Instantaneous Frequency Measurement Based on Low-Cost Six-Port Technology

S. Lindner, G. Vinci, F. Barbon, S. Linz, S. Mann, R. Weigel, and A. Koelpin
Institute for Electronics Engineering, University of Erlangen-Nuremberg
91058 Erlangen, Germany
Email: {lindner, vinci, barbon, linz, mann, weigel, koelpin}@lte.eei.uni-erlangen.de

***Abstract*—This paper describes a new approach for absolute, high accuracy and fast responding millimeter wave frequency measurement. The shown system is based on the reduction of the frequency detection to a phase measurement with a delay line and a subsequent determination of the phase. By using a Six-Port structure, this phase can be evaluated very precisely, leading to a accurate frequency detection. Another remarkable point is the fast system response, because there is neither time consuming transformation to frequency domain nor long integration time required.**

***Index Terms*—Delay line, Frequency measurement, Instantaneous, Interferometry, Phase measurement, Six-Port**

I. INTRODUCTION

Detecting the frequency of a signal is an everyday measuring task in electronic engineering. For low frequencies up to the range of a several 100 MHz this can be performed by counters [1] or by digitizing the signal, calculating the spectrum and a subsequent peak detection. Nevertheless, the accurate evaluation of very high frequencies is complicated, because of a limited speed of the digital circuitry used in counters. A common approach is mixing the RF-Signal down to a lower band where the frequency detection is realized. Besides arise the problems of higher costs, additional noise sources and the loss of accuracy caused by the mixing.

Another remarkable problem for the shown counter, as for the digital back-end, is the latency of the frequency calculation. In both cases the accuracy of the measured frequency is proportional to the observed time. This is caused by the needed integration time of the counter or by the FFT, where the distance between the discrete frequency points is inverse proportional to the observed time.

A low cost solution for the direct analog measurement of frequency, providing an instantaneous output of the signal frequency, will be presented on the following pages. The shown system is based on an interferometric approach, determining the phase between two radio frequency (RF) signals. This concept can be used with every system capable of measuring phase differences, for example diode-based IQ-mixer. In this publication a Six-Port structure [2] will be used, because of its low cost design along with its high bandwidth and superior phase resolution [3], [4].

II. THE SIX-PORT STRUCTURE AS FREQUENCY DETECTOR

Measuring frequencies with a Six-Port receiver is based on an interferometric method. The basic principle setup is shown in Fig. 1. The VCO under test generates an RF signal I with unknown frequency, which is split in two parts by a power divider. While one is fed directly to the Six-Port, the second part is delayed by a delay line with the length d before entering the second input port of the passive Six-Port structure. Measuring the phase between the two input signals I_1, I_2, the frequency dependent phase shift, caused by the delay line, can be measured and the frequency of the incoming signal calculated.

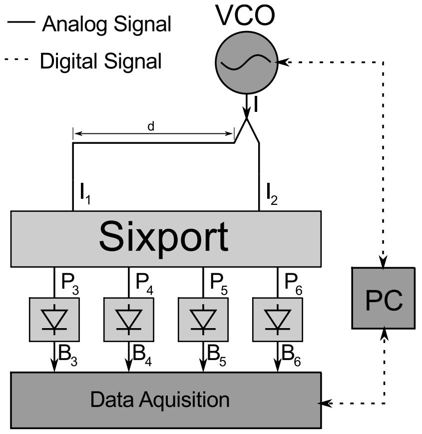

Fig. 1. Overview of the Six-Port frequency measurement system.

$$
\begin{aligned}
I &= A\cos(2\pi f t) && (1)\\
I_1 &= A_1\cos(2\pi f t + \varphi_0) && (2)\\
I_2 &= A_2\cos\left(2\pi f t + \varphi_0 + 2\pi f\frac{d}{c}\right) && (3)
\end{aligned}
$$

The Six-Port structure itself can be understood as a homodyne concept, transferring the two input signals I_1 and I_2, superimposed with discrete phase shifts of 90 °, 180 °, 270 °, and 360 ° into baseband by diode detectors [5]. These detectors measure the power at the four ports (P_3 to P_6) producing four DC-voltages (B_3 to B_6), from which the complex vector $\underline{z}$ can be calculated [3]:

$$\underline{z} = (B_3 - B_4) + j(B_5 - B_6). \quad (4)$$

The phase and amplitude of this vector exhibit the information of the input signal powers, as well as the phase difference $\Delta\sigma$ between them. In this scenario we are primary interested in the phase, because it includes the information on the delay between the signals. This phase can be calculated by building the argument of the complex vector, for example using the *atan2* function:

$$\Delta\sigma = \arg\{\underline{z}\} = \operatorname{atan2}\left(\Im\{\underline{z}\}, \Re\{\underline{z}\}\right). \tag{5}$$

Knowing the exact length d of the used delay line and the measured phase $\Delta\sigma$, the frequency f of the generated signal can be calculated using the following equation:

$$f = \Delta\sigma \cdot \frac{c}{d \cdot 2\pi}. \tag{6}$$

Nevertheless, this calculation is ambiguous if the length of the delay line is longer than the wavelength of the smallest detectable frequency. This lower detection boundary, as well as the upper one, is limited by the used RF front end bandwidth. But if the coarse range of the frequency is known, an appropriate offset can be added to to the measured phase difference $\Delta\sigma$ to get the correct result. To get this offset, the frequency must be known within the unambiguous bandwidth f_B, which depends on the delay line and their transmission velocity, i.e. the speed of light c:

$$f_B = \frac{c}{d}. \tag{7}$$

Assuming a phase accuracy of $\delta = \frac{1}{\sigma_{err,max}}$, which depends on the maximum phase error $\sigma_{err,max}$ of the system, the minimal error of the frequency measurement can be estimated by:

$$f_{err} = \pm\frac{1}{2}\frac{c}{\delta d} = \pm\frac{1}{2}\frac{f_B}{\delta}. \tag{8}$$

This means, a longer delay line allows a more accurate frequency detection, but also a smaller unambiguous measurement range. Thus, the used length is a point of optimization.

For the Six-Port system presented here, the value of δ is in the range of 10000 to 20000 leading to low measurement errors in the range of a few kilohertz.

III. SIMULATION RESULTS

To prove the concept and verify the influence of different delay lines, various simulations were performed. The results show, that the principle is working as expected and the equations are correct.

Fig. 2 shows the simulated phase responses for different lengths d of the delayline, using a frequency range from 24 GHz to 24.5 GHz. Three different lengths are shown, one with $d = 1.2$ m suitable to verify the measurement setup, a second with a multiple of 10 times the wavelength λ_m of the center frequency and a third one between. It is clearly visible, that the used phase span depends on the length d. Therefore, maximum performance of the system can only be achieved, if the delay line is long enough to cover a whole circle in the constellation diagram.

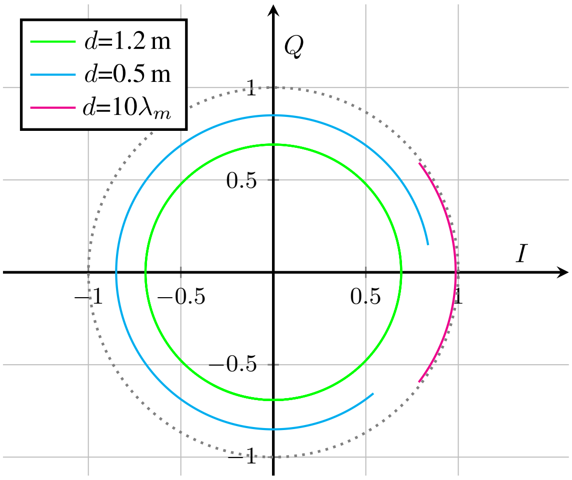

Fig. 2. Constellation diagram of the simulation result at different lengths of the delay line d.

Nevertheless, the ambiguity occurring if $\Delta\sigma$ covers more than 2π has to be considered and removed for absolute measurements, or the coarse frequency has to be known, which is possible in most applications. The ambiguity can be solved by knowledge of the system under test or using two switchable delay lines with different lengths.

The different diameter of the circles are caused by the assumption of the damping of the delay line of 0.5 $\frac{\text{dB}}{\text{m}}$ leading to different amplitudes depending on the length. The dotted circle shows as a reference the result for zero attenuation.

Another interesting fact is the symmetrical phase response around $\varphi = 0$, as long as d is a multiple of λ_m. In reality this is difficult to realize due to tolerances in manufacturing, leading to a rotation of the constellation diagram, as it can be seen for the case $d = 0.5$ m in Fig. 2. This problem can easily be solved by measuring the exact length d with a known frequency and rotating the phase response to the correct position.

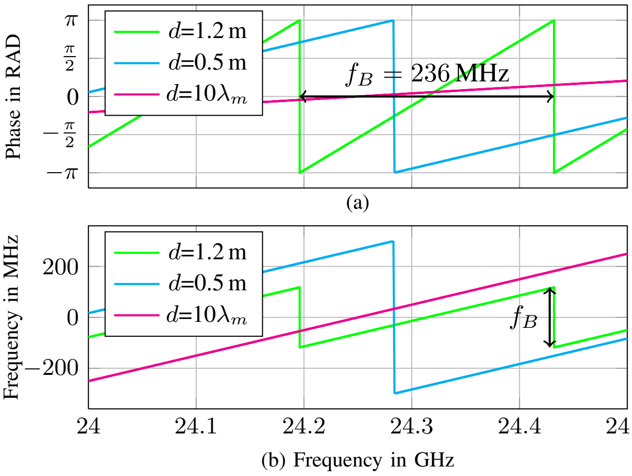

Fig. 3. Simulated results of the phase responses and frequency calculation for different values of d.

Fig. 3 shows the calculated phases according to the previously described constellation diagram. In this representation, the unambiguity is clearly visible for the delay with $d = 1.2$ m and can be determined by measuring the distance between two jumps (a), or the height of the jump at the calculated frequency (b). By knowing this ambiguity, also the exact length d can be calculated.

The displayed frequency response, calculated using (6) shows a range of $\pm\frac{1}{2}f_B$ depending on the delay length. This means that an appropriate frequency offset has to be added to reach the correct ambiguity range and frequency f, respectively.

IV. MEASUREMENT

The measuring setup is shown in Fig. 1. The signal is generated by an *Agilent PSG E8267D* signal generator as VCO which is capable of producing a stable output frequency and power. The RF signal is split with a power divider after which one signal is fed directly to the first input of the Six-Port-structure, while the other is delayed using a cable and fed to the second input. The used 3.5 mm coaxial cable has a geometrical length of $d_g = 1.02\,\mathrm{m}$. Although the length of the cable sounds quite long, it can be realized on a relatively small PCB, because the geometrical length d_g can be dielectrically shortened to the effective length d. According to (9) d_g is shortened by the inverse of the square root of the effective relative permittivity $\epsilon_{r,eff}$ of the used PCB material.

$$d = \frac{d_g}{\sqrt{\epsilon_{r,eff}}} \tag{9}$$

The same effect can be seen with the used cable. It achieves an unambigous measuring bandwith of $f_B = 236\,\mathrm{MHz}$. Thus, the crucial electrical length of the delay line is $d = 1.2\,\mathrm{m}$.

Fig. 4 shows the connections of the Six-Port test setup. The passive Six-Port structure, as well as the diode detectors are designed for the ISM band at 24 GHz. The detector outputs are connected with SMA cables to two dual channel *Keithley SMU 2612A* source measuring units, where the voltages are measured and transferred to a local PC for further data processing. Each measuring point of the shown plots is evaluated using the average of only two consecutive measurements for noise suppression.

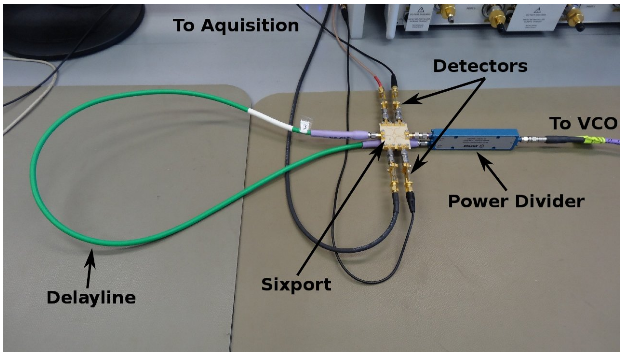

Fig. 4. RF frontend including the passive Six-Port structure, the diode detectors and the delay line (green cable).

This measurement equipment can be easily replaced by a small micro-controller with four analog to digital converters leading to a low-cost implementation of the system.

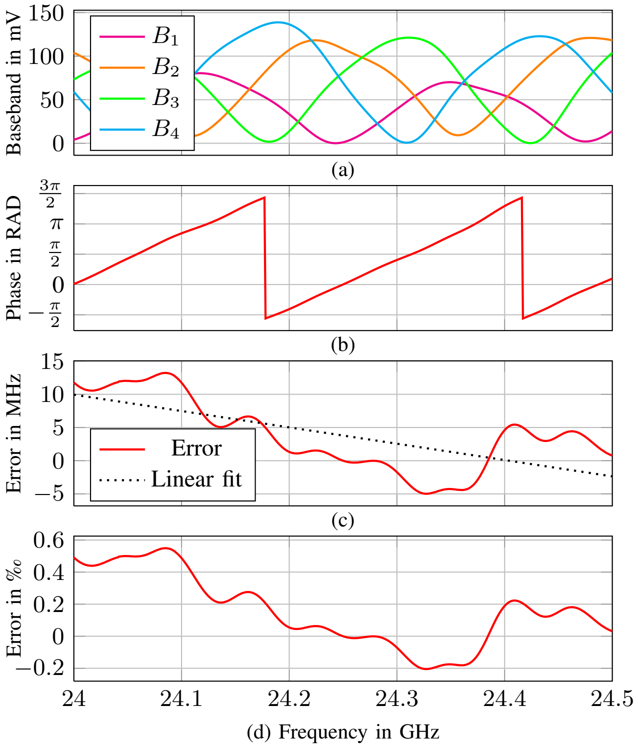

Fig. 5. Raw measured baseband and voltages, recovered phase response and calculated frequency error without compensation.

For the whole demonstration setup there is no amplifier used, neither at the RF nor at the baseband signals, therefore a power level of 0 dBm was used for the measurements. This results in further performance improvement possibilities using an additional LNA-stage at the input and proper amplification and filtering at baseband for future setups.

The measurements were done around the ISM band at 24 GHz with a bandwidth of 500 MHz, to detect the unambiguity range of the used delay line. Examining the positions of the phase jumps is an easy way for an exact detection of the delay line length d. This is necessary, because an uncertainty of this length leads directly to an error.

Fig. 5 shows the raw Six-Port output voltages (a) and the calculated frequency (c) based on the phase shift of the delay line (b). It is obvious, that the performance of the diode detectors as well as the matching of the structure is dispersive. Therefore, a compensation has to be done to get an accurate frequency detection. Nevertheless, the uncompensated results are impressive, showing a maximum relative error lower than 1‰. For the frequency calculation a phase unwrap algorithm was used to eliminate the unambiguity. Furthermore, a phase offset is added to center the frequency calculation to the used middle frequency. This is necessary, because d is not exactly a multiple of the wavelength of the center frequency.

The linear error term, plotted in Fig. 5c (dotted), is caused by an inaccuracy fur the evaluation of the length d. This results from the discrete nature of frequency steps during the measurements. Thus, the length can be exactly measured

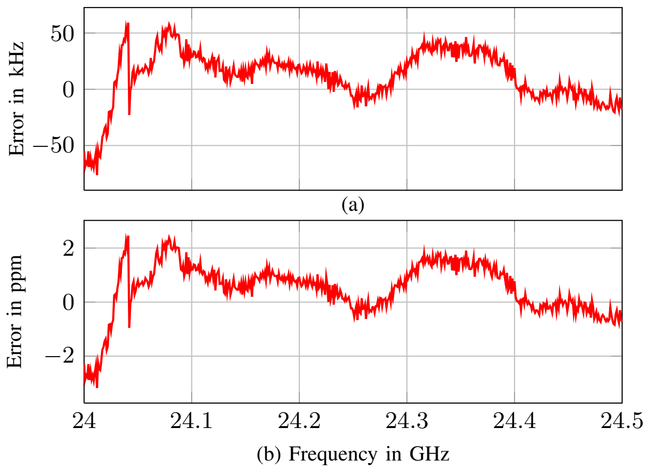

Fig. 6. Calculated error for a compensated measurement for a bandwidth of 500 MHz around the ISM band at 24 GHz.

by minimizing this linear error term. The remaining error is caused by imperfections in the Six-Port structure, the nonlinear diode characteristics and dispersive effects of the used components. Anyway, these errors are static, thus they can be compensated.

Fig. 6 shows the results of a measurement compensated with the prior mentioned calibration run. The error is now below ±50 kHz, achieving a relative error of approximately ±2 parts per million (ppm) over the observed bandwidth.

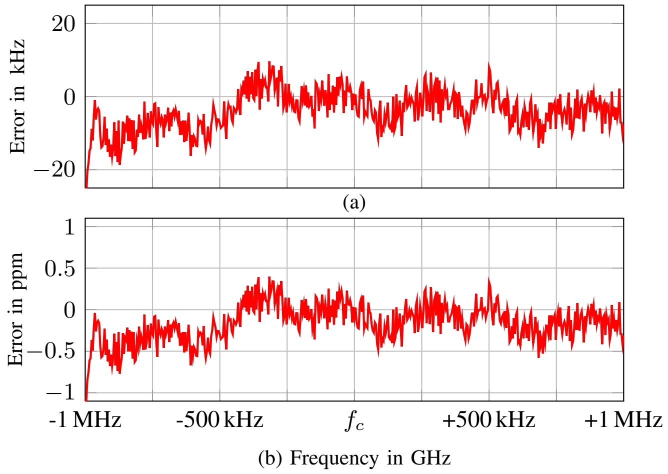

Fig. 7. Calculated error for a compensated, fine stepped measurement within a bandwidth of 2 MHz.

To round up the measurements, an additional fine stepped acquisition with a step size of 100 Hz was performed to observe the system in a small bandwidth. The results, which are shown in Fig. 7, were achieved with the same compensation as for Fig. 6. Within this small bandwidth of 2 MHz around the center frequency of 24.25 GHz a relative error smaller than ±1 ppm, for most points even smaller ±0.5 ppm could be demonstrated.

This system was measured only for a fixed input amplitude, but it can also be used for variable signal power, because the power of the signal can be extracted from the magnitude of the complex vector $\overline{z}$. Thus, with a proper calibration over power, the frequency measurement accuracy depends not on the applied signal power. To lower the calibration requirements, it is also possible to include an automatic gain control in front of the Six-Port ensuring a constant power level at the input ports.

V. CONCLUSION

In this paper a concept for measuring RF frequency with a Six-Port based interferometric system is presented. By using a delay line causing a frequency dependent phase shift, it is possible to determine a very high frequency signal without the need of a high accurate frequency reference. The concept of the system has been analyzed with various simulations and the feasibility of the system has been proved at 24 GHz with appropriate measurements.

The results of these measurements show, that the system is capable of measuring frequencies with relative errors lower than ±2 ppm within a bandwidth of 500 MHz at 24 GHz. The Six-Port concept also works for higher frequency, up to more than 100 GHz [6], [7] where the proposed system is a very interesting possibility to determine the frequency with a low budget solution, due to the mainly passive structures. Another point is the low latency of the system and the high measuring rate, because no integration time is needed to compute the frequency leading to an instantaneous frequency measurement of an received signal.

This system concept shows excellent performance and can be used for high frequency PLL or FLL circuits, as high speed FSK-demodulator [8] and for cheap and fast testing procedures, e.g. for industrial manufacturing of RF devices like synthesizers or radar modules.

REFERENCES

[1] S. Johansson, “New frequency counting principle improves resolution,” in *Frequency Control Symposium and Exposition, 2005. Proceedings of the 2005 IEEE International*, aug. 2005, p. 8 pp.

[2] G. Engen, “The six-port reflectometer: An alternative network analyzer,” *Microwave Theory and Techniques, IEEE Transactions on*, vol. 25, no. 12, pp. 1075 – 1080, dec 1977.

[3] G. Vinci, S. Lindner, F. Barbon, R. Weigel, and A. Koelpin, “Promise of a better position,” *Microwave Magazine, IEEE*, vol. 13, no. 7, pp. S41 –S49, nov.-dec. 2012.

[4] F. Barbon, G. Vinci, S. Lindner, R. Weigel, and A. Koelpin, “A six-port interferometer based micrometer-accuracy displacement and vibration measurement radar,” in *International Microwave Symposium (IMS) 2012, Montreal, Canada*, 2012.

[5] S. Winter, H. Ehm, A. Koelpin, and R. Weigel, “Diode power detector dc operating point in six-port communications receivers,” in *Microwave Conference, 2007. European*, oct. 2007, pp. 795 –798.

[6] B. Laemmle, G. Vinci, L. Maurer, R. Weigel, and A. Koelpin, “An integrated 77-ghz six-port receiver front-end for angle-of-arrival detection,” in *Bipolar/BiCMOS Circuits and Technology Meeting (BCTM), 2011 IEEE*, oct. 2011, pp. 219 –222.

[7] S. Abou Chahine, B. Huyart, E. Bergeault, and L. Jallet, “Measurement performance of a millimetric dual six-port network analyzer in the w frequency band (75-110 ghz),” in *Precision Electromagnetic Measurements, 1994. Digest., 1994 Conference on*, jun-1 jul 1994, pp. 9 –10.

[8] L. Qiu-na, L. Dong-hua, and Y. Si-jie, “Research on the method of demodulation for pcm/fm signal based on instantaneous frequency measurement,” in *Computational Engineering in Systems Applications, IMACS Multiconference on*, vol. 1, oct. 2006, pp. 93 –96.