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W-band vector network analyzer based on an audio lock-in amplifier*

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Abstract

The design and calibration of a W-band network analyzer is described. This analyzer was constructed from general purpose RF components wherever possible and uses an audio frequency lock-in amplifier as the phase and amplitude detector. S-matrix and non-resonant perturbation measurements are shown as illustrations of the analyzer capabilities

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Introduction

Interest in short wavelength, RF based accelerators has been stimulated by advances in micromachining and by the poterntial of high gradient because of the wavelength dependences of dark current capture and RF breakdown.[1] Development of these accelerators depends critically on an iterative process of design, fabrication, inspection, and RF characterization. This paper describes a vector network analyzer built for the RF characterization.

A frequency of ~ 90 GHz, in the middle of W-band that extends from 75 to 110 GHz, was chosen for two reasons:

i) the eighth harmonic of the Next Linear Collider (NLC) frequency, 11.424 GHz, is in that region, and a 91.392 GHz structure could be driven subharmonically by beams available at SLAC;

ii) There is military interest in 94 GHz where there is a transmission window in air, and as a result components are available near that frequency.

Hewlett Packard sells W-band vector network analyers, the E7350A and the 85106D with 85104A test set modules, but the costs are high for the early stages of a speculative research program. It was decided to build a vector network analyzer using general purpose RF components wherever possible to take advantage of available equipment or, when purchasing was necessary, to buy equipment with a variety of potential uses.

Network Analyzer Description

Figure 1 is a schematic of the network analyzer, and component information is given in Table I. W-band RF is generated by a five times frequency multiplier with a frequency range of 75 Ghz to 100 GHz. Input power is 10 to 20 dbm and output power is in the -10 to 0 dbm range with a conversion efficiency that is frequency dependent. The multiplier is driven by a GPIB controlled synthesizer with 1 kHz resolution and provision for external leveling. A microwave power amplifier is used to input adequate power to the multiplier. A circulator is placed on the output of the frequency multiplier to isolate it from the downstream load.

The reference, forward power is monitored through a 20 db coupler with a specified coupling flatness of 0.7 db and a minimum directivity of 40 db. A second, signal coupler can be connected to measure either transmitted or reflected power. Figure 1 shows it connected to make S_{11} measurements. This coupler has a coupling of 20 db with a flatness of 0.7 db and a minimum directivity of 30 db. The coupled outputs are connected to harmonic mixers with an internal frequency multiplication of eighteen times and a conversion loss of approximately 47 db. These mixers are intended as external mixers for spectrum analyzers with 310.7 MHz intermediate frequency (IF), but they have an IF bandwidth extending from dc to 1.3 GHz.

There are two local oscillators (LO's) in the system. The first runs at approximately 5 GHz and with 18 dbm power. The output power is divided and then sent to the harmonic mixers after passing through isolators that are necessary to prevent IF crosstalk through the LO lines. The synthesizer used for this local oscillator has a minimum frequency step of 1 kHz, and it is adjusted to make the IF frequency f_{IF} = 835.218 MHz as the W-band frequency is varied. Given the source and mixer frequency multiplications and the minimum frequency steps of the source and LO synthesizers, the minimum W-band frequency step is Δf_W = 90 kHz which is a small fraction of the width of cavity resonances with typical Q's of 2000 or less.

The mixer IF ouputs are amplified with low noise (Noise Figure = 0.9 db max), narrowband (824 to 849 MHz), 40 ± 1 db gain amplifiers. The outputs of these amplifiers are mixed with an 835.200 MHz LO generated by a phase locked loop. The W-band source synthesizer, the 5 GHz LO synthesizer and this phase locked loop have a common 10 MHz reference taken from the W-band source synthesizer. The outputs of the second stages of mixing are filtered with 1.9 MHz low pass filters, and the resultant 18 kHz signals are processed.

The reference arm is amplified by an amplifier with a gain of 34 db and a bandpass of 3 to 30 kHz. The output of that amplifier is:

i) Read by a true RMS digital voltmeter;

ii) Measured with a true-RMS integrated circuit with a logarithmic output that is used to level the W-band source power;

iii) Used as the reference input of a lock-in amplifier.

The signal arm is connected to the signal of a DSP lock-in amplifier which measures the amplitude and phase of the signal that is synchronous with the reference input. Major advantages of the lock-in amplifier are the high sensitivity and the control of the properties of the filtering of the measured outputs. Typically this filter is set with a 24 db/octave roll-off and an 100 msec time constant.

Calibration

Amplitude calibrations are performed using a power meter as the reference. Linearity at a fixed frequency is shown in Figure 2 which covers a power range from the minimum measurable power to the maximum source power.

Reference and signal arm voltages are related to power by

$$\mathrm{Voltage(dbV)} = \mathrm{Power(dbm)} + \mathrm{Intercept}$$

where the intercepts are functions of frequency. The reference arm intercept is measured by connecting the power meter directly to the reference arm coupler. The signal arm intercept is measured by connecting the power meter to the signal arm coupler with a 1 inch long WR10 waveguide that is necessary because of the mounting flanges of the coupler and power meter. The waveguide attenuation is measured by connecting the power meter to the reference arm with this piece of waveguide and comparing the result with that obtained without the waveguide.

The frequency dependences of the intercepts are shown in Figure 3a. They vary by about 1 db over a frequency range of 85 - 96 Ghz. Figure 3b shows the differences between the intercepts measured in July, 1998 and those measured a year before. The RMS differences in the intercepts are less than 0.1 db, although the signal arm intercept had a shift in the mean value of 0.33 db. We conclude that calibrations should be performed before making measurements requiring better than ~0.4 db absolute or 0.1 db relative variation with frequency.

The manufacturer provides conversion loss data for the harmonic mixers. These are not in good agreement with the measurements in Figure 3. Possible explanations are that our measurements include the directional couplers and contain any deviation from constant coupling, and that they are at an IF frequency of 835.2 MHz rather than 310.7 MHz where the mixers are calibrated and normally used.

The actual and measured phases between the signal and reference arms, θ_A and θ_M respectively, are related by a phase offset, $\Delta\theta$ that depends on the frequency

$$\theta_M(f) = \theta_A(f) + \Delta\theta(f)\,.$$

The phase offset is measured by connecting different lengths of WR10 waveguide between the couplers and measuring phase versus frequency. For a length L of waveguide the actual phase depends on two unknown parameters, L_0 and θ_0 which are the path length in the couplers and a constant, frequency independent offset,

$$\theta_A(f) = \theta_0 - 360^{\mathrm{o}}\frac{(L + L_0)f}{c}\sqrt{1-(f_c/f)^2}$$

where f_c = 59 GHz is the cutoff frequency and c is the speed of light. A least squares fit to a frequency scan can be used to determine L_0 and θ_0 , and the residual of the fit is $\Delta\theta(f)$.

Measurements are performed for three different values of L, and reasonable agreement on the fit values for L_0 provides a cross check. Figure 4 shows the results of two phase calibrations performed at two different signal arm power levels. The reference arm power was at its usual value of - 10 dbm for both measurements, and an attenuator was used to reduce the signal arm power for the results in Figure 4b. The agreement between these two measurements is excellent demonstrating that the phase offset does not depend on the signal arm power. This method of calibration has been developed recently and is a substantial improvement over the previous method, so there is no information about the long term temporal stability of this calibration.

Sample Results

This network analyzer is being used for a variety of measurements and has been central to the development of W-band accelerating structures. Two illustrative measurements are discussed in this section.

A seven-cell traveling wave structure was fabricated by electrodischarge machining.[2,3] Masurements of $|S_{11}|$ and $|S_{12}|$ are shown in Figure 5a. These measurements are corrected for losses in the waveguides attaching the structure to the network analyzer. Above and below the passband $|S_{11}| \approx 0.96$, or there is 0.35 db of loss. There are waveguide transitions that are part of the structure, and separate measurements show that they can account for about 0.2 db of that loss.

One half of the power is transmitted in the passband. Figure 5b shows that roughly 40% of the power is lost as compared to less than 10% expected for this structure. We have concluded that this is due to the structure being clamped rather than brazed or diffusion bonded. The design was modified to allow diffusion bonding, and measurements of this new structure are beginning.

The fields of this structure were perturbed by a 20 μm diameter nylon fiber oriented perpendicular to the beam direction. (This was possible because a narrow slot cut in that direction is cutoff and does not affect the fields.) The fiber was translated using a positioning stage with sub-micron accuracy, and S_{11} was measured with the network analyzer. The measurements are shown in Figure 6. These data can be analyzed to determine the phase shift per cell and field uniformity.[4] The change in S_{11} depends on the position of the perturbation, z, the structure period, d, and the phase advance per cell, $\Delta\varphi$,

$$\Delta S_{11}(z) = \exp\left[j\left(\varphi_0 - 2\Delta\varphi\frac{z}{d}\right)\right]\sum_{p=-\infty}^{\infty} F_p \exp\left[-j\left(2\pi p\frac{z}{d} + \varphi_p\right)\right].$$

For this particular mode and for this position of the perturbation the phase shift per cell is 66.2º and the field is dominated by space harmonics with p =0, +1, -1. Measurements similar to this are being used to study machining precision and field profiles.

Acknowledgements

The W-band network analyzer development had important contributions from P. J. Chou, A. Menegat and D. Pritzkau. This work was support by U. S. Department of Energy, contract DE-AC03-76SF00515.

Table I: Manufacturers and Model Numbers for Network Analyzer Components and Associated Apparatus

Component	Manufacturer	Model Number
W-Band Power Source		
Synthesizer	Hewlett Packard	8653D
Power Amplifier	Hewlett Packard	8349B
Frequency Multiplier	Hewlett Packard	85100W*
Circulator	NW Solid State mm-wave Products	45166H-1000**
W-Band Couplers and Mixers		
Forward Power (Reference) Coupler	Hughes	45326H-1120**
Signal Coupler	Hughes	45326H-1320**
W-band mixers	Hewlett Packard	11970W
5 GHz Local Oscillator		
Synthesizer	Hewlett Packard	83620A
Power Splitter	NARDA	3324-2
Isolator	TRAK	60A6001
835 MHz Circuit		
Amplifiers	Q-Bit	QBS-135
LO Phase Locked Loop	EM Research	SLS-849-ER-01
Power Splitter	Pulsar	P2-10-414
Mixers	Pulsar	X2L-06-414
Audio Signal Components		
1.9 MHz low pass filters	Mini Circuits	SLP 1.9
Amplifier	Stanford Research Systems	SR560
Lock-in Amplifier	Stanford Research Systems	SR830
RMS Voltmeter	Hewlett Packard	3457A
RMS circuit for W-band power leveling	Analog Devices	AD637
W-Band Power Measurements		
Power Meter	Hewlett Packard	437B
Power Meter Sensor	Hewlett Packard	W8486A
Translation Stage for Field Perturbation		
Translation Stage	Newport	UTM100CC.100
Control and Readout		
Software	National Instruments	LabView
Data Bus	Misc.	GPIB

* The 85100W has been replaced by the 83558A which is a six times multiplier and has a frequency range of 75 to 110 GHz.

** Obsolete; purchased from used equipment supplier.

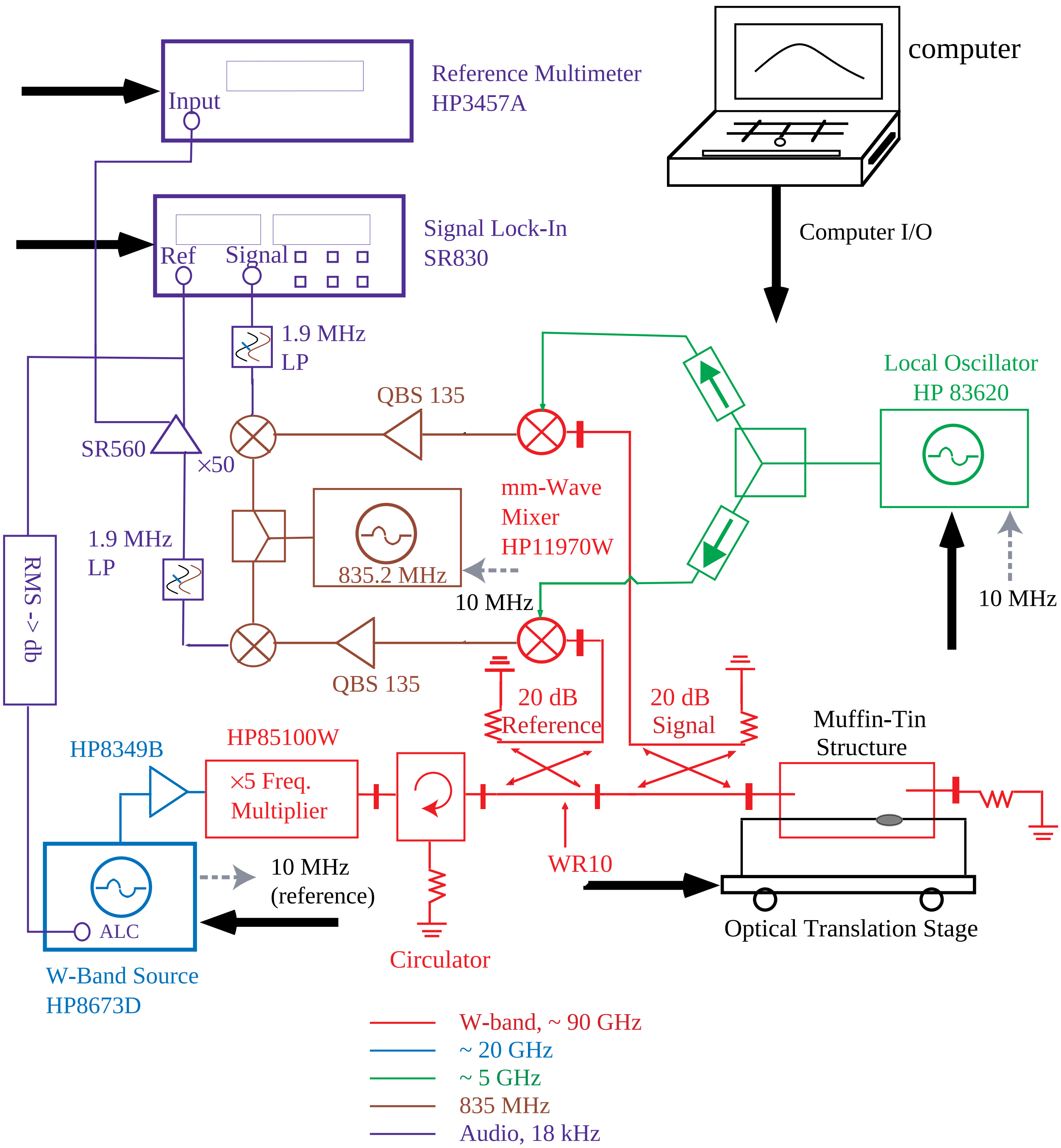

Figure 1: W-band network analyzer schematic connected for an S_{11} measurement, in this case a non-resonant perturbation measurement of a muffin-tin structure. The colors denote the approximate frequencies.

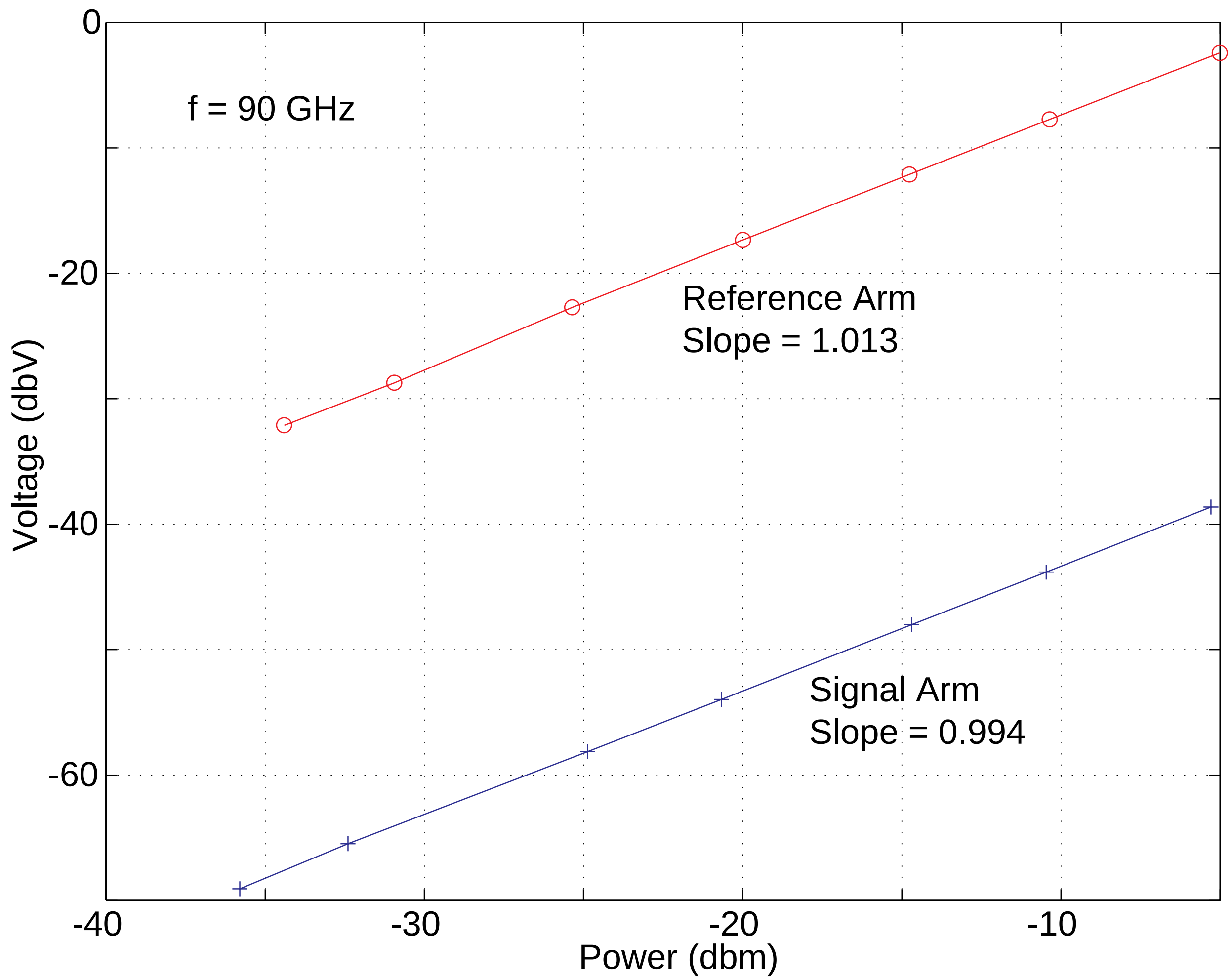

Figure 2: Linearity of the reference and signal arms with slopes from linear fits to the data. The lowest measureable power was roughly -35 dbm.

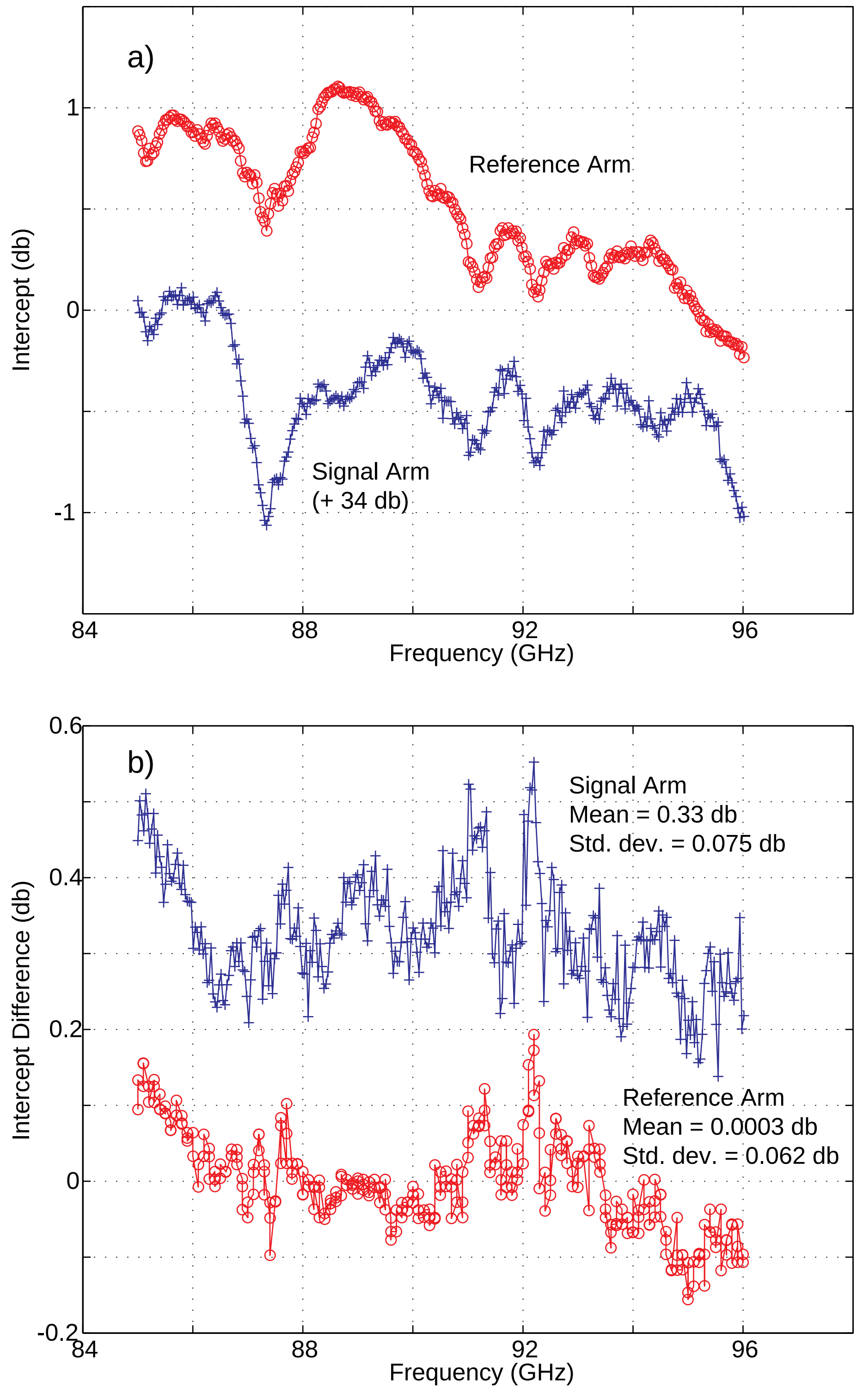

Figure 3: a) Intercepts measured in July, 1998. The signal arm intercept is offset by +34 db to display both intercepts on the same graph. b) Differences in intercepts measured in July 1998 with those measured one year earlier.

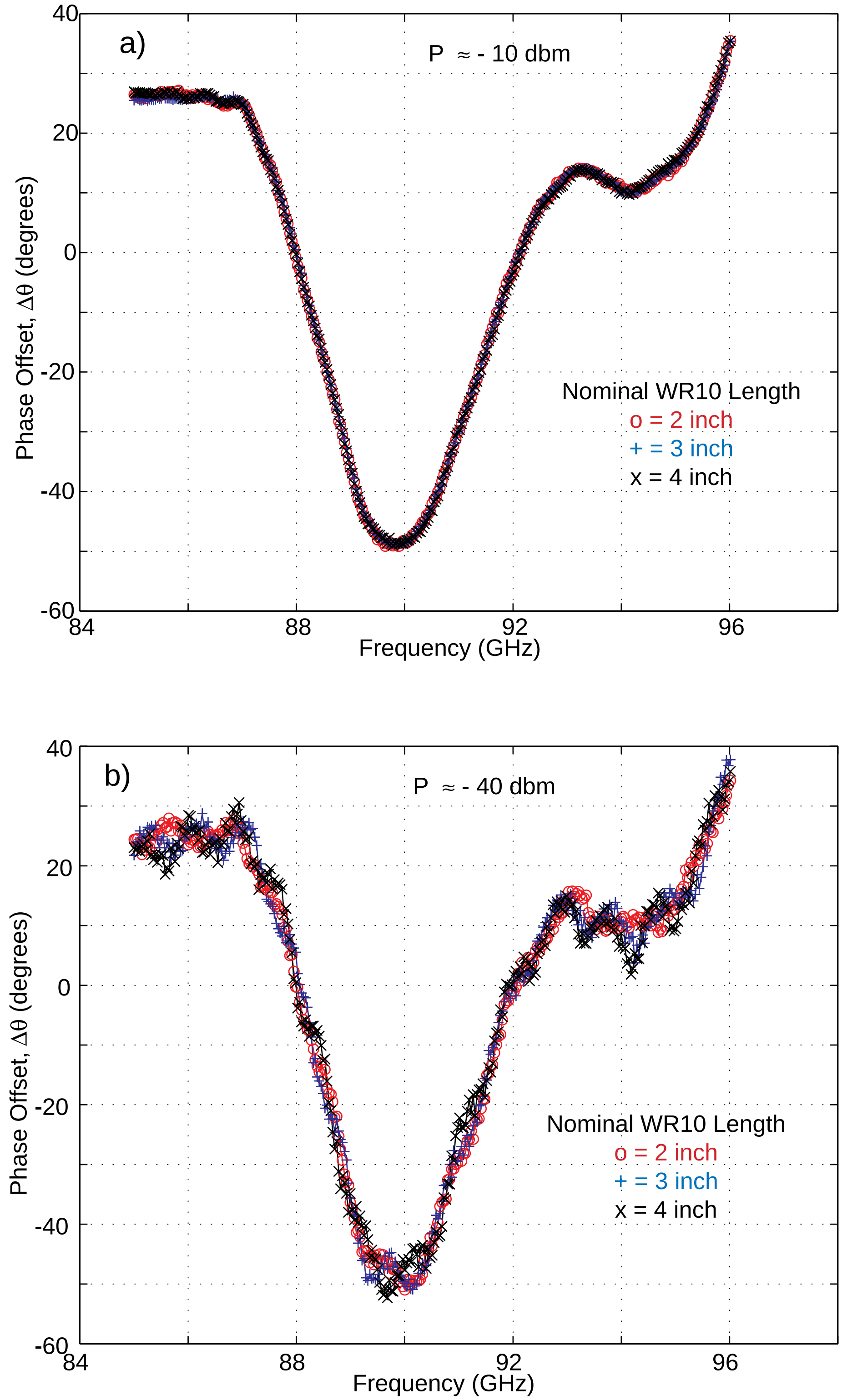

Figure 4: Phase offsets measured at a) ~ -10 dbm and b) ~ -40 dbm signal arm power. To set a scale, the measured phase changes between 1000° and 3000° over the frequency range covered by the data in this figure.

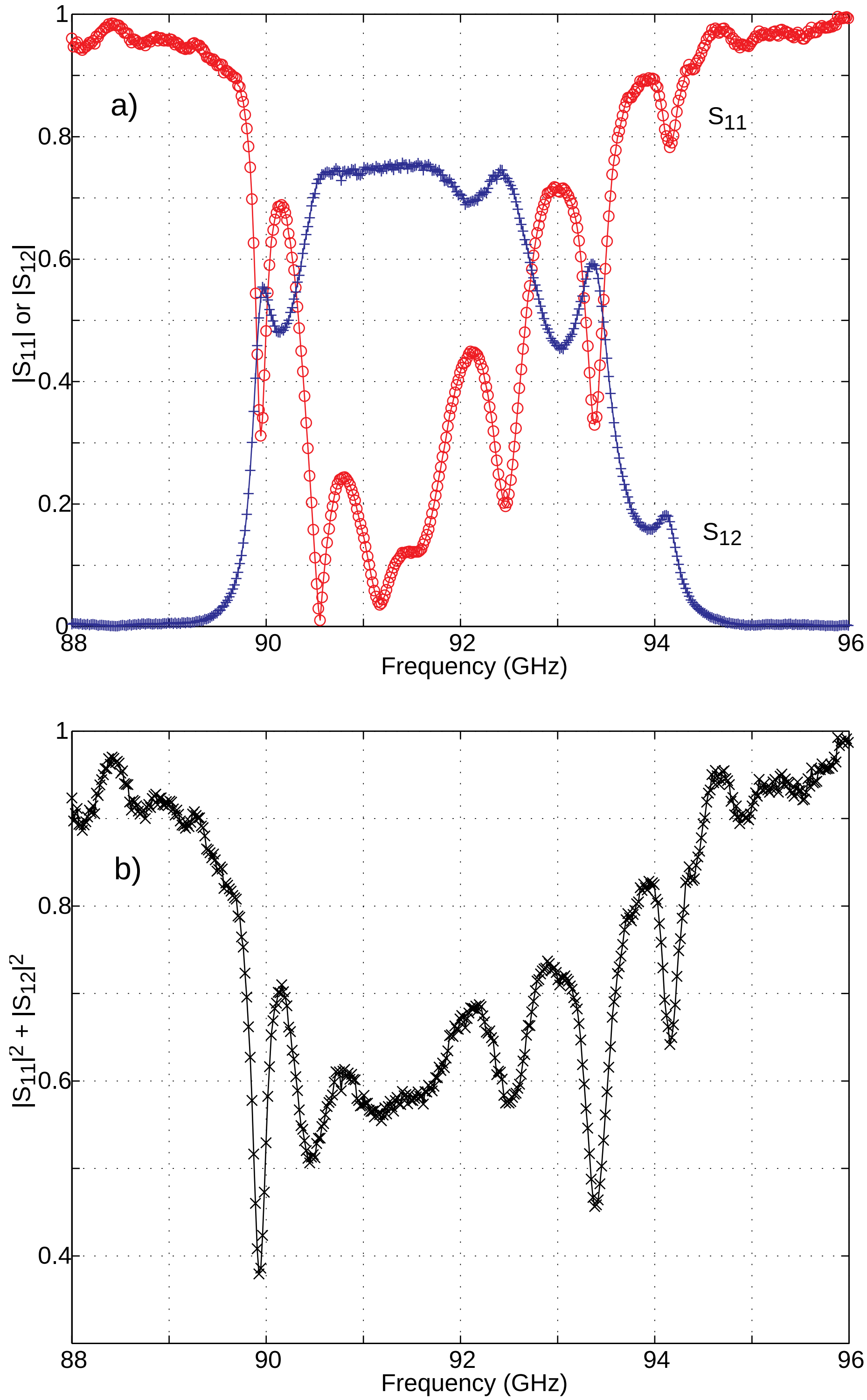

Figure 5: a) Measurements of the S-matrix for a seven-cell W-band structure. b) Measured energy based on the S-matrix measurements in a).

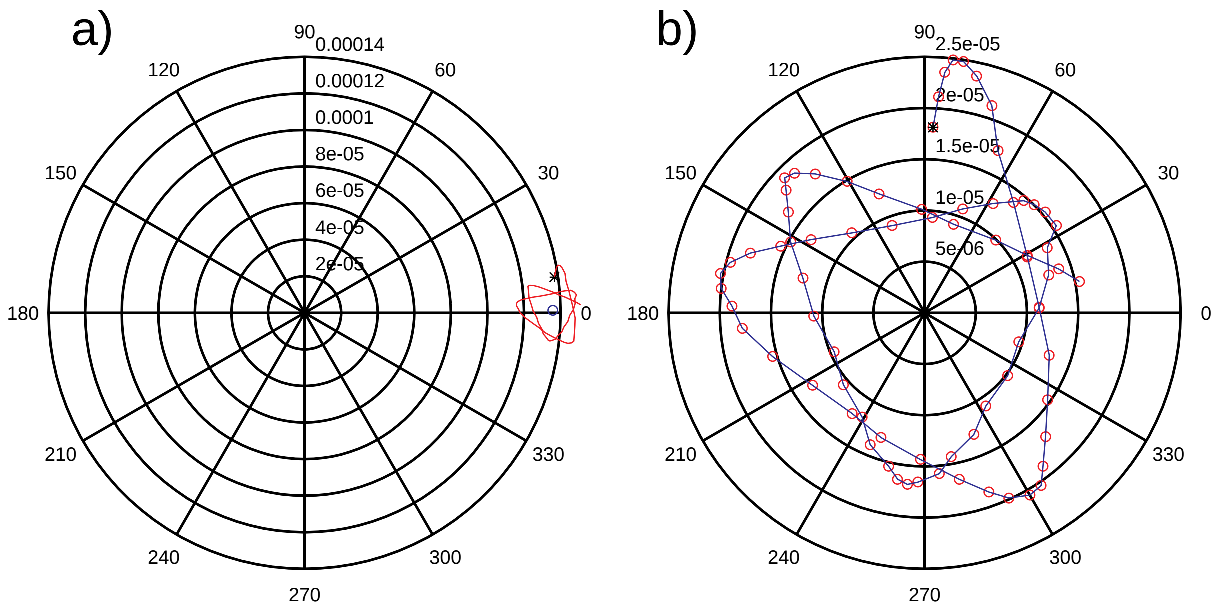

Figure 6: Polar plots of S_{11} measurements at 91.17 GHz a) without and b) with the offset subtracted. The * indicates the end near input power coupler.

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[3] P. J. Chou et al, SLAC, SLAC-PUB-7499 (1997).(to be published).

[4] K. B. Mallory and R. H. Miller, IEEE Trans. Microwave Theory and Techniques **MTT-14**, 99 (1966). (In print)