 90 GHz frequency bands. These bands can support data rates up to 10 Gbit/s.

In order to enable even higher capacity wireless data systems, the THz frequency region (0.1 -10 THz), which offers considerable, currently unallocated, bandwidth has been little exploited for wireless communication. This region is currently being investigated for a much larger bandwidth systems, ranging from a few GHz to over 100 GHz [3]. The lack of compact, efficient generation and detection systems have limited the access to the THz communication bands. However, advances in device technologies can enable short range (< 100m) high capacity (> 10Gbit/s) transmission in the THz region. Besides the potential for THz wireless applications, THz spectroscopy and imaging systems have become important for several industries; applications include explosive and concealed weapon detection, pharmaceutical quality control, and non-destructive evaluation/quality control. In wireless communication, the range of mm-wave and THz systems is limited by free space attenuation and atmospheric absorption peaks, particularly due to water vapour molecules. The free space loss rises with the square of the carrier frequency and this limits the transmission link. For 10 m link, THz system will have losses around 100 dB at a carrier frequency 300 GHz. In addition, the molecular absorption by water vapour molecules divides the spectrum into several spectral transmission windows. The high losses in the path require high antenna gain with line-of-sight operation compared with the low gain weakly directional antennas used at the low GHz radio frequencies. Given the limited range of THz wireless systems, wireless over fibre technology can play an important part in the distribution of the mm-waves, and THz signals over long distance due to the low losses in the optical fibre cables. Many solutions have been introduced to show the synergy between THz and optical fibre communication for fixed links outdoors and inside the buildings such as office blocks, shopping malls, and airport terminals. Depending on the link distance, this frequency band can support potential applications for THz communications including wireless front and backhauling systems, wireless personal area networks in smart homes, kiosk downloads, and device to device communications.



Specific attenuation due to atmospheric gases based on calculated model ITU-R P676-10 for an air pressure of 1013 hPa, a temperature of 15 C and a water vapor density of 7.5 g/m . This figure highlights the available transmission band for wireless communication.

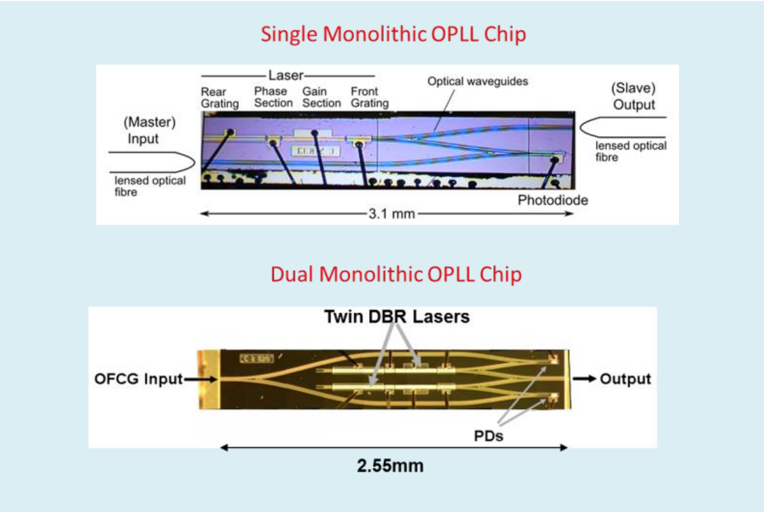
In the spectrum regulations, frequencies beyond 275 GHz have not yet been assigned. The International Telecommunication Union (ITU) study group for Radio Communication regulations is working to uncover the technical and operational characteristics of active services in the frequency range 275- 1000 GHz [4]. They expect to publish their initial report in 2017. In IEEE 802.15 standards for wireless personal area network (WPAN), the Terahertz Interest Group is now exploring the technical and operational characteristics in order to standardize the frequency band from 252- 325 GHz for 100 Gbits/s radio transmission [5]. Moreover, there are many active research groups supported by industry and government schemes to move forward with the research and development of THz wireless link technology. In Europe, the European Commission Seventh Framework Programme has supported the IPHOS project for the development of a compact and low power transceiver at sub-THz carrier. In Germany, the TERAPAN project, which was funded by the German Federal Ministry of Education and Research, aimed to develop an electrical beam steering wireless point to point terahertz communication system for indoor environments at 300 GHz with data rate of more than 40 Gbps. In the UK, the Engineering and Physical Sciences Research Council (EPSRC) COherent Terhertz Systems (COTS) programme grant is developing new and compact semiconductor devices for the entire THz spectrum and applying these to THz applications including communications. The research groups in Japan are supported by the Ministry of Internal Affairs and Communications for the development in 300 GHz wireless link technology.

Photonic approach for wireless THz

Wireless THz generation and detection methods have been advancing over recent years. The main objective is to obtain high quality THz signals with high output power necessary for radio communication and other THz applications. There are two main approaches based on either electronics or photonic techniques for THz generation. In the THz electronics based approach, there have been many reported demonstrations achieved based on Schottky diodes, GaAs and InP integrated circuits, resonant cavity diodes, or Si integrated circuits. However, the photonic approach technology for THz wireless generation offers a solution to generate THz signals that is compatible with wireless over fibre distribution technology [6]. It also allows amplitude and phase modulation with high-speed data. Additionally, it is directly integrable with low loss existing optical fibre networks. Recent progress in photonic integration technologies for optical components could enable the generation of compact and power-efficient coherent THz systems with high spectral purity.

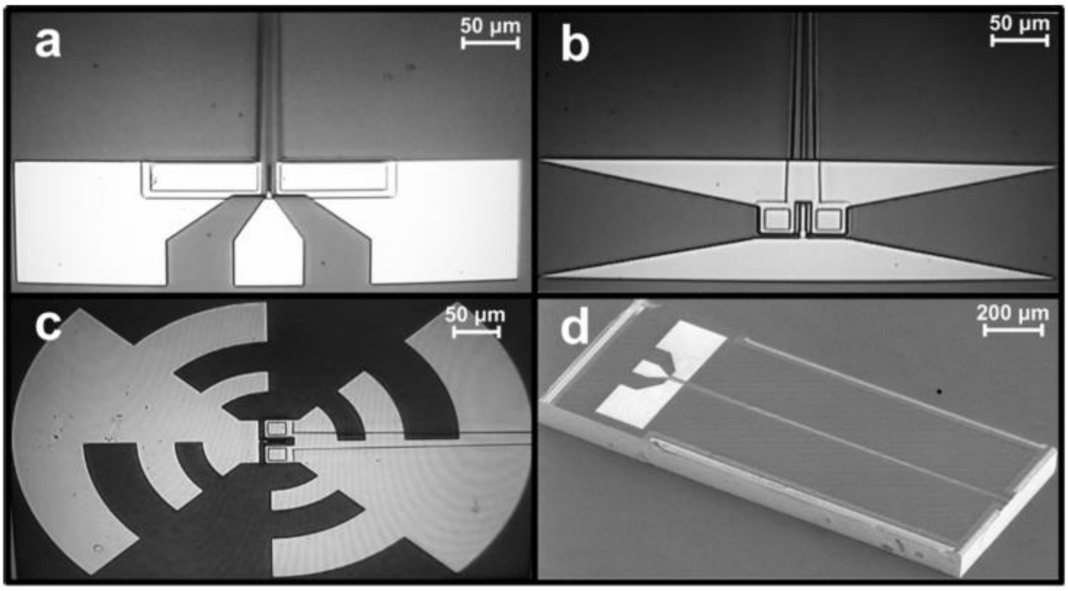
The most promising photonic technique for optical signal generation is the photomixing of two optical sources with different frequencies in a photodiode or photomixer [7]. The generated signal is an electrical signal at a frequency equal to the frequency difference between the two optical sources, and exhibits phase noise fluctuations due to the linewidths and relative frequency fluctuations of the two laser sources. Photonic integration of a monolithic dual-wavelength source for mm- and THz-wave generation is attractive as it provides more compact, tuneable sources and can result in improved spectral purity. One approach is based on the monolithic integration of distributed feedback (DFB) lasers, whereby two DFB-lasers are grown side by side and the wavelengths are combined using a multimode interference (MMI) coupler. This approach is compact and both lasers encounter the same environmental fluctuations. However, the system suffers from thermal instability and phase noise, which deteriorates the system performance. A fully integrated transmitter has also been proposed in which two DFB sources are integrated with an optical modulator and photodetector. This can provide continuous tuning over the frequency range from 5 GHz to 110 GHz, with linewidth depending on the DFB laser linewidth, typically < 1 MHz.

Several methods have been developed to achieve higher spectral purity THz signals, based on optical phase locked sources. Among these are locking techniques based on optical phase locked loops (OPLL) combined with an optical comb source. The optical comb source provides optical phase correlated lines spaced in frequency by a supplied RF reference signal. In the OPLL technique, the slave laser is locked to the incoming optical reference signal through a negative feedback loop to compensate the phase variation between the slave laser and the selected comb line. The main limiting parameter is the delay of the feedback loop; this has to be sufficiently short to enable tracking of the phase variation of the heterodyne between comb line and slave laser. A hybrid OPLL integration system was achieved at a frequency of up to 300 GHz with a small optical delay of less than 50 ps. A monolithic photonic integrated circuit (PIC) for single and dual OPLL systems has been developed for a compact cost effective THz system. The single OPLL PIC contains a distributed Bragg reflector (DBR) laser, and a PIN photodiode with passive optical waveguides for coupling the light. The optical delay is reduced to few tens of picoseconds and the external electronic circuit for the feedback loop delay was carefully designed. This PIC showed a phase noise < - 80 dBc/Hz at offset frequency of 10 kHz. The dual OPLL chip can be tuned up to 1 THz; the limit is determined by the tuning range of the slave lasers and the frequency span of the optical comb source.



Microscope view of photonic integrated chip for single, and dual monolithic OPLL

Another key component of the THz system is the photomixer. In order to obtain high output power in the THz range, the photomixer needs to have high responsivity, high saturation output power, and a broad bandwidth response. The uni-travelling carrier photodiode (UTC-PD) can meet these key requirements. The short transit time of electronics and low space charge effect in the depletion layer enable the high bandwidth response > 1 THz for UTC devices. A UTC- PD can be integrated with a broadband log periodic antenna. This produced a radiated power of 2.3 µW at 1.04 THz for an optical power input of 430 mW. An enhancement in the radiated output power, and bandwidth was also obtained in a travelling wave (TW) UTC-PD. When the TW UTC-PD is integrated with a resonant antenna, it achieved 24 µW at 914 GHz for 100 mW optical power. Nevertheless, the emitted power is still restricted by UTC power dissipation limits. Therefore, a power combining technique based on an array of photodiodes can produce higher output power levels than that produced in a single UTC device. This has been shown in dual UTC photodiodes in a single monolithic chip for output power more than 1

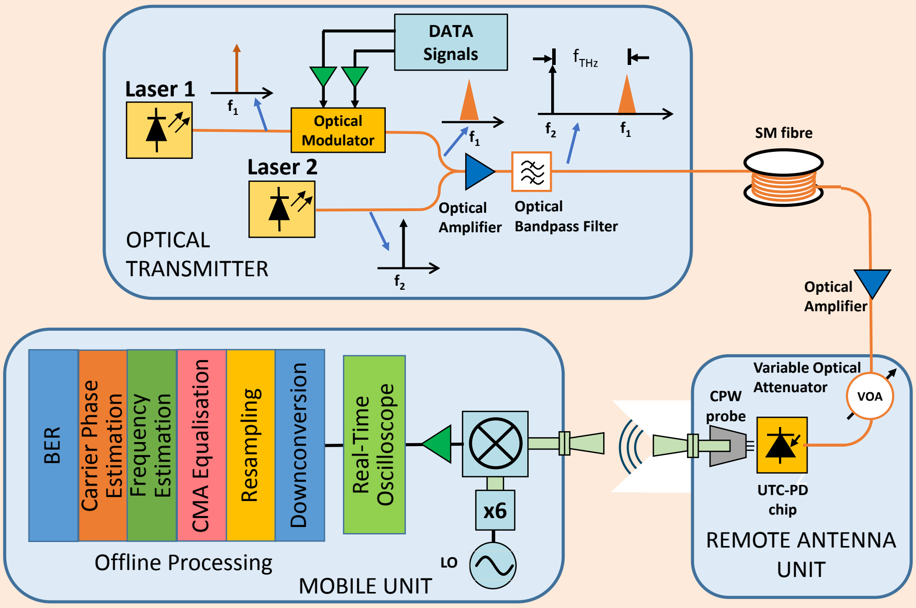


SEM pictures of the different TW-UTC devices fabricated with: (a) coplanar probe contacts, (b) Bow-Tie antennas, (c) Log-Periodic antennas, d) resonant antennas.

mW achieved at 300 GHz with 20 mA photocurrent per PD.

THz wireless communication systems

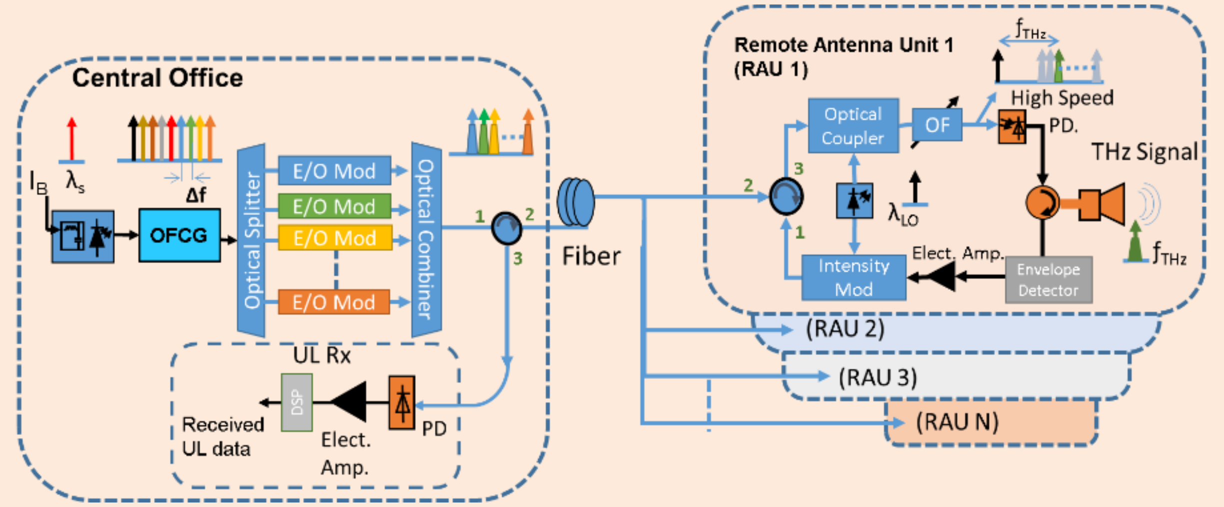
Several research groups have demonstrated communication in the W-band (75- 95 GHz) and for frequencies above 100 GHz. Real time transmission was reported for a single carrier with amplitude modulation using the direct detection scheme, whereby the modulated signal is recovered by a square law detector. The First demonstration of wireless transmission was achieved at 120 GHz for 10 Gbps over 400 m in 2012, and the highest data rate obtained for a real time single channel has reached 48 Gbit/s at 300 GHz, using dual polarization transmission. Phase modulated transmission has also been investigated in many systems to achieve higher spectral efficiency. A THz wireless over fibre system schematic is shown in the figure below. The first laser is optically modulated with the data signal using an optical IQ modulator for phase-modulated signals suitable for different modulation formats. Then, the output is combined with a second free-running laser with offset frequency equal to the desired THz signal frequency. The combined optical signal is amplified and transmitted to one or multiple remote antenna units (RAUs) through single mode fibre (SMF). At the RAU, the optical signal is converted to electrical THz waves through an UTC-PD, and then radiated to the user's mobile unit (MU). The THz signal is down-coverted to IF signal using a second harmonic mixer driven by 6^{th} harmonic from electrical LO source. Afterwards, the electrical signal is processed using digital signal processing (DSP). The receiver detection is based in an offline digital signal processing for signal down-converison, down-sampling, equalization, frequency estimation, carrier phase estimation, and BER detection.



Schematic diagram for the conventional experimental setup used in the photonic generation of THz signals and digitally processing it offline at the receiver.

In order to use the whole spectrum resources, a multicarrier based THz system has been investigated to maximize the overall data rate and achieve higher spectral efficiency. An example for the arrangement of the multiband sub-THz wireless-over-fibre system for up and down links is shown in the figure below. For the downlink stream, a single wavelength laser is used to generate optical coherent tones in an optical comb, which is a very convenient way to create a number of phase-correlated optical carriers. These optical carriers are spaced by the driving RF frequency and are then de-multiplexed and individually modulated. Afterwards, the modulated optical signals are combined and transmitted over a length of standard single mode fibre (SSMF). At the RAU, the received optical multiband signal is coupled with a local oscillator (LO) light source to generate an optical heterodyne. An optical filter (OF) is used to select one sub-band and the LO laser, which is launched into a high-speed photodiode (PD) to generate the sub-THz modulated signal. This sub-THz signal is then radiated through an antenna to the user mobile unit (MU). This configuration has advantages over other solutions. It allows the RAU to be reconfigurable and enables frequency reuse capability by using a tuneable LO laser to adjust the transmit carrier frequency, giving it more flexibility for picocell system architectures. This system also enables the aggregate transmitted data rate to be increased while using limited bandwidth opto-electronic devices. For the uplink stream, the received THz signal is envelope detected and electrically amplified before being used to drive an intensity modulator. The antenna is connected to a microwave circulator for up/down link separation. The LO laser used for up-converting the downlink is also used for the uplink stream. The baseband signal is then transmitted over the same fibre to the central office where it is photodetected and demodulated. This scheme is flexible in terms of the signal modulation format and baud rate, the number of sub-channels in the multiband, and the THz carrier frequency. The multiband photonic THz generation scheme has been demonstrated by generating a signal with an aggregate downlink data rate of 100 Gbit/s in five sub-bands modulated with quadrature phase shift keying (QPSK) over the full band 220 – 280

GHz and an uplink signal with 10 Gbit/s on-off keying (OOK) [8]. Even though the system has been demonstrated over a very short link (~ 2 cm) due to the limited UTC power, by using polymethylpentene lenses at both the transmitter and receiver, the transmission link distance can be increased to over 70 cm while



The schematic diagram for the full duplex transmission for multiband THz wireless signal over the full operating band 220 -280 GHz.

keeping the error rate well below the correction limits.

Conclusions

THz wireless links are attracting significant interest as a solution for the ultra-broadband wireless link needed to accommodate the continuous increase in data rate requirements. Recent progress in THz photonics technology and integration makes THz wireless links feasible for achieving 100 Gbit/s using a multi-band scheme. However, there are many challenges still facing the full development of THz-based wireless links, mainly in the wireless transmitted power, beam directivity, and power consumption. The THz transmitter still lacks output power, and is limited by UTC photomixer optical responsivity, frequency response and generated output power. Photonic integration plays an essential role in improving the overall system performance in terms of cost, size, and reducing the coupling losses between photonic components. A full integration system with multiple photodiodes may be needed to enhance the transmitted THz power. The design of multiple photodiode arrays and antenna arrays can also overcome the power limitation in a long distance transmission, and allow for mobile device tracking. The beam steering capability is still difficult to achieve for large bandwidth for multi-Gbit/s. THz transistor amplifiers integrated with UTC-PDs are a further technique to increase THz power. The combination of integrated solutions and receivers of lower noise figure should enable THz wireless links with throughputs matching optical communication systems.

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