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TEST OF 10 GHz sin-cosin MICROWAVE REFLECTOMETER ON CASTOR

Žáček F., Kletečka P.

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Žáček F., Klečka P.
Institute of Plasma Physics, Za Slovankou 3, 182 00 Prague 8,
Czech Republic

INTRODUCTION

Measurements of the plasma density fluctuations is the basic requirement for the experimental study of anomalous transport in tokamaks [1]. While such measurements are currently carried out in the scrape-of-layer of tokamaks using Langmuir probes, contactless methods are needed for the measurement deeper in the plasma. One of such method is microwave reflectometry working on the principle of probing wave reflection on the plasma layer, where the refractive index of the wave goes to zero (see e.g. overview of the method in [2]). The method is relatively simple and under some conditions it exhibits a sufficient accuracy. The application of the method, within the frequency region 10-40GHz, is envisaged also on the tokamak CASTOR.

This report brings the first results obtained on CASTOR. The first section shows the situation concerning the tokamak CASTOR plasma. Further, it describes briefly the construction of the first reflectometric device working on the fix frequency 10,26 GHz (section 2). In section 3 it is demonstrated the proper function of this device using so called sin-cosin detection system [3] and the results obtained are discussed.

1. MICROWAVE REFLECTOMETRY ON THE CASTOR

Reflectometry is based on injection of a microwave beam into the inhomogeneous plasma (usually in the direction of the density gradient, i.e. perpendicularly to the toroidal magnetic field $\vec{B}_{tor}$ in tokamaks). In the case that the index of refractivity is approaching to zero for the given frequency of the propagating probing wave, the total reflection of the beam occurs. If the plane geometry can be supposed, the phase of the reflected beam bears an information about the position of the reflecting layer.

Because two different perpendicular ($\vec{E}_{wave} \perp \vec{k}_{wave}$, with $\vec{E}_{wave}$ and $\vec{k}_{wave}$ the electric field and the wave vector of the probing wave) electromagnetic waves with different phase velocity (i.e. different index of refractivity) can propagate in the magnetoactive plasma in dependence on their polarization, the place of reflection depends on the polarization of the incoming microwave beam as well.

In the case of so-called O-mode ($\vec{E}_{wave} \parallel \vec{B}_{tor}$) the reflection occurs, where the plasma frequency $f_p[Hz] = (ne^2/m\varepsilon_o)^{1/2}$ raises to the probing wave frequency f_{wave} (the plasma density reaches so-called critical density $n_{crit}[m^{-3}] = 1.24 \times 10^{16} f_{wave}^2[GHz]$).

In the case of so-called X-mode ($\vec{E}_{wave} \perp \vec{B}_{tor}$) two cut-offs can appear at the frequencies $f_{U,L}$ (so called upper and lower cut-offs): $f_{U,L} = \pm f_c/2 + [(f_c/2)^2 + f_p^2]^{1/2}$, where $f_c(r) = 28 B_{tor}(0)/(1 + r/R)[GHz, T]$ is the radially depending electron cyclotron frequency ($B_{tor}(0)$ is the value of the magnetic field on the tokamak axis, R is the tokamak major radius).

Comparison of the phases of the reflected wave (see further Fig.2) with a reference wave gives information about the location of the reflecting layer, if many different probing frequencies are used [2], or about the fast movement of this reflecting layer (or about its fluctuations), if the only *one* fix frequency is used. The second case will be applied on the CASTOR.

The situation, concerning the tokamak CASTOR plasma, is given in Fig. 1 for $B(0)_{tor} = 1T$. Fig. 1a shows the frequencies $f_p, f_{U,L}$ and f_c for higher value of the central plasma density $n(0) = 10 \times 10^{18} m^{-3}$, fig. 1b for lower value $n(0) = 5 \times 10^{18} m^{-3}$. The density radial dependence is supposed to be parabolic in both cases: $n(r) = n(0) \cdot (1 - r^2/a^2)$, where a is the minor plasma radius. It is possible to see from the figure that using the frequencies of probing wave 10-40GHz and both O and X polarizations, nearly the whole plasma radius will be accessible.

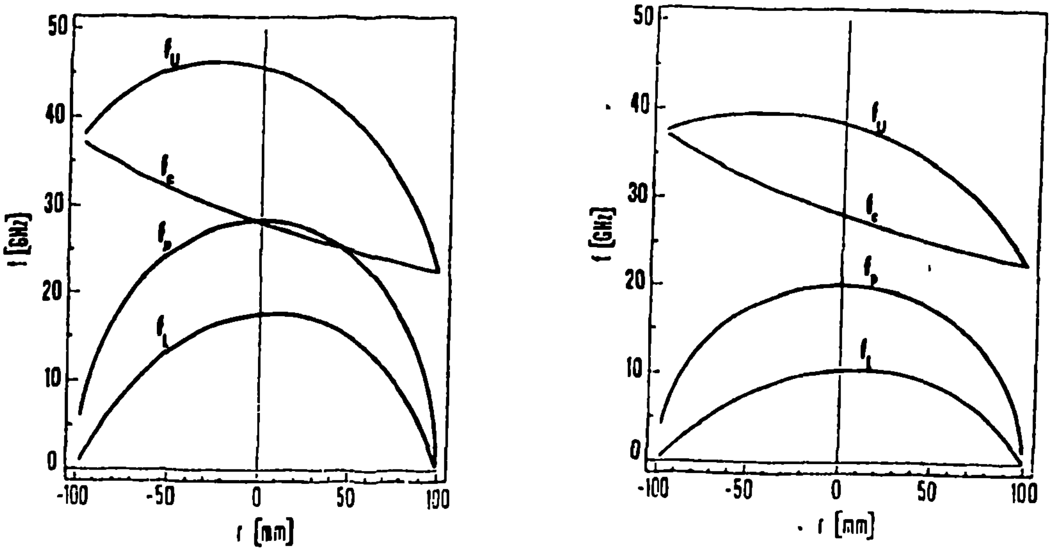

Figure 1: Radial profiles of the cut-off frequencies f_p (O-mode), $f_{U,L}$ (X-mode) and cyclotron frequency f_c in CASTOR for parabolic density distribution with central density value a) $10 \times 10^{18} m^{-3}$, b) $5 \times 10^{18} m^{-3}$.

2. REFLECTOMETER WITH sin-cosin PHASE DETECTION

Heterodyne scheme and electronic phase counters are usually used for measurement of the phase shift in the microwave interferometers (average density measurement). Namely, the phase of the probing wave, *passing through* the plasma, is changing relatively slowly (the *total* number of electrons is measured). However, such systems have low time resolution and they are therefore inconvenient for the measurement of much faster phase changes of the *reflected* signal, given by *local* density fluctuations. For this reason, a homodyne scheme working with two detectors (so called sin-cosin scheme), is usually used for the reflectometric measurements [3].

The Fig. 2 shows schematically such reflectometer built for the CASTOR. As a generator a Gunn oscillator with power $200mW$ is used. There are two interferometric arms for measurement of phase shift φ caused by plasma, with two independent mixers 1 and 2 (both reference $\vec{E}_r$ and measured $\vec{E}_m$ waves are equally splitted using hybrid T-junction). The information about the phase shift φ is involved in the measured (in this case reflected) wave $\vec{E}_m = E_m(t)sin(\omega t + \varphi)$. Setting a phase shifter PS, placed in the interferometric arm 2, in such position that the mutual phase of waves interfering at the mixer 2 is about 90^o higher as that at mixer 1 and supposing that the both mixer detectors are quadratic and moreover quite identical, the both mixer's signals can be written as follows (from here name "sin-cosin" detection):

$$U_1 \approx E_r^2(1 + \epsilon^2(t) + 2\epsilon(t)cos\varphi)$$
$$U_2 \approx E_r^2(1 + \epsilon^2(t) + 2\epsilon(t)sin\varphi).$$

Here $\epsilon(t) = E_m(t)/E_r$ is amplitude of the measured wave (strongly changing in the time in the case of the plasma, see e.g. further Fig. 3), normalized to the amplitude of the reference wave (steady in the time).

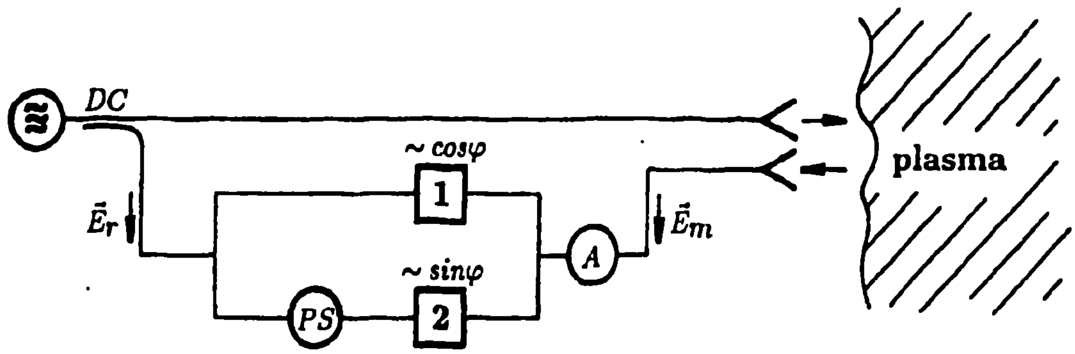

Figure 2: Scheme of the sin-cosin reflectometer working on the frequency $10.26GHz$: DC-directional coupler $-10dB$, A-attenuator, PS-phase shifter, 1 and 2 are mixing detectors.

Taking the AC component of the signals only and arranging the signal's level in such way that $\epsilon(t) \ll 1$, the simple expression for the phase shift φ can be derived:

$$\varphi \doteq arctg(U_2/U_1).$$

In this way, effect of reflected signal amplitude variations can be excluded and determination of the phase shift is reduced to evaluation of the both signals (sin-cosin) ratio only. If $\epsilon(t) \neq 0$, the maximal phase error $\delta\varphi = \epsilon/\sqrt{2}$ can be simply estimated (about 4^o for $\epsilon = -20dB$).

3. TEST OF THE REFLECTOMETER ON THE CASTOR PLASMA

Tokamak CASTOR [1] is small device with $R/a = 0.4/0.08m$ (R is major and a minor plasma radius), toroidal magnetic field $B_{tor} \leq 1T$, plasma current $I_p \leq 30kA$.

plasma average density $\bar{n} \leq 2 \times 10^{19} m^{-3}$ and pulse duration $\tau \leq 40 ms$. A transient recorder with maximum sampling rate $1 MHz$ and memory $4kB$ for each channel has been used for data collection.

The Fig. 3 illustrates the behaviour of the alone reflected signal $U_m \equiv U_1$ from detector 1 (reference signal U_{ref} is disconnected) and plasma average density $\bar{n}$ during the first three milliseconds of the discharge. Before the discharge, the probing wave penetrates through the vacuum chamber and it is reflected on the chamber inner wall (registered signal $U_1 \doteq 15 mV = const$). It may be seen from the figure that the signal reflected from the plasma is strongly fluctuating within roughly two orders during the tokamak discharge.

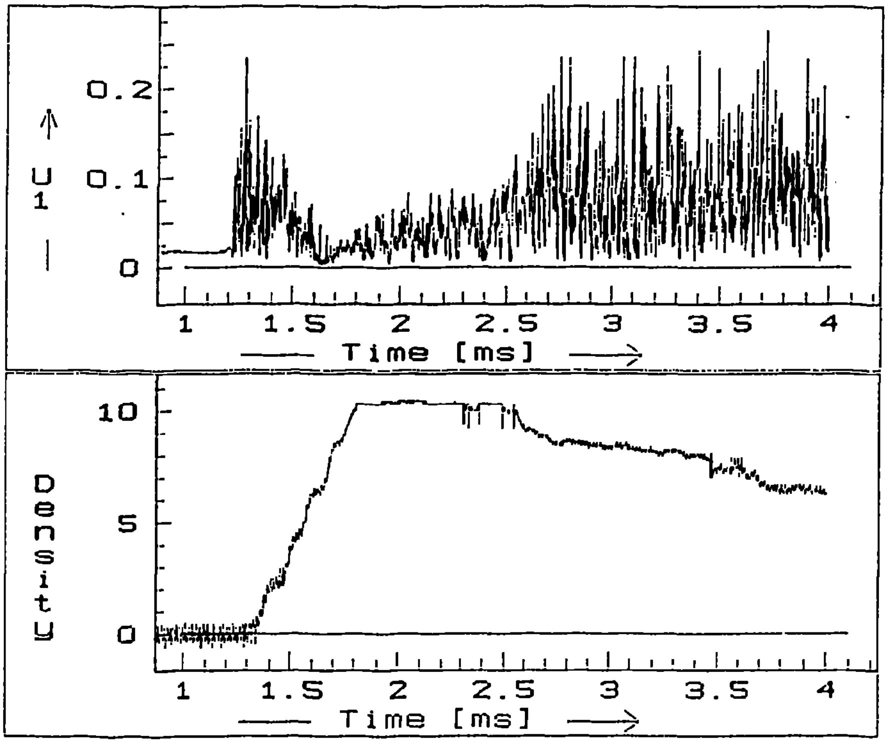

Figure 3: Time course of the reflected signal U_1 in Volts (upper trace) and of the line averaged density $\bar{n}$ in units $10^{18} m^{-3}$ (lower trace) during the first part of the tokamak discharge.

Note, that the maximum of the reflected signal U_1 is comparable with the value of the reference signal ($U_{ref} = 270 mV$, see further interference picture in Fig. 4). To fulfil the requirement $\epsilon \ll 1$ (see foregoing paragraph 2), an attenuation $-20 dB$ (using the attenuator A, see Fig. 2) of the reflected signal has been introduced for the phase measurements given in Fig. 4. It may be seen from the upper trace of this figure, where an absolute value of the interferometric signal U_1 is shown, that condition $\epsilon \ll 1$ is well fulfilled.

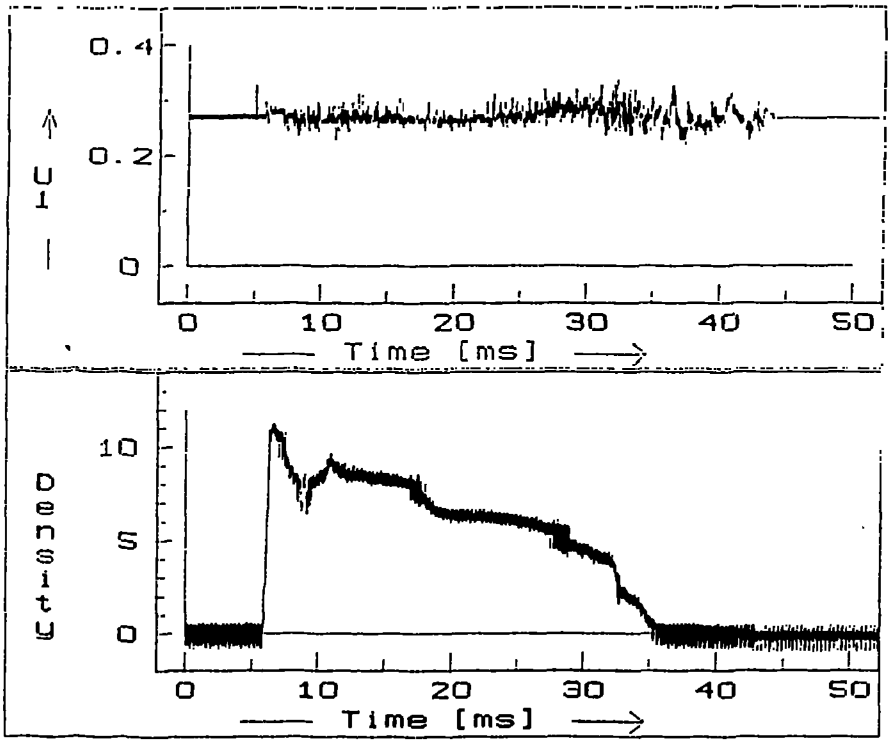

Figure 4: Time course of the interference signal U_1 in Volts (upper trace) and of the line averaged density $\bar{n}$ in units $10^{18}m^{-3}$ (lower trace) during the whole tokamak discharge.

Taking the AC component of signals only, the both interferograms U_1 and U_2 (mutually shifted about 90°) of the measured and reference signals could be registered with correspondingly greater sensitivity. The following serie of Figs. 5-8 shows successively the interferogram U_1 for the discharge beginning (Fig.5), stationary phase (Fig. 6), the late discharge phase (Fig. 7) and discharge decay (Fig. 8). The following results can be driven from these figures:

1. Start-up phase (Fig. 5):
   - at the moment $t \doteq 1.35ms$ the cut-off layer arises in the center of the plasma (see also course of density $\bar{n}$ in Fig. 3);
   - till this moment the probing wave penetrates through the plasma being reflected on the inner liner wall;
   - the scheme is working, therefore, in the regime of double-pass interferometer and line averaged density $\bar{n}$ is measured;
   - about 10 fringes can be read from the interferogram before the cut-off is appearing;

- a very flat radial density distribution during this start-up discharge phase can be deduced from the observed number of fringes, because their maximum number can not exceed 11 (exactly $4a/\lambda_o$, where λ_o is the probing wavelength);
- only after the cut-off layer appearance the scheme starts to work in the regime of reflectometer, which results in the change of the interferogram U_1 character.

2. Quasistationary phase with $\bar{n} \geq 5 \times 10^{18} m^{-3}$ (Fig. 6):
   - owing to the sufficiently high density, the cut-off layer exists just in the front of the transmitting and receiving horns ($n_{cutoff} \doteq 1 \times 10^{18} m^{-3}$);
   - position of this layer is fast fluctuating in the range $\pm 2mm$ (phase changes don't exceed 90°) with the frequency about $5kHz$.

3. The late phase with density decrease $\bar{n} \rightarrow n_{crit}$ (Fig. 7):
   - an uniform movement of the cut-off layer from the periphery to the center is observed;
   - the velocity of this movement is about $15m/s$ (about 4 fringes, which means $6cm$, is measured during $4ms$);
   - even during this movement is the cut-off layer position fast fluctuating $\pm 2mm$ with the frequency about $3kHz$.

4. Discharge decay (Fig. 8):
   - the cut-off layer disappears at the moment $t \doteq 39ms$;
   - after this moment the scheme is working in the regime of interferometer;
   - opposite to the strongly fluctuating signal in the reflectometer regime, no fluctuations of the signal are observed after cut-off disappearance.

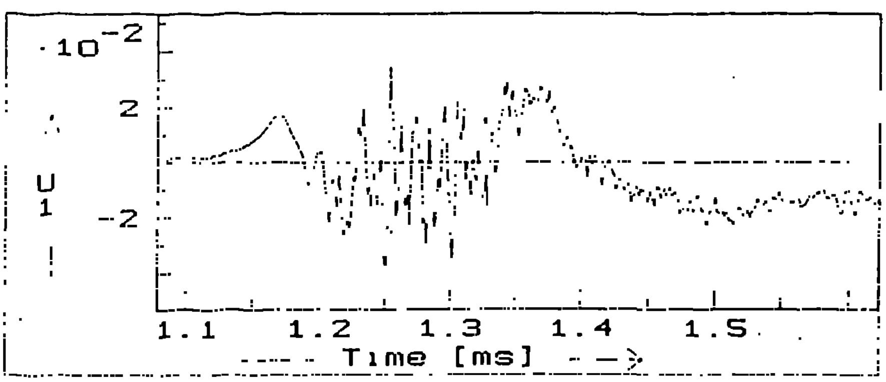

Figure 5: Interferogram U_1 during the start-up phase of the tokamak discharge.

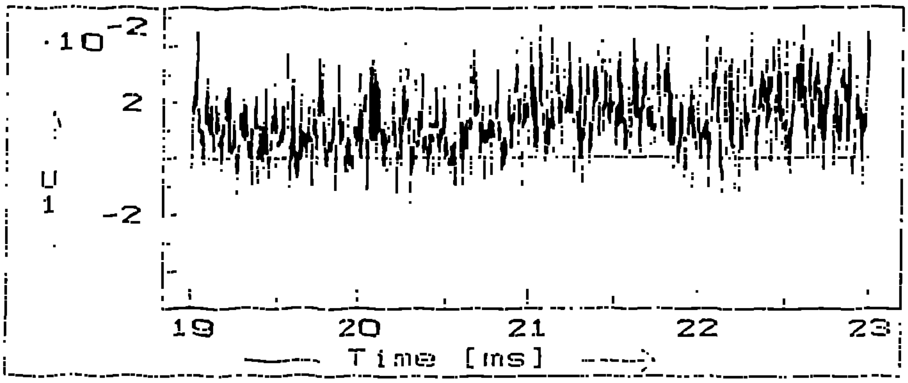

Figure 6: Interferogram U_1 during the high density quasistationary phase of the tokamak discharge.

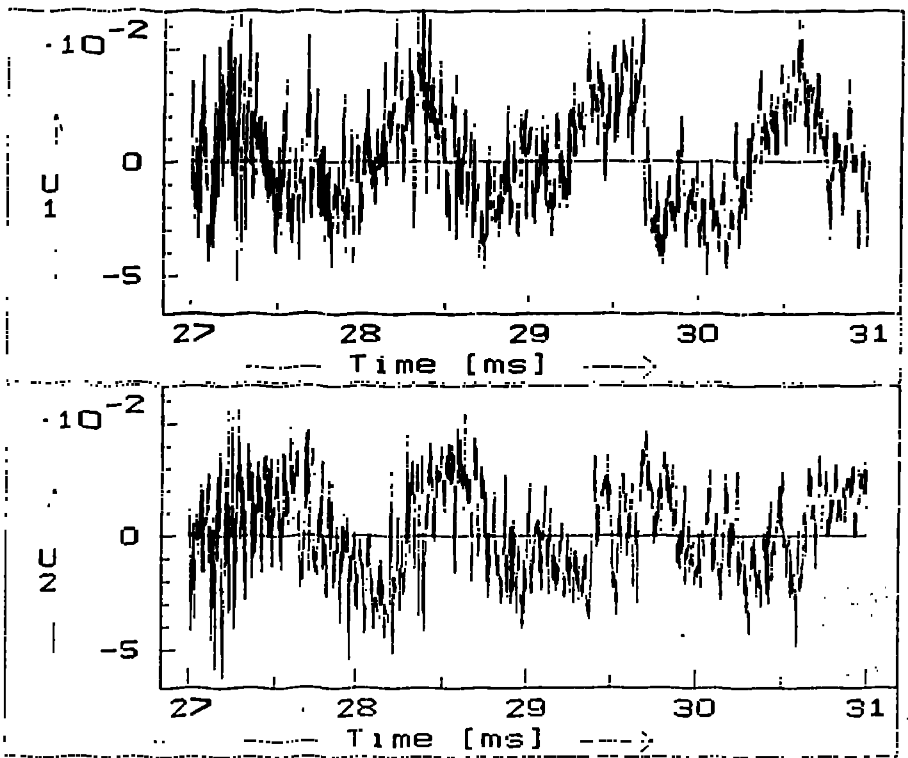

Figure 7: Interferograms $U_1(\sim sin\varphi)$ and $U_2(\sim cos\varphi)$ during the late phase of the tokamak discharge.

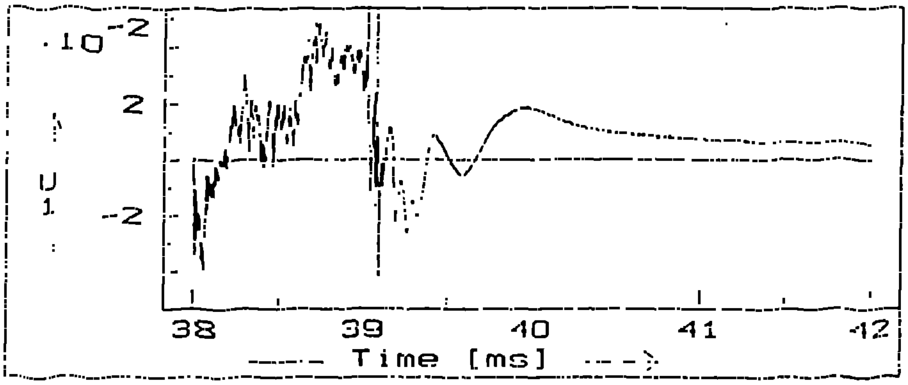

Figure 8: Interferogram U_1 during the plasma decay.

4. CONCLUSION

The report describes the first microwave reflectometric scheme, which was used on the tokamak CASTOR for the measurement of the fast density fluctuations. The scheme is working on the fix frequency 10.26GHz, i.e. the fluctuations near to the plasma periphery are detected.

It was proved that scheme is working properly during the whole tokamak discharge despite the fact that level of the reflected signal is strongly varying within two orders of its magnitude.

It is necessary to note that so called *sin – cosin* detection system is used for the phase evaluation. Such system requires to use two detectors with quite identical characteristics. This fact can bring some limitations on the method accuracy in the future.

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