IC 1407 ACCREDIT

SIGNAL PROCESSING

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19.04.2018

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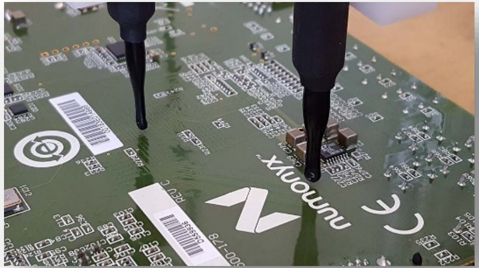
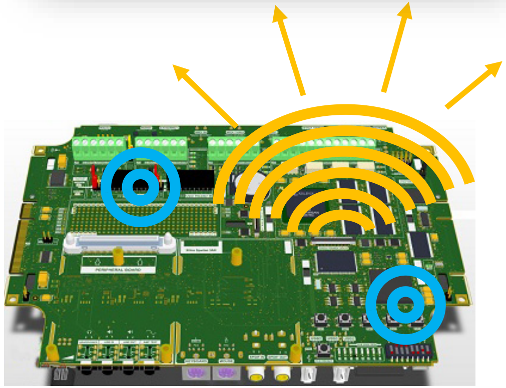
Outline

- Motivation
- Near-field probe characterization
- Signal processing of spread-spectrum signals

Motivation

➢ State of the art in COST Action





- ✓Traditionally, measurements of electromagnetic interference are performed in the frequency domain
- ✓Radiated emission measurements according to CISPR 16-2-3
- ✓Time-domain measurements using the short-term fast Fourier transform have been introduced in the standards CISPR 16-1-1 and CISPR 16-2-3. They allow to reduce the test time significantly

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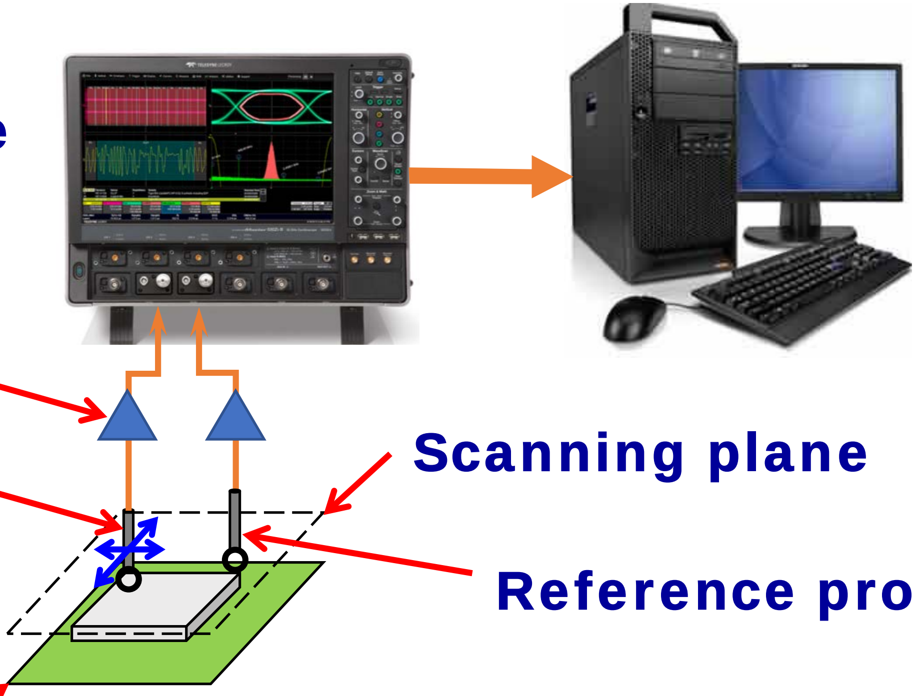
Motivation

- ➢ **Electromagnetic radiation of the DUT**
  - ✓ **periodic deterministic: frequency synthesizer, power supply units, etc.**
  - ✓ **stochastic: data transferring, thermal noise, jitter**
- ➢ **Near-field probe characterization**
  - ✓ **probe characterization in time- and frequency domains**
  - ✓ **restoration of the EM field by deconvolution procedure**
- ➢ **Analysis of signals with spread spectrum**
  - ✓ **extraction in information about spread spectrum**
  - ✓ **de-spreading procedure for statistical analysis**

Outline

- Motivation
- **Near-field probe characterization**
- Signal processing of spread-spectrum signals

Time-domain measurement system

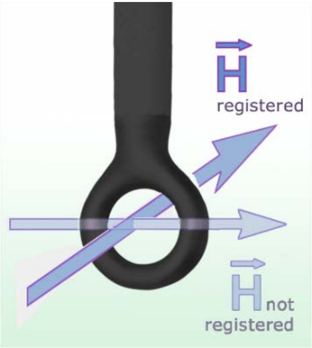


Probe characterization

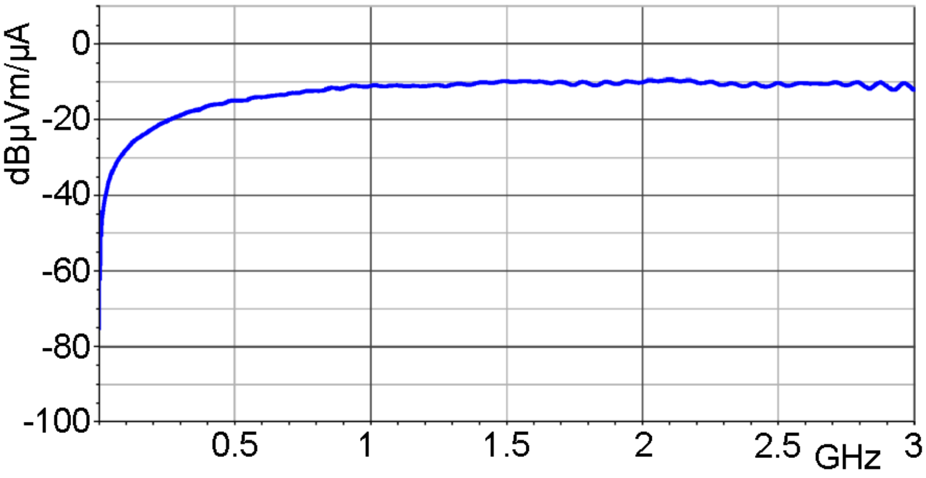
- The radiated EMI can be sensed by near-field magnetic probes and used for prediction of the field distribution by cross-correlation algorithm
- Probe manufacturers presents only scattering parameters including amplitude characteristics which is not enough for applying in the time domain signal processing algorithms
- The characterization of the probe in time and frequency domains can be used for improvement of the cross-correlation analysis of the radiated EMI

Langer magnetic near-field probe

➢ RF-R 50-1 H-Field Probe[1]



✓ Frequency response



- ✓ 30 MHz up to 3 GHz
- ✓ ∅ ≈ 10 mm

✓ Phase characteristic is not available

[1] https://www.langer-emv.de/en/product/rf-passive-30-mhz-3-ghz/35/rf-r-50-1-h-field-probe-30-mhz-up-to-3-ghz/14

Linear Time-Invariant System

✓ **Convolution integral:**

$$y(t) = \int_{-\infty}^{+\infty} x(\tau) \cdot h(t-\tau) d\tau$$

Fourier Transform ⟷

✓ **Frequency response:**

$$Y(f) = X(f) \cdot H(f)$$

Two excitation signals for LTI system

$x(t)$	$y(t)$	$Y(f)$
$\delta(t)$	$h(t)$	$H(f)$
$u(t) = \int_{-\infty}^{t} \delta(\tau)\, d\tau$	$g(t) = \int_{0}^{t} h(\tau)\, d\tau$	$\frac{H(f)}{j2\pi f}$

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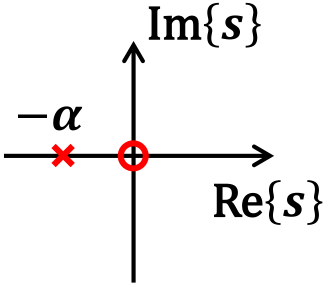
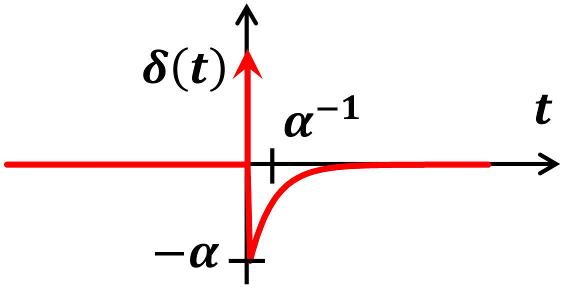
Linear Time-Invariant System

➢ High-pass filter

✓ **Poles and zeros diagram**



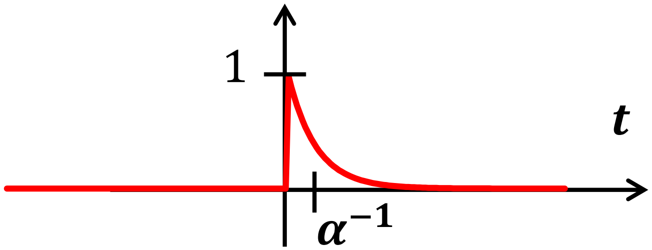
✓ **Impulse response $h(t)$**



✓ **Transfer function:**

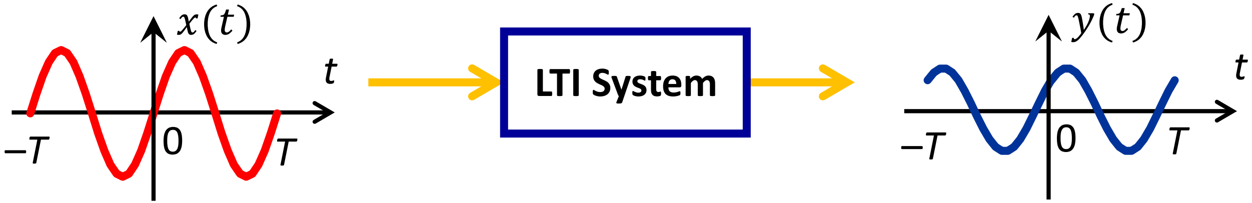
$$H(s) = \frac{Y(s)}{X(s)} = \frac{s}{s+\alpha}$$

✓ **Step response $g(t)$**



Linear Time-Invariant System

➢ Single harmonic response



✓ **Input signal:**

$$x(t) = A \cdot \cos\left(2\pi \frac{t}{T} + \theta\right)$$

✓ **Output signal:**

$$y(t) = A \cdot K \cdot cos\left(2\pi \frac{t}{T} + \theta + \phi\right)$$

✓ **Magnitude response:**

$$K = \left| H\left(\frac{1}{T}\right) \right|$$

✓ **Phase response:**

$$\phi = arg\left\{ H\left(\frac{1}{T}\right) \right\}$$

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Linear Time-Invariant System

➢ Fourier series response

$$\omega_n = \frac{2\pi n}{T}$$

✓ **Fourier series of input signal:**

$$x(t) = A_0 + \sum_{n=1}^{\infty} A_n \cos(\omega_n t + \theta_n)$$

✓ **Fourier series of output signal:**

$$y(t) = A_0 K_0 + \sum_{n=1}^{\infty} A_n K_n \cos(\omega_n t + \theta_n + \phi_n)$$

✓ **Magnitude response:**

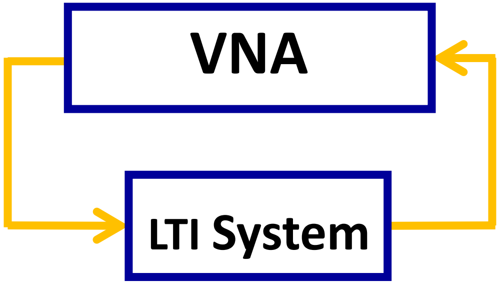
$$K_n = \left| H\left(\frac{n}{T}\right) \right|$$

✓ **Phase response:**

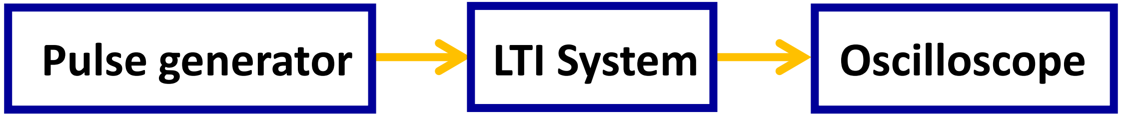
$$\phi_n = arg\left\{ H\left(\frac{n}{T}\right) \right\}$$

Probe characterization

- Frequency-domain analysis

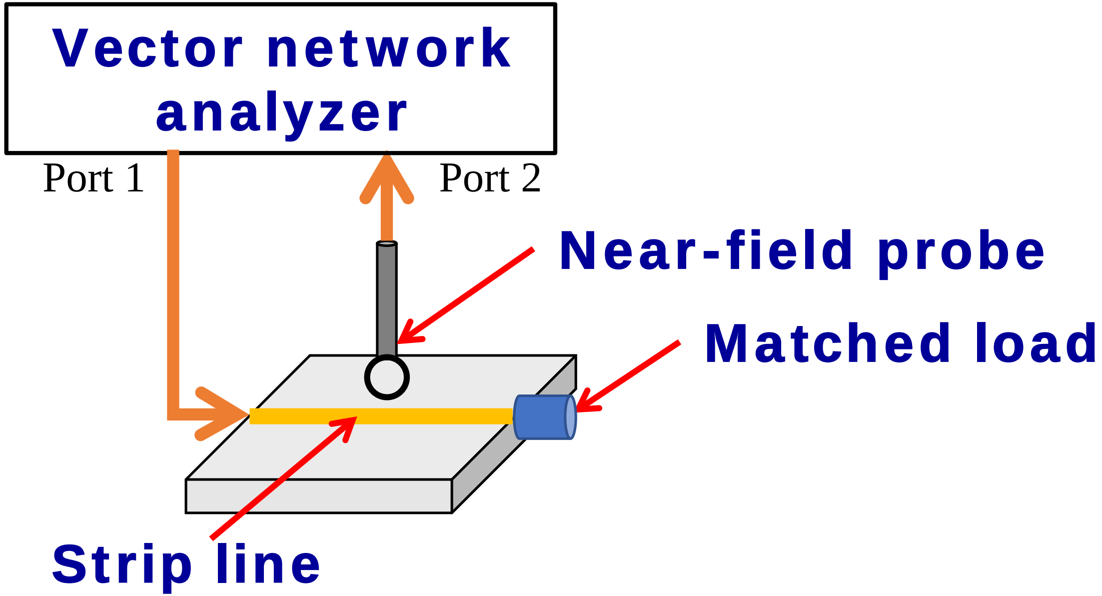


- Time-domain analysis



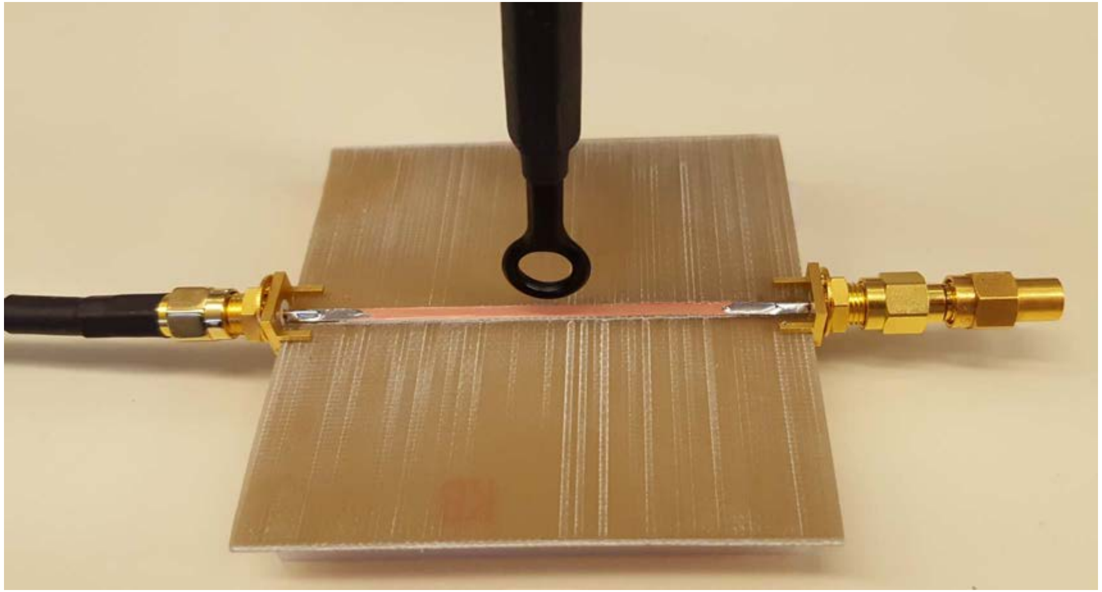
Frequency-domain analysis

➢ Measurement setup



✓ **Keysight E5063A ENA Vector Network Analyzer**

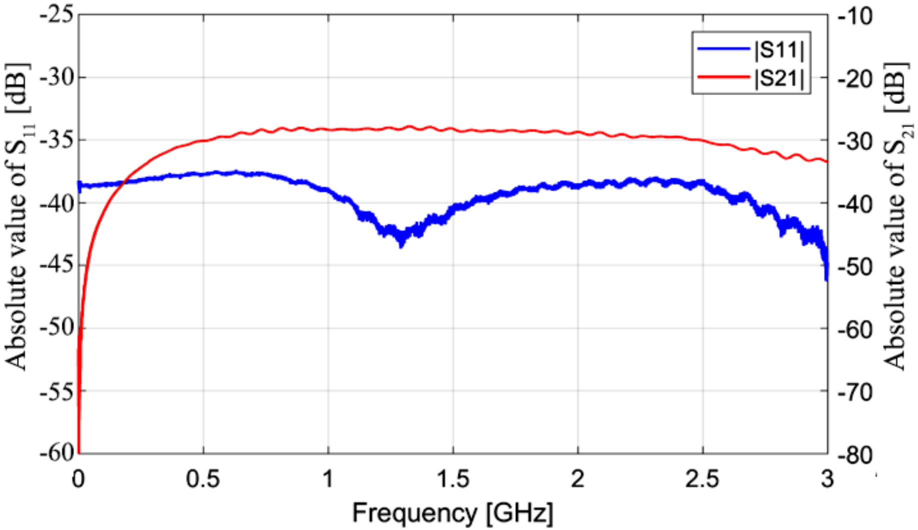
Frequency-domain analysis

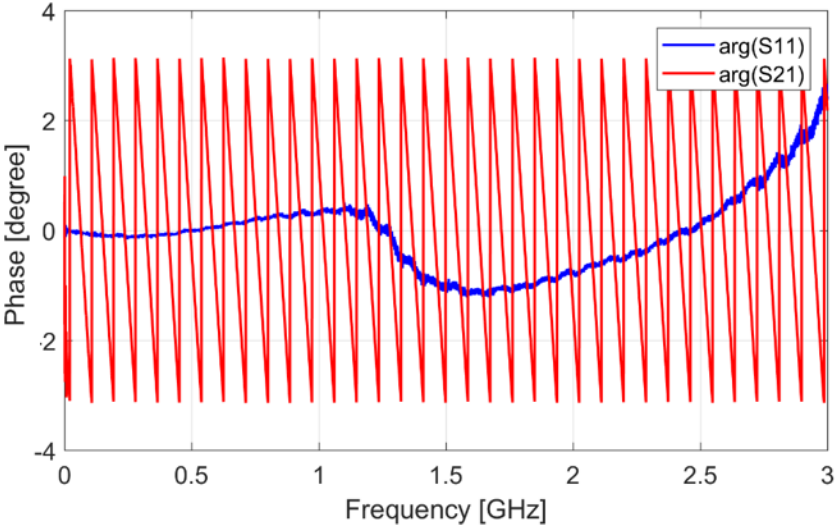


✓ **The distance between strip line and probe is 2 mm**

Frequency-domain analysis

➢ S-parameters of the RF-R 50-1 probe





✓ **Frequency range from 300 kHz till 3 GHz**

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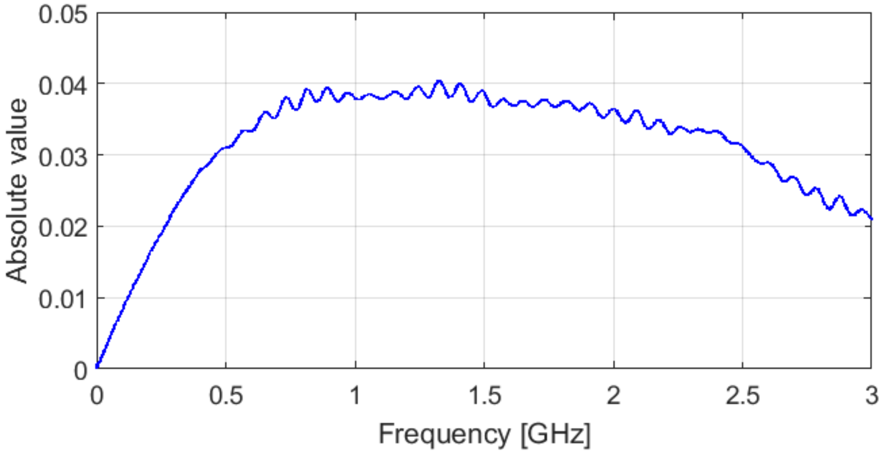
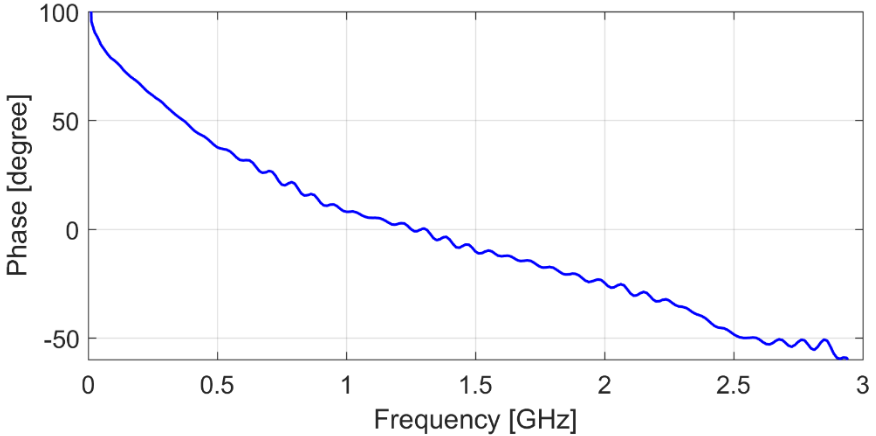
Frequency-domain analysis

➢ Transfer function of the RF-R 50-1 probe





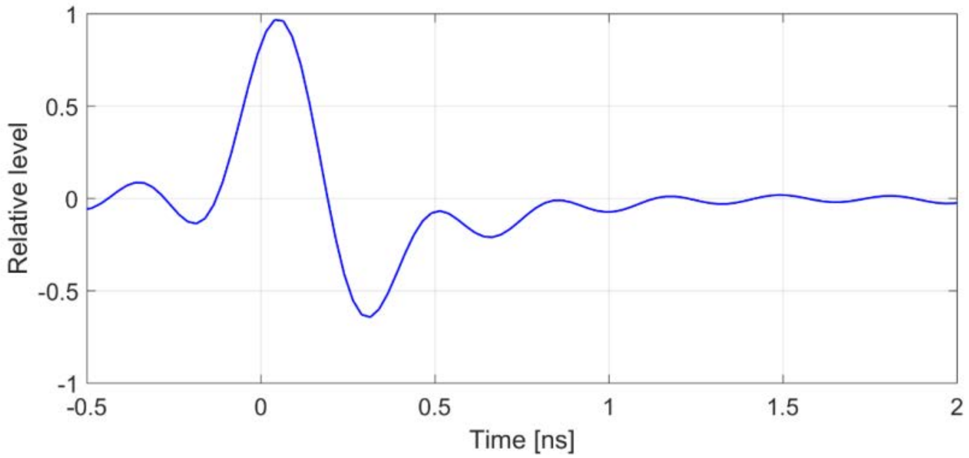
- ✓ **Amplitude transfer function in linear scale**
- ✓ **Phase characteristic obtained by a compensation of time delay**

Probe identification

- **The inverse Fourier transform of the transfer function**

$$h_{pr}(t) = 2 \cdot \mathrm{Re}\left(\int_{300\ \mathrm{kHz}}^{3\mathrm{GH}} H_{pr}(f) \cdot e^{j2\pi f t} df\right)$$

- **The impulse response of the RF-R 50-1 probe**



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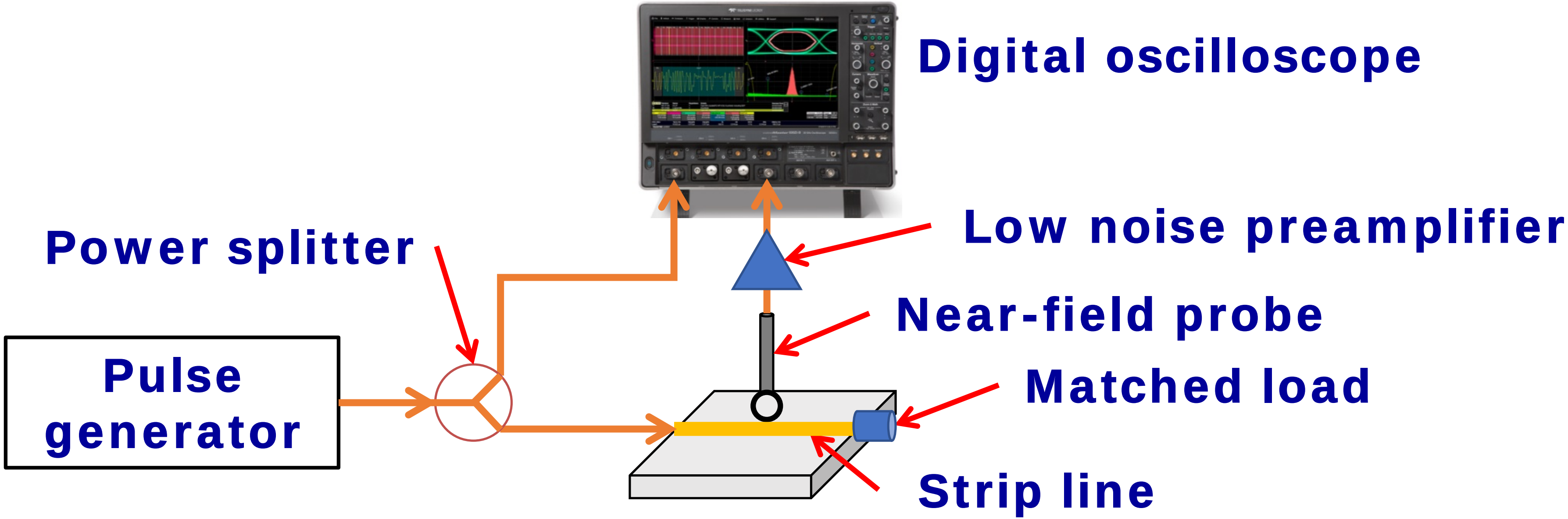
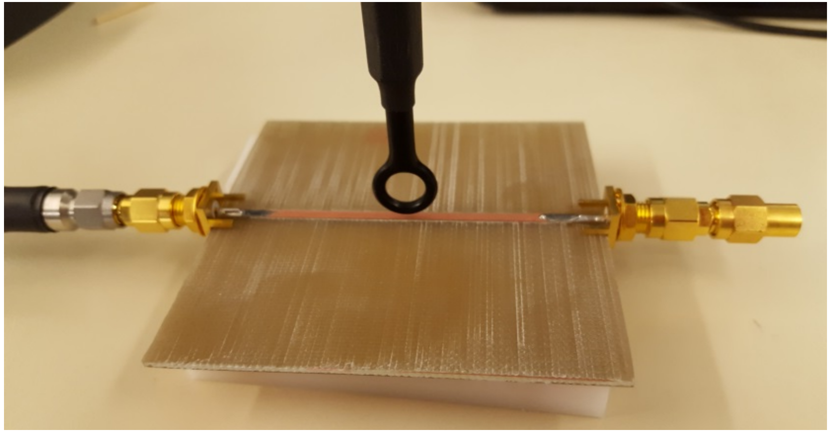
Time-domain analysis

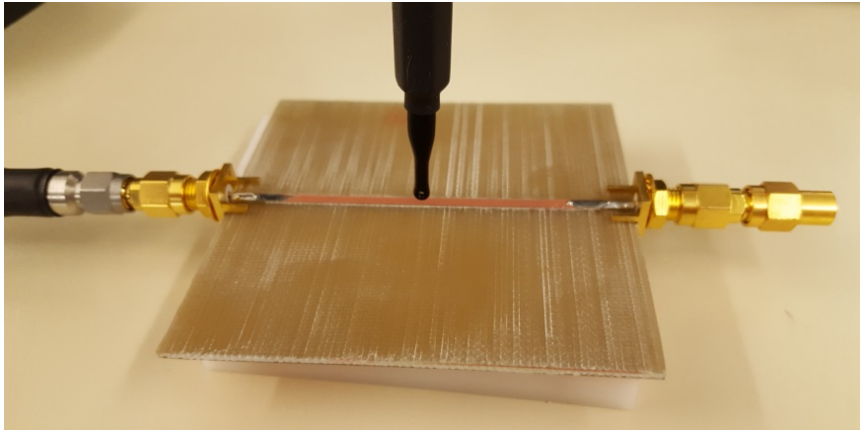
➢ Measurement setup



✓ Sampling rate is 40 GS/s

Time-domain analysis





- ✓ Langer RF-R 50-1
- ✓ ∅ 10 mm

- ✓ Langer RF-R 3-2
- ✓ ∅ 3 mm

Time-domain analysis

➢ The model of the pulse generator signal

$$v_{in}(t) = \sum_{n=-\infty}^{+\infty} A \cdot \mathrm{rect}\left(\frac{t - n \cdot T}{\tau}\right) \qquad \mathrm{rect}(x) = \begin{cases} 1\ for\ |x| \leq 1/2 \\ 0\ for\ |x| > 1/2 \end{cases}$$

✓ **T = 80 ns; τ = 5 ns**

➢ The model of the measured signal

$$v_{out}(t) = v_{in}(t) * h_{pr}(t) + w(t)$$

$v_{in}(t)$ – **input signal**

$v_{out}(t)$ – **measured signal**

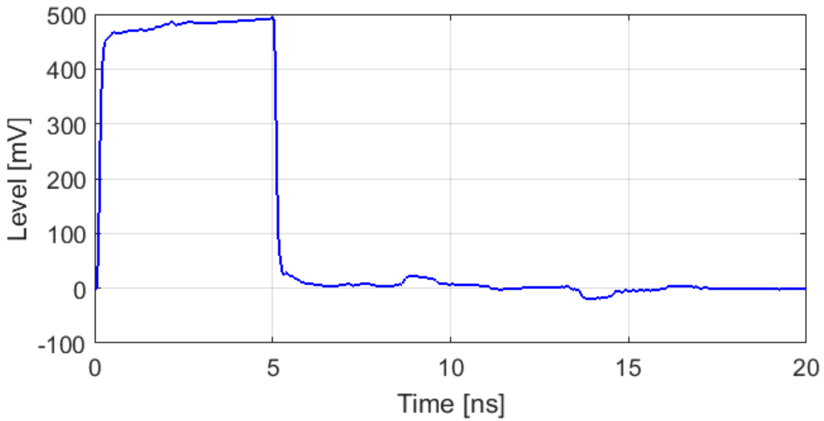
$h_{pr}(t)$ – **impulse response of the probe**

$w(t)$ – **additive noise**

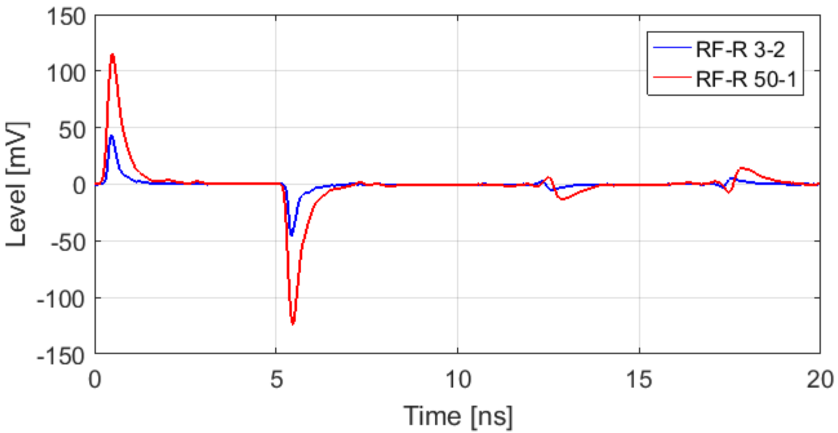
Time-domain analysis

➢ Ensemble averaged measured signals

$$\bar{v}_{out}(t) = \frac{1}{M}\sum_{m=0}^{M-1} v_{out}(t - m \cdot T)\,, 0 \le t < T$$



✓ **Generator signal**

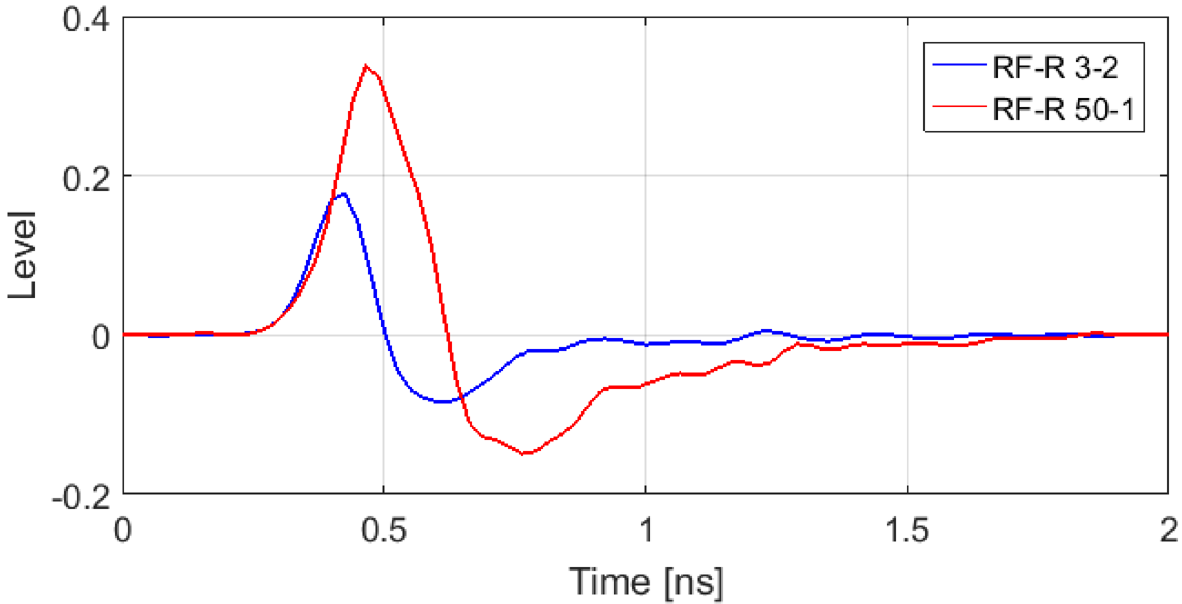


✓ **Mean values of the measured signals**

Time-domain analysis

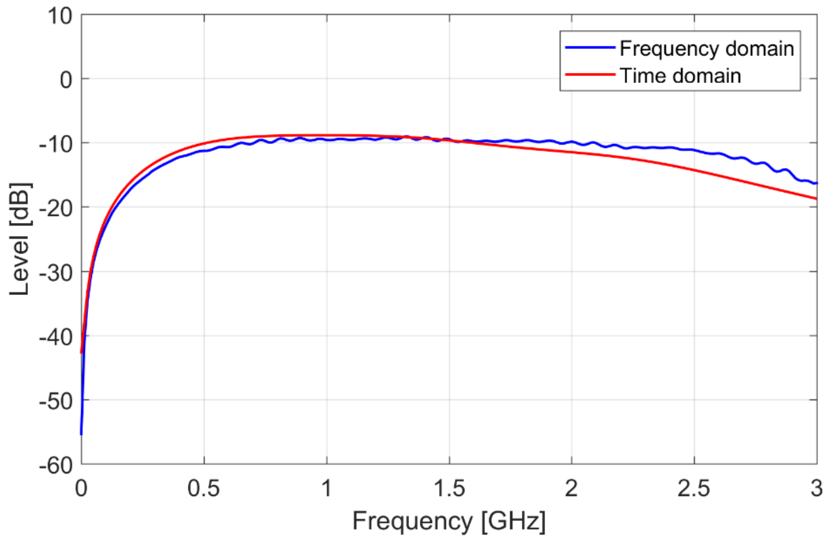
➢ **Impulse characteristics of the near-field probe**

$$h_{pr}(t) = \frac{d\bar{v}_{out}(t)}{dt}$$

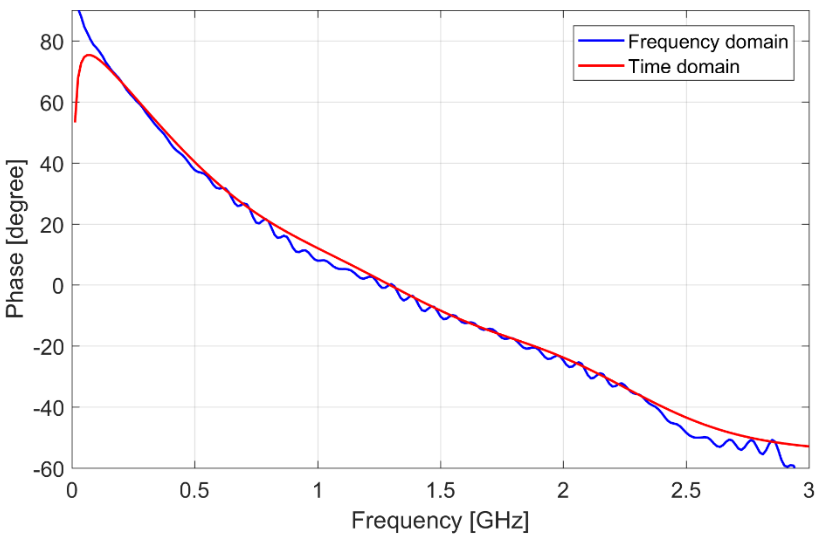


Frequency characteristics

➢ Amplitude



➢ Phase



✓ **Amplitude and phase characteristics are coincident in frequency band up to 3 GHz**

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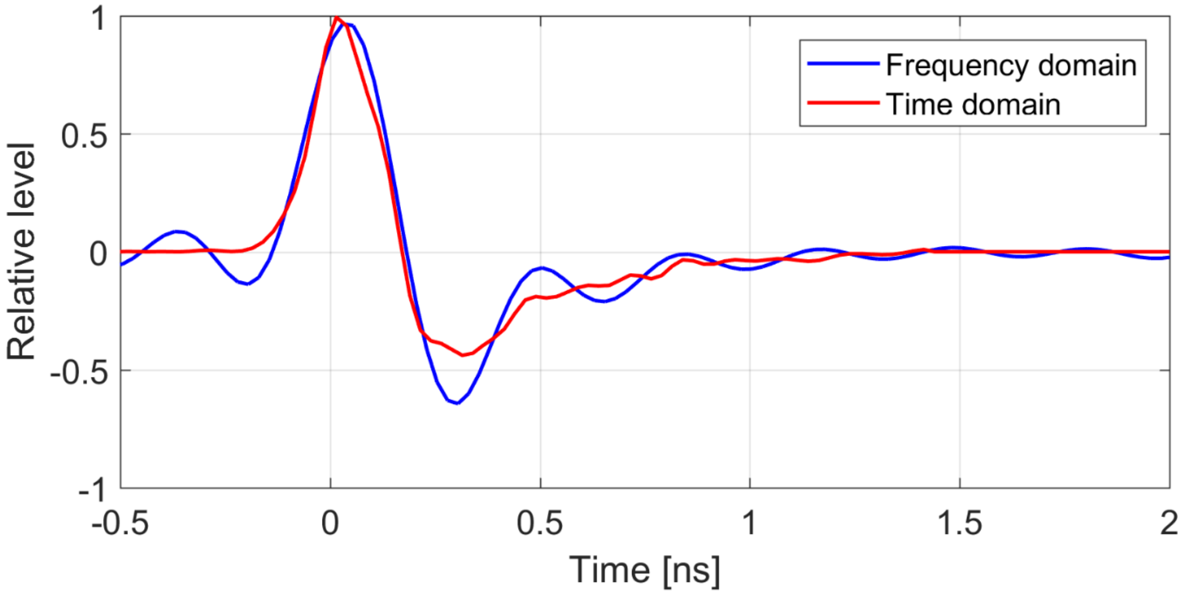
Impulse characteristics



- ✓ **Distinction between extracted impulse characteristics is due to the parameters of the measurement equipment**
- ✓ **Impulse response obtained in time domain is relevant till 5 GHz**

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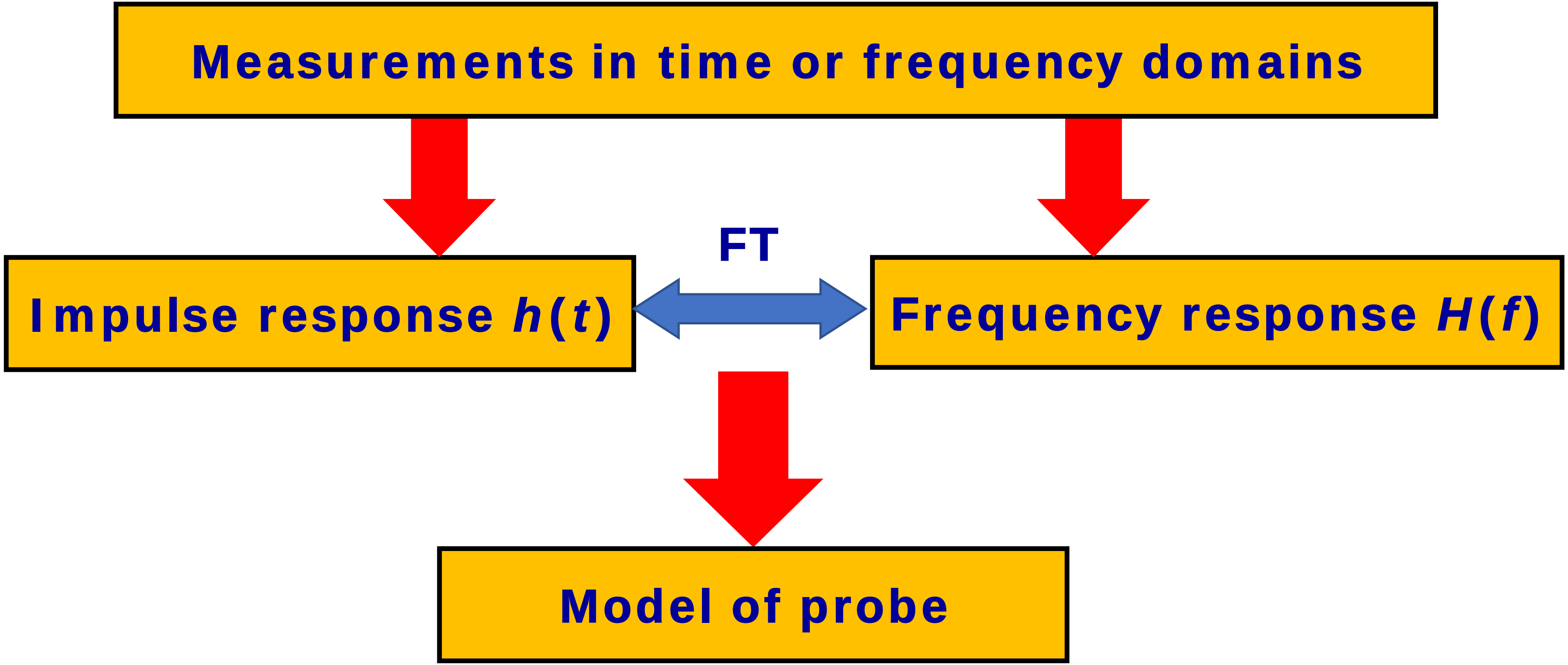
Parametric identification of the probes



Near-field probe characterization

➢ Impulse response

$$h(t) = h^{ENT}(t) + 2\sum_{n=1}^{N/2} |\beta_n| \exp(\sigma_n t) \cos(\omega_n t + \varphi_n)$$

- ✓ $s = \sigma_n + j\omega_n$ *are the poles on complex s-plane*
- ✓ α_n, β_n *are the residues of n-th pole for reaction and response*

➢ Transfer function

$$H(f) = H^{ENT}(f) + \sum_{n=1}^{N} \frac{\beta_n}{j2\pi f - s_n}$$

Matrix Pencil Method

➢ Pole part of the model

$$h_{pole}(t) = \sum_{n=1}^{N} \beta_n \cdot e^{s_n t} \qquad H(s) = H_{ENT}(s) + H_{pole}(s) = H_{ENT}(s) + \sum_{n=1}^{N} \frac{\beta_n}{s - s_n}$$

$$h[n] = h(nT_s), k = 0, 1, \dots, K-1$$

✓ ***T_s is a sampling interval***

$$\mathbf{H}_1 = \begin{bmatrix} h_0 & \cdots & h_{L-1} \\ \vdots & \ddots & \vdots \\ h_{K-L-1} & \cdots & h_{K-2} \end{bmatrix} \qquad \mathbf{H}_2 = \begin{bmatrix} h_1 & \cdots & h_L \\ \vdots & \ddots & \vdots \\ h_{K-L} & \cdots & h_{K-1} \end{bmatrix}$$

✓ **Singular value decomposition:**

$$\mathbf{H}_{1,2} = \mathbf{U}_{1,2} \cdot \mathbf{\Sigma}_{1,2} \cdot \mathbf{V}_{1,2}^{H}$$

✓ **Pole model parameters estimation:**

$$\boldsymbol{Z} = \mathbf{\Sigma}_1^{-1} \cdot \mathbf{U}_1^{H} \cdot \boldsymbol{H}_2 \cdot \mathbf{V}_1$$

Parametric identification of the probes

➢ Pole part of the probe's transfer function:

$$H_{pole}(s) = K\frac{\alpha s}{s^2 + 2\alpha s + \alpha^2 + \beta^2}$$

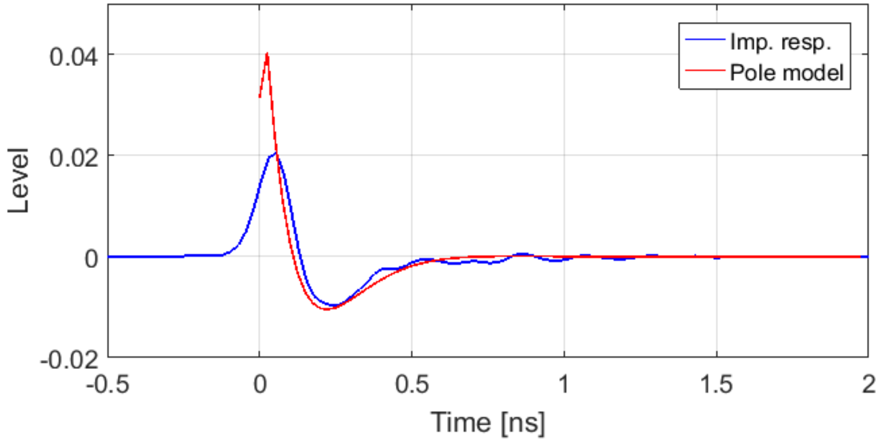
➢ Impulse response:

$$h_{pole}(t) = K\alpha e^{-\alpha t}\left(\cos(\beta t) - \frac{\alpha}{\beta}\sin(\beta t)\right)$$

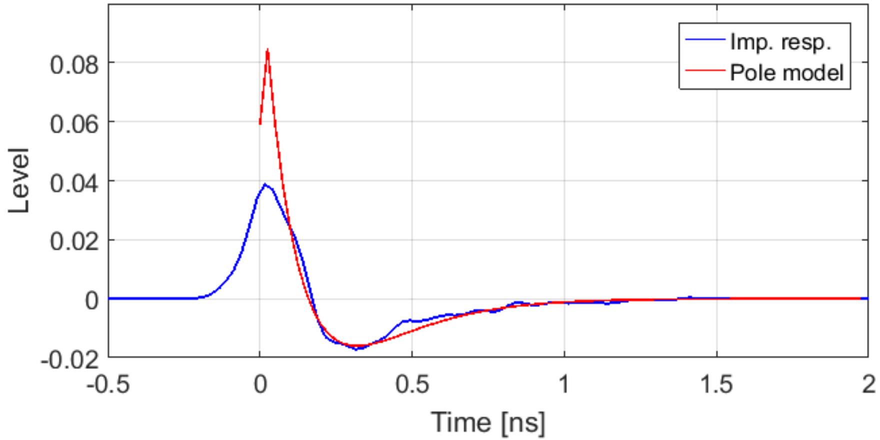
- ✓ **RF-R 3-2 probe:** $K = 0.28$, $\alpha = 2\cdot\pi\cdot1.3\cdot10^9$ rad/s, $\beta = 2\cdot\pi\cdot0.8\cdot10^9$ rad/s
- ✓ **RF-R 50-1 probe:** $K = 0.7$, $\alpha = 2\cdot\pi\cdot1.0\cdot10^9$ rad/s, $\beta = 2\cdot\pi\cdot0.05\cdot10^9$ rad/s

Parametric identification of the probes

➢ **Impulse characteristics of the near-field probes**



✓ **RF-R 3-2 probe**



✓ **RF-R 50-1 probe**

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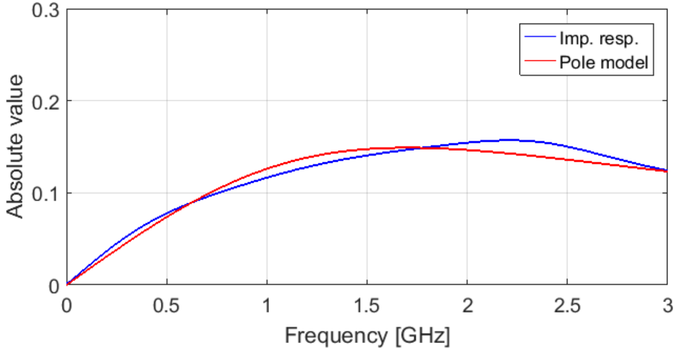
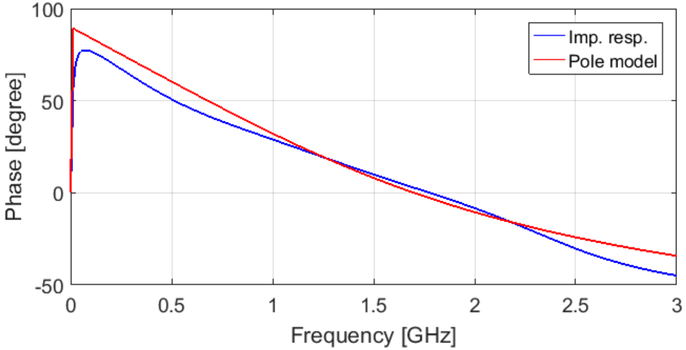
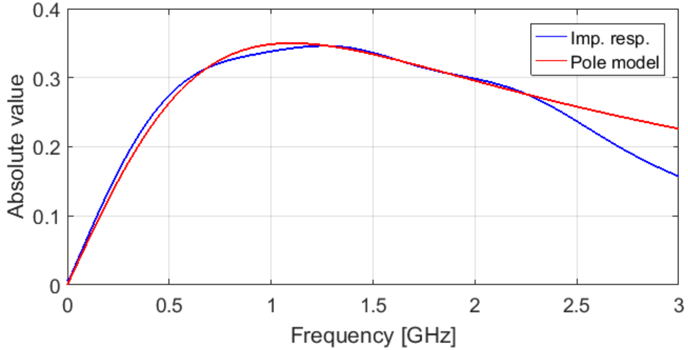
Parametric identification of the probes

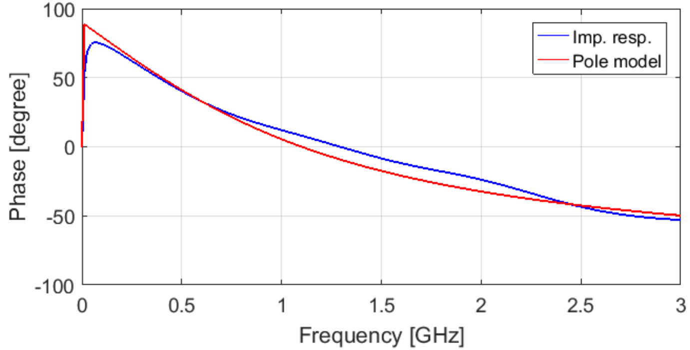
➢Frequency characteristics of the near-field probes





✓ **RF-R 3-2**





✓ **RF-R 50-1**

Agenda

- Motivation
- Near-field probe characterization
- **Signal processing of spread-spectrum signals**

Spread-spectrum signals

- Most digital transmission systems (TV and radio broadcasting, mobile phone systems) operate at frequencies that are regulated. In order to limit interference, agencies such as the Federal Communications Commission in the United States have put strict limits on the energy that a device may emit.
- Many systems therefore use a spread spectrum (SS) PLL, which adds a small amount of low-frequency modulation to the central clock source. However, it does not reduce the total emissions of the system.
- If the modulation parameters are chosen carefully such that all parts of the system can track the spread spectrum clock, the system performance is not affected; typical values are 0.5% and 30 kHz.

Mathematical model of SS clock signal

- ✓ **The initial clock sequence accompanying the data coding procedure can be assumed as a square wave with predefined frequency f_0 and can be represented as follow:**

$$s(t) = A\,\mathrm{sign}\,[\cos(2\pi f_0 t + \theta_0) + a] = \begin{cases} 1, & \cos(2\pi f_0 t + \theta_0) + a \geq 0 \\ -1, & \cos(2\pi f_0 t + \theta_0) + a < 0 \end{cases}$$

where $-1 < a < 1$ is a constant using for adjusting the relative pulse duration of the clock sequence, *A* is the amplitude of the clock signal, θ_0 is the initial phase of the harmonic.

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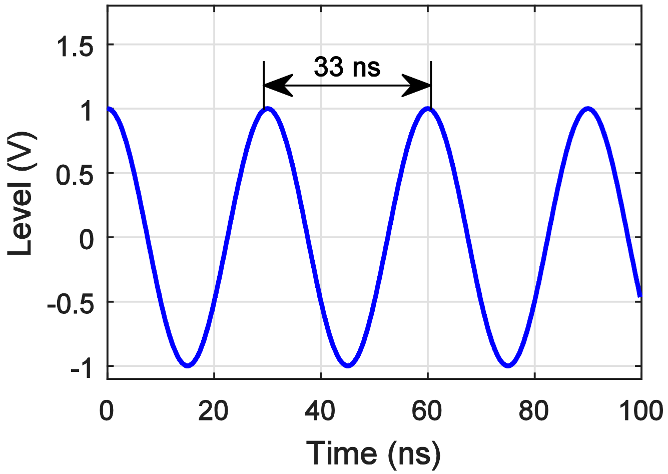
Mathematical model of SS clock signal

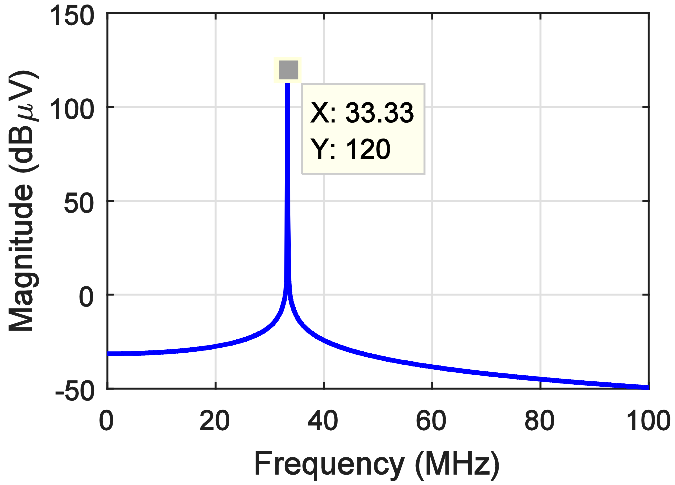
- ✓ One of the widely used realization of the spreading spectrum technology is a periodical angular modulation of the clock sequence. If the modulating function $f(t)$ describing the instantaneous frequency of the fundamental harmonic f_0 of the clock sequence is known, the resultant angular modulated clock signal can be written in the form:

$$v(t) = A\,\mathrm{sign}\left[\cos\left(2\pi f_0 t + 2\pi\int_0^t f(\xi)d\xi + \theta_0\right) + a\right]$$

Mathematical model of SS clock signal

➢ **An example the unmodulated fundamental clock harmonic**



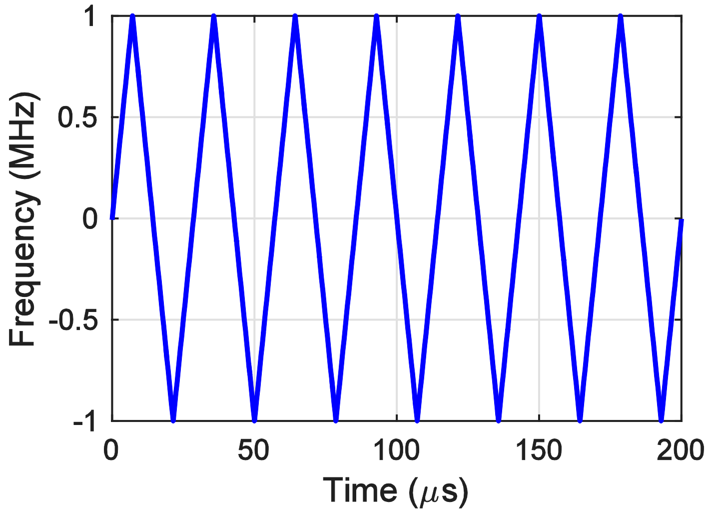


✓ **Fundamental clock harmonic**

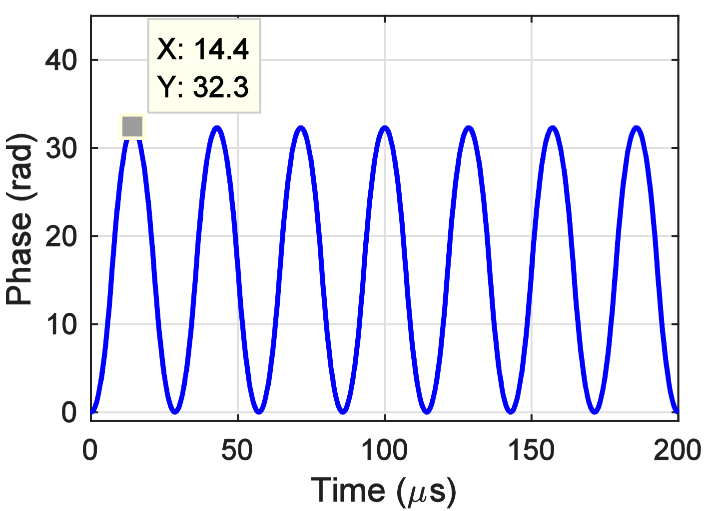
✓ **Spectrum of the fundamental clock harmonic**

Mathematical model of SS clock signal

- The modulating function $f(t)$ has a triangular shape with the frequency deviation $f_d = 2\ \mathrm{MHz}$ and the period of modulation $T_m = 28.6\ \mu\mathrm{s}$



✓ Frequency modulating function $f(t)$



✓ Instantaneous phase of the angular modulated harmonic

Mathematical model of SS clock signal

- The time-frequency spectrogram of the spread spectrum clock signal can be obtained by using the windowed short-time Fourier transform:

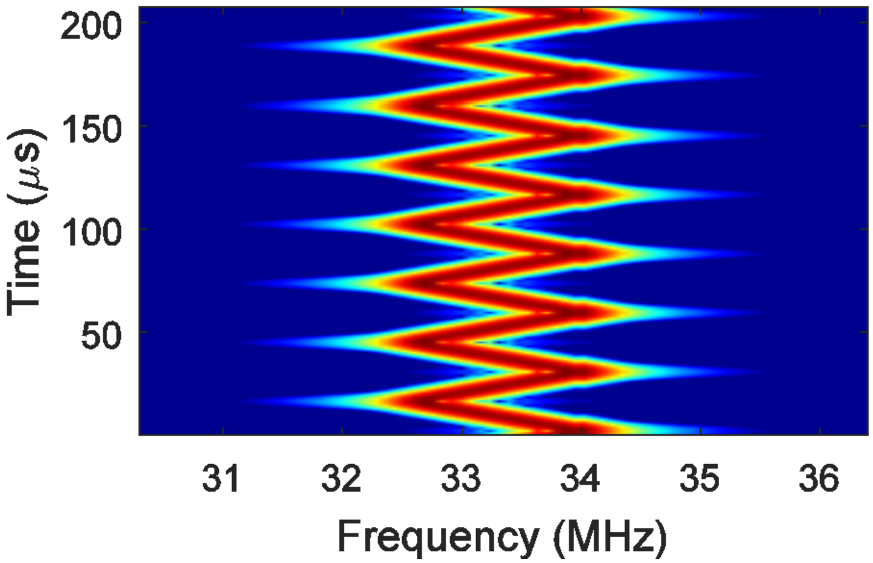
$$V(f,t) = \int_{0}^{T_W} v(\tau - t)\, w(\tau) e^{-j2\pi f\tau} d\tau,$$

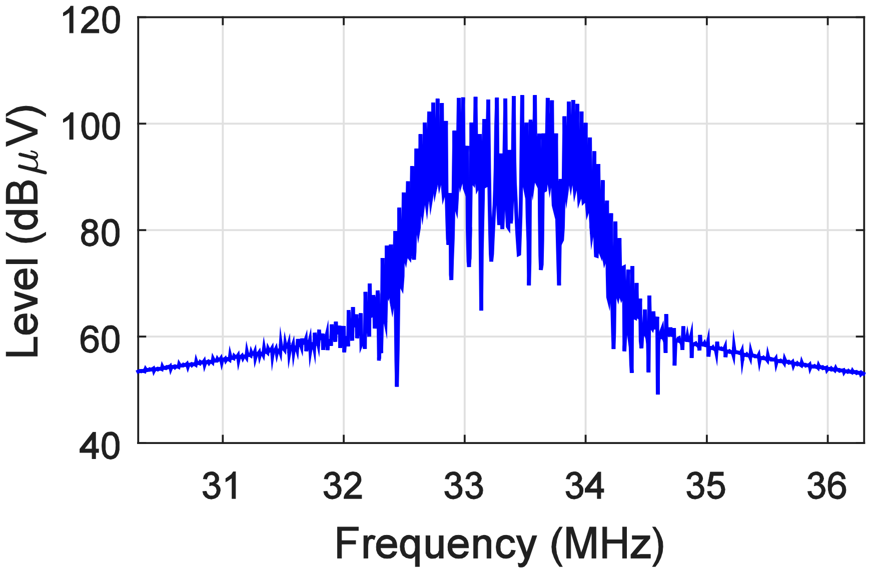
where $w(\tau)$ is Blackman-Harris window with the duration T_W.

- The Fourier spectrum of the clock signal

$$V(f) = \int_{-\infty}^{\infty} v(t) e^{-j2\pi f t} dt$$

Mathematical model of SS clock signal





✓ Time-frequency spectrogram of the clock harmonic

✓ Fourier spectrum of the clock harmonic

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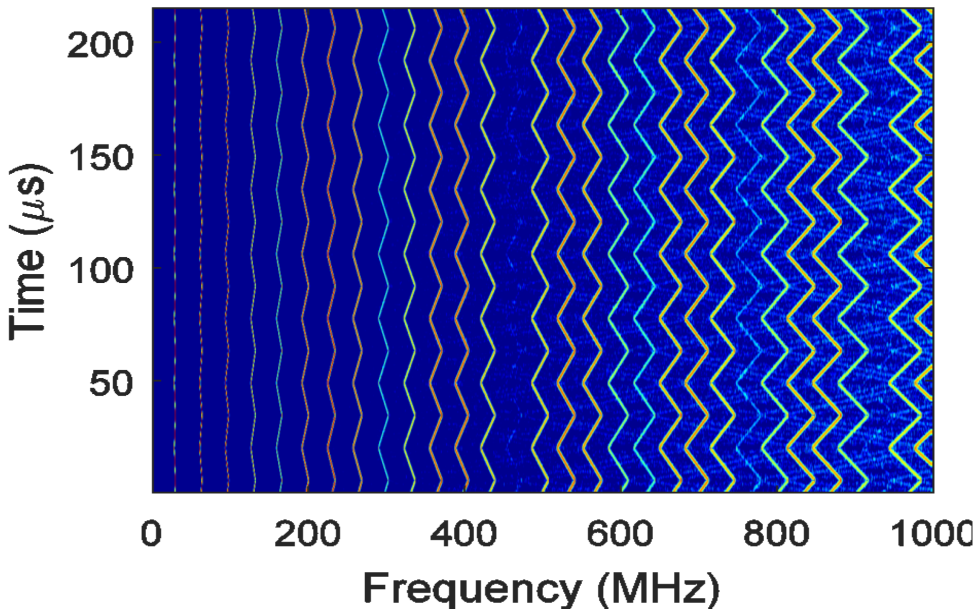
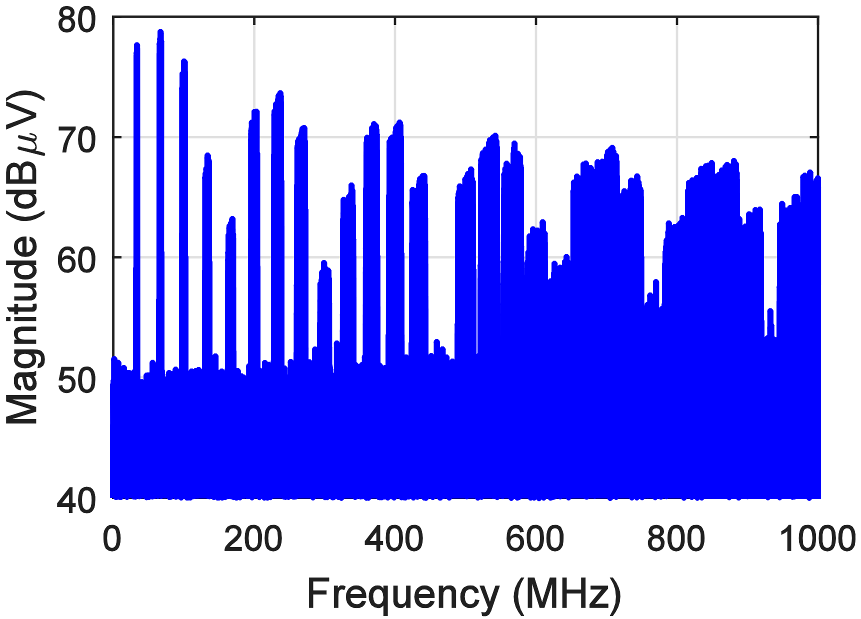
Mathematical model of SS clock signal



✓ The time-frequency spectrogram of the clock signal model



✓ The Fourier spectrum of the clock signal model

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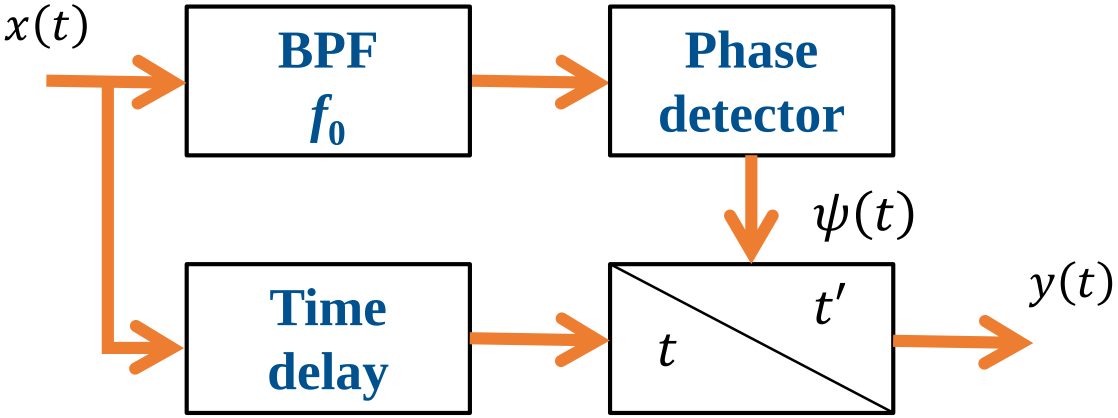
De-spreading algorithm

- Block-diagram for de-spreading procedure

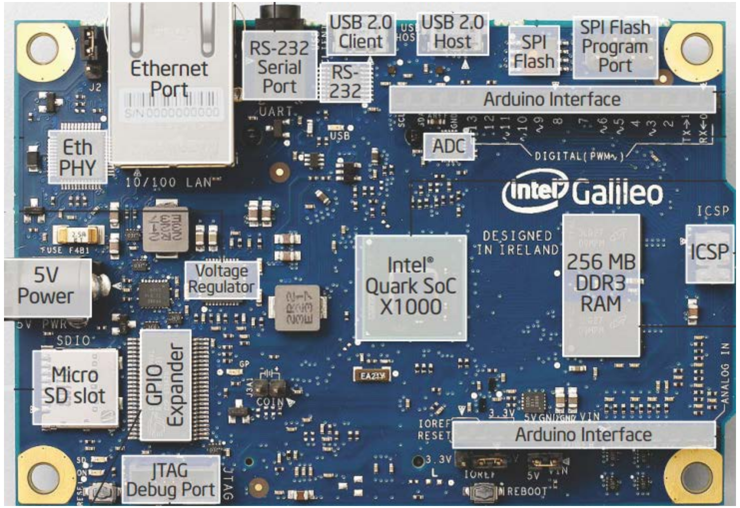


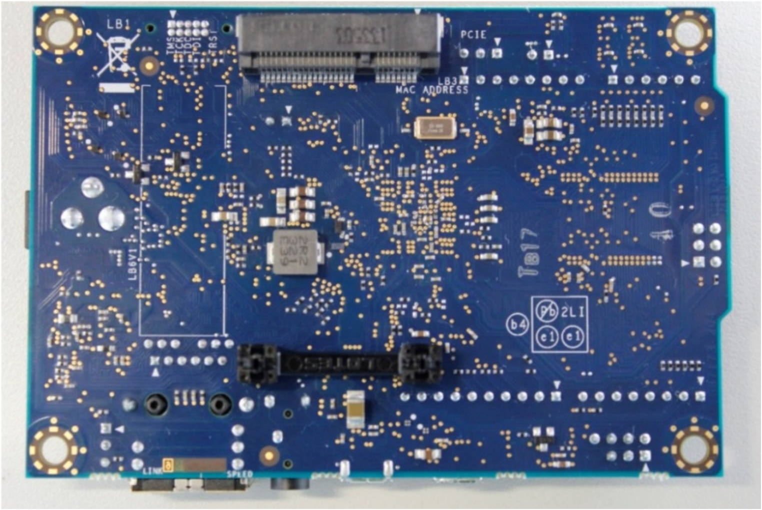
- ✓ **Corrected time**

$$t' = t + \frac{\psi(t)}{2\pi f_0}$$

Numerical example

➢ Arduino Intel Galileo





✓ **Test mode: data transferring between CPU and internal memory**

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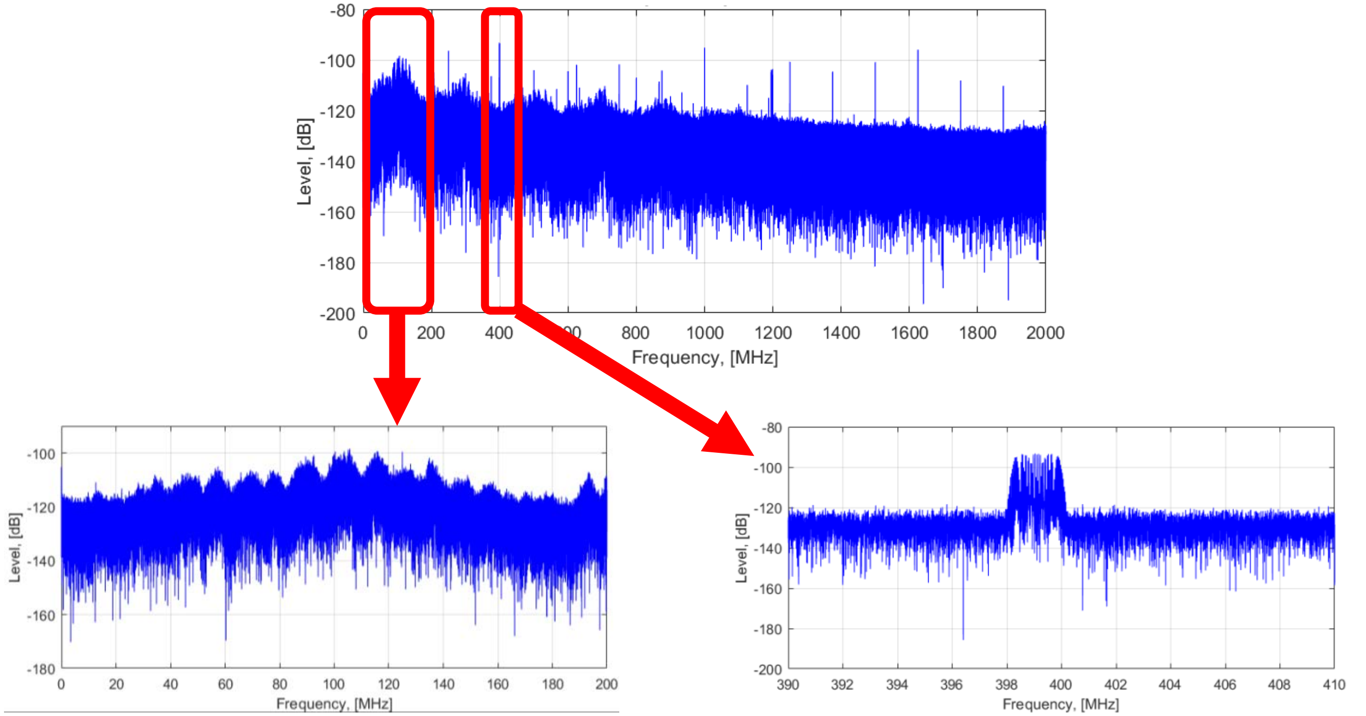
- ➢ **Frequency-domain of EM emissions**



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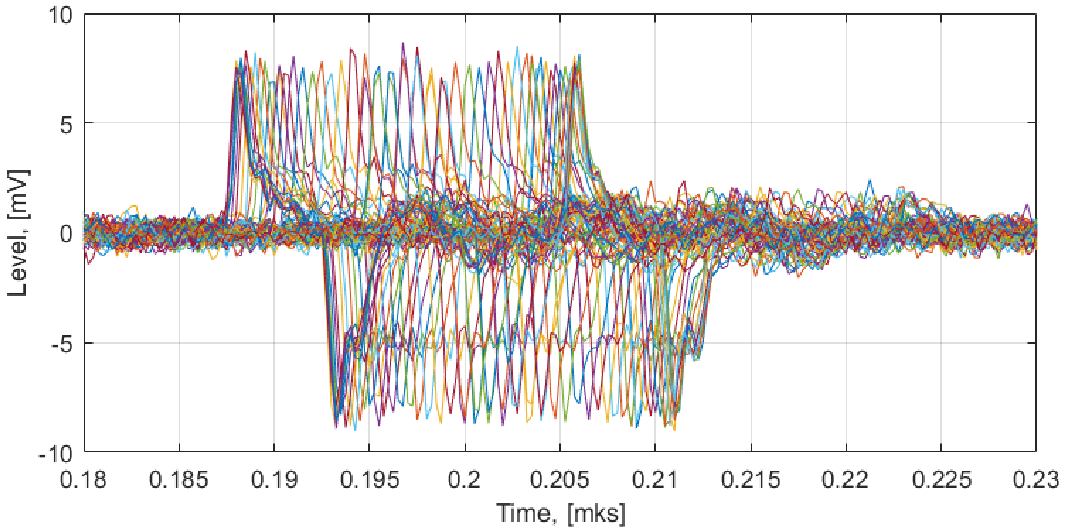
➢ Ensemble of pulses



✓ **Pulses are shifted along the time in the interval equal to 20 nsec**

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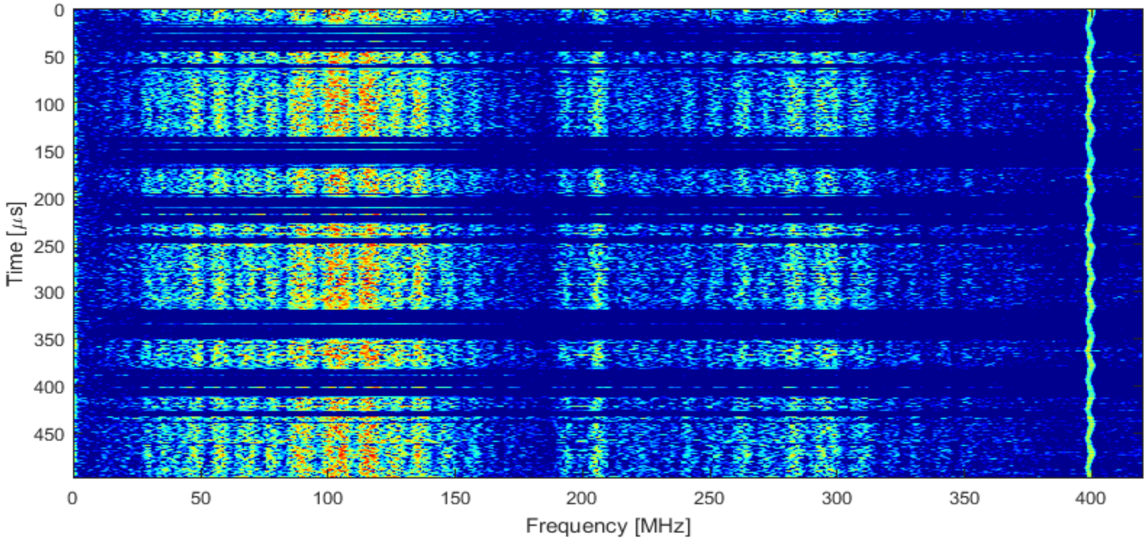
➢ **Spectrogram of EM emissions**



✓ **Ultra-wideband spectrum of short pulses**

✓ **Clock synchronization continuous component**

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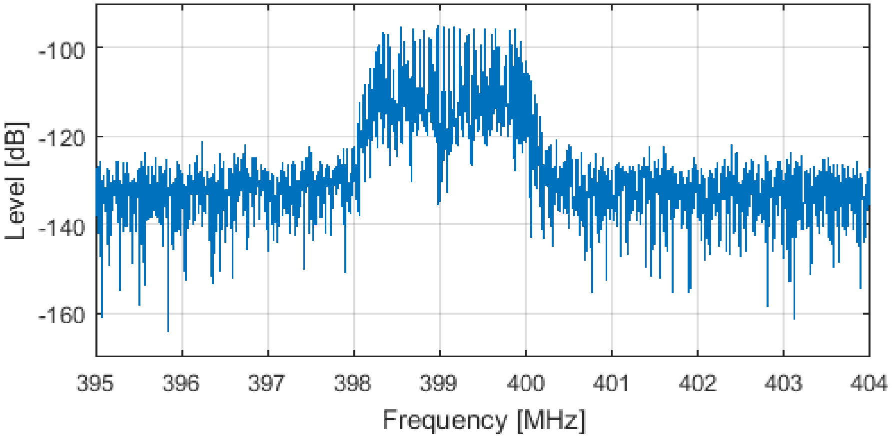
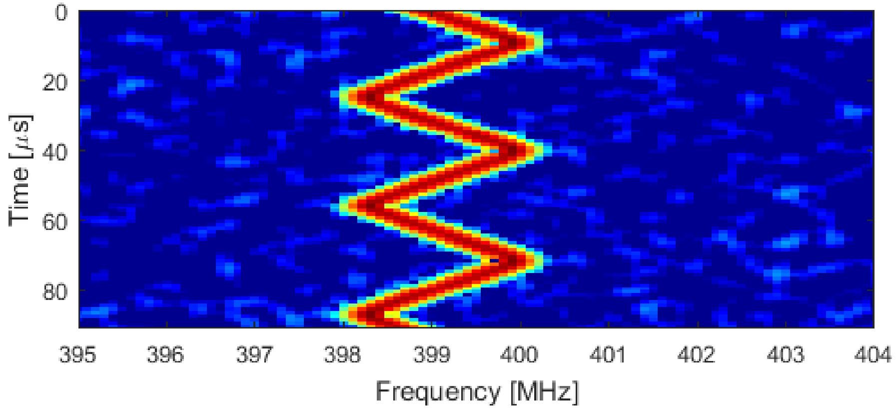
➢ Amplitude spectrum



➢ Spectrum vs. time



- ✓ **Clock frequency 399 MHz**
- ✓ **Frequency deviation 1 MHz**
- ✓ **Triangular waveform frequency 32 kHz**
- ✓ **Spread spectrum technology**

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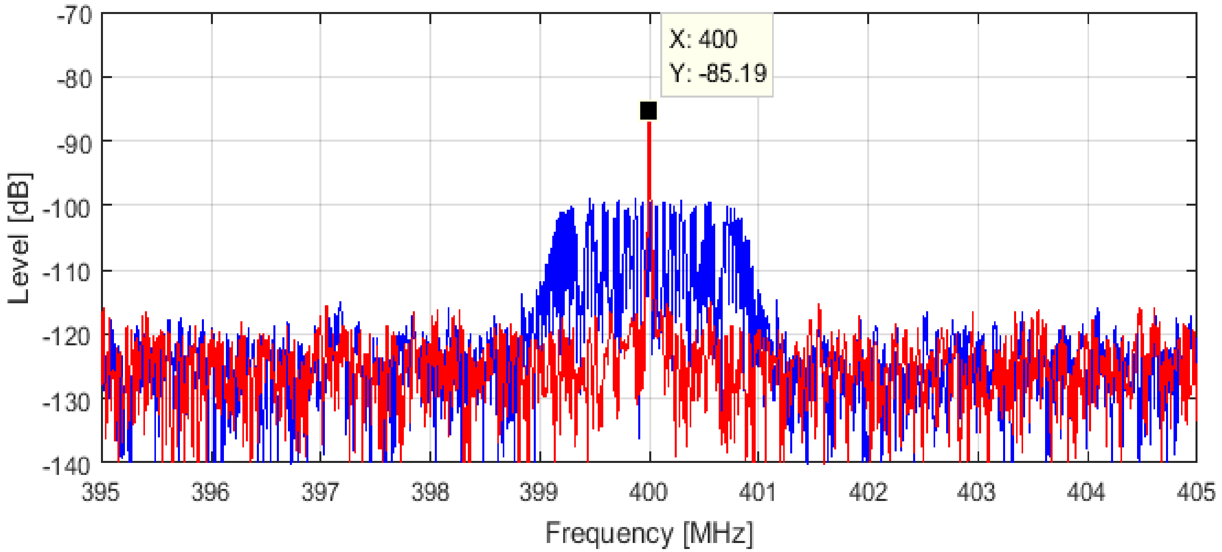
➢ Amplitude spectrum of clock signal



✓ **The recovery of the demodulated clock waveform and its resampling in accordance with the sampling rate of the oscilloscope**

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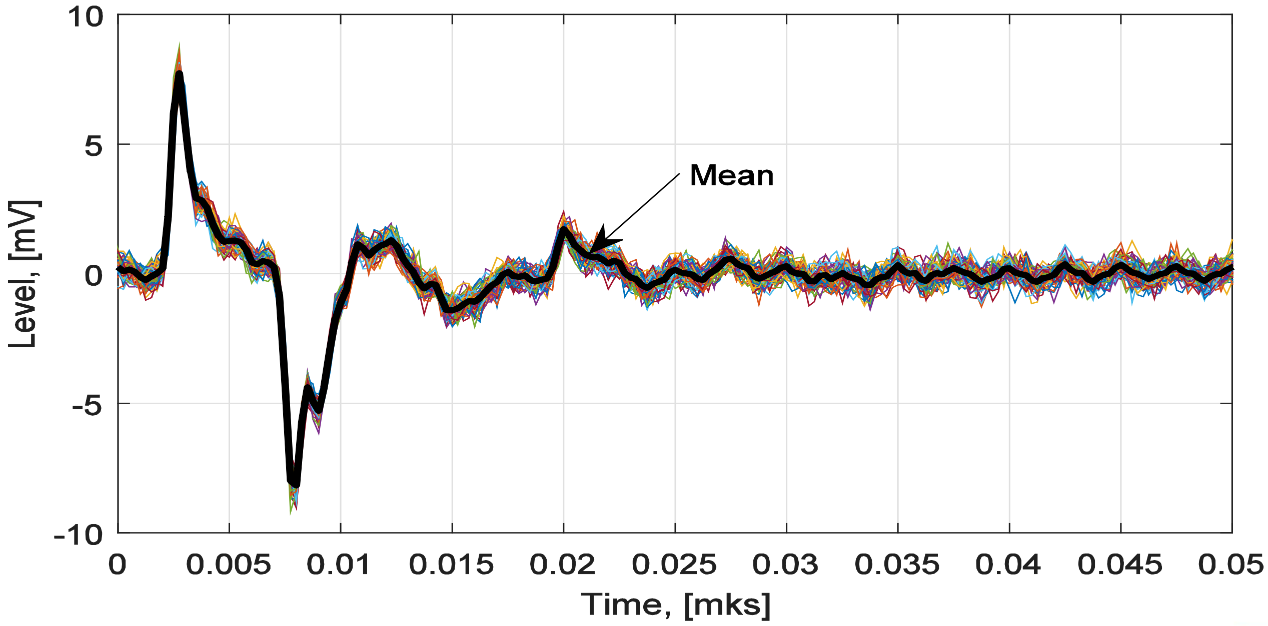
➢ Ensemble averaged signal

$$\mu_X[n] \triangleq E\{X[n]\} = \mu_X[n + kN], \forall k \in \mathbb{N}$$



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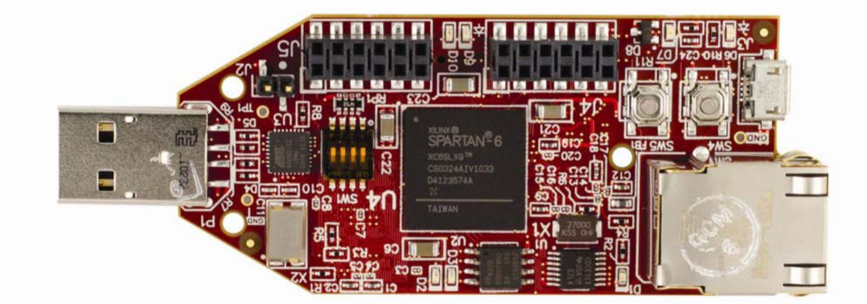
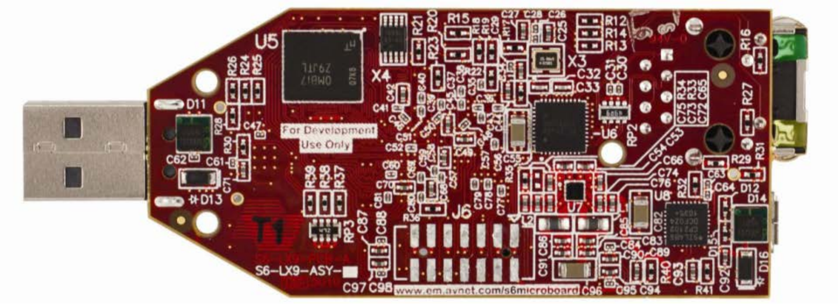
Numerical example

➢ **Spartan-6 FPGA LX9 Micro Board**

✓ **Front view**



✓ **Back view**



✓ **Test mode: filling the DDR memory by “1”**

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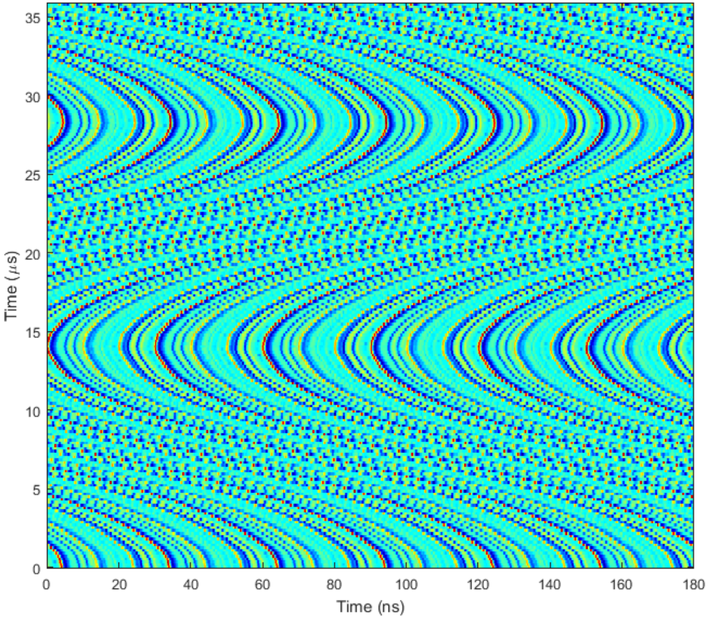
Spartan-6 FPGA LX9 Micro Board

➢ Time evolution of the clock signal



✓ **Period of clock frequency modulation is 28.6 μs**

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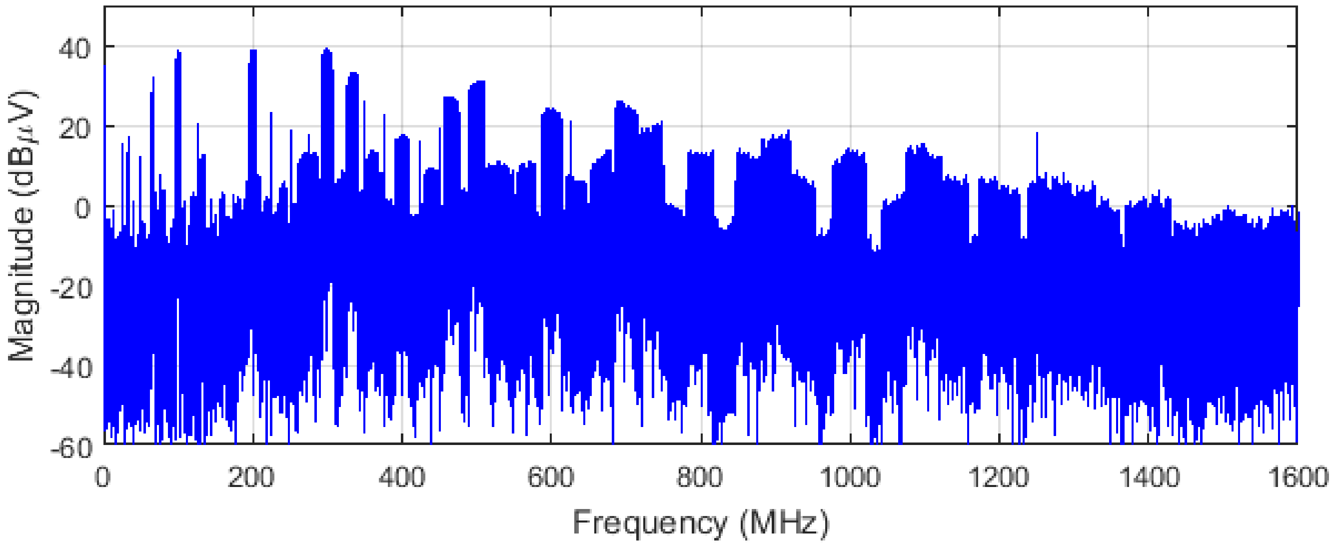
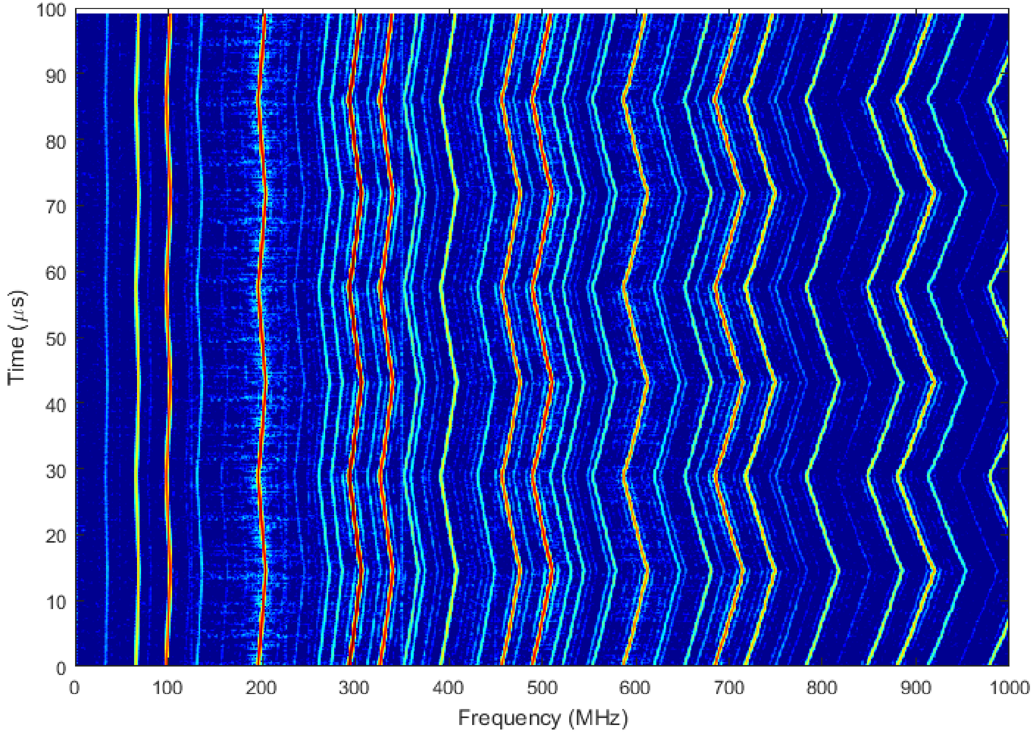
- ➢ **Frequency-domain analysis of EM emissions**



✓ **Clock frequency modulation is used for spreading spectrum**

Spartan-6 FPGA LX9 Micro Board

➢ **Periodogram of EM emissions**



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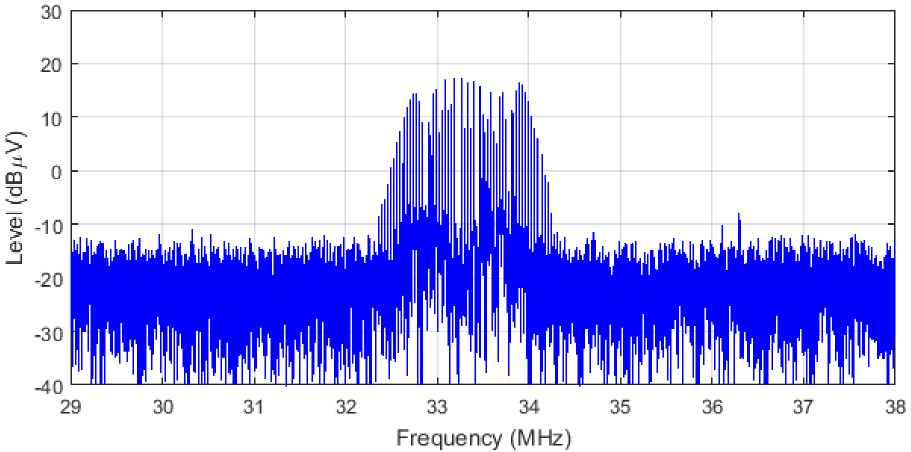
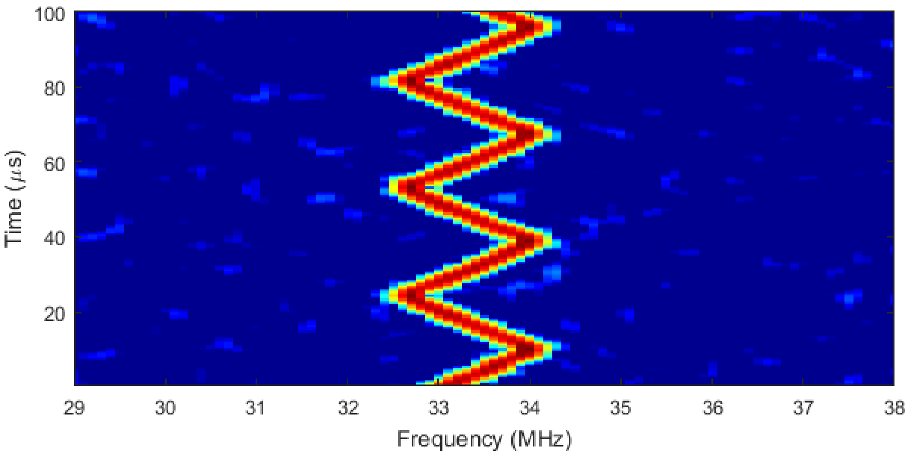
➢ Amplitude spectrum



➢ Periodogram



- ✓ **Fundamental clock frequency is 33.3 MHz**
- ✓ **Frequency deviation is 0.66 MHz**
- ✓ **Triangular waveform frequency is 35 kHz**

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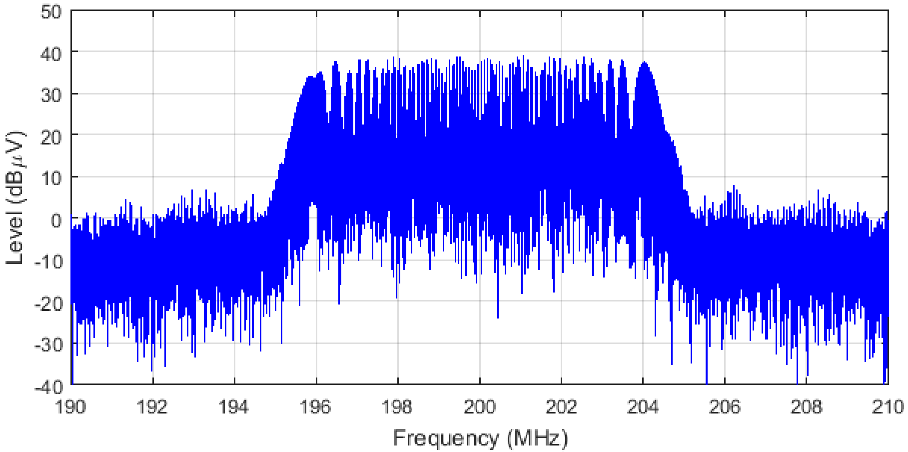
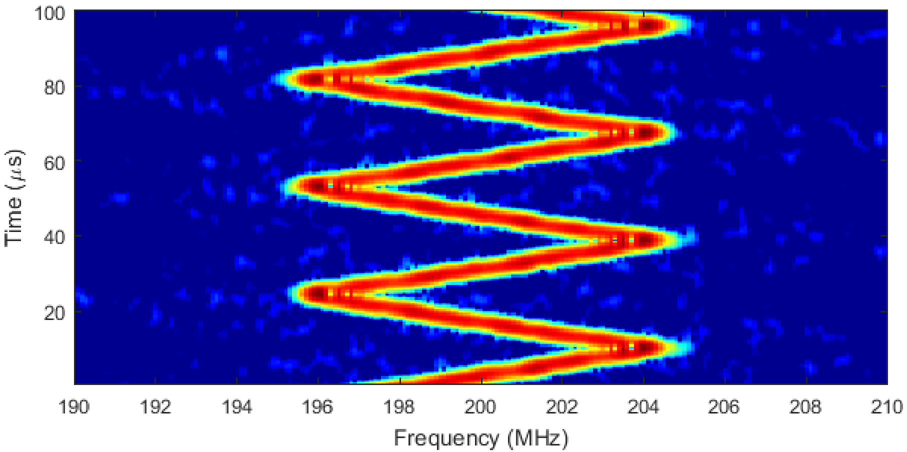
➢ Amplitude spectrum



➢ Periodogram



✓ **Central frequency is 200 MHz**

✓ **Frequency deviation is 4 MHz**

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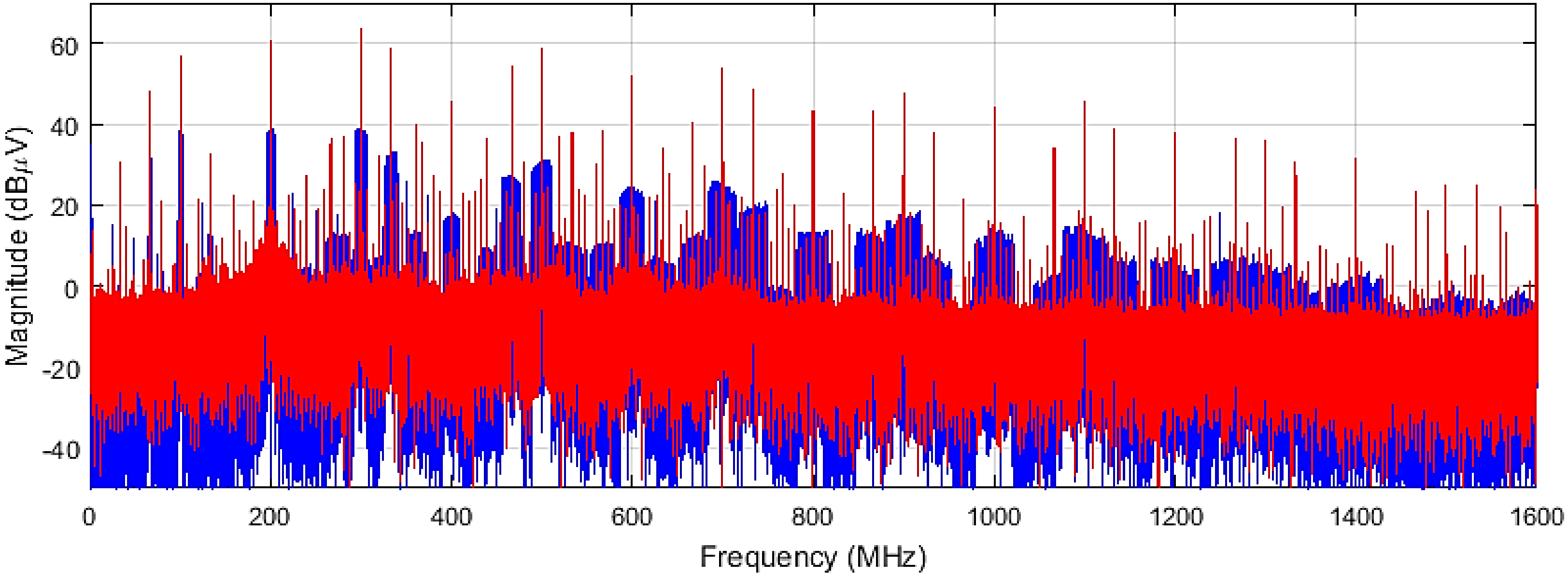
- Amplitude spectrum after clock signal de-spreading



Thank you for your attention!