IMPROVING THE FREQUENCY AND PHASE STABILITY OF A COMMERCIAL MILLIMETER WAVE VECTOR NETWORK ANALYZER

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ABSTRACT

A principle of constant frequency offset between the receiving and transmitting elements is used in a commercial millimeter wave vector network analyzer, mostly canceling the effects of oscillator drift through subtraction. Despite the selected scheme, the internal crystal oscillators seem to cause some short-term phase and frequency uncertainties at millimeter wave frequencies. Phase drifting of close to 2 degrees at 100 GHz during a measurement period of 4 hours is observed. Antenna pattern measurements with near-field methods over periods up to tens of hours may suffer from these analyzer instabilities. An improvement based on optically isolated clock signals from a GPS-disciplined and software-controlled rubidium oscillator is outlined.

INTRODUCTION

The use of millimeter wave frequencies is rapidly expanding in wideband communications, astronomy and radar. However, a limited number of high performance facilities for antenna measurements beyond 300 GHz and diameters exceeding 1 m exist. Only one or two commercial network analyzers are available for millimeter wave work. Fig. 1 shows a schematic presentation of the particular device, which has been studied in this evaluation. Its operating principle is documented e.g. in [1]. As is seen, the manufacturer has chosen not to phase-lock the local oscillators. Instead, a phase comparator is connected to the difference of those two microwave sources. This means that the millimeter wave test signal may freely drift as long as the frequency difference between the two sweepers equals the selected reference. The low-cost design is based on the assumption of identical sweepers, noise-free digital dividers and associated phase-locks. Any phase errors within the sweeper arrangement should cancel out before the signal reaches the vector receiver [1]. This assumption is relies on the calculated phase-noise of the IF-signal and is valid for high signal-to-noise ratio (SNR) in the receiver as documented by the authors in [2].

Because many specialized pattern measurements of millimeter and submillimeter wave antennas, see e.g. [3], require a distinct and stable frequency and phase, an external frequency counter (EIP 575B) is used in the analyzer system to frequency steer the first sweeper but without a phase-locking feature found e.g. in [4]. The counter has its own internal crystal time base. A comprehensive discussion of typical phase and amplitude error budgets and their computation for near-field pattern measurement arrangements in [5] gives no pre-processed numerical values.

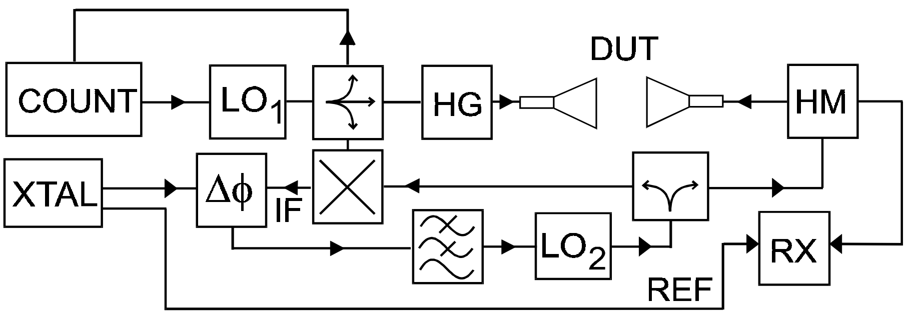

Fig.1. A schematic block diagram of the evaluated millimeter wave vector network analyzer. Two microwave sweepers (LO_1 and LO_2) are used to generate the test signal in the harmonic generator (HG) and to regenerate a lower frequency replica of it in the harmonic mixer (HM). The difference of the two local oscillator frequencies is phase-locked to a low-cost crystal unit (XTAL). Additional coarse frequency steering is provided by the external counter (COUNT) to LO_1.

THE TEST ARRANGEMENT

Millimeter wave component measurements and experiments with a submillimeter wave compact antenna test range (CATR) suggested that there might be some phase stability problems within the analyzer. Phase recordings (up to several hours) of e.g. straight waveguide sections showed either a drift of measured phase or alternatively abrupt jumps of arbitrary duration. An analysis of the problem is rather complicated because we basically need a second, considerably better millimeter wave source for a direct comparison. Even if such a device were at hand, the operating principle of the analyzer practically precludes this kind of a test as the original signal comes from a more or less free-running oscillator. As a substitute, an attempt was made to trace these phenomena back to the system's internal reference oscillators and particularly down to their frequency and phase characteristics [2]. After that, the single-sideband (SSB) phase-noises for both YIG sweepers were measured. The results are shown in Fig. 2. The increased phase-noise of LO_2 compared to LO_1 is seen clearly, and it is due to the PLL loop between the oscillators. The added phase-noise varies between 2–5 dB across the measured offset frequencies of 5–100 kHz. Close-carrier phase-noise of the free-running YIG-oscillator could not be measured. The effect of the added phase-noise on the observed phase instabilities is not clear, but it may increase the phase measurement uncertainty at low received signal levels.

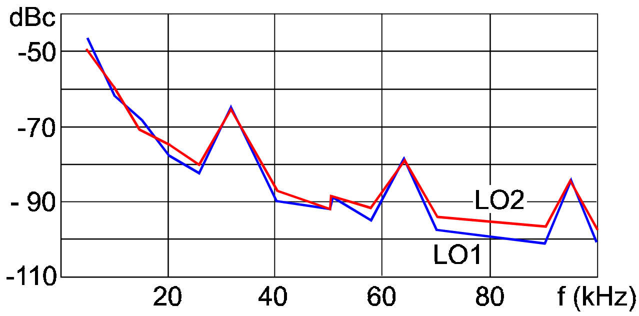

Fig. 2. The measured single-sideband phase-noise of the YIG sweepers LO_1 and LO_2 between offset frequencies of 5 kHz – 100 kHz. The measurements were done with the TEK2782 spectrum analyzer at 17 GHz (RBW=1 kHz, VBW=30 Hz, averaging=10). The added phase noise in LO_2 due to the PLL loop varies between 2–5 dB.

The test arrangement was supplemented by an adjustable synthesizer to eliminate the effects of the intrinsic frequency offset of about 10^{-6} in the millimeter wave analyzer's 10 MHz clock. Much of the test procedures were adopted from the author's recent work in GPS timing [6]. Measurement noise could be effectively reduced e.g. by the method of [7] but as it will be shown below, the DUT performance really did not require this. Helpful ideas regarding short-term phase fluctuations were obtained from [8].

SOME OBSERVATIONS

First of all we noted that there is a direct correlation between the phase of the analyzer's internal oscillator (marked XTAL in the schematic of Fig. 1 and that of the millimeter path as measured by the analyzer system itself. A straight waveguide section was used throughout the experiments and the test frequency was set to 100 GHz for mechanical convenience although any changes in the sweeper phase would be multiplied by even larger integers if a higher output frequency were chosen. Fig. 3 demonstrates a recording over 100 seconds during which we notice a frequency drift and a couple of phase jumps - the most interesting at around 80 seconds. It seems that a linear, slow shifting in reference phase is not coupled to the output whereas rapid deviations are.

The measured phase response of the straight waveguide section at 100 GHz during a 4 hour measurement period is shown in Fig. 4. The warm-up time for the system was 24 hours. First, a phase jump of about 0.5 degrees is observed when the sampling period starts. This is due to the fact that the analyzer relocks the YIG-oscillators each time a new data-taking session begins. A more serious problem is the observed phase drift of close to 2 degrees. The drifting is believed to be caused by drifting of the analyzers internal reference crystal and the frequency counters timebase crystal.

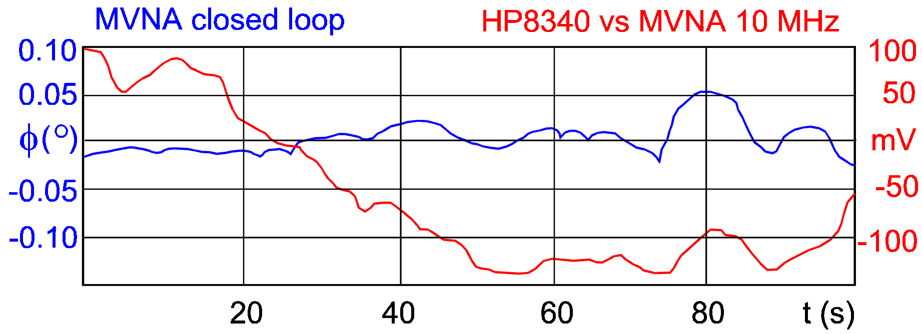

Fig. 3. Phase changes in the millimeter path (lower plot) correlate well with those of the analyzer's internal crystal reference; see e.g. the jumps at around 40 and 80 seconds. The linear drift, caused by a difference in the reference frequencies seems to be filtered out.

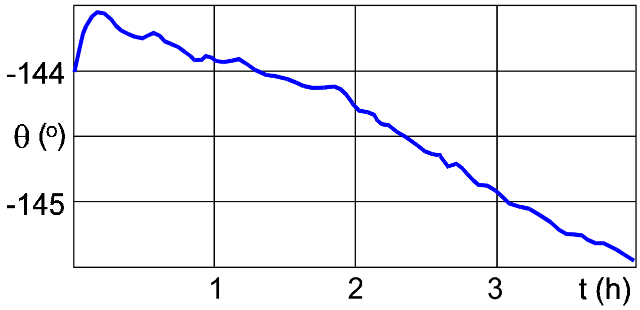

Fig. 4**.** Measured phase response through a straight piece of waveguide at 100 GHz during a 4 hours sampling period (after warm-up time of 24 hours). Phase drift of close to 2 degrees is observed.

Load-pulling effects were studied from the analyzers 10 MHz and 50 MHz output ports. Inside the analyzer, there is an internal 50 MHz crystal oscillator from which e.g. the distributed 10 MHz is obtained through digital division. This 50 MHz clock in the analyzer suffers from load pulling effects (applied at the 10 MHz output) as can be seen in Fig. 5. The problem, which was first reported by the authors in [9], is quite astonishing as the clock circuit looks like having two cascaded isolation amplifiers and a complete chain of TTL dividers for the separation of the 10 MHz output and the 50 MHz oscillator signal.

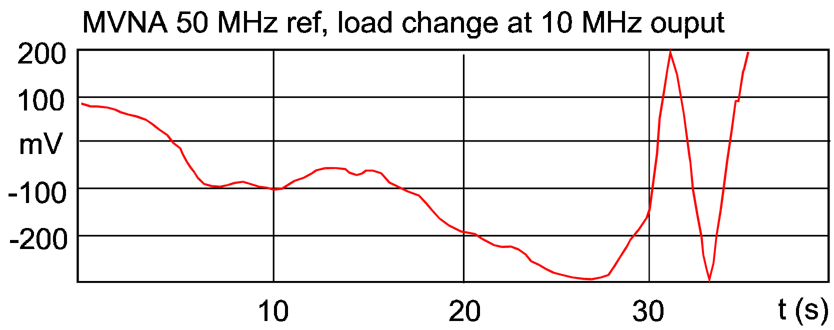

Fig. 5. One of the most primitive defects of the network analyzer's synchronization scheme is the heavy dependence of the 50 MHz reference oscillator's output frequency on the loading (changed at 30 seconds) of adjacent 10 MHz lines, which do not have a direct connection to it. Such load pulling effects seriously hamper any sensible frequency calibration efforts.

The dependence of the observed millimeter wave phase at 100 GHz on the EIP counter 10 MHz reference crystal oscillator was also studied but only minor correlation between the counter phase and the millimeter wave result was found.

SUGGESTED IMPROVEMENT SCHEME

The stability of a frequency generation system is fundamentally limited by its master oscillator [10]. Here - instead of trying to fix the unfortunate crystal unit - a straight forward improvement is possible by discarding all of the present distributed crystal oscillators and by replacing them with a stand-alone centralized rubidium standard, supplemented by e.g. optically isolated outputs and dividers. This means that first of all, the EIP counter and the MVNA base block will share a coherent source signal but the proposed arrangement also removes most of the errors caused by the various digital dividers, which are currently spread all over the printed circuit boards in the two synthesizer assemblies. However, because practical millimeter wave measurements often require the shortest possible physical distances from the microwave sources to the harmonic generators or mixers, we have to allow a distribution of the common clock up to about five meters from the master rubidium. For this purpose, a fiber optic transmission system has given promising results. It prevents load pulling, provides galvanic isolation and does not cause unpredictable phase or risetime changes, which frequently appear in a coaxial time and frequency distribution network.

The measured frequency uncertainty of the rubidium-based system is $2 \cdot 10^{-11}$ over a typical two-hour antenna test interval in the hologram setup whereby an improvement by a factor of 10^5 is achieved compared to the basic MVNA concept. Temperature effects are below 10^{-10} for a range of at least 20 degrees and the disturbances caused by load changes are simply buried in random measurement noise. The obtained results closely match those indicated by the manufacturer of the rubidium unit itself [11]. Carefully optimized microwave phase locks can keep the tracking error below 10^{-12}. An additional improvement has turned out useful for repeated measurements extended over a time span of several months for which even the stability of the rubidium would not guarantee adequate repeatability. The centralized rubidium oscillator should thus further be disciplined through a GPS receiver but in an intelligent way in order to prevent any phase jumps - due to a possible control action - happening during an ongoing pattern measurement. At the time of writing, a software-based correction system for this task is being outlined, following the promising scheme presented by the authors in [9] and [12].

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