Alternative fringe sensor for DARWIN mission

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ABSTRACT

Large stellar telescope is indispensable for astronomy. Aperture synthesis is a well-known technique to simulate a large space telescope by an array of small telescopes. Condition for aperture synthesis is that the light of the telescopes have to be combined coherently. Therefore, an interferometric Fringe Sensor (FS) to detect and stabilize the Optical Path Difference (OPD) between light from the different telescopes is required. Conventional Fringe Sensor for Space Interferometer utilizes either Quadrature Stabilization or Double Synchronous Detection to find and control OPD=0. OPD demodulation based on Quadrature Stabilization is sensitive to change in the visibility V of the interferometric signal, while Double Synchronous Detection requires an active modulation of the OPD to generate the required carrier signal. To overcome these problems, TNO develops a Fringe Sensor based on a 3x3 Fiber Optic (FO) coupler. A breadboard demonstrator operating around 830 nm is built. A piezo stretcher and a translation stage are used to generate the OPD. High-speed OPD measurement down to 0.15 nm is demonstrated. The influence of the visibility V of the interferometric signal is also investigated. Even for V=0.2, an OPD modulation of 0.4 nm can still be detected.

Keywords: fiber optic, interferometer, interferometry, astrometry

1. INTRODUCTION

Various space telescope array systems are in development to investigate other terrestrial planets orbiting around nearby stars in order to find extra-terrestrial life. One of them is the DARWIN mission of the European Space Agency (ESA). The star/planet systems of interest are those with stars having properties similar to our Sun and with planets located at a reasonable distance from the star in a way similar to our Earth in the so called habitable zone. System issues such as the available flux from the stars and the possible size of the satellites restrain the search zone to nearby stars located at a distance around 20 parsec. Seen at this distance the angular separation between our Sun and Earth is 50 milli-arcsec. A telescope wanting to separate these two objects at a wavelength of 5 microns would need a diameter of 50 m. A smaller diameter could be sufficient at visible wavelengths. However in the visible spectrum the signal from the planet is much smaller with respect to the star signal than in the thermal infra-red. This is because in the visible the planet only reflects a part of the light emitted by the star whereas in the thermal infra-red it has a proper thermal emission. This imposes the choice of the long wavelengths and thus the need for large telescopes. A monolithic telescope with a 50 m diameter is presently not considered as a feasible option. This led to the proposal to use aperture synthesis technology. Small telescopes separated by a 50 m distance will have the same resolving power providing the light of the telescopes are recombined coherently. For the DARWIN mission Nulling Interferoemter, the Optical Path Difference (OPD) between the beams has to be stabilized to about 1 nm. The OPD measurement is performed by the Fringe Sensor (FS).

1.1. Fringe sensor

The Fringe Sensor detects the interferometric signal that is generated by recombining the beams from two telescopes. OPD measurement is actually the detection of the phase in the interferometric signal. The requirements for the DARWIN Fringe Sensor are listed in Table 1. The most important requirement for the Fringe sensor is the OPD measurement accuracy of 0.75 nm (rms). For example, measuring an OPD error of 0.75 nm with a wavelength of 7.5 micron implies an accuracy of 1/10000 of a fringe. This is clearly a difficult task and would require a very high available flux even in the best theoretical case of a purely photon noise limited optimal algorithm. There is thus a high incentive to lower the operating wavelength for the Fringe Sensor. Operating in the visible around 0.5 micron reduces the difficulty to 1/700 of a fringe. This is still a demanding task for the fringe sensing technique but is comparable to

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results already obtained in some laboratories and thus much more realistic. In addition, the stars of interest have, like our Sun, a maximum of emission in the visible spectrum which maximizes the available number of photons for the task.

Table 1 : Requirements for the DARWIN Fringe Sensor.

Requirements	Value
OPD accuracy	0.75 nm (rms)
Frame rate	10 Hz
Operating wavelength	within 0.4-4 μm
Operating temperature	40 K
Lifetime	5y on ground + 7y in orbit

1.2. Conventional Fringe sensor technologies

The Fringe Sensor detects the interferometric signal that is generated by recombining the beams from two telescopes. OPD measurement is actually the detection of the phase in the interferometric signal. Conventional Fringe Sensors are based on the following two techniques for OPD measurement to stabilize the OPD:

- Quadrature detection in conventional interferometer [1]
- Double synchronous detection [2, 3]

Quadrature detection in conventional interferometer

When interferometric signal is generated in a conventional interferometer by combining two beams using a beam-splitter, the two beam-splitter outputs (I and II) will have a phase difference of π:

$$I_I(OPD) = A_0\,(1 + V\sin(\frac{2\pi}{\lambda}OPD))\ , \tag{1}$$

$$I_{II}(OPD) = A_0\,(1 + V\sin(\frac{2\pi}{\lambda}OPD + \pi)) = A_0\,(1 - V\sin(\frac{2\pi}{\lambda}OPD))\ . \tag{2}$$

In Eq. (1) and (2), the cos term is changed to sin. This is due to the conventional symmetric beam splitter property that the transmitted and reflected beams have a phase difference of π/2 [4].

The condition of $I_I=I_{II}$ is called the quadrature condition. For OPD=0, the interferometer is in quadrature. Small OPD drift can be measured using the quadrature demodulation:

$$OPD = \frac{\lambda}{2\pi}\arcsin\left(\frac{1}{V}\frac{I_I - I_{II}}{I_I + I_{II}}\right)\ . \tag{3}$$

The quadrature demodulation relies on a predetermined and constant V, the contrast of the interferometric signal. In practical application, V has to be monitored constantly, which implies additional measurement using an additional system. An improved Quadrature detection system is proposed by ONERA for the fringe tracker for the ESO/VLTI [1]. This approach utilizes achromatic π/2 phase shifters to generate 2 extra interferometric signals for the calculation of the OPD. Therefore, a high-precision, wide spectral range achromatic phase shifter has to be developed.

It will be possible to lock the interferometer in quadrature by using the error signal of Eq. (3). This approach requires an intelligent close-loop control system to reduce the problem of varying visibility. Furthermore, this technique can only be used for interferometer in quadrature. This implies that the quadrature condition for the FS interferometer must be identical to perfect nulling of the Nulling-interfermeter for the science beams.

Double synchronous detection

In the Double synchronous detection system, the interferometric signal is modulated by introducing an active oscillation (< λ) in the length of one of the beams. The oscillation frequency is f. Two lock-in amplifiers operating at f and 2f are used to process the modulated interferometric signal. The output signals are proportional to the first and second derivative of the interferometric signal respectively. The first derivative has a zero-crossing for the maxima in the interferometric signal and is used for high accuracy OPD stabilization. The amplitude of the second derivative is proportional to the amplitude of the interference signal and is used to find the largest peak with corresponds to OPD=0 (coherencing). An advantage of the Double synchronous detection is that the coherencing is performed without extra optical component/system and flux loss (as in other methods). The same signal from the detector is analyzed at 2f. By this means, we have a direct absolute measure of the contrast and identification of the central largest fringe.

1.3. TNO Fringe Sensor based on 3x3 fiber optic coupler

We recognize the advantage of using optical fiber for suppressing the undesirable influence of wavefront distortion on the performance of the Nulling interferometer in IRSI/DARWIN. Furthermore, application of optical fiber is already presented/proposed in several Fringe Sensor systems likes FINITO [11] and the VLTI PRIMA Fringe Sensor Unit. So, application of optical fiber components for IRSI/DARWIN Fringe Sensor is found to be feasible. TNO developed a new Fringe Sensor by combining the two beams with a special beam combiner: a 3x3 FO coupler. The three output signals will have a fixed phase difference depending on the design of the waveguide coupler. The TNO Fringe Sensor concept is sketched in Fig. 1.

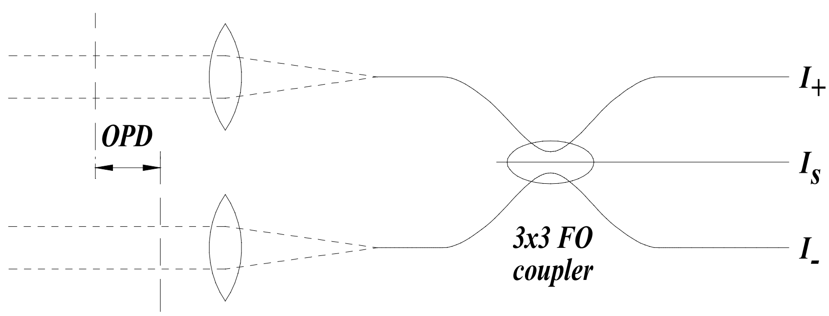

Figure 1TNO Fringe Sensor with a 3x3 Fiber Optic coupler as beam combiner to create 3 interferometric output signals.

The three output signals have a fixed phase difference depending on the design of the coupler. For a symmetric 3x3 fiber optic coupler, the phase difference is 2π/3 [4]. The three output signals can be described with:

$$I_S(OPD) = A_0\,(1+V\cos(\frac{2\pi}{\lambda}OPD)). \tag{4}$$

$$I_+(OPD) = A_0\,(1+V\cos(\frac{2\pi}{\lambda}OPD+\frac{2\pi}{3})). \tag{5}$$

$$I_-(OPD) = A_0\,(1+V\cos(\frac{2\pi}{\lambda}OPD-\frac{2\pi}{3})). \tag{6}$$

Several schemes can be used for the demodulation of the OPD from the three interferometric signals I_s, I_+ and I_-. TNO has developed an electronic signal processing board with a phase noise level of about 20 µrad/√Hz @ 1000 Hz. However, this hardware board can only be used for AC signal. Therefore, another demodulation scheme has to be used for the Fringe Sensor to determine the OPD. For the presented configuration with a symmetric 3x3 coupler, the OPD can be calculated as follows:

$$OPD = \frac{\lambda}{2\pi}\arctan\left(\sqrt{3}\,\frac{I_+ - I_-}{2I_s - I_+ - I_-}\right). \tag{7}$$

In contrast to the Quadrature Stabilization, this technique is insensitive to changes in the visibility V and the amplitude A_0 of the interferometric signal. In comparison to the Double Synchronous Detection, the proposed technique doesn't require continuous active oscillation in the beam. Furthermore, this technique can be applied to the calculation of the phase term in Eq. (7) between $-\pi/2$ and $+\pi/2$ (modulo π). So, OPD stabilization can be performed within a certain range of OPD. The results of the phase difference ϕ calculation has a modulo of π . These phase jumps can easily be removed by a proper filter. Trough coherencing using multi-wavelengths (Figure 2), the true zero-OPD can be identified.

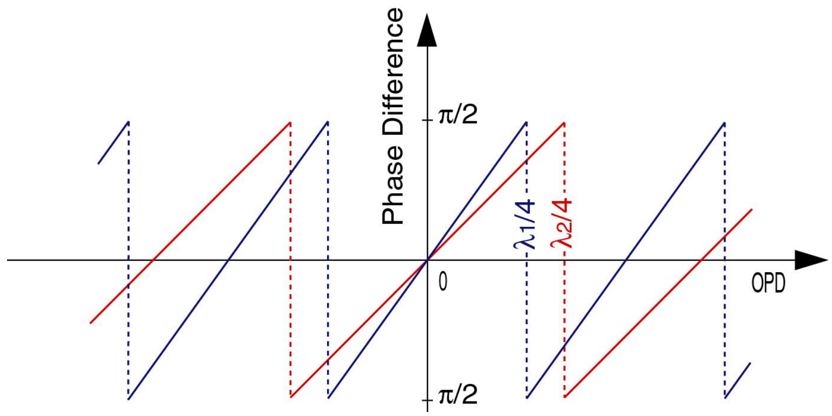

Figure 2: zero-OPD calibration through coherencing with 2 wavelengths.

A brief comparison among Quadrature demodulation, Double synchronous detection and the TNO 3x3 concept for OPD measurement is performed (see following table).

Table 2 Comparison among Quadrature demodulation, Double synchronous detection and TNO concept.

	Quadrature demodulation	Double synchronous detection	TNO concept
Visibility measurement required	Yes	No	No
OPD modulation required	No	Yes	No
High accuracy	+/-	+	+
OPD=0 finding	Additional coherence measurement	Second derivative measurement @ 2f	Additional coherence measurement
Sensitivity to vibration	Low	Low	Expected to be low
Number of detector	2	1	3
Measurement range	in quadrature	at extremes of fringes	between $-\pi/2$ and $+\pi/2$ (modulo π)

2. TEST SETUP

A breadboard demonstrator for the Fringe Sensor based on a 3x3 FO coupler is designed (Figure 3), built and various tests are performed. The demonstrator is shown in Figure 4. The light-source is a Super Luminescent Diode (or SLD) manufactured by Superlum Diodes. It has a center wavelength of 824.5*nm* and a bandwidth (*FWHM*) of 23.6*nm*. The symmetric couplers (2x2 and 3x3) are manufactured by Gould. The 2x2 coupler is used to split the light and to generate 2 beams for the simulation of light arriving to two telescopes. One of the fiber of the 2x2 coupler is wrapped on a piezo element to create small OPD modulation. The two beams are collimated by two optical units and are sent to the delay-lines of the Delft Testbed Interferometer (DTI) [6] which has a scanning range of about 40mm. After passing the DTI, the beams are coupled into the 3x3 FO coupler. The 3 output interferometric signals are detected by a detector unit and digitized by an AD converter (NI PCI-6110) in a computer system. The data are stored to the computer. The software demodulation of the signal is performed afterward.

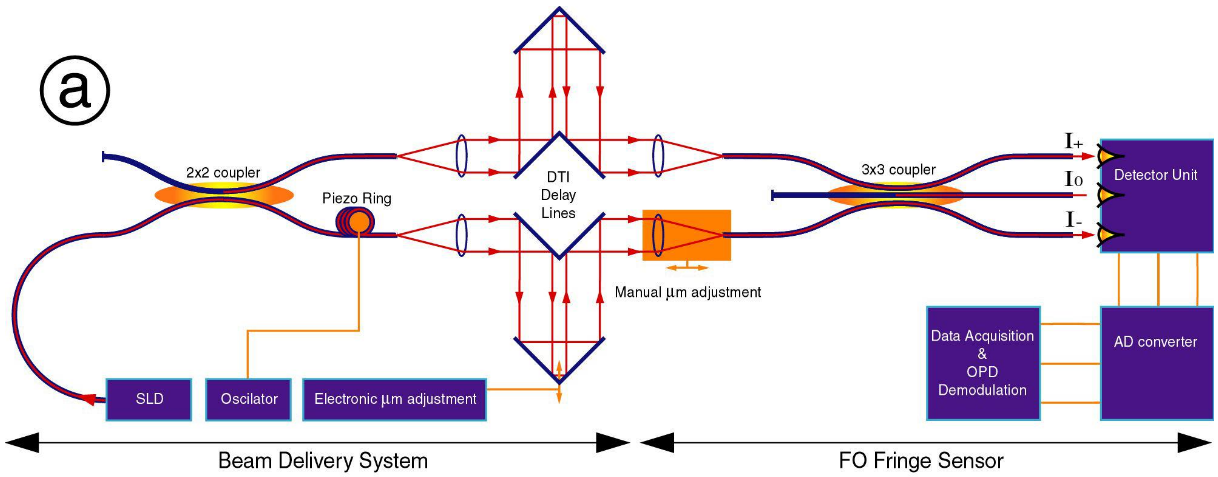

Figure 3 Basic setup of the demonstrator Fringe Sensor based of a 3x3 FO coupler.

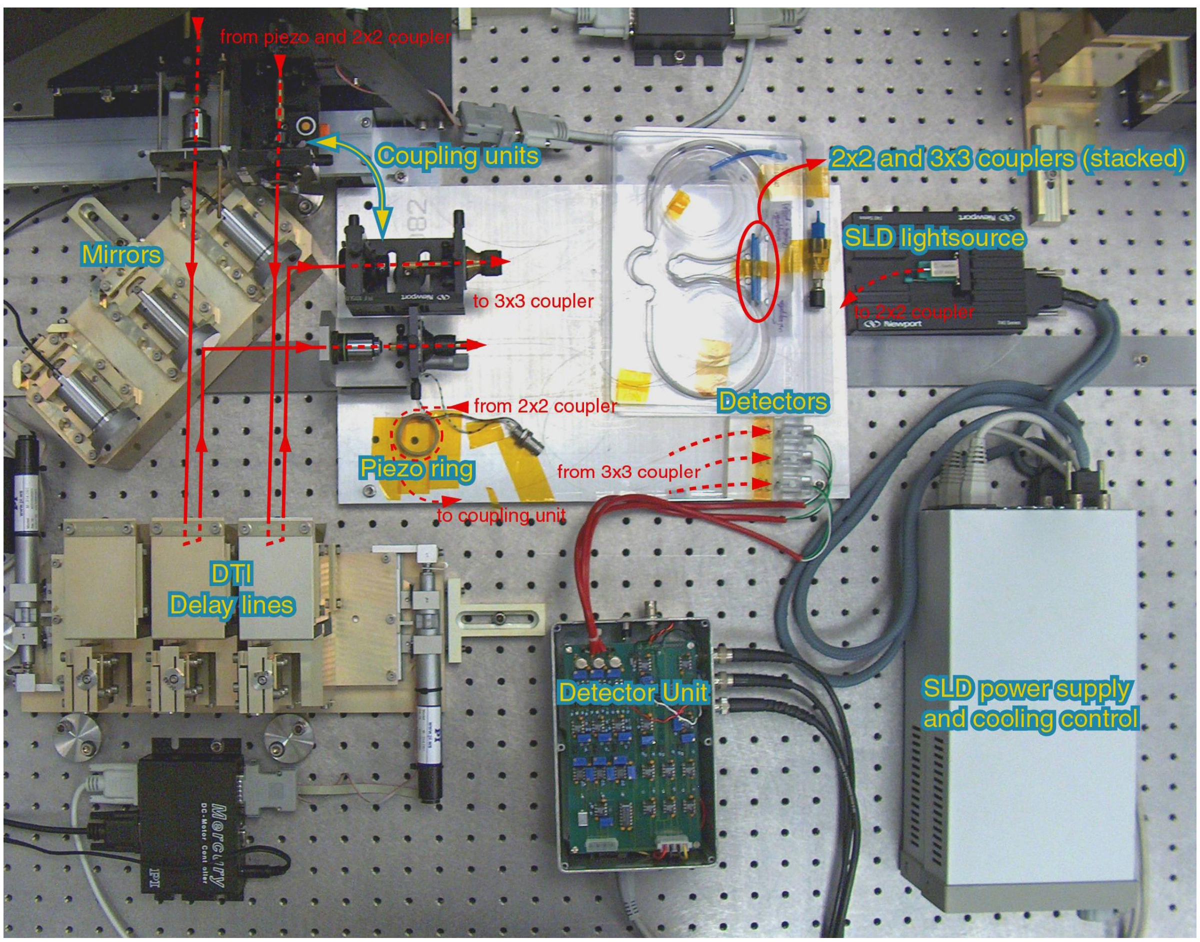

Figure 4 The demonstrator Fringe Sensor based of a Mach-Zehnder fiber optic interferometer using the DTI delay lines.

3. TEST RESULTS

Several test including the linearity, resolution and sensitivity to low visibility of the interferometric signal are performed using the breadboard demonstrator.

3.1 Linearity

Different level of OPD modulation is generated using the piezo stretcher. Figure 5 shows the measured amplitude of the OPD modulation plotted against the applied voltage amplitude in terms of V_0. The plots show a nicely straight line for the for both high sampling frequency (1 MHz) as well as low sampling frequency (1 kHz).

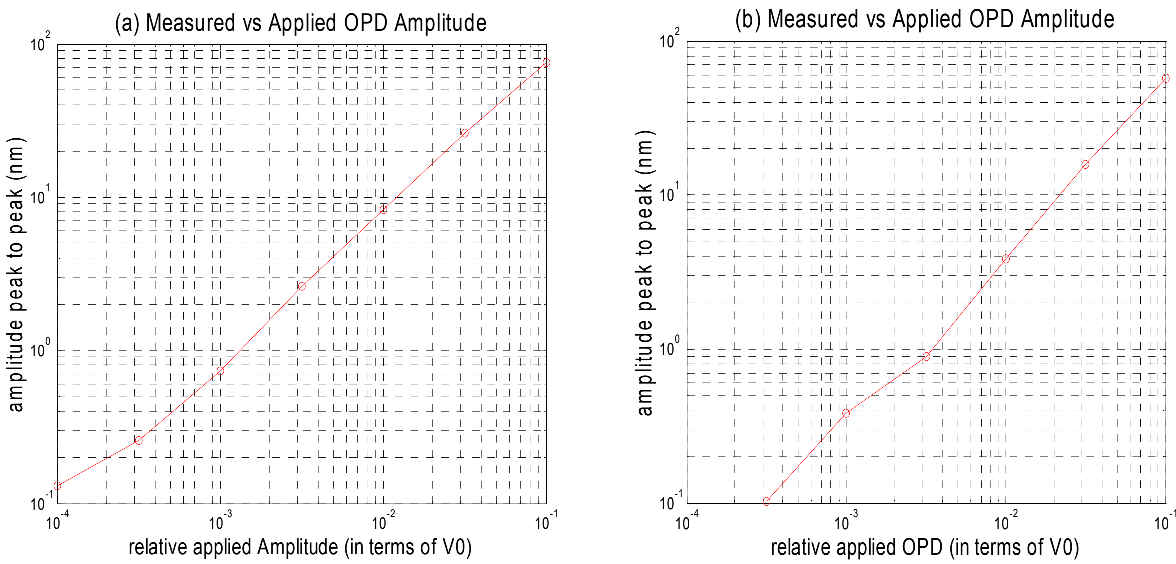

Figure5 Measured OPD amplitude as a function the voltage applied to the piezo for (a) 1*MHz* and (b) 1*kHz* measurements.

3.2 Resolution

To investigate the high resolution capability of the breadboard demonstrator, sub-nm OPD modulation is generated using the piezo stretcher. OPD modulation remains distinguishable down to an amplitude of 0.4*nm* peak-to-peak for the FS operating at a sampling frequency of 1 *MHz* (Figure 6). The high sampling frequency can be used for averaging to improve the resolution. .

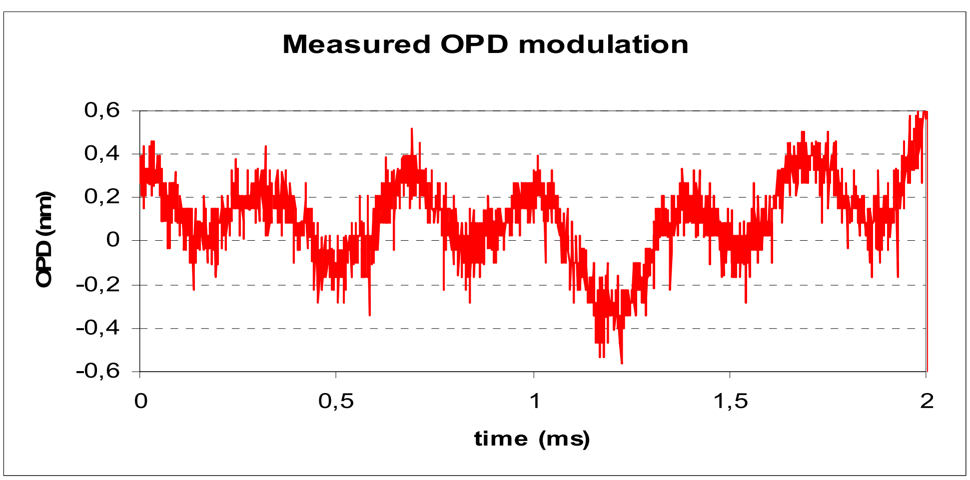

Figure 6 OPD modulation of 0.4nm can clearly be measured by the Fringe Sensor operating at a sampling frequency of 1MHz.

Tests are also carried out at lower sampling frequency and smaller OPD modulation. The results of 0.15 nm (peak-peak) OPD modulation is shown in the figure below.

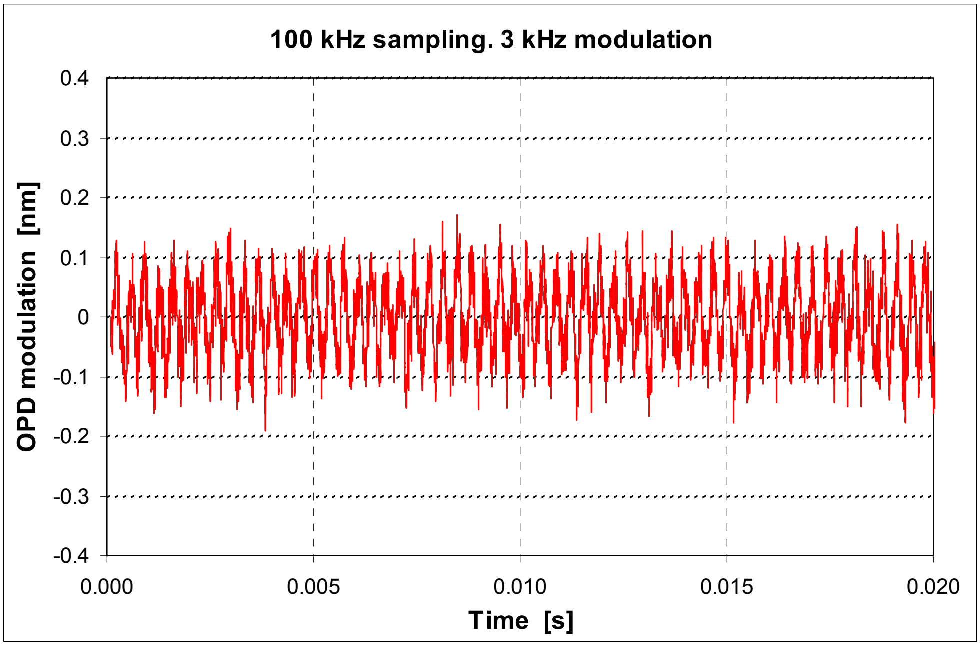

Figure 7 A 3 kHz OPD modulation of 0.15nm can clearly be measured by the FS operating at a sampling frequency of 100 kHz.

3.3 Influence of visibility

The influence of the visibility V of the interferometric signal is also investigated. This can be realized by reducing the intensity of one of the beams. Even for V=0.2, an OPD modulation of 0.4 nm can still be detected. Plotting the measured OPD amplitude against the applied voltage amplitude shows a straight line which has remarkable resemblance with previous measurement with high visibility measurements (see section 3.1).

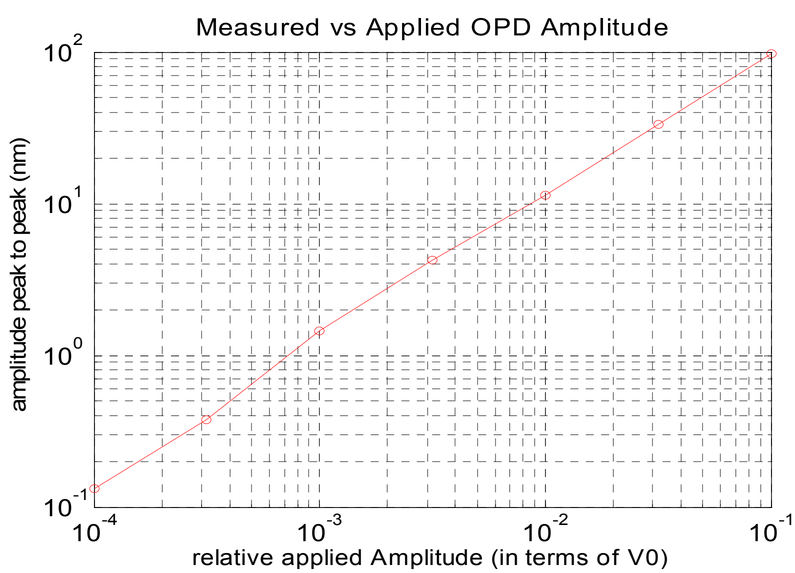

Figure 8 Measured OPD amplitude as a function the voltage applied to the piezo for 1*MHz* sampling frequency and *V*=0.2.

4. CONCLUSIONS

The TPD concept offers a new approach for Fringe sensor for stellar interferometer based on a 3x3 FO interferometer. In contrast to the Quadrature demodulation, this technique is insensitive to changes in the visibility V and the amplitude A_0 of the interferometric signal. In comparison to the Double synchronous detection, the proposed technique doesn't require continuous active oscillation in the beam. Additional advantage is the wavefront filtering by the optical fiber. This enhances the quality of the interferometric signal. A breadboard demonstrator of the Fringe Sensor based on a 3x3 FO coupler is built and tested. Linear response of the OPD calculation is demonstrated and sub-nm resolution is shown. An OPD modulation of 0.15 nm can easily be detected at a sampling frequency of 100 kHz which meets the requirement for FS in DARWIN. Reduction of the visibility of the interferometric signal down to 0.2 shows that it has hardly any effect on the resolution of the FS.

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