# A 1.485-Gbit/s Video Signal Transmission System at Carrier Frequencies of 240 GHz and 300 GHz

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*A 1.485-Gbit/s video signal transmission system at carrier frequencies of 240 GHz and 300 GHz was implemented and demonstrated. The radio frequency front-ends are composed of Schottky barrier diode subharmonic mixers (SHMs), frequency triplers, and diagonal horn antennas for the transmitter and receiver. Amplitude shift keying with an intermediate frequency of 5.94 GHz was utilized as the modulation scheme. A 1.485-Gbit/s video signal with a high-definition serial digital interface format was successfully transmitted over a wireless link distance of 4.2 m and displayed on an HDTV with a transmitted average output power of 20 µW at a 300-GHz system.*

*Keywords: THz communication, video signal transmission, ASK modulator, SHM, heterodyne receiver.*

## I. Introduction

An increasing demand for wireless multimedia transmission services have been seen over the last ten years. To cope with high data rates, higher frequency bandwidths are needed, and higher carrier frequencies above 100 GHz, namely, the THz region, will give rise to very attractive solutions for ultra-wide bandwidths. There have been some promising experimental results on THz communication systems reported [1]-[3]. Furthermore, wide, continuous bandwidths can make related hardware very simple to construct, allowing communication systems that use a lower spectral efficiency below 1 bit/s/Hz, such as amplitude shift keying (ASK) or on/off keying and binary phase shift keying.

Jastrow and others demonstrated a digital video broadcasting transmission system for 1,080p HDTV data over a 52-m indoor wireless link at 300 GHz [1]. They used Schottky diode-based subharmonic mixers (SHMs) and frequency multipliers as radio frequency (RF) front-ends at both transmit and receive chains. The transmitted power was 3.2 µW. Song and others demonstrated 8-Gbit/s wireless data transmission at 250 GHz [3]. They used a photonic transmitter and direct detection receiver. An average transmitted power of 26 µW was implemented using a uni-traveling carrier photo diode with a 7-mA photocurrent, and error-free transmission of over 2 m was achieved. An ASK with an electro-optic modulator was used as the modulation format.

In this letter, we present the experimental results for a 1.485-Gbit/s video transmission system at 240 GHz and 300 GHz using an ASK modulation scheme. A video signal with a resolution of 1,280×720p was successfully transmitted to an HDTV over a distance of 4.2 m at an output power of 20 µW in a 300-GHz system.

## II. H-Band Transmission Systems

Functional block diagrams of an H-band transmission system consisting of a transmitter and two receiver units are shown in Fig. 1. The first receiver has a heterodyne architecture, and the other uses direct detection through a zero bias detector (ZBD) for THz link performance investigation of the receiver.

The RF front-ends of the transmitter and heterodyne receiver, shown in Figs. 1(a) and 1(b), respectively, are composed of H-band Schottky diode SHMs (WR3.4SHM), frequency triplers (WR6.5×3), and diagonal horn antennas (WR3.4), as well as H-band ZBD (WR3.4ZBD), shown in Fig. 1(c), which are commercially available from Virginia Diodes, Inc. To implement carrier frequencies of 240 GHz and 300 GHz in the
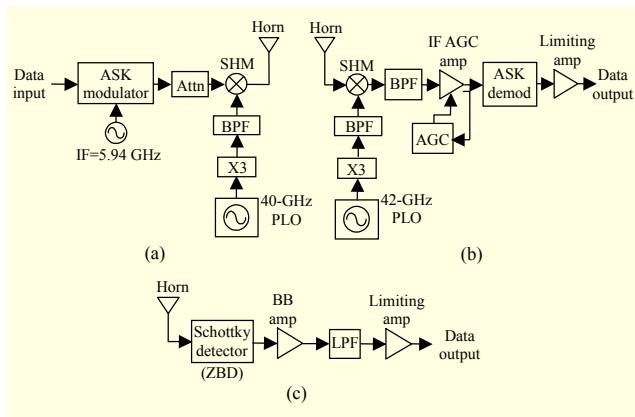
Fig. 1. Block diagrams of (a) transmitter, (b) heterodyne receiver, and (c) direct detection receiver (ZBD) for a 240-GHz system. 50/52-GHz PLO and no LO BPF are used for a 300-GHz system.



Fig. 2. Measured output spectrum of (a) 5.94-GHz ASK modulated signal and (b) 50-GHz PLO module.

H-band, we designed two pairs of phase-locked oscillators (PLOs), 40/42 GHz for a 240-GHz system and 50/52 GHz for a 300-GHz system, for LO chains of the transmitter and receiver, respectively. Since the LO frequency of SHM is half the RF carrier, the 40-GHz PLO in combination with the frequency tripler gives an output frequency of 120 GHz, which generates an RF of 240 GHz. Likewise, the 50-GHz PLO generates an RF of 300 GHz. The LO power of the SHMs is injected from the respective PLO modules via a frequency tripler.

To solve the image problem, we used a different PLO frequency between the transmitter and heterodyne receiver, enabling the double sideband (DSB) operation of SHM. In our design, the intermediate frequencies (IFs) are three times IF apart at the output of the SHM in the receiver, which can easily reject an upper IF using an IF-band pass filter (BPF).

For the transmitter, we designed an ASK modulator with an IF of 5.94 GHz, which is four times the data rate of 1.485 Gbit/s, and a modulation bandwidth of 3 GHz. The ASK demodulator with automatic gain control (AGC) and a baseband amplifier module were designed for the heterodyne and direct detection receivers, respectively. Our transmission system was compactly designed for use with any carrier frequency within the H-band, with only the replacement of PLO modules, and is demonstrated at carrier frequencies of 240 GHz and 300 GHz in this research.

## III. Experimental Results

### 1. ASK Modulator and Demodulator

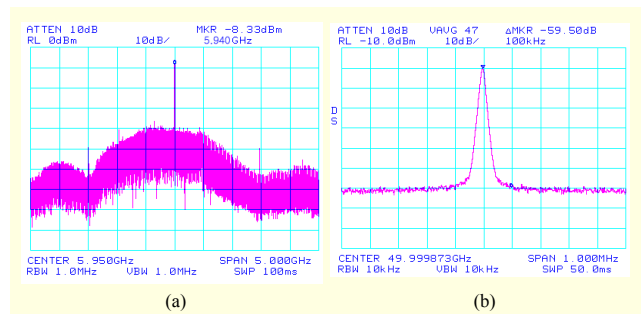The SHMs based on a Schottky diode can be used as frequency up-converting transmitters, even though they were designed as small-signal frequency mixers, primarily for detection. These mixers use an anti-parallel diode pair, where the current voltage (*I-V*) characteristics of the diode pair are symmetric, and thus the on/off data signal for ASK modulation cannot be directly applied to the IF port of the SHM or to the DC bias through the bias-T. Applying modulating signals with a DC component will negate the symmetry operation of the diode pair, which gives rise to a reduction of the input power damage threshold. This means that SHMs for this experiment cannot be used as a direct ASK modulator for the baseband on/off signal. Therefore, to safely interface with the IF port of Schottky diode-based SHMs, the ASK modulator in front of the SHMs must be designed in the IF bands that result in a symmetrical modulated signal with no DC component.

The ASK modulator was composed of a baseband low-pass filter (LPF), a double-balanced mixer (DB-mixer) with 5.94-GHz oscillator (+13 dBm), an IF amplifier, and a BPF in the output. The DC bias voltage of 0.4 V was applied to the IF port of DB-mixer for ASK modulation.

The output power of the ASK modulator was limited to –6 dBm due to the power limitation of the IF input of the H-band SHM. The measured spectrum of the 5.94-GHz ASK modulated signal is shown in Fig. 2(a).

The ASK demodulator was implemented using an envelope detection method in the IF band for the heterodyne receiver.

The measured IF input power range was from –45 dBm to –15 dBm with an AGC of 30 dB and –62 dBm to –25 dBm with no AGC for the heterodyne and direct detection receivers, respectively.

### 2. 40/42-GHz and 50/52-GHz PLO Modules

We designed four kinds of PLO modules for LO power injection of the SHMs via a frequency tripler: 40 GHz, 42 GHz, 50 GHz, and 52 GHz. The optimum power level of the SHMs is 2 mW to 4 mW. The output power of the PLO module was designed taking the power efficiency of the frequency triplers into account, which are 3% to 5% depending upon the input frequencies. For our system, the output power level of the

Table 1. Phase noise characteristics of PLOs.

| PLO module (GHz) | VCO (GHz) | Phase noise (dBc/Hz) @ offset freq. | | | Output power (dBm) |
|---|---|---|---|---|---|
| | | 1 kHz | 10 kHz | 100 kHz | |
| 40 | 2.500 | −70 | −88 | −105 | +20 |
| 42 | 2.625 | −66 | −84 | −96 | +20 |
| 50 | 3.125 | −58 | −87 | −100 | +18 |
| 52 | 3.250 | −57 | −84 | −98 | +18 |

respective PLOs ranged from +18 dBm to +20 dBm. Basically, the outputs of the PLOs were generated by phase-locked loop (PLL) circuits with voltage controlled oscillators (VCOs) using a reference oscillator frequency of 50 MHz, and the output of the VCO is cascaded by blocks of 4×4 frequency multiplication, an amplifier, and a BPF. For a 50-GHz PLO, the frequency of the VCO is set to 3.125 GHz, which gives a 50 GHz output with a multiplication factor of 16. The measured output spectrum of the 50 GHz PLO is shown in Fig. 2(b), including 30 dB attenuation and a cable loss of 8 dB. The phase noise characteristics of the PLOs are also summarized in Table 1. The actual phase noises are calculated by $\Delta$MKR+10 log (1/RBW), where $\Delta$MKR and RBW are reading results of spectrum analyzer.

The phase noises of the frequency triplers can be estimated from a degradation factor of 20 log (3)=9.54 dB. The 120/126-GHz waveguide BPFs for a 240-GHz system were inserted between the output of the tripler and LO input of the SHMs to reduce harmonics from internal power amplifiers of the 40-GHz PLO and 42-GHz PLO modules, respectively. The measured insertion loss of the 120/126-GHz BPF was approximately 1.2 dB within a 5-GHz bandwidth.

## 3. DSB Transmission and Heterodyne Reception

There are two approaches for solving the image problem in a heterodyne receiver. One is using a high-pass filter (HPF) at the transmitter output. An HPF can be designed using the waveguide tapering and transition such as in [4], where the design and manufacturing of such filters are challenging technologies for the THz range. The other is the DSB operation of the transmitter and receiver, as in a typical application within the THz range. In this letter, we implemented the transmission system using the latter method. In a heterodyne receiver, down-converted IF signals with two sidebands can be easily selected by the BPF in the IF bands. Therefore, we used different PLO frequencies in the receiver than in the transmitter, 42 GHz and 52 GHz for 240-GHz and 300-GHz systems, respectively. The
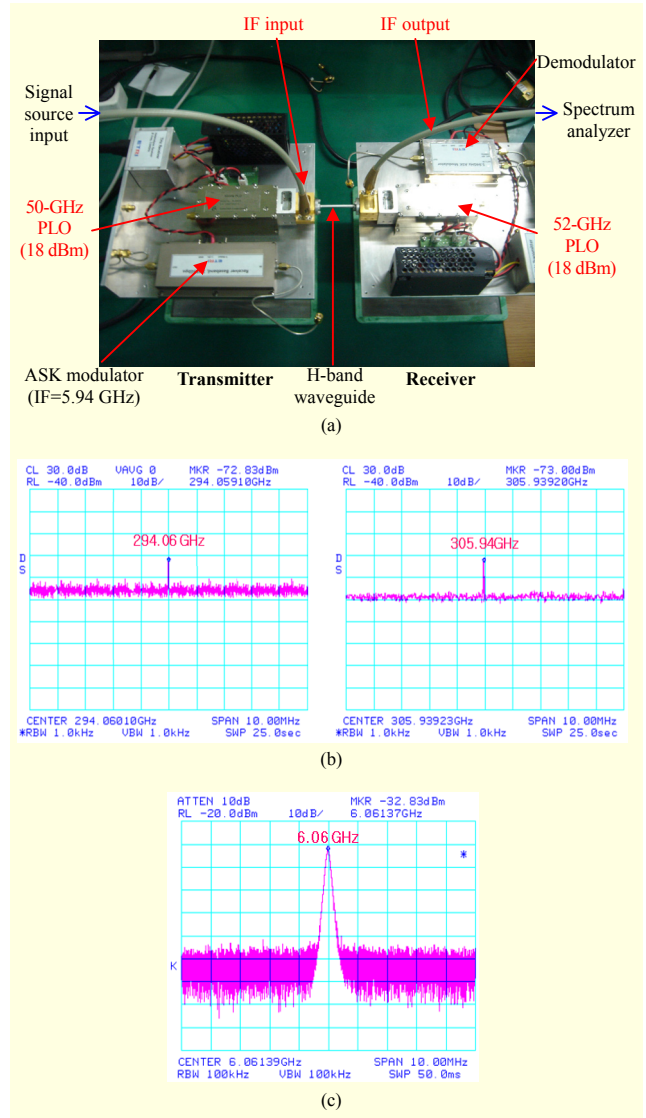


Fig. 3. (a) Measurement setup and measurement of (b) transmitter DSB spectrum and (c) received IF spectrum.

DSB carrier frequencies were measured at the output of the transmitter connected to a spectrum analyzer (Agilent E4440A) through an H-band external harmonic mixer (H03HWD, OML, Inc.) as shown in Fig. 3(a). The calibrated conversion loss of the external mixer at the measured frequencies was approximately 53 dB. Applying a 5.94-GHz continuous wave signal with a power level of −10 dBm to the IF input of the SHM from a signal generator with a disconnecting ASK modulator output, DSB carrier frequencies of 305.94 GHz and 294.06 GHz for a 300-GHz system are as shown in Fig. 3(b). The difference in power levels between the two sidebands is 0.34 dB. A received IF spectrum of 6.06 GHz at the IF output of the SHM is shown in Fig. 3(c). For a direct detection receiver using ZBD, if the power levels of the two sidebands are equal, the responsivity is twice that of a single

sideband carrier.

## 4. Video Signal Transmission

The experimental test setup is shown in Fig. 4. To compensate for the high free-space loss at the chosen transmitted carrier frequencies of 240 GHz and 300 GHz in the H-band, we used a high-density polyethylene lens (HDPE-2-150, Zomega Terahertz, Co.) with a diameter of 5.08 cm and focal length of 15 cm.

To transmit and receive a 1.485-Gbit/s non-return-to-zero video signal, digital visual interface (DVI)-to-HD-SDI and HD-SDI-to-DVI converters were connected to the transmitter input and receiver output sides, respectively. The video



Fig. 4. Experimental setup for video transmission system.

Table 2. Wireless link distances for good video quality reception.

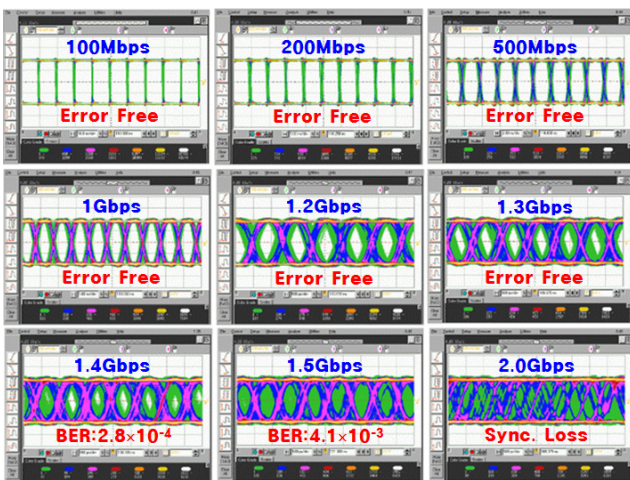| Tx/Rx system | Link distance | | Remark |
| --- | --- | --- | --- |
| | Without lens | With lens | |
| 240 GHz | 50 cm | 4.7 m | 1.485 Gbps |
| 300 GHz | 40 cm | 4.2 m | 1.485 Gbps |
| ZBD (240 GHz) | 3.5 cm | 1.0 m | 268 Mbps (video Tx test)* |

*640×480p video resolution



Fig. 5. Eye-diagrams of ZBD receiver at distance of 3.5 cm (data rates: 100 Mbps to 2.0 Gbps).

resolution was set to 1280×720p at 60 Hz.

The transmitted average output power was –17 dBm (20 μW). The gains of the diagonal horn antennas were 25 dBi with a 3 dB beamwidth of 10°, and HDPE was located between the transmitter and receiver for wireless link budgets.

A 1.485-Gbit/s video signal was successfully transmitted to an HDTV with good video quality over distances of 4.7 m and 50 cm with and without a lens using a heterodyne receiver for a 240-GHz system, respectively. For the ZBD detector, the link distances were 1 m and 3.5 cm with lens and without a lens, respectively. In summary, Table 2 shows the wireless link distances used in our experiments. The video bandwidth of the ZBD was limited to 1.2 Gbit/s due to an internal electro static discharge protection circuit. Figure 5 shows the received eye-diagrams of the ZBD receiver at various data rates for the 240-GHz system experiment. The commercial H-band ZBD has a tangential sensitivity of –44 dBm, a responsivity of 2,500 V/W, and noise equivalent power of 100 pW/Hz$^{1/2}$ from the manufacturer's data sheet.

Video signal transmission experiments at two different carrier frequencies showed similar performances in terms of link distance and conversion loss of the SHMs. The link distance of the 300-GHz transmission was a little shorter than that of the 240-GHz transmission because the free space attenuation at 300 GHz is higher by 2 dB than 240 GHz based on the Friis equation.

## IV. Conclusion

We have demonstrated a video signal transmission system in the H-band using a simple ASK modulation scheme. If the 40/42-GHz PLO modules are replaced with 50/52-GHz PLO modules, a 300-GHz transmission system can be easily configured without hardware modification, and furthermore, the transmitter and receiver can be operated in full range of the H-band. In particular, direct detection using a ZBD can make the communication system very simple and compact since no LO chain modules are required.

## References

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