Phase-Shifting Interferometry for RF Phase Measurement

Karl Will [1]***, Tobias Meyer*** [2]***, Abbas Omar*** [3]

Chair of Microwave and Communication Engineering, Otto-von-Guericke University of Magdeburg,
P.O.Box 4120, 39016 Magdeburg, Germany
[1] karl.will@ieee.org, [2] tobias.meyer@ovgu.de, [3]asomar@ieee.org

Abstract

This paper introduces an interferometric technique for the phase measurement of microwave devices. A handheld vector network analyzer (VNA) is presented for HF and VHF applications. A wideband synthesizer with multiple synchronized outputs is developed for extending the frequency range to the microwave band. The phase differences between the output signals can be set digitally with sub-degree accuracy using direct digital synthesizers (DDS). The phase measurement based on the superposition of these phase adjustable signals is fairly independent of the absolute magnitude of the measured signal. Reflection test sets using the introduced RF interferometry for HF/VHF and microwave signals are presented. The accuracy of the phase measurement is verified by measurements.

1. Introduction

Interferometry is an established technique not only in astronomy but also in fiber optics and plasma physics. Optical coherent interferometry uses a coherent source of light, e.g. a laser. The laser beam is split into two or more coherent beams traveling along different paths. These beams are than combined again in order to create an interference pattern. This pattern depends on the relative phase of the superimposed waves. Hence the laser beams can be used to measure path lengths or refractive indexes responsible for changing the phase of a wave traveling through materials. The most popular method for interferometric phase detection in optics is realized by stepping phase-shifting piezoelectric transducer (PZT) and detecting the resulting interference pattern. The phase shift between the combined waves defines uniquely the appearance of the pattern while its contrast is determined by the amplitudes of the superimposed beams. Hence the phase shift can be detected independently of the wave amplitudes by stepping the phase of one signal and detecting the resulting interference pattern. The common technique for phase measurement in the frequency range from HF to millimeter wave (mmW) is the heterodyning I/Q-demodulation. The received signal is separated into its inphase and quadrature components using two orthogonal carriers. The phase calculation depends however on the amplitudes of these signal components. A drawback of this approach is that the error of the phase calculation depends on the amplitude of the signal components. The uncertainty of the phase measurement increases if weak signals have to be measured.

2. RF Interferometry for HF/VHF/UHF

The development of DDS techniques allows for generating phase adjustable signals with sub-degree resolution. Thus the interferometric phase detection by phase stepping used in optics can be applied to RF signals as well. The detection of the interference pattern yields an amplitude independent phase information in contrast to the common I/Q-demodulation technique. The interferometric phase detection using coherent signals and stepping phase-shifting elements in one of the transmission paths is hard to exploit for RF signals due to the lack of suitable phase shifters. Mechanical phase shifters are bulky and hard to automate. Electronic phase shifters presently do not achieve sufficient accuracy. The presented technique enables interferometric phase detection by using DDS technology that is capable of generating phase adjustable signals electronically. These output signals are fed through different paths, a test and a reference path of a test set, and are superimposed afterwards in order to generate the interference pattern. A test set using RF interferometry for reflection measurements is shown in Fig. 1. The signal of a reference oscillator is split in order to provide coherent clock signals for two DDS systems. The internal circuits of the DDS cores are synchronized to each. The frequencies of the output $\mathbf{S}_1(U_1,\varphi_1)$ and $\mathbf{S}_2(U_2,\varphi_2)$ where $U_{1,2}$ is the voltage amplitude and $\varphi_{1,2}$ the phase of the corresponding signal, are programmed by using the same frequency tuning word for the two DDS devices. The phase shift between these output signals can be stepped by adjusting the phase offset word of one of the DDS. The minimum phase step is determined by the number of phase offset bits. A

14-bit phase offset word leads to a resolution of about 22 Millidegrees (mdeg). The signal $\mathbf{S}_1(U_1,\varphi_1)$ is used to feed the device under test, which is connected to the test port. Directional couplers separate the signal into its forward and reverse components, $\mathbf{S}_F(U_F,\varphi_F)$ and $\mathbf{S}_R(U_R,\varphi_R)$ respectively. Differential logarithmic amplifiers are used as scalar detectors that sample the voltage differences between the signal component and a reference signal $\mathbf{S}_2(U_2,\varphi_2)$ provided by the second DDS. In the following we will assume $\varphi_2 = 0$ as a reference phase and $\Delta\varphi$ as the phase shift of the signal component with respect to this reference. The RF signal components can be written as:

$$\mathbf{S}_{F/R} = \mathrm{Re}\{U_{F/R} \cdot \exp(j(\omega t + \Delta\varphi))\} \tag{1}$$

and the reference signal:

$$\mathbf{S}_2 = \mathrm{Re}\{U_2 \cdot \exp(j\omega t)\} \tag{2}$$

where ω is the common frequency. Hence, the superimposed signal at the differential scalar detector is:

$$\mathbf{S}_{DET} = \mathbf{S}_{F/R} + \mathbf{S}_2 = \mathrm{Re}\{(U_{F/R} \cdot \exp(j\Delta\varphi) + U_2) \cdot \exp(j\omega t)\} \tag{3}$$

The magnitude of the complex input signal is compressed by the logarithmic detector having a slope U_{slope} and intercept $U_{intercept}$:

$$U = U_{slope} \cdot \log_{10}\left(\sqrt{(U_{F/R} + U_2)^2 - 4U_{F/R}U_2 \sin^2\left(\frac{\Delta\varphi}{2}\right)} \cdot U_{intercept}^{-1}\right) \tag{4}$$

The phases φ_F and φ_R are detected by enabling $\boldsymbol{S}_2(U_2,\varphi_2)$ and stepping the reference phase φ_2 with respect to the phase φ_1 of the first DDS output signal over 360 degrees with very high resolution. This phase stepping $\Delta\varphi$ results uniquely in the interference function given by (4) as shown in Fig. 2.

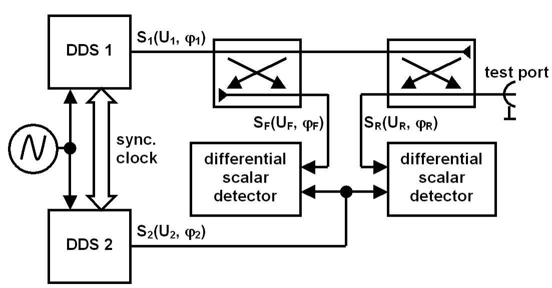

Figure 1: Reflectometer using RF interferometry

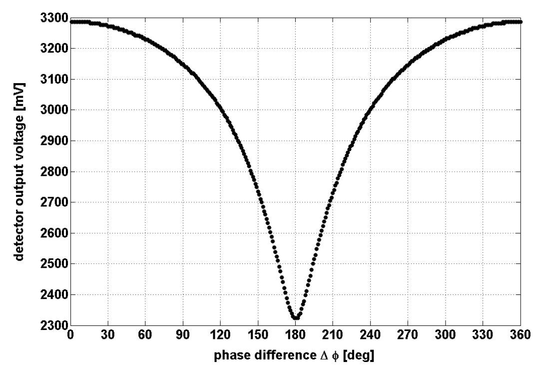

Figure 2: Interference function

The phase shifts that lead to the minimum and maximum of the interference function do not depend on the absolute amplitudes of the superimposed signals. As the analytical form of the interference function is known, the phase is calculated by curve fitting giving additional noise rejection. The controlling computer fits the measured data to the expected interference function and returns the phase difference between the two interfered signals. The scalar amplitudes U_F and U_R of the incident and reflected waves at the DUT can be measured by disabling the reference signal $\boldsymbol{S}_2(U_2,\varphi_2)$.

3. RF Interferometry for Microwave Band

The output frequency of commercially available DDS devices is presently limited to a few hundred MHz. Therefor a synthesizer architecture using heterodyne phase-locked loops (hPLL) as shown in Fig. 3 has been developed to transform the multiple phase adjustable DDS output signals into the microwave band without changing the phase resolution [1].

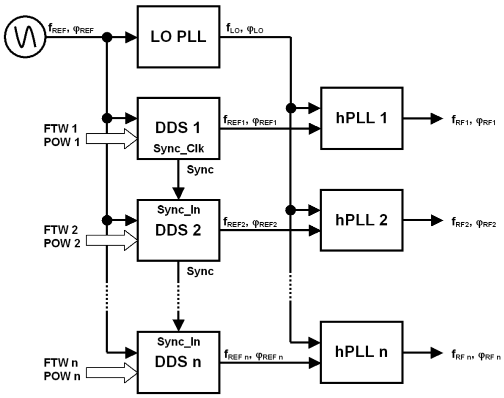

Figure 3: Multiple phase adjustable output synthesizer

Heterodyne PLLs combine the advantages of frequency mixing using a local mixer and frequency multiplication using a PLL. The frequency divider in the feedback path of a conventional PLL is replaced by a frequency mixer for this purpose. The phase resolution of the reference signals (φ_{REF1}, φ_{REF2} ... φ_{REFn}) generated by the multiple synchronized DDS can be transformed to the (φ_{RF1}, φ_{RF2} ... φ_{RFn}) of the hPLL because of the phase coherent mixing. The advantage of using a PLL design is the suppression of harmonics and spurious signals. The local signal f_{LO} for downconverting the feedback in the hPLL is synthesized by a conventional PLL. It generates a phase offset that has no effect as it is common to all heterodyne PLLs. The relative phases of the output signals (φ_{RF1}, φ_{RF2} ... φ_{RFn}) are adjusted by changing the reference phases (φ_{REF1}, φ_{REF2} ... φ_{REFn}), namely by setting the phase offset word (POW) of the corresponding DDS accordingly. All synchronized DDS are programmed using the same frequency tuning word (FTW). The frequency of the multiple output signals (f_{RF1}, f_{RF2} ... f_{RFn}) is changed by tuning the frequency of the local oscillator f_{LO} while the reference frequencies (f_{REF1}, f_{REF2} ... f_{REFn}) remain constant.

4. Accuracy of RF Interferometry

To prove the validity of the proposed synthesizer architecture a multiple phase adjustable output synthesizer for the frequency range from 1 GHz to 2 GHz along with a reflection test set as shown in Fig. 1 for the same frequency range have been built. The range of values of the interference function measured by the scalar detector depends on the level difference between the two superimposed signals. Figure 4 shows multiple interference functions seen at the scalar detector output when shifting the phase of the reference signal over 360 degrees. The parameter is the absolute level difference between the interfered signals. The unique pattern of the interference function is still detectable up to a level difference of more than 20 dB using a low-cost logarithmic amplifier with 50 mV/dB detector slope and a 16-bit A/D-converter. Consequently, a dynamic range of more than 40 dB for phase detection can be realized by setting the level of the reference signal to 20 dB less than the maximum level of the interfered test signal. If this is not sufficient, the reference signal level can be reduced using an attenuator additionally to match the power range of low level test signals in order to measure their phase. A sequence of 30.000 phase measurements was performed at a frequency of 1500 MHz to verify the accuracy of the novel measurement technique. The level difference between the superimposed signals was set to 20 dB, a phase step of 100 mdeg was used for the phase sweeps. The results of these phase measurements follow a standard distribution. The standard deviation for this distribution is 0.19 degrees. This indicates that the phase measurement using the introduced RF interferometry works reliably.

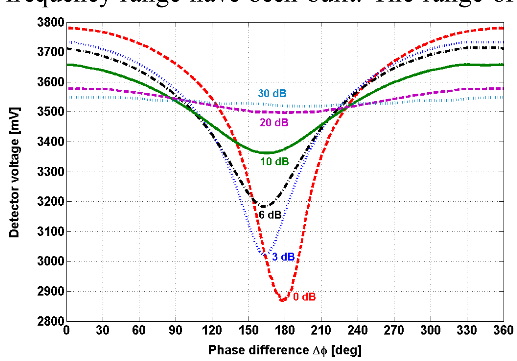

Figure 4: Detector voltage swing for multiple power differences between the superimposed signals

5. Applications using RF Interferometry

A low-cost high-resolution handheld VNA for HF and VHF using the architecture shown in Fig. 1 was developed [2]. A calibrated reflection measurement of a 90 MHz elliptic low pass filter using the developed interferometric VNA and a commercially heterodyning VNA (R&S ZVR) are plotted in Fig. 5. The differences in magnitude of up to 3 dB are caused by the nonlinear slope error of the uncalibrated low-cost detectors. It varies not only due to the absolute power level but also due to frequency and temperature. The phase measurement shows larger deviations up to about 10 degrees near DC and about 30 MHz. Because the uncalibrated phase measurements are very accurate the deviations in the vector corrected S-parameter measurements can be traced back to amplitude errors caused by the detectors.

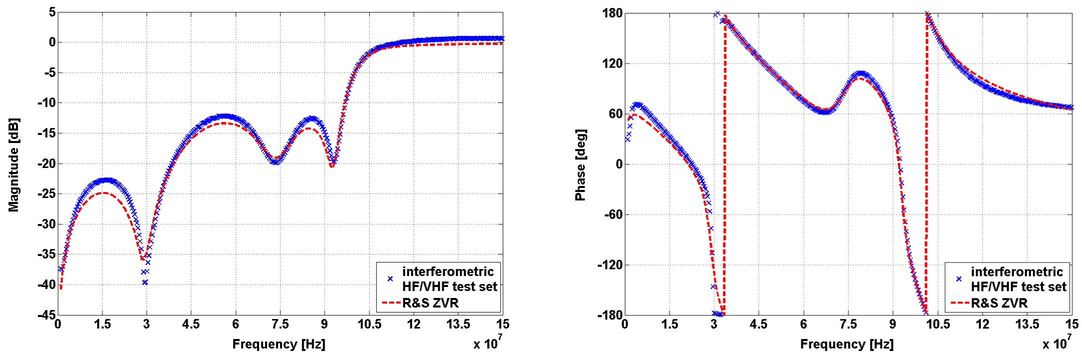

Figure 5: Magnitude and phase of S_{11}-measurement or an elliptic low pass filter used as a verification device

The RF interferometry shows similar results for the microwave band. A 10dB-attenuator terminated by a short circuit was used to verify the performance of the developed reflection test set using the multiple output phase adjustable synthesizer in a frequency range of 1 GHz to 2 GHz. Again the measured magnitude of reflection is shown in Fig. 6. The nonlinear detector slope introduces a maximum error of more than ±1 dB. The corresponding phase of the reflection measurement is also plotted in Fig. 6. The absolute phase error between the measurements and the simulated linear phase of the shorted 10dB-attenuator is also shown in this graph.

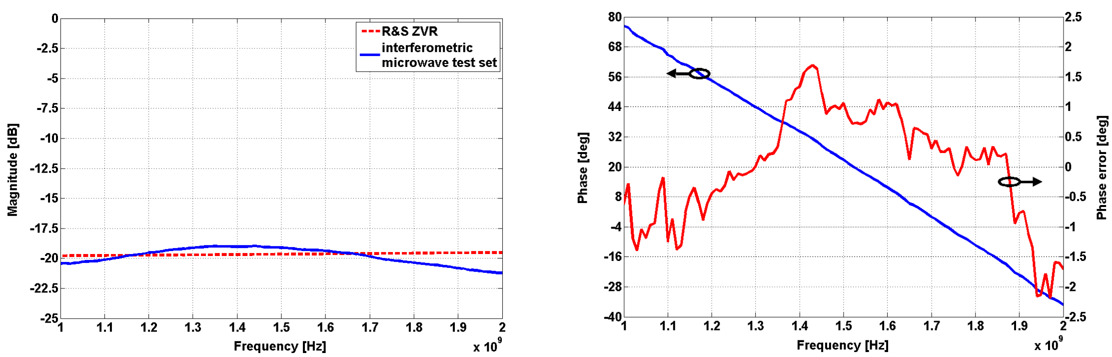

Figure 6: Magnitude and phase of S_{11}-measurement of a shorted 10dB-attenuator used as a verification device

6. Conclusion

The technique of interferometric phase detection has been applied in the RF frequency range in this paper. An architecture for calibrated reflection measurements working from HF to VHF has been presented. Making use of scalar detectors and two synchronized DDS reduce both hardware complexity and costs. Furthermore a synthesizer architecture has been introduced to transform the multiple phase adjustable signals of the synchronized DDS into the microwave band without changing the phase resolution. This prooves that the interferometric phase detection can also be applied to the microwave band. The accuracy of the novel phase measurement technique has been verified by multiple measurements. The results resembled an error distribution having a small standard deviation. Measurement examples have been shown for calibrated reflection measurements. The detector slope of the low-cost logarithmic amplifiers should be calibrated to allow a more accurate correction. This will also reduce the error seen in the phase measurement when a linear correction is applied. The accuracy is still comparable to commercial VNAs at vastly reduced hardware costs and volume. It is sufficient for many practical applications and production testing.

7. References

1. K. Will, T. Meyer, A. Omar, „Microwave Synthesizer with Multiple Phase Adjustable Output“, *Proceedings of the 37th European Microwave Conference,* October 2007, pp. 344-347

2. K. Will, T. Meyer, A. Omar, „Low-Cost High-Resolution Handheld VNA using RF Interferometry“, *Accepted for presentation at the International Microwave Symposium 2008,* WE2C-02, June 2008