Development Status of a 420-1980 GHz Vector Network Analyzer for Time-Domain Reflectometry and Imaging Applications

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Abstract—With recent progress in the area of electronically tunable solid-state sources it is possible to fully extend microwave measurement techniques into the THz frequency range. In this paper we present the development status of a 420-1980 GHz Vector Network Analyzer and illustrate how phase-sensitive heterodyne techniques can be used in the area of THz reflectometry and imaging.

Index Terms—THz, submillimeter-wave, heterodyne, phase-sensitive, reflectometry, imaging, vector network analyzer.

I. INTRODUCTION

Over the last decades considerable interest for THz instrumentation with applications ranging from industry to biology has developed. With recent progress in the area of electronically tunable solid-state sources, providing high output power over large bandwidth, the possibility opens up to fully extend radio and microwave measurement techniques into the THz frequency range. Now sensitivity and bandwidth are no longer limiting factors phase-sensitive heterodyne techniques such as vector network analysis, transmission and reflection spectroscopy at arbitrary frequency resolution, near-field antenna measurements, time-domain reflectometry, FMCW radar and even spectroscopic imaging at THz frequencies appear entirely feasible.

In this paper we present the development status of a 420-1980 GHz submillimeter-wave vector network analyzer potentially offering measurement capability as referred to above. We present first results obtained for the 720-830 GHz subband, for which we demonstrate over 80 dB signal-to-noise ratio and more than 100 GHz RF bandwidth at room temperature conditions. Making use of the capability of direct phase measurement of the reflected field we provide some illustrative examples of how this system can be used for very sensitive millimeter range reflectometry, coarse absolute and accurate relative metrology as well as spectroscopic two-dimensional and monochromatic three-dimensional imaging within a single measurement system.

II. DESCRIPTION OF MEASUREMENT SYSTEM

A. System Concept

The 420-1980 GHz Vector Network Analyzer is based on transceiver modules composed of a harmonic generator and a subharmonic mixer[1]. Each module operates at a specific harmonic of a fundamental driver source. The drivers are CW sources (multiplied up from Ku-band synthesizers) operating in the 70-110 GHz or 160-220 GHz band providing sufficient output power to pump a Schottky diode or superlattice device[2] used as a transmitter or subharmonic mixer. The entire frequency range is spanned by (partially overlapping) subbands with harmonic numbers 6, 8, 9 and 10 for the 70-110 GHz driver and harmonic numbers 3, 4, 5, 6, 8 and 9 for the 160-220 GHz driver source. Up to frequencies of 1100 GHz we use both Schottky and superlattice devices. Beyond 1100 GHz and up to 1980 GHz we plan to use superlattice devices. In each subband the number of output harmonics are limited by a waveguide high-pass filter section and a feedhorn which are mounted on both the transmitter and mixer. The driver sources are offset such that the IF frequency of the mixer is at 3 GHz. The IF signal passes through a low-noise amplifier, a narrow-band IF filter and is finally processed by a Vector Network Analyzer. The reference signal for the VNA is obtained by mixing the two fundamental Ku-band synthesizer signals and multiplying the difference signal by the same harmonic number as applicable to the transmitter and mixer. We finally measure the system signal in phase and amplitude in narrow-band detection using the standard functionality offered by a VNA. An equivalent functional block diagram applicable to this system is provided in [3].
B. The 720-830 GHz Reflectometer Configuration

In this paper we present first results for the 720-830 GHz subband (harmonic number 4, 180.0-207.5 GHz driver). We mount the harmonic generator and mixer in compact reflectometer modules comprising an off-axis elliptical mirror and an optional folding mirror collimating the F/4.25 beam emerging from the feedhorns. The reflectometer is based on a classical Michelson arrangement where one arm forms the test port and the other provides a beam dump. We use a 40 μm Kapton beamsplitter. All components are mounted on an optical baseplate which is mounted on a XYZ mechanical scanner. For near-field applications we mount a f = 38 mm HDPE lens in front of the test port. The reflectometer configuration is shown in Fig. 1.

![Reflectometer configuration](image)

**Fig. 1.** Reflectometer configuration of the 720-830 GHz subband mounted on a XYZ scanner.

III. MEASUREMENT EXAMPLES

A. Time-Domain Reflectometry and Metrology

As an example we show the optical pathlength stability measurement of the Local Oscillator path of a submillimeter-wave heterodyne receiver (HIFI). In this case the LO is mounted inside a cryostat and cooled by means of a closed-cycle refrigerator. The vibrations of the cryo-cooler induce optical pathlength changes which limit receiver stability. Since the LO horn is not visible from outside, hidden behind opaque windows and THz optical components, measurement of the phase of the reflected wave directly translates in optical pathlength knowledge. We first carry out a 110 GHz full frequency sweep, calibrate the reflectometer relative to a mirror and load in front of the system and determine the distances (within 1.5 mm) of reflecting objects along the optical path by Fourier-Transforming the calibrated frequency response into the time domain (TDR). We next measure in the time-domain the phase of the reflected wave and subtract out unwanted reflections by frequency-switching at the appropriate throw. The results are shown in Fig. 2. At the top of the figure a mechanical resonance inside the cryostat is revealed by a gentle knock on the cryostat. The central and bottom plots show the closed-cycle cooler vibration level of about ± 2μm. We achieve a measurement accuracy of about 0.5μm.

![Pathlength stability measurement](image)

**Fig. 2.** Measurement of optical pathlength instability due to a cryocooler.

B. Imaging

The imaging capability of the system is illustrated in Fig. 3. In the upper-right corner the optical image of a test object is shown. The test object is an absorbing aperture with a circular Al flange. Immediately behind the aperture we put a piece of Al tape. We block the entire test object by a 4 mm slab of HDPE. During the measurement we put a piece of Eccosorb in the background. The upper-left image shows the THz image taken at 780 GHz. Clearly visible are the shiny surfaces. In the bottom-left image the object is shown on a dB scale, the SNR is about 60 dB. Note that the weak reflection from the dielectric slab of HDPE is now visible. We finally show the phase-image in the bottom-right figure. The contours of the dielectric slab are clearly visible. Note the phase discontinuity near the edges of the label on the clamp explaining the edge contrast seen in the THz intensity images.

![THz images](image)

**Fig. 3.** THz images of an absorbing aperture behind a HDPE dielectric slab.

REFERENCES