A Low-Noise Time-Domain EMI Measurement System for Measurements up to 26 GHz

Christian Hoffmann[1], ***Alexander Böge***[1], and ***Peter Russer***[2]

[1] Institute for High-Frequency Engineering, Technische Universität München, Arcisstrasse 21, 80333 München, Germany, c.hoffmann@tum.de

[2] Institute for Nanoelectronics, Technische Universität München, Arcisstrasse 21, 80333 München, Germany, russer@tum.de

Abstract

In this paper, a low-noise time-domain EMI measurement system for the frequency range from 9 kHz - 26 GHz is presented. It combines ultra-fast analog-to-digital-conversion and real-time digital signal processing on a field-programmable-gate-array (FPGA) with ultra-broadband multi-stage down-conversion. By using low-loss components, the system noise floor power spectral density is decreased to below -150 dBm/Hz, yielding an ultra-low noise floor of typically below -115 dBm with a 9 kHz IF-filter. The high system sensitivity allows for the characterization of broadband, low-level signals near the noise floor, like ultra-wideband (UWB) communication. Defected ground structures increase the return loss of the low insertion loss SP5T PIN-diode switches. The system IF dynamic range exceeds the requirements of CISPR 16-1-1 by over 20 dB and allows for the measurement of high-dynamic range signals like radar pulses. Scan time is decreased by several orders of magnitude. A scan from 9 kHz to 26 GHz with a 9 kHz IF-filter bandwidth is completed in under 200 s, while over $5{\cdot}10^6$ frequency points are calculated.

1 Introduction

Electromagnetic interference (EMI) has traditionally been measured with heterodyne EMI receivers. The measurement over a very large number of frequencies increases scan times to hours or even days. Time-domain EMI measurement systems can decrease scan times by several orders of magnitude in comparison to traditional EMI receivers. With the presented system, an EMI measurement over the complete band from 9 kHz to 26 GHz with an IF bandwidth of 9 kHz takes less than 200 s. With a traditional EMI-receiver, the sequential measurements of over $5{\cdot}10^6$ frequency points with a dwell-time of 100 ms, would take more than one day.

2 Time-Domain Measurement System

Fig. 1 shows the block diagram of the presented time-domain EMI measurement system. For measurements below 1.1 GHz, the EMI-Signal is lowpass-filtered to enforce the Nyquist criterion and directly sampled by the multiresolution analog-to-digital converter (ADC) [1]. The amplitude spectrum is calculated via the Fast-Fourier-Transform (FFT) on an FPGA. The Short-Time-Fast-Fourier-Transform (STFFT) is defined as

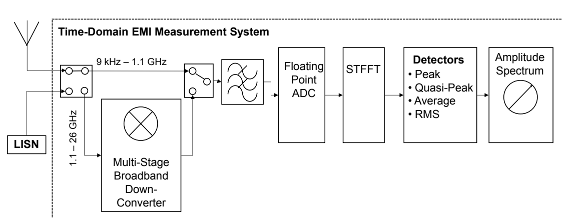

Figure 1: Time-domain EMI measurement system.

an FFT performed over a limited time-interval. A Gaussian window function $w[n]$ is applied, corresponding

978-1-4244-6051-9/11/$26.00 ©2011 IEEE

to the IF-filter of a conventional measurement receiver. By application of the STFFT, a spectrogram is calculated. The STFFT is calculated by [2]

$$X[\tau, k] = \sum_{n=0}^{N-1} x[n+\tau] w[n] e^{\frac{-j2\pi kn}{N}}, \tag{1}$$

where τ is the discrete time coordinate of the window and k is the discrete frequency.

3 Multi-Stage Broadband Down-Converter

For measurements above 1.1 GHz, the multi-stage broadband down-converter was added to the system [3]. A block diagram is shown in Fig. 2. The band from 1.1-6 GHz is down-converted to the frequency range below 1.1 GHz by the 1.1 - 6 GHz down-converter. The signal is sampled and the amplitude spectrum is calculated. The frequency band from 6-26 GHz is first down-converted to the band from 1.1-6 GHz by the 6 - 26 GHz down-converter. The 1.1 - 6 GHz down-converter then down-converts the EMI signal into the band below 1.1 GHz.

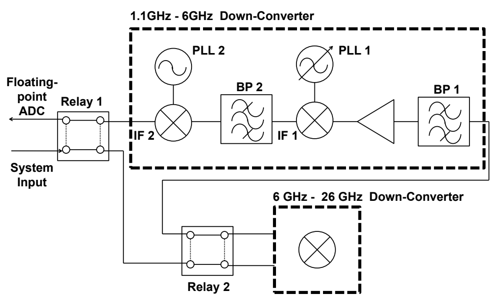

Figure 2: Multi-Stage broadband down-converter.

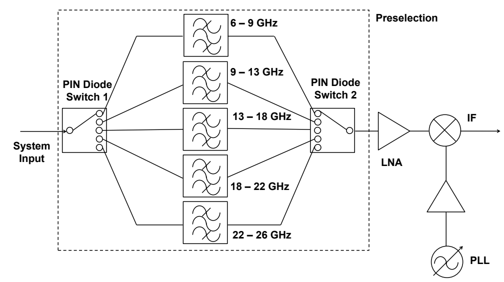

Figure 3: 6 - 26 GHz down-converter.

3.1 1.1 - 6 GHz Down-Converter

The block diagram of the 1.1 - 6 GHz down-converter is shown in Fig. 2. The signal is down-converted in two steps by two mixing stages. This mixing scheme allows for a sufficient suppression of the image band by a single fixed preselection bandpass filter, because the input frequency band and the image frequency band do not overlap spectrally. The first mixer up-converts the input signal to a first intermediate frequency band above the input band. The local oscillator frequencies are generated by a low-noise PLL-Synthesizer. A second mixer finally down-converts the IF-band to the frequency band from 9 kHz to 1.1 GHz, where it is sampled and further digitally processed by FFT to compute the amplitude spectrum. The preselection filter suppresses out-of-band narrowband and broadband interference, thus increasing system dynamic range. A low-noise InGaP/GaAs HBT amplifier (LNA) yields a low noise figure and high system sensitivity.

3.2 6 - 26 GHz Down-Converter

A third mixer stage is added to extend the frequency range of the measurement system to 26 GHz. Fig. 3 shows the block diagram of the 6 - 26 GHz down-converter. The preselection consists of 5 bandpass filters, that divide the EMI input signal above 6 GHz into 5 ultra-wide subbands: band 1 from 6-9 GHz, band 2 from 9-13 GHz, band 3 from 13-18 GHz, band 4 from 18-22 GHz and band 5 from 22-26 GHz. The switching between the bands is done via broadband, low insertion loss single-pole-quintuple-throw (SP5T) PIN-diode switches. The filtered signal is amplified by a low-noise amplifier with high gain and then down-converted to the input frequency range of the 1.1 - 6 GHz down-converter by a broadband mixer with low conversion loss. The local oscillator frequencies are generated by a low phase noise PLL-Synthesizer.

4 Hardware Implementation

The switching between the five preselection filters is done via broadband, low-noise SP5T PIN diode switches. Because of the high electron mobility of AlGaAs and the low diode junction capacitance, a AlGaAs SP5T PIN-diode switch chip was used. The switches were fabricated on a glass reinforced hydrocarbon/ceramic RF substrate. The control current is injected via broadband bias circuits (Bias-Tees). Broadband, low-loss SMD capacitors and conical coils are used. The width of the capacitors yields discontinuities with the inherent decrease in the return loss and increase in insertion loss. To diminuish this problem, a defected ground structure (DGS) below the discontinuity was designed. By cutting out parts of the ground-layer below the capacitors, the capacitance per unit length C' is lowered, yielding a matched line despite its greater width. The simulation results obtained with a 3D electromagnetic field simulator are shown in Fig. 4. The return loss is increased by up to 15 dB, while the insertion loss is decreased by about 0.1 dB.

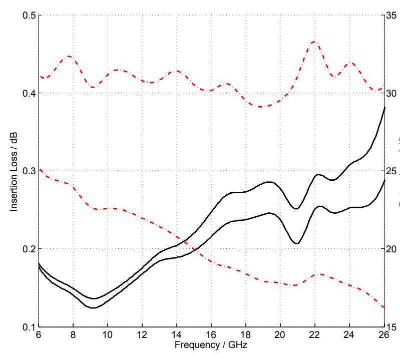

Figure 4: Simulated insertion loss (straight line) and return loss (broken line).

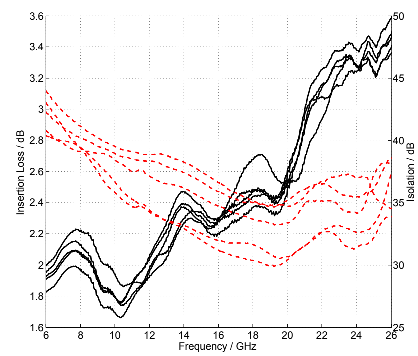

Figure 5: Measured insertion loss (straight line) and isolation (broken line).

To characterize the switches performance, the scattering parameters were determined with a vector network analyzer (VNA). The results are given in Fig. 5. The insertion loss for all paths stays below 3.6 dB. The isolation exceeds 30 dB over the complete frequency range from 6-26 GHz.

5 System Measurements

In order to measure the system noise floor from 6-26 GHz, the noise voltages V_N were measured at distinct frequencies using the average detector and a matched input and the respective noise powers P_N were calculated. As the bandwidth of the used IF-filter with a Gaussian characteristic was 9 kHz, the resulting powers were normalized to an IF bandwidth of 1 Hz, using $P_{\mathrm{NF,AV}} = P_N / B_{\mathrm{ENB,IF}}$, where $P_{\mathrm{NF,AV}}$ is the average power of the system noise floor, and $B_{\mathrm{ENB,IF}}$ is the equivalent noise bandwidth of the IF-filter. Assorted measurement results are listed in Table 1. The system exhibits a low noise floor power spectral density of under -150 dBm/Hz over the complete frequency range.

CISPR 16-1-1 [4] requires an IF dynamic range of over 40 dB for measurements above 1 GHz. The difference in level between the peak and average detector measurements of a pulse modulated signal is defined as the IF dynamic range. A pulse generator fed a pulse modulated sinusoidal signal with a frequency

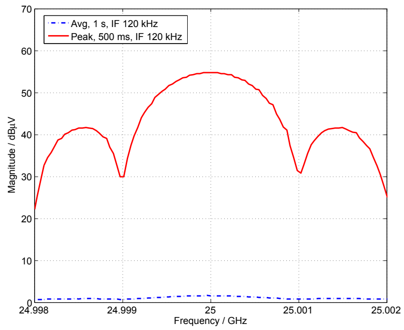

Figure 6: Measured pulse-modulated signal.

Frequency / MHz	Power Spectral Density / $\frac{dBm}{Hz}$
6000	-160.4
10000	-158.6
14000	-157.5
18000	-153.8
22000	-150.1
26000	-150.1

Table 1: Measured noise floor power spectral density.

of 25 GHz to the system input. The signal pulse width was set to 1 μs and the pulse period to 40 ms. The spectra are shown in Fig. 6. The measurements demonstrate an IF dynamic range of over 62 dB for an IF bandwidth of 1 MHz, exceeding CISPR 16-1-1 requirements by over 20 dB.

6 Conclusion

A low-noise, real-time time-domain EMI measurement system for the frequency range from 9 kHz - 26 GHz has been presented. Scan times can be reduced by several orders of magnitude in comparison to traditional measurement receivers. The IF dynamic range was shown to exceed CISPR 16-1-1 requirements by over 20 dB and allows for the measurement of high-dynamic range signals like radar pulses. The system noise floor power spectral density is decreased to below -150 dBm/Hz, yielding an ultra-low noise floor of typically below -115 dBm with 9 kHz IF bandwidth. The resulting high system sensitivity allows for the characterization of narrowband interference near the noise floor or the broadband characterization of UWB communication up to 26 GHz.

7 Acknowledgments

The authors would like to thank the Bayerische Forschungsstiftung and GAUSS INSTRUMENTS GmbH, Munich, Germany for funding this project.

8 References

1. S. Braun and P. Russer, "A low-noise multiresolution high-dynamic ultra-broad-band time-domain EMI Measurement System," *IEEE Transactions on Microwave Theory and Techniques*, vol. 53, pp. 3354 - 3363, Nov. 2005.

2. J. G. Proakis and D. G. Manolakis, "Digital Signal Processing, third edition," Pearson Prentice Hall, 1996.

3. C. Hoffmann, S. Braun and P. Russer, "A Broadband Time-Domain EMI Measurement System for Measurements up to 18 GHz," *EMC Europe 2010, Wroclaw, Poland*, pp. 34 - 37, 2010.

4. CISPR 16-1-1, Ed. 3.1 Am. 1, "Specification for radio disturbance and immunity measuring apparatus and methods Part 1-1: Radio disturbance and immunity measuring apparatus Measuring apparatus," *International Electrotechnical Commission*, 2010.