THz Wireless Communications: 2.5 Gb/s Error-free Transmission at 625 GHz using a Narrow-bandwidth 1 mW THz Source

***Lothar Moeller*[1], *John Federici*[2], *Ke Su*[2]**
[1]Bell Laboratories / Alcatel-Lucent, 791 Holmdel-Keyport Rd, Holmdel, NJ 07733, USA
lothar.moeller@alcatel-lucent.com
[2]New Jersey Institute of Technology, 323 King Boulevard, Newark, NJ 07102, USA
federici@adm.njit.edu, ks265@njit.edu

Abstract

THz wireless communications has established itself as a self-contained research field within THz technology. Following the field's general trend to enhance system transport capacity by increasing the formats' carrier frequencies and payloads, we report a novel scheme for generating a 2.5 Gb/s data signal on a 625 GHz carrier, its transmission over lab distance, and error-free detection. Duobinary baseband modulation on the transmitter side generates a signal with a sufficiently narrow spectral bandwidth to pass an up-converting frequency multiplier chain. Power, bit-error rate (BER), and signal-to-noise ratio (SNR) measurements on the receiver side describe the signal performance.

1. Introduction

Advantages of THz communications have been recognized over the recent years by the research community and a trend in THz signaling to increase carrier frequency, pay load, and transmission distance is noticeable[1]. The rapidly growing interest can be attributed mainly to three intrinsic advantages, which THz communications possess compared to its rivals at shorter infrared (IR) wavelengths and at longer wavelength (millimeter-wave). While generating THz signals is relatively complex they degrade less than IR beams under certain weather conditions. For example, T-rays (around 250 GHz) show several orders of magnitudes smaller attenuation in fog at a visibility of a few hundreds meters compared to IR light. Also scintillation effects caused by local refractions index changes impair T-ray propagation less but limit the reach of IR beam[2,3] based systems. Furthermore, the useable bandwidth of T-rays at a same modulation index is higher than of mm-waves. These advantages become accessible when T-rays reside in the 200-300 GHz band and in the 600-700 GHz band where atmospheric absorption is relatively small. Secure communication is another but currently a less recognized feature of THz communications that could become important in future.

While THz links have been suggested for short distance indoor communications[4], current literature contributions emphasize its potential for long distance point-to-point applications[5]. One reason for this could be its advantages under certain weather conditions but also cost analysis can play a rule. Several approaches for THz communications have been published[1] showing the progress in device design towards higher modulation rates. But to simultaneously obtain high output power and large transmitter bandwidth at high carrier frequency remains in general challenging. Often THz sources are operating in resonance to efficiently generate output power. This reduces their potential as transmitter source twofold: Typically their narrow resonance limits the transmission bandwidth to a few hundreds of MHz and their passbands possess ripples that can cause signal distortion due to group delay variation and amplitude filtering[6].

Our approach takes advantages of a format similar to duobinary modulation - a technique known from wire line and optical communications[7,8] that leads to a narrow signal spectrum - which our frequency multiplier chain based THz source can support. Compared to other transmitter architectures (*e.g.* comprised of THz mixers[9]) our setup seems to have advantages in terms of maximum output power when considering currently commercially available components. On the receiver side, a Schottky diode operated in direct detection mode, converts the THz signal into baseband. This approach is less complex than mixer based receivers. We envision one application of our setup in studying and comparing propagation features of THz links with those of IR links under different weather conditions.

2. High-speed Modulation of a Frequency Multiplier Chain based THz Source

We use a commercially available THz source with about 1 mW output power when operated in a continuous wave (CW) mode. The source consists of 4 cascaded frequency doublers followed by a frequency tripler, all based on biased Schottky diodes, which feed a horn antenna with 2.4 mm aperture (Fig.1). A launched tone within the frequency

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acceptance band between 12.2 GHz and 13.6 GHz saturates the 2W input amplifier at about 5 dBm and gets up-converted into a frequency band between 585 GHz and 653 GHz. The biasing of the Schottky diodes is actively controlled. However, the feedback loop can not counteract amplitude variations by a data modulation due to its bandwidth limitation to the kHz range.

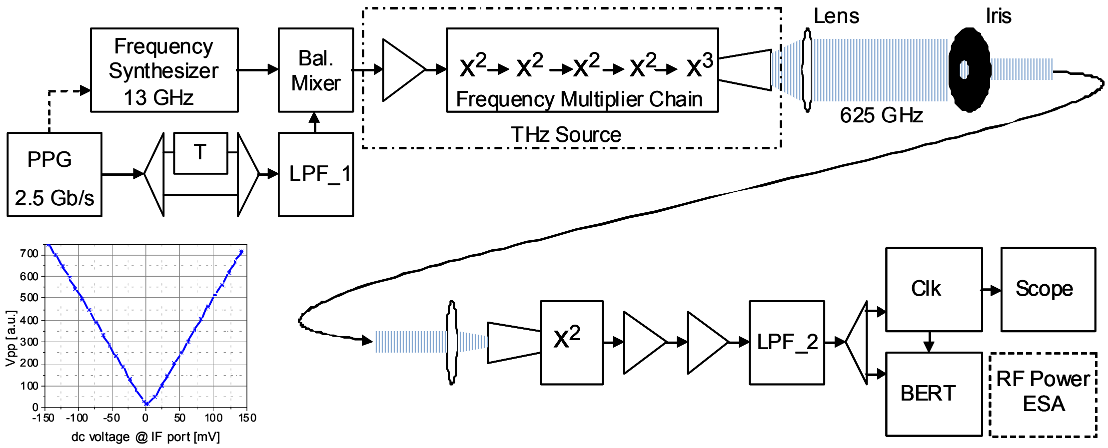

Fig.1: Schematic of THz transmission link and balanced mixer characteristics.

Two identical THz lenses with short focal lengths (~32 mm) allow source beam transmissions over distances of a few meters (beam diameter ~ 20 mm) followed by refocusing of the beam on the receiver side into a horn antenna that is identical to the one used in the transmitter. The receiver horn is connected to a zero biased Schottky diode, which functions in the low power regime (input power <10 µW) as square law detector with large baseband bandwidth and a responsivity of about 2500 V/W. We characterize the “power transfer function” of our system by sweeping the input frequency of the THz source across its acceptance band and record the output voltage of the Schottky diode in the receiver. Fig.2 indicates a passband that is impaired by a ~4dB dip and 1dB ripples. These ripples cause group delay variations across the filter passband and amplitude fluctuations, which together with the limited bandwidth make this source less suitable for signal modulation with a comparable wide spectrum (*e.g.* direct 2.5 Gb/s non-return-to-zero (NRZ)). We indicate in Fig.2 the optimal frequency position of the carrier at 12.933 GHz (corresponding to T-rays frequency at ~625 GHz) where best system performance is achieved.

Pre-coding the data reduces the signal bandwidth but keeps its payload the same. Thus the aforementioned filter impairments affect the signal performance less. Our pulse pattern generator (PPG) produces a 2.5 Gb/s NRZ signal (Fig.2a) that gets split into two branches using a wideband 6dB electrical power splitter. One version is delayed by the duration of a bit (400 ps) before both replicas are combined using another wideband 6dB power splitter. To achieve better impedance matching and reduce reflections at the input of the combining 6dB power splitter, its ports are terminated with two 50 Ohm 10 dB attenuators. The resulting signal (Fig.2b) possesses three amplitude levels (-1, 0, 1) and an advantageous phase coding, which significantly shrinks its bandwidth compared to its corresponding NRZ format. A following quasi Gaussian low pass filter (LPF_1) with about 1700 MHz 3dB-bandwidth reduces further the

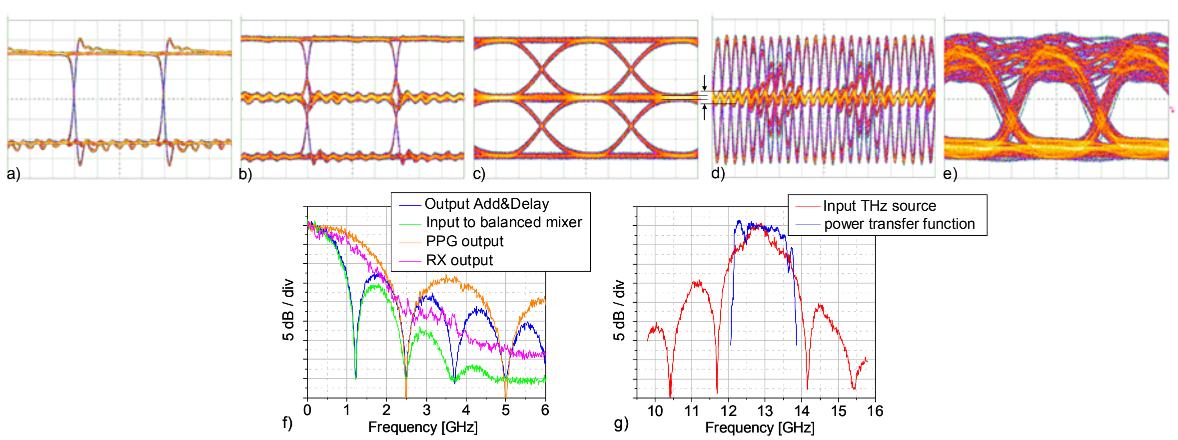

Fig.2: Eye diagrams @ 100 ps /div, a) output PPG, b) output add & delay filter, c) after low pass filter (LPF 1), d) input to THz source (carrier @12.5 GHz), e) output RX LPF, f) corresponding signal spectra and g) power transfer function of setup.

signal spectrum, mainly by cutting off its tail (Fig.2c,f). The almost rectangular NRZ eye at the PPG output and its converted three level version, which is 'smoothed' by the Gaussian filter but without introducing inter-symbol interference (ISI), drive as baseband signal a balanced mixer to imprint its data on a carrier at a frequency accordingly to the acceptance band of the THz source. It is a specific feature of the balanced mixer that negative amplitudes of the driving signal result in a 180 degree phase shift of the carrier. A high-speed scope can conveniently be triggered to visualize the output of the balanced mixer as eye diagram when the product of carrier frequency and bit duration equals an integer. Therefore, we choose for the eye recording a 12.5 GHz carrier frequency, which is close to our operation frequency of 12.933 GHz, where the system best performs (Fig.2d). Both, frequency synthesizer and PPG are coupled to a 10 MHz reference tone to achieve synchronization. The center level of the eye appears to be broadened compared with the mixer input, which can be explained by the small offset of the mixer transfer function at 0 volt input (Fig.1). For dc-voltages in the range of the voltage swing of the launched data signal and applied to the intermediate frequency (IF) port of the mixer we record the amplitude swing of the output signal when a 12.933 GHz tone is connected to the local oscillator port of the mixer. A small offset for applied dc-voltage between -5 mV and +5mV is visible and could explain the un-proportional widening of the '0' level at the mixer output (Fig.2d).

We record the spectrum of the data signal at the THz source input (Fig.2g) for the carrier frequency that gives best system performance. Its center resides at a position within the passband of our system with relatively small filterband tilt and ripples. It has to be further investigated if our source and detector system can support even wider signal spectra by using different modulation formats and perhaps by including signal equalization techniques. We recorded the corresponding eye diagrams and spectra including those of the receiver output (Fig.2e) under ideal measurement conditions (ultra wideband sampling scope, high resolution electrical spectrum analyzer, negligible noise) to visualize signal distortions stemming from bandwidth reduction, system non-linearities, and filter effects.

3. Receiver Design and Performance Analysis of Detected Signal

On the receiver side the output of the Schottky diode is amplified by about 42 dB using two amplifiers (80 kHz - 7 GHz passband, 6dB noise figure, maximum output power ~19dBm) and filtered by a quasi Gaussian lowpass filter (LPF_2) with 3GHz 3dB-bandwidth. A 6dB electrical power splitter launches one output (Vpp~500mV) to a high-speed scope or a Bit Error Rate Tester (BERT) and the other to a 2.5 Gb/s NRZ clock recovery circuit that synchronizes our measurement equipment.

Power decay of the THz beam caused by longer propagation distances in air reduces the signal performance on the receiver side and leads to an increasing BER. In a real system several effects can contribute to such power decrease, however we emulate those by reducing the detected T-ray power with an iris inserted concentrically into the THz beam to limit its effective diameter (Fig.1). The total receiver output power is measured with a RF power meter while we record the corresponding BER with and without threshold optimization (Fig.3). After optimizing the data decision threshold at a BER of about 1x 10^{-3} (BER level that can be reduced to ~1 x 10^{-15} by forward error correction coding with 7% overhead used in lightwave transmission systems[10]) increasing of the detected THz power leads to smaller BER up to 2.5 x 10^{-7} where further power enhancement does not reduce the error count (error floor) for long PRBS (2^{31}-

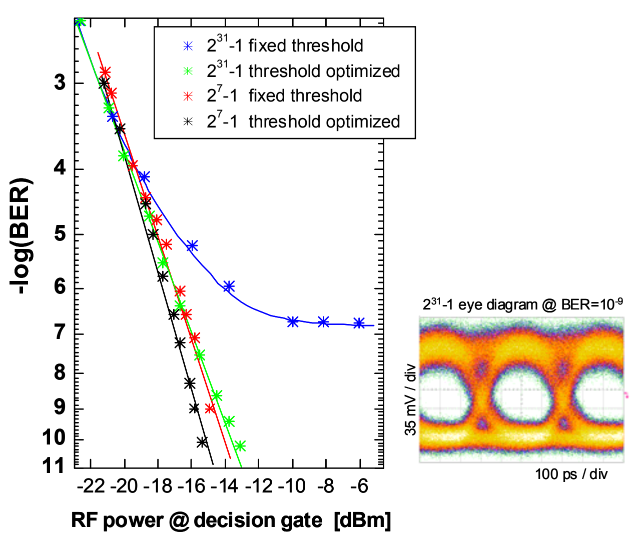

Fig.3: BER curves for long and short PRBSs with and without decision threshold optimization. Eye diagram at decision gate input.

1). In case of threshold adjustment error-free operation is achieved at power levels above -14dBm at same pattern length. We investigated the impact of the PRBS length by performing similar BER measurements with shorter patterns. For this we directly triggered the data decision with the PPG clock in order to avoid artifacts caused by the clock recovery when driven with long PRBSs. Short PRBS do not show error floors as exemplifies with a 2^7-1 pattern in both cases with and without decision threshold adjustment. Reason for this could be saturation effects of the receiver Schottky diode and bandwidth limitations of the receiver amplifiers. The clock recovery did not further degrade the system performance.

Our current detector design based on commercially available Schottky diodes is suboptimal for high-speed signaling. The video resistance of the diodes, under low input power, is nominally ~1.5k Ohm and connected via a series of 50 Ohm transmission lines and cables to an external high-speed electrical amplifier with matched input impedance[11]. For low speed applications and after replacing the amplifier with a high impedance device about -70 mV at the Schottky diode output is detectable. But with 50 Ohms termination of the diode significantly smaller voltage is accessible at the high-speed amplifier input. A rough estimate (applying voltage divider rule 50/1550) shows thus only about 3% of the signal voltage generated in the Schottky diode is applied to the amplifier input. We use this estimate to determine the operation regime of the diode. At the amplifier output RF powers of about -14 dBm for a BER around 1 10^{-9} is typically. Assuming an amplifier gain of about 42 dB, the aforementioned voltage conversion factor of the diode, and a diode responsivity of 2500 V/W yields an effective launched THz power of about 20 µW. This is significantly more than the vendor specs for the linear operation range of the device.

In order to determine the signal-to-noise ratio (SNR) we modulate with a short and periodically repeated PRBS (2^7-1, 2^{15}-1) and measure with a high resolution electrical spectrum analyzer the noise level at the receiver amplifier output. The noise level was found to be about 18 dB above the intrinsic noise floor of the electrical spectrum analyzer (ESA) and independent of the launched THz power. The total receiver noise was measured with a RF power meter to ~-36.4dB. The obtained error rates are in fair agreement with the theoretical amounts expected for bipolar coding if vertical eye closure as visible in Fig.2e is accounted for in the calculation. The internal pre-amp of the used 12.5 Gb/s BERT does not significantly add noise to the data signal.

4. Conclusion

We have demonstrated 2.5 Gb/s error-free transmission at 625 GHz carrier frequency over lab distance using a frequency multiplier chain based THz source as emitter, advanced modulation formats for compressing its spectral bandwidth on the transmitter side, and direct detection by means of a Schottky diode on the receiver side. BER curves as function of measured receiver power are discussed. Our setup has the advantages of combing high output power on the emitter side with a comparable less complex receiver architecture.

5. References

[1] J. Federici and L. Moeller, "Review of terahertz and subterahertz wireless communications," *J. Appl. Phys.* 107, 111101, 2010.

[2] L. C. Andrews, R. L. Phillips, "Laser beam propagation through random media," *SPIE PRESS*, ISBN 0-8194-2787-X, 1998.

[3] L. C. Andrews, R. L. Phillips, C. Y. Hopen, "Laser beam scintillation with applications," *SPIE PRESS*, ISBN 0-8194-4103-1, 2001.

[4] C. Jansen, R. Piesiewicz, D. Mittleman, T. Kürner, M. Koch, "The impact of reflections from stratified building materials on the wave propagation in future indoor terahertz communication systems," *IEEE Trans. Antennas Propag*., vol.56, no.5, pp. 1413-19, '08.

[5] A. Hirata, R. Yamaguchi, T. Kosugi, H. Takahashi, H.; K. Murata, T. Nagatsuma, N. Kukutsu, Y. Kado, N. Iai, S. Okabe, S. Kimura, H. Ikegawa, H.Nishikawa, T. Nakayama, T. Inada, "10-Gbit/s Wireless Link Using InP HEMT MMICs for Generating 120-GHz-Band Millimeter-Wave Signal," *IEEE Trans. Microw. Theory Tech*.,vol.57, no. 5, pp. 1102-1109, 2009.

[6] X. Liu, L.F. Mollenauer, X. Wei, "Impact of group-delay ripple in transmission systems including phase-modulated formats," IEEE Photonics Technology Letters, Vol.16, No.1, pp. 305-307, 2004.

[7] A. Lender, "The duobinary technique for high-speed data transmission," *IEEE Trans. Commun. Electron*. vol. 82, pp. 214-18, 1963.

[8] D. Penninckx, M. Chbat, L. Pierre, J.-P. Thiery, "The phase-shaped binary transmission (PSBT): a new technique to transmit far beyond the chromatic dispersion limit," *IEEE Photonics Technology Letters*, vol.9, no.2, pp. 259-261, 1997.

[9] C. Jastrow, K. Münter, R. Piesiewicz, T. Kürner, M. Koch, T. Kleine-Ostmann, "300 GHz transmission system," *Electron. Lett*, vol.44, no. 3, 2008.

[10] Takashi Mizuochi, "Recent progress in forward error correction and its interplay with transmission impairments," *IEEE J. of Selected Topics in Quantum Electronics*, vol. 12, no.4, pp. 544-54, 2006.

[11] T.W. Crowe, D.W. Porterfield, J.L. Hesler, W.L. Bishop, "Submillimeter-wave and Terahertz Diodes, Components and Subsystems," *Infrared Millimeter Waves and 14th International Conference on Terahertz Electronics*, p. 396, 2006.