# A 500 GHz Transmitter/Receiver System for Phase/Magnitude Measurements

Neal R. Erickson

Millitech Corp.
PO Box 109
S. Deerfield, MA 01373

## Abstract

A complete synthesized transmitter and tracking receiver have been built for a frequency of 500 GHz, with a swept bandwidth of >5 GHz. The system uses direct multiplication of a microwave synthesizer, with no intermediate oscillator. Both the transmitter and receiver use the same synthesizer reference, but the transmitter frequency is offset by an upconverter to produce a 3 GHz receiver IF. The receiver reference is derived without the use of a separate receiver channel. With the inclusion of a backend processor, the system is used to make vector reflectivity measurements with high phase and amplitude stability. The transmitter output power is >100 $\mu$W and the receiver noise figure is 15 dB.

## Introduction

Vector measurements are commonly performed using network analysers at microwave and mm–wave frequencies, but become much more difficult in the submillimeter. The highest standard commercial bands end at 110 GHz, while some custom equipment has been built up to 160 GHz [1]. Applications for vector measurements on waveguide networks are few at much higher frequencies, but at these short wavelengths, quasi–optical techniques are widely used. Vector measurement techniques can be of considerable value in characterising dielectric materials and various optical devices, and undoubtedly will find many other uses. One major problem with implementing these measurements has been with source capabilities in the submillimeter, particularly regarding swept bandwidth and power output.

Most higher power submillimeter sources to date have used Gunn oscillators as drivers, which have very limited electronic tuning while maintaining a high output power. These oscillators must be phase locked for this use, which limits the rate of frequency change to that which is within the loop bandwidth. If the frequency steps become too large the lock is broken and the loop must search and recapture which can take several milliseconds. A typical problem with phase locked Gunns is a lack of loop stability at some frequencies related to the varying tuning sensitivity of the oscillator. Aging and temperature drifts compound this problem. A further concern is phase and amplitude stability, since network analyser algorithms to correct for finite directivity or background effects require a constant signal to be effective. Phase jitter in the lock loop and amplitude drifts in the Gunn oscillator with temperature are potential problems.

Receiver sensitivity has been less of an issue, in that very high sensitivity is not normally required for these measurements, but moderate sensitivity is required in systems with weak returns from objects under measurement, particularly if the integration time must be short. Receivers using high harmonic mixers typically are not sufficiently sensitive for this application, and require an LO source with a low (1–3) harmonic number. Receivers also tend to be expensive, and the use of a separate receiver to derive the reference frequency and phase can significantly increase the system cost.

A further complication is with frequency control of the transmitter and receiver LO so that the receiver IF remains at a constant frequency. One method is to use separate synthesizer references for the transmitter and receiver which track each other with an offset so as to maintain a fixed IF. This is expensive, and requires very good synthesizers since the phase noise is increased by the harmonic number $N^2$, and spurious outputs show a similar increase.

The system described here eliminates the need for Gunn oscillators through direct x48 multiplication from a microwave reference frequency up to 500 GHz, and achieves a transmitter output power comparable to that obtained using a fixed frequency Gunn source. The receiver is based on a second harmonic mixer, with its LO also derived from a direct frequency multiplication of the same synthesizer. A frequency difference between the transmitter and receiver is produced by upconversion of the synthesizer output in the transmitter channel by 62.5 MHz, which after multiplication by 48 produces a 3 GHz receiver IF.

The advantage of using the same reference source for both halves of the system, besides a considerable cost saving, is that any source phase noise exactly cancels, so that the overall phase stability is unaffected. This is only strictly true if the coherence length of the synthesizer is greater than any uncompensated signal paths in the system, and for best results may require some equalization of paths. This method also permits the generation of a reference signal for the receiver IF in a particularly simple fashion, without the use of a second channel. The only particular synthesizer requirement is that the true

BB

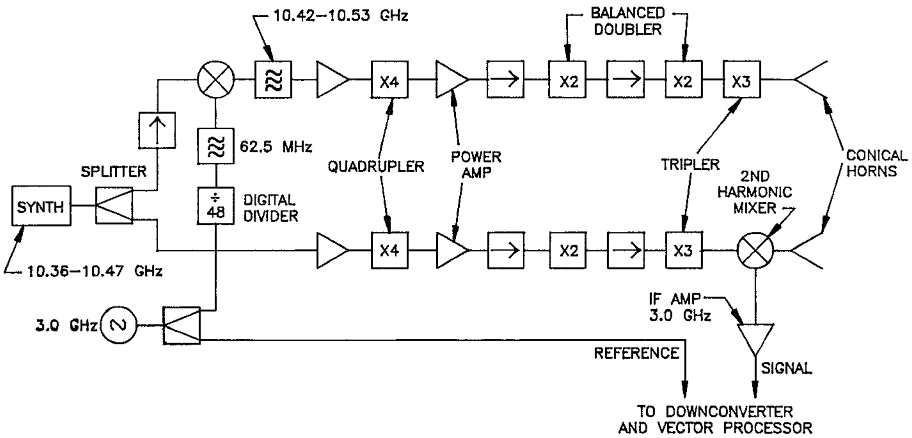


Fig. 1. Block diagram of the complete transmitter/receiver showing the upconversion method used to generate tracking signals, and the simplified method of producing a phase reference.

(submillimeter) measurement linewidth does include the multiplied–up phase noise, which must be within the resolution bandwidth required for the measurements.

The measurement bandwidth is limited largely by hardware bandwidths and spurious signals produced in the upconverter. This application required a swept bandwidth of 5 GHz, but the technique has no inherent limitations to narrow bandwidths, and is capable of substantially more.

**System design**

The system block diagram is shown in Fig. 1. Both the transmitter and receiver use input frequency quadruplers followed by FET power amplifiers in the 41 GHz range. These are followed by passive multipliers up to the final frequency. For the transmitter these consist of a doubler followed by another doubler followed by a tripler. For the receiver these consist of a doubler followed by a tripler which pumps a second harmonic mixer. Critical to the ability to build such a system are the relatively high power amplifiers now available which provide over 200 mW output over a moderate bandwidth near 41 GHz. This is more than enough power to drive a further multiplier chain. Much higher power has been reported from such amplifiers over a wide bandwidth [2].

Of comparable importance is a new doubler design able to utilize the full output power of these amplifiers, and produce the second harmonic with high efficiency. This doubler, used in the transmitter following the power amplifier, is a balanced design using a pair of whisker contacted varactors, with parameters $C_j(0) = 0.12$ pF, $R_s = 3\ \Omega$ and $V_b = 21$ V. This is a design similar in concept to that in ref [3], but is designed to match to the very low impedance levels presented by these diodes. For improved mechanical stability and to facilitate impedance matching at the output, the second harmonic output is coupled to the output waveguide using a quartz filled stripline (rather than coax) followed by a dipole probe into the waveguide. Impedance matching is difficult here because the two diodes are in parallel, but the stripline width is varied in two $\lambda/4$ steps to achieve a good match. To improve the heat sinking of the diodes, the two varactors are mounted on pins connected directly to the waveguide walls, with the contact whiskers connected to the center strip. Input matching is easier because the diodes are in series at this frequency, although the load impedance is well below that of any convenient waveguide.

The optimum input power for this doubler is 180 mW, and the measured efficiency is about 35%, producing up to 60 mW output. Measurements on a second doubler of the same design showed an efficiency of up to 45%. These doublers have a 3 dB bandwidth of over 10 GHz with fixed mechanical tuning. While even higher output power has been reported using ISIS type varactors at comparable frequencies [4,5], the efficiency is much lower due to the use of PN junctions in these diodes (and the higher package parasitics tend to limit the bandwidth), so the whiskered design is still desirable for this type of application. With higher input power, these would become the preferred type of doubler diode.

This doubler is followed by a second balanced doubler nearly identical to that in ref [3], except optimized for a wider bandwidth. To avoid interactions, the first two doublers are separated by an isolator. The input to the second is 48 mW and its output is 9 mW. Since no isolator is available with low loss at the output near 166 GHz, this doubler drives the final tripler directly. To avoid an adverse interaction, a thin waveguide shim was used between them, selected to achieve the maximum power over the band. With the 9 mW input, the output of the final tripler is 0.42 mW maximum for an efficiency of 4.7%. Because the favorable interaction can not be maintained over the bandwidth, the minimum output power was 0.10 mW. This tripler is identical to that of ref [3], except that the efficiency is higher. The previous result showed 3.5% efficiency at 20 mW input, which is well above the predicted optimum input power. The new results may also reflect a higher available source power than 9 mW, which is better coupled into the tripler than into a matched power sensor because the choice of spacers allows it to present close to a conjugate match.

The receiver system uses a conventional single diode doubler for the first stage, since less power is needed, followed by an isolator and a conventional tripler, both optimized for the band of operation. The total output power near 250 GHz is 0.5–1.0 mW. This provides the LO to a harmonic mixer nearly identical to that of ref [6]. This type of mixer offers no rejection of AM noise on the LO source, since only a single diode is used. The power amplifier in the LO chain has the potential to add considerable noise, due to its high input noise figure and gain, but the overall system noise is not seriously affected. This is most likely due to the narrow bandwidth of the amplifier which is considerably less than the receiver IF. The mixer IF output at 3 GHz is amplified with a 0.9 dB NF amplifier with 45 dB gain. The overall receiver noise figure is about 15 dB across the band.

The bias and mechanical tuning of all the multipliers and mixers is fixed so that the system may be operated on a regular basis without any need to periodically tune–up the system. This makes the system equivalent to a conventional microwave analyser from a user's point of view, since no interaction with the hardware is required except at the test ports.

The reference system is designed to avoid potential for leakage into the receiver IF, to maintain the widest possible dynamic range. Because the upconverter produces some significant spurious content, it is used in the transmitter chain, leaving a spectrally pure signal for the receiver LO. The simplicity of the system design requires only one connection between the transmitter and receiver module, which is at a frequency where an isolator can provide excellent isolation. A 3 GHz oscillator with its own crystal standard drives a digital divide–by–48 network to produce the 62.5 MHz reference for the upconverter. An important feature of this system is that this oscillator also provides the reference phase for the receiver IF output, since it is exactly phase coherent with the x48 multiplied output. This eliminates the need for a separate submillimeter mixer to produce the reference, which greatly reduces the cost, and has the additional advantage that the reference signal is spectrally pure with an excellent signal to noise ratio. It has been found that deriving the reference in this manner has little impact on the phase stability, since the multiplier chains show very low phase drift.

The upconverter (in USB) was tuned to produce the least possible spurious output, both in carrier feedthrough and LSB output, both being about 35 dB down. However, the x48 multiplication is equivalent to a phase noise increase of 33.6 dB, and so this is not sufficient for their contribution to be small. Additional spurious outputs of the upconverter at multiples of the 62.5 MHz offset were even stronger. The upconverter was followed by a filter to reduce the contribution of these signals, but since some are actually in–band they could not be fully eliminated. None actually fall within the narrow receiver IF bandwidth, so they are not directly observable. However the number of spurious signals results in an output spectrum resembling a comb, with several tones of comparable amplitude. This reduces the transmitter power in the carrier by several dB, but has no other adverse consequences to the measurements (assuming that the materials being measured show linear behavior).

To increase the useful bandwidth and effective output power, a better upconverter has been devised based on an upconversion process in both the transmitter and receiver with a higher offset frequency, as shown in Fig. 2. This system produces no in–band spurious signals, up to

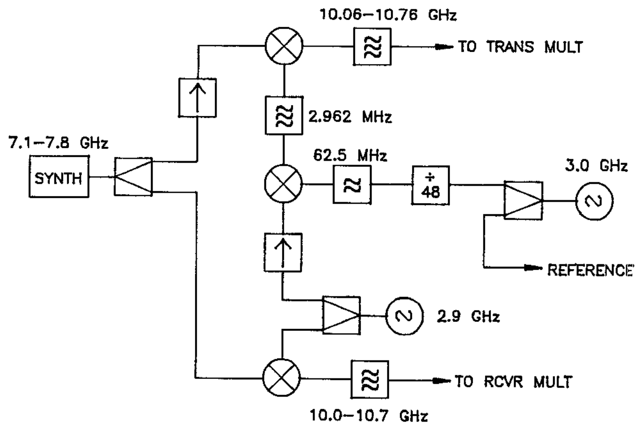


Fig. 2. Block diagram of an improved frequency upconverter to reduce the spurious content in the transmitter output. Ideally the 3.0 GHz reference oscillator should be increased in frequency to better avoid the receiver spurious signal due to the 2.9 GHz oscillator.

rather high order mixing products, and permits the filtering of the outputs for the near band spurious signals. This improved reference system should allow coverage of a very wide band (~30 GHz) with minimal spurious signals, although the fixed tuned bandwidth of existing submillimeter hardware is less than this at present.

To cover a bandwidth the equivalent of a full waveguide band, it is better to use comparable input frequencies but to downconvert in the mixer. This approach would be of use at lower frequencies where the hardware can cover such bandwidths. Downconversion causes most of the strong spurious products to end up well above the band of interest, while the lower frequency products can be made to fall to either side of the band. However the price is a more stringent specification on synthesizer stability, since the converter output frequency is about half the value achieved using upconversion.

## Applications

This system is designed to make quasi–optical reflectivity measurements, so the transmitter and receiver use feed horns to couple to the objects under test. The system is sufficiently stable in phase to permit a full vector calibration, with the usual error reduction and background subtraction. Phase drift is about 3° per hour in a normal laboratory environment, while amplitude drift is about 2% per hour. It is notable that these numbers were obtained with the halves of the system in a transmission measurement mode resting on a wooden bench top separated by about 3 ft, and much of the variation is likely to be due to thermal expansion of the wood and variation in the ambient humidity. The dynamic range of the system is well over 60 dB, and is determined in large part by the signal processing and the typical power return.

The approach to the system permits additional features. As mentioned above, substantially wider bandwidths may be covered. It is also possible to introduce either phase or pulse modulation by breaking the 10 GHz signal before the transmitter and adding a modulator. Pulses will propagate with little change through the transmitter system due to the bandwidth of the components. Amplitude modulation is not possible because the system is not linear, and in fact the mm amplifiers are operated in saturation. Frequency step or sweep rates are limited only by the bandwidth of the backend processor and the sweep speed of the reference source. The frequency range of application is not limited to the submillimeter, and in fact becomes much easier at lower frequencies. A network analyser in the 200 GHz range would be quite straightforward, although at present only about half of a waveguide band could be covered in a single sweep.

While the present system was designed for use with a custom backend processor, it appears that this technique could be made to work with a standard commercial detector/processor such as the HP–8510. This would greatly reduce the amount of work required for the downconversion and detection and would utilize the available software.

## Conclusions

A vector analyser has been built for 500 GHz which is highly phase and amplitude stable, permitting the full range of enhanced directivity calibrations. Ease of use and reliability are such that the user can regard the equipment much like any other microwave test equipment. This is believed to be the highest frequency at which such an analyser has been built. The approach is suitable for application in the mm–wave bands as well.

## References


[1] J. Steimel Jr. and J. East, "D–Band Vector Network Analyser," *Proceedings, Second Int. Symp. on Space THz Technology*, 1991, pp. 573–584.

[2] C. Creamer, P. Chye and B. Sinclair, "43.5–45.5 GHz Active Times–4 Frequency Multiplier with 1.4 Watt Output Power," *1991 IEEE MTT–S Int. Microwave Symp. Digest*, pp. 939–942.

[3] N. Erickson, "High Efficiency Submillimeter Frequency Multipliers," *1990 IEEE MTT–S Int. Microwave Symp. Digest*, pp. 1301–1304.

[4] J.F. Cushman, F. Occhiuti, E.M. McDonagh, M.E. Hines and P.W. Staecker, "High Power Epitaxially–Stacked Varactor Diode Multipliers: Performance and Applications in W–Band," *1990 IEEE MTT–S Int. Microwave Symp. Digest*, pp. 923–926.

[5] Steinbrecher Corp. product description for model VFD–9400 (94 GHz doubler).

[6] N.R. Erickson, "Low Noise 500–700 GHz Receivers Using Single Diode Harmonic Mixers," *Proceedings, First Int. Symp. on Space THz Technology*, 1990, pp. 399–408.