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Photonic Generation and Distribution of Coherent Multiband THz Wireless Signals

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***Abstract*— We discuss photonic generation of high-speed THz wireless signals, with particular reference to how multiband signals could be distributed over fibre networks from a central baseband unit equipped with a pool of optoelectronic components, allowing the remote antenna unit to be very simple, while delivering flexibility in terms of data rate and THz carrier frequency. The proposed scheme is demonstrated experimentally by generating a 5-channel multiband signal with aggregate data rate of 100 Gb/s and investigating the performance of each 20 Gb/s sub-band after transmission over a wireless link in the 220 – 280 GHz band.**

***Index Terms*—THz communications, photonic heterodyning.**

I. INTRODUCTION

The demand for wireless data transmission at ever higher rates, for applications such as video streaming, is driving investigation of wireless transmission at frequencies in the millimetre-wave and higher bands [1]. Spectrum is available at low THz frequencies (200 GHz – 500 GHz) with potential bandwidths of tens of gigahertz, limited by the location of water absorption peaks at longer transmission distances (100 m upwards) and by practical considerations such as the frequency range of standard waveguides or regulatory requirements. Fundamental to operating at these frequencies is the extremely high free-space path loss (more than 100 dB for link lengths greater than 10 m). When the low power of compact sources for these wavebands and the large noise bandwidth associated with high-baud-rate transmission are taken into consideration, highly directional antennas are essential to achieve an adequate signal-to-noise ratio at the receiver. Even so, most demonstrations of wireless data transmission at these low THz frequencies have been limited to short distances, a few centimetres to a few tens of metres.

To illustrate the challenges, Table 1 presents a power budget calculation for a wireless link at 300 GHz. A transmitter output power of 10 mW is assumed, based on the maximum reported output power of state-of-the-art InP high-electron-mobility transistor monolithic millimeter-wave integrated circuit (MMIC) electronic amplifiers at around this frequency [2]. Antenna gain for both transmitter and receiver is taken to be 25 dBi, typical of compact horn antennas, while the loss for downconversion to the IF is assumed to be 10 dB, similar to the performance of commercially available sub-harmonic mixers based on Schottky diodes. This simplified calculation shows that there is around 5 dB margin for transmission of 10 Gbaud quadrature phase shift keying (QPSK) over a link length of 10 m with a bit error ratio (BER) of 10^{-3}, thus allowing for some implementation penalty. Such a wireless system might be compatible with high data rate transmission to nomadic devices within an office, for example. Using more highly directional antennas (e.g. Cassegrain) with gain of 50 dBi at both transmitter and receiver, a similar calculation shows that 100 Gb/s QPSK could be transmitted with similar performance over more than 1 km, which might be suitable for mobile front- or back-haul applications.

TABLE I. EXAMPLE THZ WIRELESS LINK POWER BUDGET

Parameter	**Value**	**Unit**	**Assumptions**
Source power	10	dBm	
Tx antenna gain	25	dBi	
Transmission loss	102	dB	At 300 GHz; link length = 10 m; absorption negligible
Rx antenna gain	25	dBi	
Received power	**-42**	**dBm**	
IF power	-52	dBm	10 dB down-conversion loss
IF input equivalent noise	-167	dBm /Hz	NF = 7 dB
E_b/N_0	**12**	**dB**	Data rate = 20 Gb/s
System margin	~5	dB	c.f. BPSK or QPSK at BER = 10^{-3} (E_b/N_0 = 6.8 dB)

II. PHOTONIC GENERATION OF THZ SIGNALS

Most experimental demonstrations of high-speed THz-wireless data transmission have employed photonic generation [3 – 7], making use of optoelectronic components and sub-systems developed for optical fibre communications systems. High symbol rate (10 – 30 Gbaud) signals can be modulated onto optical carriers in various formats, including on-off keying (OOK), QPSK and 16-QAM (quadrature amplitude modulation), and then downconverted to the THz band by heterodyning the modulated optical signal with a continuous wave laser (optical local oscillator, LO) on a high-speed photodiode (PD), which acts as a mixer. The critical component is the PD, which needs to respond at the THz frequency of interest. High bandwidth PDs, such as the uni-travelling carrier (UTC) PD, are required, but even so, at frequencies above 200 GHz these are almost always operating beyond their -3-dB bandwidth.

Due to the reduced PD response at high frequencies and the need to operate at relatively low photocurrents to avoid damage, the power generated photonically at THz frequencies is quite low. The maximum generated to date at 300 GHz is 1 mW, obtained by combining the output of two monolithically integrated UTC-PDs [8]. It is likely that electrical amplification of the PD output will be required to achieve significantly more transmitter power, although, as noted earlier, the output power of state-of-the-art amplifiers in the 300 GHz band is itself currently 10 mW or less [2].

Photonic THz generation has been used to demonstrate transmission of a total of 100 Gb/s in three sub-channels at a carrier frequency of 237.5 GHz, over a distance of 20 m [3]. A MMIC was used at the receiver to recover in-phase and quadrature signals, which were then digitised and processed offline to recover the data and to estimate the BER. An alternative receiver architecture is to use a sub-harmonic mixer (SHM), usually based on a high-speed Schottky barrier diode, to downconvert to an intermediate frequency (IF), which is then digitised and processed offline to recover the baseband data. This approach has been used to demonstrate 20 Gbaud QPSK (40 Gb/s) at 325 GHz over 15 m [4], and 46 Gb/s at 400 GHz over 2 m [5]. Employing direct detection using an SHM, real-time, error-free transmission of 48 Gb/s data has been achieved at 300 GHz, using polarisation multiplexing and OOK [6].

The link budget calculations described in the Introduction show that, unless extremely highly directional antennas are used, THz wireless transmission will be possible (at least in the foreseeable future) over only short distances, a few tens of metres at most. This implies that a large number of small cells would be needed to build a THz wireless mobile communications network, even in a relatively small area, such as a sports stadium. Alternatively, THz wireless might be used within a room, to deliver ultra-high-speed broadband access. Distribution of the high-speed data to the radio access point in each cell or room is likely to be done on optical fibre, and hence photonic generation of the THz-wireless signal directly from the optical signal is very attractive, because of the greatly simplified equipment required at the remote antenna unit (RAU), as illustrated in Fig. 1.

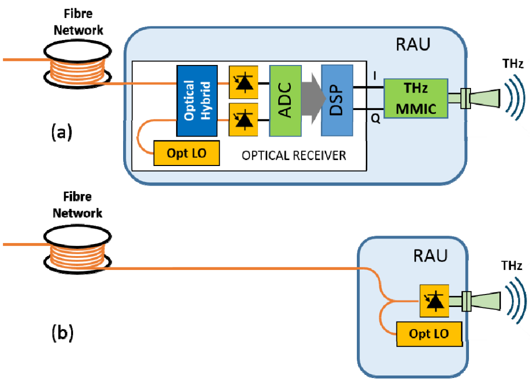

Fig. 1. Conversion of high-speed optical signals to THz signals using (a) optoelectronic detection followed by a THz MMIC upconverter, and (b) photonic heterodyning.

III. Multiband Generation and Distribution

The spectral windows being considered for THz wireless transmission are very wide, for instance IEEE 802.15 TG3d is considering the band from 252 to 325 GHz (i.e. 73 GHz bandwidth) [9]. Even assuming double sideband modulation, a single-carrier signal requiring the whole of this bandwidth is beyond the capabilities of photonic generation using the optoelectronic modulators typically employed in commercial optical communications systems. Furthermore, although a maximum data rate of 100 Gb/s is being discussed [9], it is unlikely that all of the available bandwidth would be dedicated to one user to deliver this data rate. It seems more realistic to assume that the spectrum will be divided into sub-bands to deliver lower rate data (e.g. 10 or 20 Gb/s) to more than one user. Here, we propose a scheme for photonically generating and distributing multiband signals which offers great flexibility in terms of data rate and THz carrier frequency, while maintaining a simple RAU architecture. Our proposal builds on concepts being considered for variable bandwidth transceivers for software defined optical networks [10], and shares elements of optical fronthaul architectures.

The basic scheme is illustrated in Fig. 2. The baseband unit (BBU) includes a number of lasers at different wavelengths which may be reconfigurably connected to a bank of optical modulators through an optical space switch. The modulators may have different maximum baud rate capabilities, being selected to match the required baud rate for each sub-band. The outputs of several of the modulators are combined with one or more CW optical LO lasers (shown as tuneable lasers in Fig. 2) in an optical space / wavelength switch to form a multiband multiplex (as illustrated in the inset of Fig. 2) which is transmitted to a RAU over optical fibre. A passive optical network (PON) could be used to distribute the multiband signals for several RAUs situated close to each other. At the RAU, optical filtering is used to select the sub-band(s) and optical LO required for each antenna at the RAU, and converted to THz signals by heterodyning on a PD. This allows signals to be transmitted on the same or different frequencies from different antennas covering different sectors, or to support MIMO transmission.

The scheme may be extended by replacing the banks of carrier and LO lasers with an optical frequency comb generator (OFCG). This improves the frequency accuracy of the generated THz signals, since the carrier frequency is an integer multiple of the comb line spacing, which is determined by the frequency of the RF oscillator driving the OFCG, rather than being determined by the frequency difference between free-running lasers. In addition, the phase noise of the generated THz carrier is greatly reduced, since the optical comb lines are phase correlated. Although simulations show that digital signal processing (DSP) at the receiver using phase-estimation techniques based on the Viterbi-Viterbi algorithm can be used to track and correct for phase noise in the case of free-running lasers, giving demodulation with low penalty (Fig. 3), the coherent approach based on an OFCG could simplify the DSP, which could be important for low-power real-time systems, as well as ensuring that the carrier frequency is accurately defined.

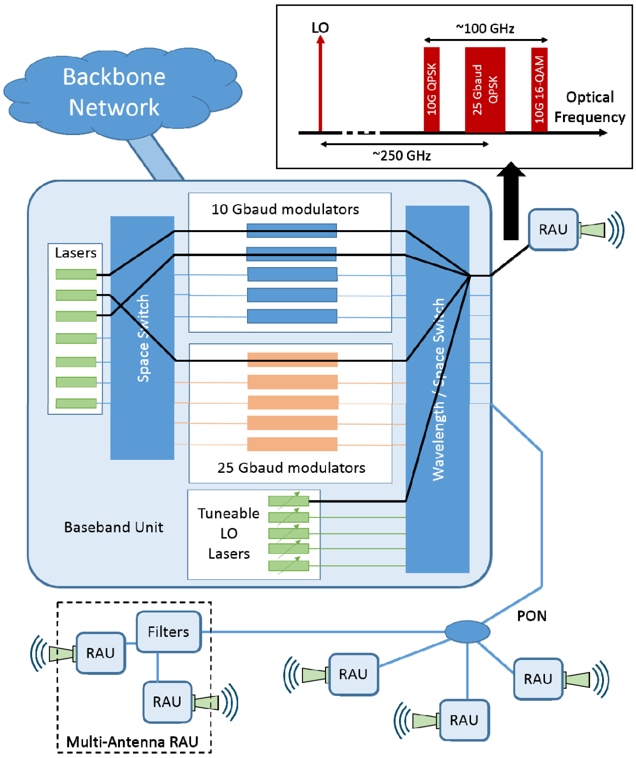

Fig. 2. Schematic of the proposed multiband photonic THz generation scheme. The inset shows the optical spectrum of one of the optical multiband signals that could be generated for distribution to a remote antenna unit (RAU) for conversion to a THz wireless signal.

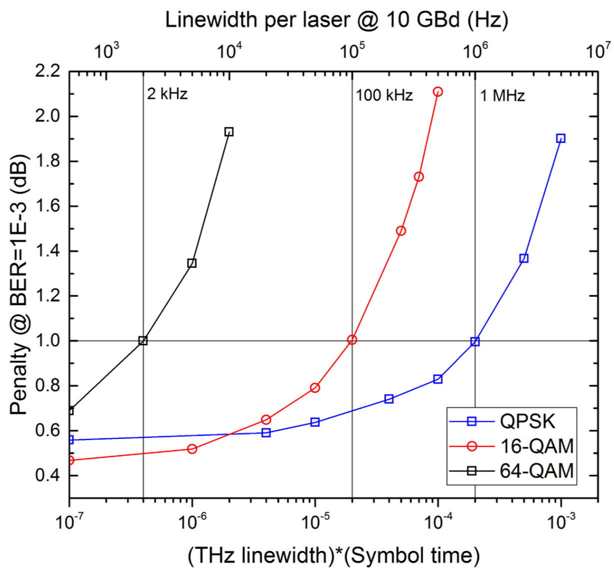

Fig. 3. Penalty as a function of normalised THz linewidth for different modulation formats, obtained by simulation, using an M-th power block algorithm for phase estimation at the receiver.

A drawback of transmitting the LO (or several LOs) from the BBU is that it is wasteful of optical spectrum, with only about half of the optical spectrum being available to transmit data from the BBU to RAUs in the case of 100 GHz multibands and 250 GHz carrier frequency, even if multiplexes for different RAUs are interleaved to improve spectral efficiency. Despite this, up to 20 RAUs, each fed with around 100 Gb/s aggregate data, could be served using a single PON operating in the optical C-band (1530 – 1565 nm).

IV. Experimental Demonstration

We have carried out an experimental demonstration to explore some of the key aspects of the multiband distribution scheme, using the arrangement shown schematically in Fig. 4. In this case a free-running LO laser was placed at the RAU, to allow a scheme for using the LO laser to transmit an upstream signal to the central office to be demonstrated as well [11]. However, we have previously demonstrated photonic THz generation using a line from a comb source, transmitted with the multiband signal, as the LO [7], and the phase coherence of the LO and signal carriers has also been investigated [12].

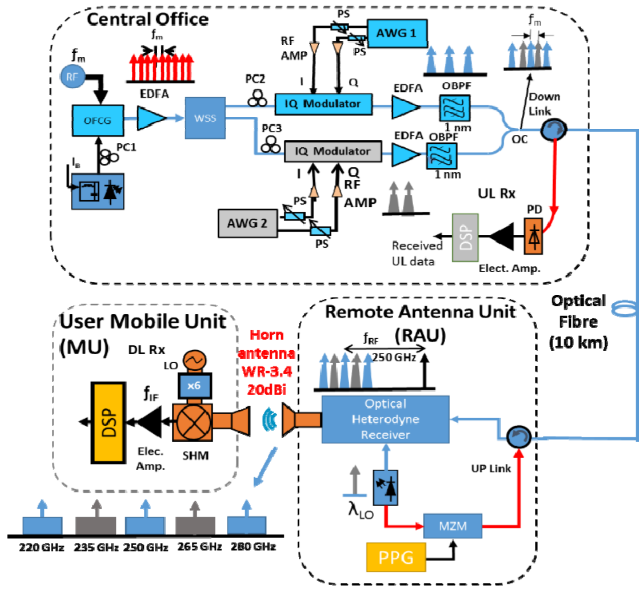

Fig. 4. Arrangement for the experimental demonstration of multiband photonic THz generation.

A narrow-linewidth (10 kHz) laser with wavelength of 1550 nm was used as the seed for the OFCG, which is based on a dual-drive Mach-Zehnder modulator driven at 15 GHz, which sets the comb line spacing. Five lines from the comb were selected and divided into odd and even groups using a programmable optical filter and the groups separately modulated using two IQ optical modulators driven by arbitrary waveform generators (AWGs). Two pseudo-random bit sequences were used to drive each modulator to give 10 Gbaud QPSK modulation (20 Gb/s per sub-band), using root raised cosine (RRC) filters with a roll-off factor of 0.01 to limit the sub-bands to the Nyquist bandwidth (10 GHz). The modulated optical signals were combined and transmitted over 10 km of standard single-mode optical fibre to the RAU.

At the RAU, the optical multiband signal was combined with a tuneable laser (optical LO) with a linewidth of 100 kHz, then amplified and optically filtered to select one of the data sub-bands and the optical LO. A THz signal was generated by heterodyning the filtered signal on a UTC PD and radiated from a 20 dBi WR-3.4 horn antenna. Depending on the sub-band selected, the signal was centred on a frequency of 220, 235, 250, 265, or 280 GHz. The THz signal was received by another 20 dBi WR-3.4 horn antenna and downconverted to an intermediate frequency (IF) of 12 GHz by using a sub-harmonic mixer (SHM) operated with an electrical LO. The IF signal was amplified and digitised using a real-time scope with sampling rate 80 GSample/s and analogue bandwidth of 36 GHz.

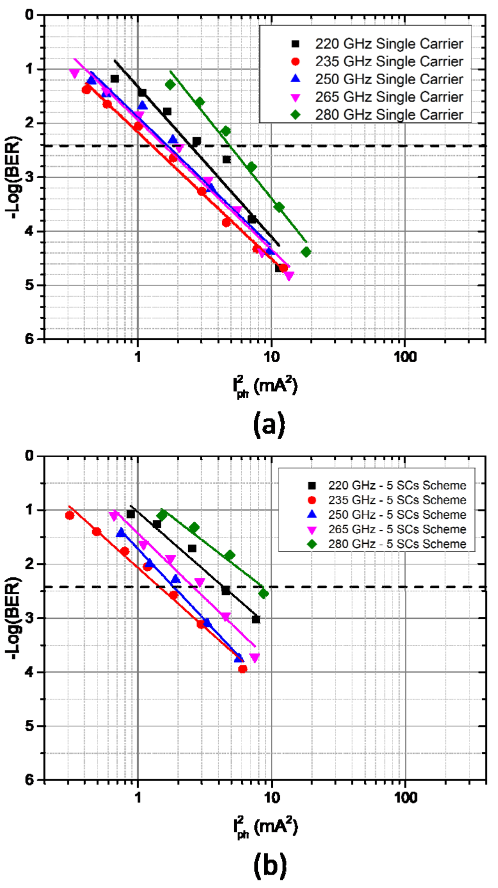

Fig. 5. Measured BER as a function of the photocurrent squared (proportional to THz power) for each sub-band after wireless transmission. In (a) the sub-bands are distributed as a single channel, and in (b) as part of a multiband signal.

The signal was recovered by offline DSP, starting by digital downconversion to baseband using the nominal value of the IF, followed by RRC filtering with 0.01 roll-off factor (to match the transmitter filter). Subsequent DSP steps included channel equalisation, carrier phase estimation, and BER calculation, as described in [13].

The system performance was first determined for each of the sub-bands transmitted over the fibre independently, and then with the multiband transmitted. The results are shown in Fig. 5. The BER is plotted against the square of the photocurrent, which is expected to be proportional to the received THz power for a fixed wireless link length. The single carrier results show some variation with frequency, with the 220 GHz and 280 GHz sub-bands showing penalties of a few dB compared to the other channels. This is due to the 220 GHz channel being close to the lower operating frequency range of the WR-3.4 waveguide, and the UTC frequency response roll-off at 280 GHz. The results for the multiband show a similar trend, but with increased penalty compared to the 235 GHz sub-band, due to the effect of optical filtering at the RAU.

In all cases, the minimum BER measured is well below 10^{-3}, so could be corrected by forward error correction techniques. These measurements were made over a very short link (~2 cm), but by using polymethylpentene lenses at both transmitter and receiver to collimate the THz emission, the transmission distance was increased to 70 cm (limited by the experimental arrangement), with a BER of approximately 2×10^{-5} [11].

V. CONCLUSION

We have proposed a scheme for distributing multiband optical signals to remote antenna units (RAUs) where the optical signals are converted into THz wireless signals by photonic heterodyning on a high-speed photodiode. All the high-speed optoelectronic components for down-stream transmission are sited in a baseband unit remote from the RAUs, allowing resources to be reconfigured according to changing requirements, while keeping the RAUs simple. The scheme gives considerable flexibility in terms of the signal modulation format and baud rate, the number of sub-channels in the multiband, and the THz carrier frequency. Key aspects of the proposed multiband photonic THz generation scheme have been demonstrated by generating a multiband with an aggregate data rate of 100 Gb/s in five sub-bands. The performance of sub-band transmission in the 220 – 280 GHz frequency band has been measured for directional links with lengths up to 70 cm.

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