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► **To cite this version:**

Philippe Delaye, Gérald Roosen. Measuring low amplitude periodical phase shift without set-up stabilization: application to Pockels effect characterization. *Optics Communications*, 2002, 214, pp.199-206. 10.1016/S0030-4018(02)02134-X . hal-00673942v2

HAL Id: hal-00673942

<https://hal-iogs.archives-ouvertes.fr/hal-00673942v2>

Submitted on 30 Mar 2012

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Measuring low amplitude periodical phase shift without set-up stabilization: application to Pockels effect characterization

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Abstract :

We present an interferometric set-up for the measurement of low amplitude sinusoidal phase shifts that releases most of the constraints of usual architectures. It allows measurement without any stabilization of the set-up and can tolerate low quality fringe pattern. Due to its ease of use and its good sensitivity, this set-up can be used to measure low amplitude electro-optic coefficients with low applied voltage (less than 1V). Test measurements on LiNbO₃ and LiTaO₃ samples show good accordance between measured and theoretical Pockels phase shifts.

PACS : 42.65.Hz, 42.62.Eh, 77.84.Dy, 78.20.Jq

The measurement of the electro-optic coefficients of materials is an important problem of optoelectronic, especially when low Pockels coefficients or low thickness samples are measured. Several techniques are used, they are presented and discussed in Ref. [1-11]. Among them, interferometric techniques are very powerful as they can reach independently several coefficients in usual crystals. One problem with these techniques is that they require to put the interferometer to a peculiar fringe position (usually at the maximal slope of the fringes), and to stabilize it at this

position. The experiment will thus be particularly sensitive to vibrations of the set-up and to thermal fluctuations of the studied crystal. In this letter we propose a new solution to this problem that works without the need of a stabilized interferometer and that even takes benefit of its drift and fluctuations for the measurement. This set-up thus enables to measure the very small phase shifts induced in Pockels crystals (such as LiNbO₃ or LiTaO₃) by AC voltage as low as some tens of mV.

In the interferometric set-up, a laser beam is separated in two arms by a beam splitter and recombined on a detector (using the same or another beam splitter). In one of the arms (the signal beam), we place the sample to be measured, whereas in the second arm a piezo-mirror allows to slowly vary the phase shift between the beams of the interferometer. When the interferometer is aligned (i.e. fringes are observed), the intensity received by the detector equals:

$$I = I_S + I_R + 2r\sqrt{I_S I_R} \cos\psi(t) \quad (1)$$

where I_S is the intensity of the signal beam, in which is placed the Pockels crystal to be characterized and I_R is the intensity of the reference beam. In this expression, r is a coefficient that renders the quality of the fringes observed on the detector. For perfectly aligned plane waves, we have $r = 1$ meaning that the phase shift between the beams does not vary on the surface of the detector. In the worst case of a large number of fringes on the surface of the detectors, meaning that the wavefronts are distorted or misaligned, we have $r \approx 0$, and no modulation signal is delivered by the detector. In the general case, we have a value of r that varies between these two extrema, with a value of r that will have to be the closest as possible to 1 as the detected modulated signal is proportional to this value. Nevertheless, as we will see in the following, the technique we developed works whatever the quality of the fringes, and thus whatever the value of r (remembering that the measurement will be all the more easy and accurate than r will be close to 1, as the measured signal will be high). Finally, $\psi(t)$ is the phase shift between the two interfering beams. It can be separated in two terms $\psi(t) = \varphi(t) + \Delta\varphi(t)$, with $\Delta\varphi(t) = \sqrt{2} \Delta\varphi_{\text{RMS}} \sin(2\pi ft)$ the sinusoidal Pockels phase shift that we want to measure and $\varphi(t)$ the mean phase shift between the beams that varies much slowly than the Pockels phase shift. The intensity measured by the detector can then be rewritten as (taking into account that for the measured phase shift we have $\Delta\varphi(t) \ll \pi/2$):

$$I = \underbrace{I_S + I_R + 2r\sqrt{I_S I_R} \cos\varphi(t)}_{I_{\text{mean}}} - \underbrace{2r\sqrt{I_S I_R} \Delta\varphi(t) \sin\varphi(t)}_{\Delta I(t)} \quad (2)$$

In an usual interferometric set-up (homodyne detection) [1], the mean phase shift $\varphi(t)$ is stabilized to a constant value equal to $\pm\pi/2$ (half fringe level), where the detected signal $\Delta I(t)$ is maximal. This requires the knowledge of the fringes contrast (to determine the half level). This value is obtained through a measurement of the maximum of the mean intensity I_{Mean} reaching the detector (corresponding to $\varphi(t) = 0$), and the minimum mean intensity (corresponding to $\varphi(t) = \pi$). This stabilization at half fringe level is the main problem of usual homodyne detection schemes. In fact, the problem is not necessarily the stabilization by itself, but to find the right level of stabilization that will vary slowly if I_R , I_S or above all r vary. This is generally obtained by a stabilization (against thermal change, vibrations, air fluctuations, ...) of the whole set-up during the measurement.

In our case, we use the same optical set-up and the same signal but we change the data processing. Our method does not require the stabilization of the interferometer to a given level, it will even use the naturally or artificially produced fluctuations of $\varphi(t)$, without the necessity to know the exact value of this phase shift. This method can be seen as a low frequency analogous to the heterodyne detection where the ratio of height of the sideband to the carrier frequency amplitude give directly the phase modulation amplitude.

Considering the intensity received by the detector given by equation (2), it can be split into two terms that evolve on very different time scales : a signal $\Delta I(t)$ modulated at the excitation frequency of the Pockels material and a mean intensity I_{Mean} that varies slowly in time but is constant at the evolution time scale of $\Delta I(t)$. The detector sees a quasi-uniform tint of an interference pattern, and the mean intensity I_{Mean} is directly linked to the interference state of the fringe seen by the detector. The phase shift due to the drift of the set-up induces a displacement of the fringe pattern in front of the detector that corresponds to a change of the mean intensity I_{Mean} and a slow variation of the amplitude of the modulated signal $\Delta I(t)$. The important point is here that the temporal variations of the mean intensity I_{Mean} and of the amplitude of the modulated signal $\Delta I(t)$ are not independent and are correlated.

We will now show that if we measure simultaneously the RMS (Root Mean Square) value of the modulated signal ΔI_{RMS} (supposed in all this study to be sinusoidal) and the mean value of the intensity, we can deduce the RMS value of the Pockels phase shift we want to determine. From equation (2), we deduce:

$$\Delta I_{\text{RMS}} = -2r\sqrt{I_S I_R} \sin\varphi(t) \Delta\varphi_{\text{RMS}} \quad (3)$$

and

$$I_{\text{Mean}} = I_S + I_R + 2r\sqrt{I_S I_R} \cos\varphi(t) \quad (4)$$

In these relation, we immediately recognize the parametric equation of an ellipse ($\varphi(t)$ being the parameter), centered in the point $(0, I_S + I_R)$ with a small axis of length $4r\sqrt{I_S I_R} \Delta\varphi_{\text{RMS}}$ and a great axis of length $4r\sqrt{I_S I_R}$. The ratio of the length of the two axes of this ellipse gives the information we want, i.e. $\Delta\varphi_{\text{RMS}}$. Nevertheless, the determination of the phase shift $\Delta\varphi_{\text{RMS}}$ through the ratio of the axes of the ellipse, only use a small part of the measured data (points around the extrema of the ellipse). The same parameter should be obtained with a better accuracy using an adjustment of the whole ellipse. As the adjustment with the ellipse equation is not really easy and common, we have chosen another treatment, that will give more easily the same result, i.e. the determination of $\Delta\varphi_{\text{RMS}}$ using all the measured data.

Eliminating the slow phase shift $\varphi(t)$ from equations (3) and (4) (calculating $\cos^2\varphi(t)$ and $\sin^2\varphi(t)$), we arrive to the relation:

$$\Delta I_{\text{RMS}}^2 = \underbrace{-\Delta\varphi_{\text{RMS}}^2}_{a1} I_{\text{Mean}}^2 + \underbrace{2\Delta\varphi_{\text{RMS}}^2(I_S + I_R)}_{a2} I_{\text{Mean}} + \underbrace{\Delta\varphi_{\text{RMS}}^2(4r^2 I_S I_R - (I_S + I_R)^2)}_{a3} \quad (5)$$

We easily see that the graphical representation of this expression $\Delta I_{\text{RMS}}^2 = f(I_{\text{Mean}})$ is a parabola, which a1 parameter directly gives the RMS value $\Delta\varphi_{\text{RMS}}$ of the phase shift $\Delta\varphi(t)$ due to the voltage applied to the Pockels crystal. This measure is completely independent of the intensity of the different beams (I_S and I_R), but also of the quality of the fringes (characterized by parameter r). Moreover the exact nature of the slow phase shift $\varphi(t)$ is not important. It does not need to vary according to a peculiar law (it can even be due to the natural drift of the interferometer) as soon as at least one fringe is scrolled ($\varphi(t) > \pi$), and the whole parabola is described by the signal with typically some cycles (two or three are usually sufficient).

Experimentally, the interferometer is of the Mach-Zehnder type, using a collimated and vertically polarized He-Ne laser emitting at 633nm (Figure 1). The Pockels crystal is placed in the signal arm. A half wave plate allows to choose the desired eigen-polarization of the crystal, a second half wave plate gives back a vertical polarization, selected by a second polarizer. At the output of the interferometer a lens makes the image of the crystal on the detector plane. The slow phase shift is created by a piezo-mirror inserted in the reference beam. The typical modulation frequency of the piezo-mirror is 20mHz with a displacement amplitude around $1\mu\text{m}$. The detected signal is sent simultaneously on one input of an oscilloscope (with an internal low pass filter) to measure the

mean intensity and on the input of a lock-in amplifier to measure the RMS value of the detected signal at the excitation frequency (the results of the measurement being sent on the other input of the oscilloscope). The Lock-In amplifier is also used to deliver the voltage applied to the Pockels crystal. Its RMS amplitude varies typically between 10mV and 2V, with a frequency varying between 1kHz and 100kHz (high frequency limitation of the Lock-In amplifier).

Typical signals are shown in Figure 2a. We see the mean signal that varies as the fringe is scrolled in front of the detector. In the same time the RMS value of the signal varies (visually in quadrature) with a maximum value at half fringe height and zero signal for absolute maximum and minimum of the mean intensity as expected. We see that tracing $\Delta I_{\text{RMS}} = f(I_{\text{Mean}})$, we obtain an ellipse as expected (Fig. 2b). After the treatment (tracing $\Delta I_{\text{RMS}}^2 = f(I_{\text{Mean}})$) we obtain the expected parabola (Fig. 3), which fit allows to measure a Pockels phase shift of $\Delta\phi_{\text{RMS}} = 13.047 \text{ mrad}$, with an accuracy given by a standard deviation of $3 \mu\text{rad}$ (in the following the standard deviation will be used as a measure of the accuracy).

We used this set-up to characterize two reference Pockels crystals of LiNbO_3 and LiTaO_3 . These crystals are of the same class of symmetry (the 3m class). All their coefficients (electro-optic, elasto-optic, piezo-electric) are perfectly known and will be used to calculate the expected phase shift that will be compared to the experimental data given by the set-up. The crystals are cut along the crystallographic axes and are used in a transverse configuration with an electric field applied along the c-axis. The propagation is along the a-axis and the beam is either ordinary (i.e. vertically polarized along the b-axis) or extraordinary polarized (i.e. along the c-axis). The phase shift ($\Delta\phi_o$ and $\Delta\phi_e$ for ordinary and extraordinary polarization respectively) acquired by the beam is then [12, 13]:

$$\Delta\phi_o = \frac{\pi}{\lambda} V \left(\frac{L}{d} \right) \left[2(n_o - 1)d_{31} + n_o^3 r_{13}^T \right] \quad (6)$$

$$\Delta\phi_e = \frac{\pi}{\lambda} V \left(\frac{L}{d} \right) \left[2(n_e - 1)d_{31} + n_e^3 r_{33}^T \right] \quad (7)$$

where V is the applied voltage, L the thickness of the crystal along the beam propagation direction, d is the inter-electrode distance, and λ the used wavelength in vacuum. In these expressions the first term is due to the change of the dimension of the crystal because of the piezo-electric effect (with the piezo-electric coefficient d_{31}). The second term is due to the Pockels effect (with the unclamped electro-optic coefficient r_{ij}^T). In both cases, n_o is the ordinary refractive index and n_e is the

extraordinary refractive index. These expressions suppose that the crystal is free, i.e. that the frequency used is low compared to the piezo-electric resonance. The values of these parameters in the crystals we used, are summarized in Table 1.

The first measurement is performed on a LiNbO_3 crystal at a fixed frequency as a function of the applied electric field, for both polarizations (Figure 4). We observed a linear dependence of the measured phase shift with a slope equal to $\Delta\phi_o/V=(2.186\pm0.003)$ mrad.V⁻¹ and $\Delta\phi_e/V=(6.305\pm0.003)$ mrad.V⁻¹. These experimental values are in good accordance with the theoretical ones given in Table 1. In the insert of Figure 4, the variation of the phase shift with the applied voltage is showed in a log-log scale. This presentation shows that the linearity of the variation extends on the whole measurement range (more than two decades), until applied voltage as low as 10mV, corresponding to measured phase shifts as low as some tens of μrad . We also measure the response as a function of the frequency of the applied sinusoidal voltage (Figure 5). The sensitivity (i.e. the measured RMS phase shift normalized to the RMS applied voltage) is constant on the whole frequency range with a small increase that appears above 30kHz. In this range (i.e. below 30kHz), the mean value of the sensitivity is 6.31 ± 0.06 mrad.V⁻¹, corresponding to a measurement accuracy of 1%. The increase corresponds to the beginning of a piezoelectric resonance situated at higher frequency (theoretically around 600kHz according to the dimensions and the orientation of the crystal). This behaviour confirms that the crystal is free in the condition of the measurement what justifies the expressions (equations (6) and (7)) used for the phase shift.

Similar measurements were performed in three LiTaO_3 crystals, with identical cut and dimensions. The obtained curves were similar to the one observed in LiNbO_3 , with nevertheless a slight dispersion of the sensitivity of the different crystals (Table 2) for the measurement at 25.7 kHz. Despite this dispersion the obtained values are in accordance with the theoretical value (Table 1). This dispersion was attributed to some problem in the application of the electric field, but considered independent of the measurement set-up. Indeed, a similar dispersion exists for both extraordinary and ordinary polarization. In all the crystals the ratio of the extraordinary phase shift to the ordinary one, is the same at a value of 3.66 ± 0.05 that corresponds to the theoretical ratio. This point is confirmed by the fact that a measurement at lower frequency (183Hz) shows a lower dispersion in the measured values with ordinary polarization (Table 2). For some samples and polarisations, measurement had been performed several times on different days, each time putting on and removing the sample from the set-up, with a new alignment and optimization for each measurement. For example for the sample LTO1 with ordinary polarization at the frequency of

51.2kHz, 5 independent measurements were made giving sensitivities of 1.003, 0.998, 1.008, 1.010 and 1.013mrad.V⁻¹, what corresponds to a mean value of 1.006±0.006 mrad.V⁻¹, i.e. a relative accuracy of 0.6% typical of the measurement performed.

The presented Pockels material characterization set-up has several advantages compared to conventional set-ups. It is simple to use and does not require any stabilisation of the set-up. It is not sensitive to external perturbations such as vibrations or thermal effects in the measured sample. It is an interferometric geometry, so contrarily to the other simple and stabilisation independent set-up, the Sénarmont set-up, it can by proper cut of the crystal allow the measurement of diverse electro-optic coefficients independently. The sensitivity of the measurement (some tens of μrad without any peculiar precautions) allows to measure low amplitude electro-optic coefficients (such as r_{13}^T in LiNbO₃ or r_{41}^T in InP) without the need to apply high voltage (some volts are sufficient). The measurement does not require very high fringe quality, even if a higher contrast will lead to higher signal and easier and more accurate measurement (see Appendix). The ultimate performances of the presented set-up should be the same than the one obtained with a classical stabilized interferometric set-up perfectly optimized and aligned. Nevertheless these performances are accessible more easily with the proposed set-up, without the need of a servo-controlled stabilization, a vibration isolated breadboard, an air flow protection or a thermal control. It can be a rather cheap and good solution for people having occasionnal needs for moderately accurate phase modulation measurements (characterization of a phase modulator, determination of electro-optic or piezo-electric coefficients of a crystal, ...), just using classical optical elements that are usually found in an optic laboratory.

Appendix : Accuracy of the measurement technique

The accuracy of the measurement technique can be theoretically estimated, using the fact that the phase shift is given by the ratio of the length of the axes to the ellipse when we trace $\Delta I_{\text{RMS}} = f(I_{\text{Mean}})$. The axes are given by $a = 4r\sqrt{I_S I_R} \Delta\varphi_{\text{RMS}}$ and $b = 4r\sqrt{I_S I_R}$. These parameters can be rewritten as a function of some other practical parameters of the fringe pattern, i.e. the maximum $I_{\text{Mean}}^{\text{Max}}$ or the minimum $I_{\text{Mean}}^{\text{Min}}$ intensity value, or the contrast C of the fringe pattern. For example, we have $b = I_{\text{Mean}}^{\text{Max}} - I_{\text{Mean}}^{\text{Min}} = 2CI_{\text{Mean}}^{\text{Max}}/(1 + C)$.

The relative accuracy on the measured phase shift is given by

$$\frac{\Delta(\Delta\varphi_{\text{RMS}})}{\Delta\varphi_{\text{RMS}}} = \frac{\Delta a}{a} + \frac{\Delta b}{b} \quad (\text{A-1})$$

We will now estimate these different terms. We have first :

$$\frac{\Delta b}{b} = \frac{\Delta I_{\text{Mean}}^{\text{Max}} + \Delta I_{\text{Mean}}^{\text{Min}}}{I_{\text{Mean}}^{\text{Max}} - I_{\text{Mean}}^{\text{Min}}} = \frac{\Delta I_{\text{Mean}} (1 + C)}{I_{\text{Mean}}^{\text{Max}} C} \quad (\text{A-2})$$

where we have considered that $\Delta I_{\text{Mean}}^{\text{Min}} \approx \Delta I_{\text{Mean}}^{\text{Max}} = \Delta I_{\text{Mean}}$, is the standard deviation of the noise on the mean intensity. The relative error on b is independent of the measured phase shift, as b does not depend on it, but depends on the intensity and on the contrast of the fringes. The lower the intensity $I_{\text{Mean}}^{\text{Max}}$, the lower the signal and the worse the relative accuracy, where as for a low contrast the fringes disappear, the mean intensity variation becomes smaller and is determined with a less good accuracy.

Then, we have $a = 2\Delta I_{\text{RMS}}^{\text{Max}}$, with $\Delta I_{\text{RMS}}^{\text{Max}} = 2(I_{\text{Mean}}^{\text{Max}} - I_{\text{Mean}}^{\text{Min}})\Delta\varphi_{\text{RMS}} = 4CI_{\text{Mean}}^{\text{Max}}\Delta\varphi_{\text{RMS}}/(1 + C)$, from which we deduce :

$$\frac{\Delta a}{a} = \frac{\Delta(\Delta I_{\text{RMS}}^{\text{Max}})}{\Delta I_{\text{RMS}}^{\text{Max}}} = \frac{(1 + C)\Delta(\Delta I_{\text{RMS}}^{\text{Max}})}{4CI_{\text{Mean}}^{\text{Max}}\Delta\varphi_{\text{RMS}}} \quad (\text{A-3})$$

where $\Delta(\Delta I_{\text{RMS}}^{\text{Max}})$ is the noise on the output of the Lock-In amplifier giving the RMS value of the modulated signal. The relative error on "a" depends on the contrast of the fringes as a lower contrast means a smaller signal. It is the same for the maximum intensity of the fringe pattern that governs the measured modulated signal. The relative error also depends on the phase modulation amplitude as smaller phase modulation means smaller signal.

At small value of the measured phase modulation, the preponderant term for the relative accuracy is $\Delta a/a$, that decreases when phase modulation increases until saturation towards a value governed by the term $\Delta b/b$ at high values of the phase modulation.

In our experiment, typical values we measure, are $I_{\text{Mean}}^{\text{Max}} = 100\text{mV}$ and a contrast of the fringes easily better than 0.5. The performances of the detection is mainly governed by the electronic noise with typical values of $\Delta I_{\text{Mean}} \approx 10\mu\text{V}$ and $\Delta(\Delta I_{\text{RMS}}^{\text{Max}}) \approx 1\mu\text{V}$. The accuracy at large value of the phase modulation would reach $\Delta(\Delta\varphi_{\text{RMS}})/\Delta\varphi_{\text{RMS}} = \Delta b/b = 0.03\%$, what correspond to the order of magnitude experimentally measured in our set-up (Fig. 3).

At low amplitude of the phase modulation we can determine the smallest measurable phase shift with our set-up, i.e. the phase modulation RMS value that would lead to a relative accuracy $\Delta(\Delta\varphi_{\text{RMS}})/\Delta\varphi_{\text{RMS}} = \Delta a/a = 1$, equal to :

$$\Delta\varphi_{\text{RMS}} = \frac{(1+C)\Delta(\Delta I_{\text{RMS}}^{\text{Max}})}{4C I_{\text{Mean}}^{\text{Max}}} \quad (\text{A-4})$$

giving a numerical value of $7.5\mu\text{rad}$, for our set-up. The order of magnitude of this value corresponds to the smallest value we were able to measure experimentally (i.e. $22\mu\text{rad}$ in Fig. 4).

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	LiNbO ₃	LiTaO ₃
Thickness L (mm)	20	12
Inter-electrode distance d (mm)	5	5
n_o	2.286 [14]	2.177 [15]
n_e	2.203 [14]	2.181 [15]
d_{31} (pm.V ⁻¹)	-1 [16]	-2 [16]
r_{13}^T (pm.V ⁻¹)	9.6 [17]	8.9 [18]
r_{33}^T (pm.V ⁻¹)	30.8 [17]	32.1 [18]
$\Delta\phi_o/V$ (mrad.V ⁻¹)	2.22	1.04
$\Delta\phi_e/V$ (mrad.V ⁻¹)	6.49	3.91

Table 1 : Parameters of the crystals used in the study

	LTO1	LTO2	LTO3
Sensitivity (mrad.V ⁻¹), ordinary polarisation at 183Hz	1.0095±0.0015	0.9362±0.0016	1.0486±0.0014
Sensitivity (mrad.V ⁻¹), ordinary polarisation at 25.7kHz	1.03814±0.00027	0.99336±0.00021	0.85363±0.00022
Sensitivity (mrad.V ⁻¹), extraordinary polarisation at 25.7kHz	3.7958±0.0011	3.5999±0.0009	3.17205±0.0010
Ratio of sensitivities	3.656	3.624	3.716

Table 2 : Measurement sensitivity of LiTaO₃ crystals

Figure captions

Figure 1 : Experimental set-up for phase shift measurement. Pol : Polarizer, $\lambda/2$: half wave plate, PM : Piezo-mirror, Det : Detector, S : sample. The laser beam is expanded and an image of the output face of the sample is made on the detector.

Figure 2 : (a) : Temporal evolution of the mean signal I_{Mean} and of the RMS value ΔI_{RMS} of the sinusoidal signal. The piezo mirror is sinusoidally excited and the secondary maximum and minimum peaks of I_{Mean} (around 10s and 35s) corresponds to the return points of the displacement of the piezomirror. (b) : Parametric plot of the curve $\Delta I_{\text{RMS}} = f(I_{\text{Mean}})$

Figure 3 : Evolution of the square of the RMS value of the sinusoidal signal as a function of the mean signal. The line in black is the fit with a parabola (the data are the ones of Figure 2).

Figure 4 : Experimental evolution of the phase shift as a function of the applied voltage, with its linear fit, for ordinary polarization (square and dotted line) and extraordinary polarization (circles and full line). In the insert, the data for ordinary polarization are shown in log-log scale. The frequency of the sinusoidal applied voltage is 12.67kHz.

Figure 5 : Evolution of the sensitivity of the Pockels LiNbO_3 crystal as a function of the frequency of the applied voltage.

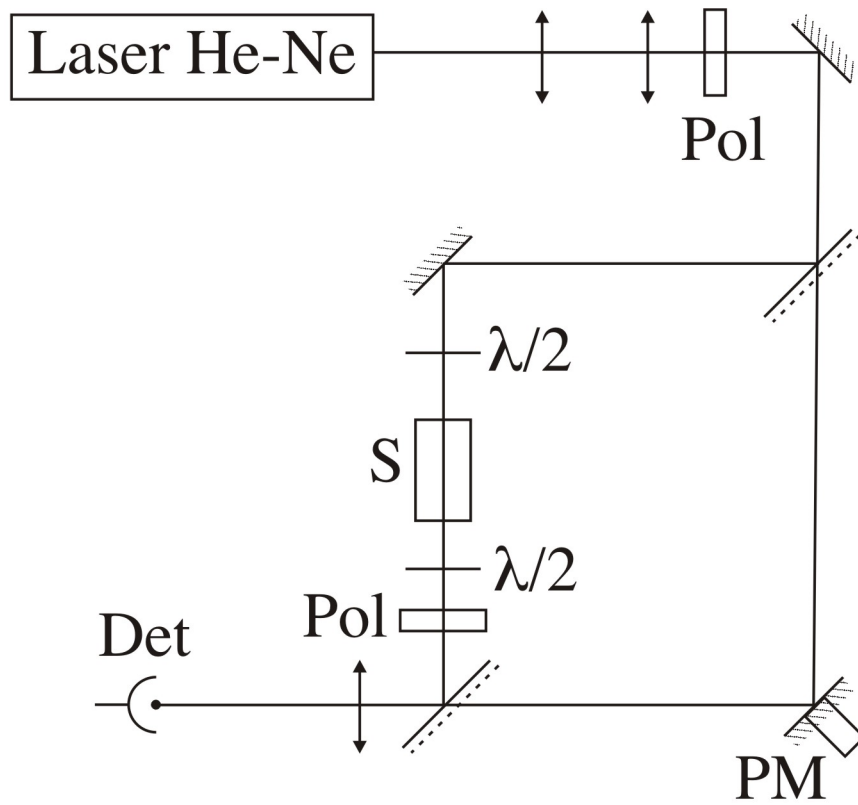


Figure 1 : Delaye et al.

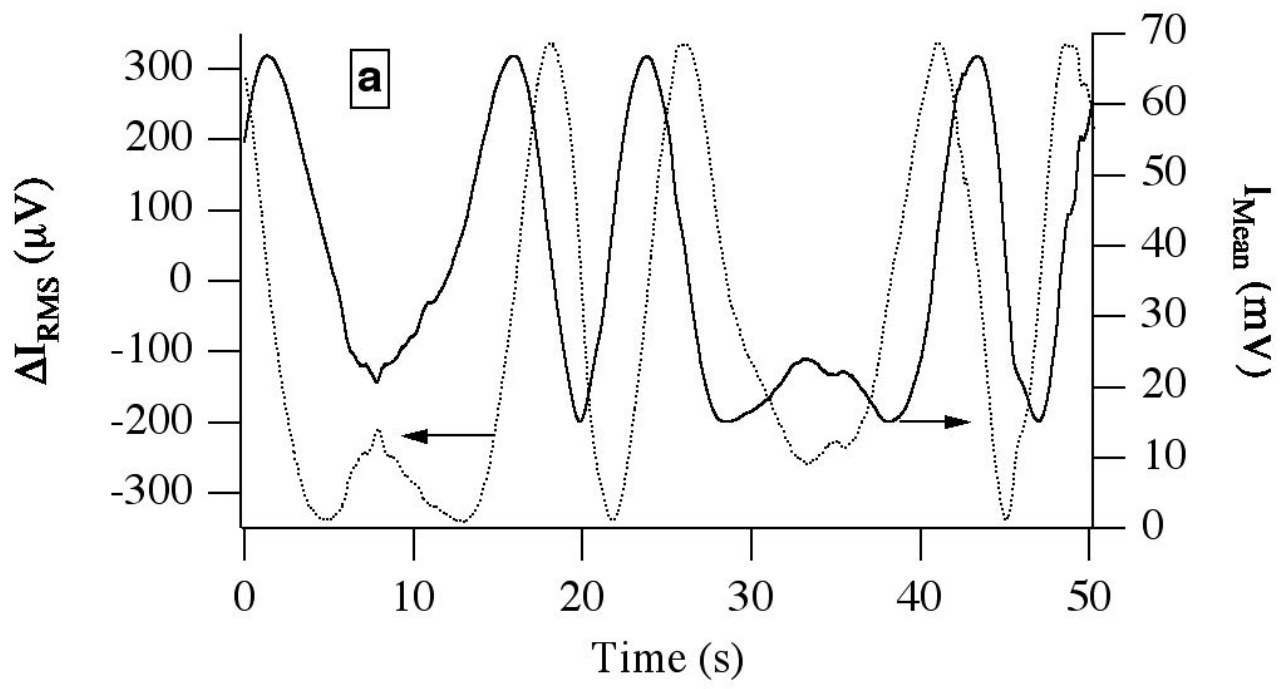


Figure 2a : Delaye et al.

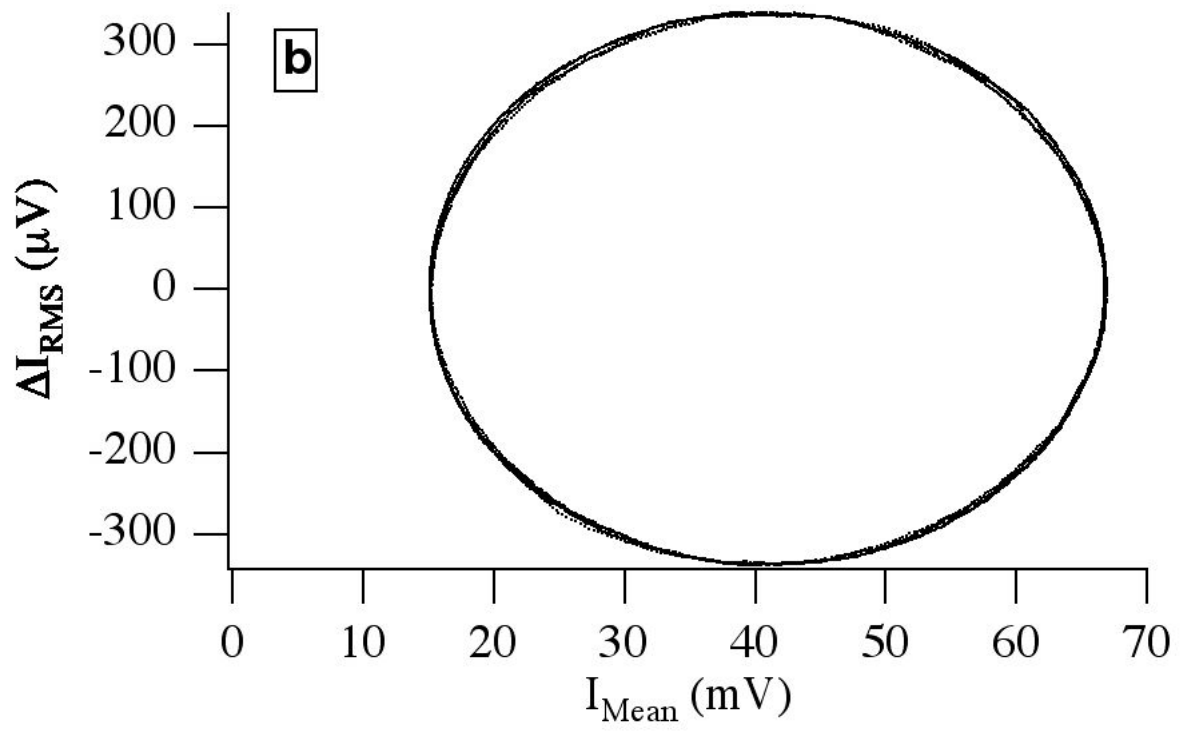


Figure 2b : Delaye et al.

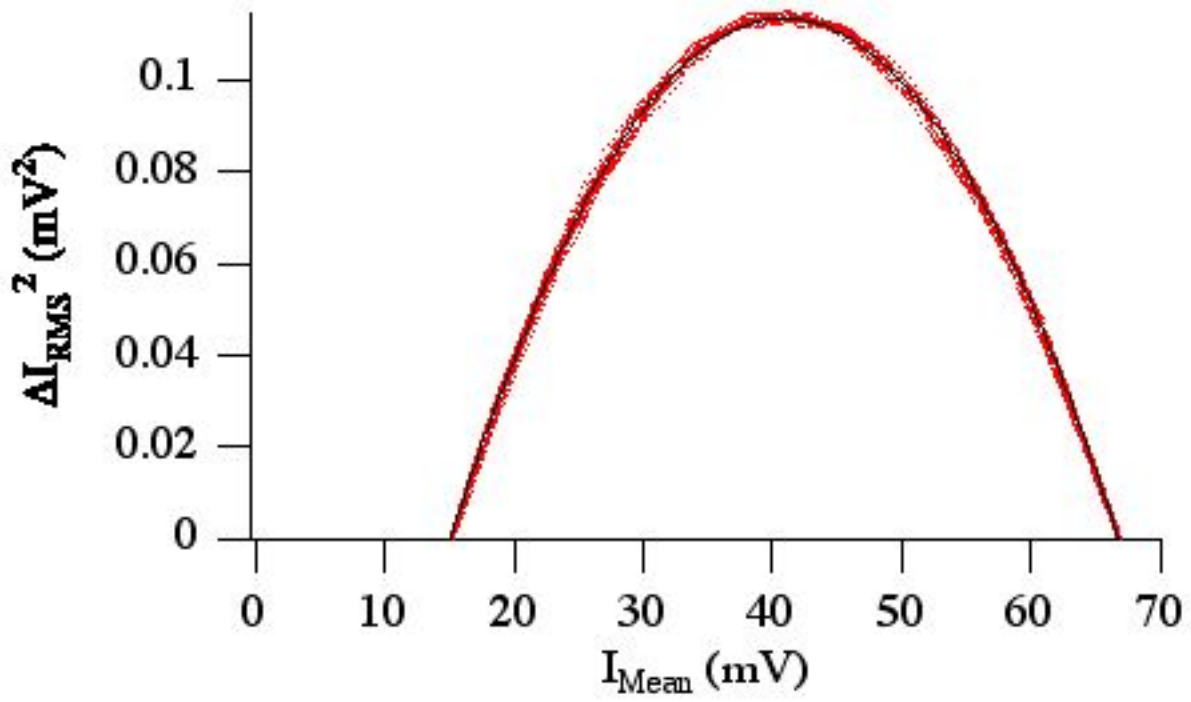


Figure 3 : Delaye et al.

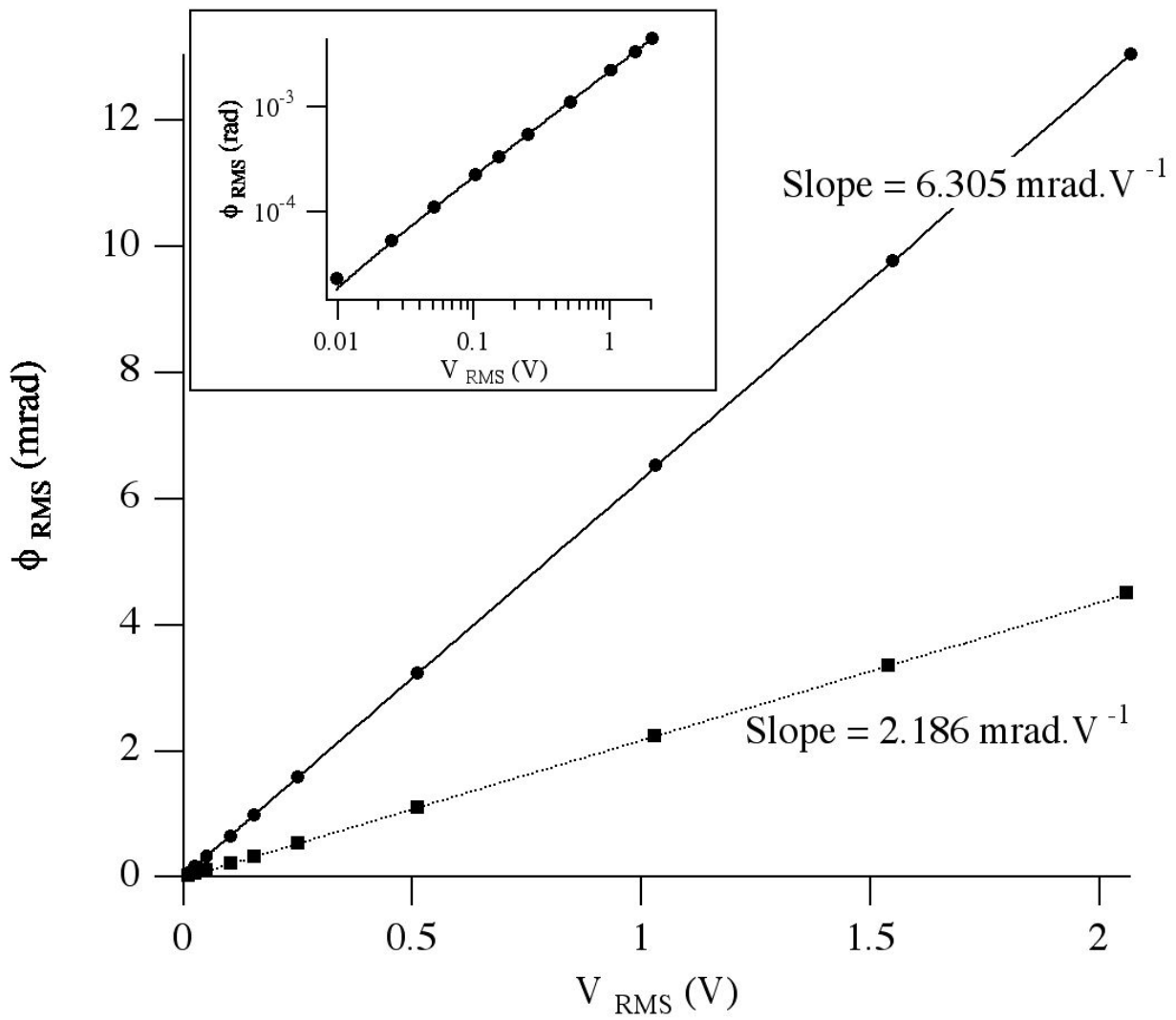


Figure 4 : Delaye et al.

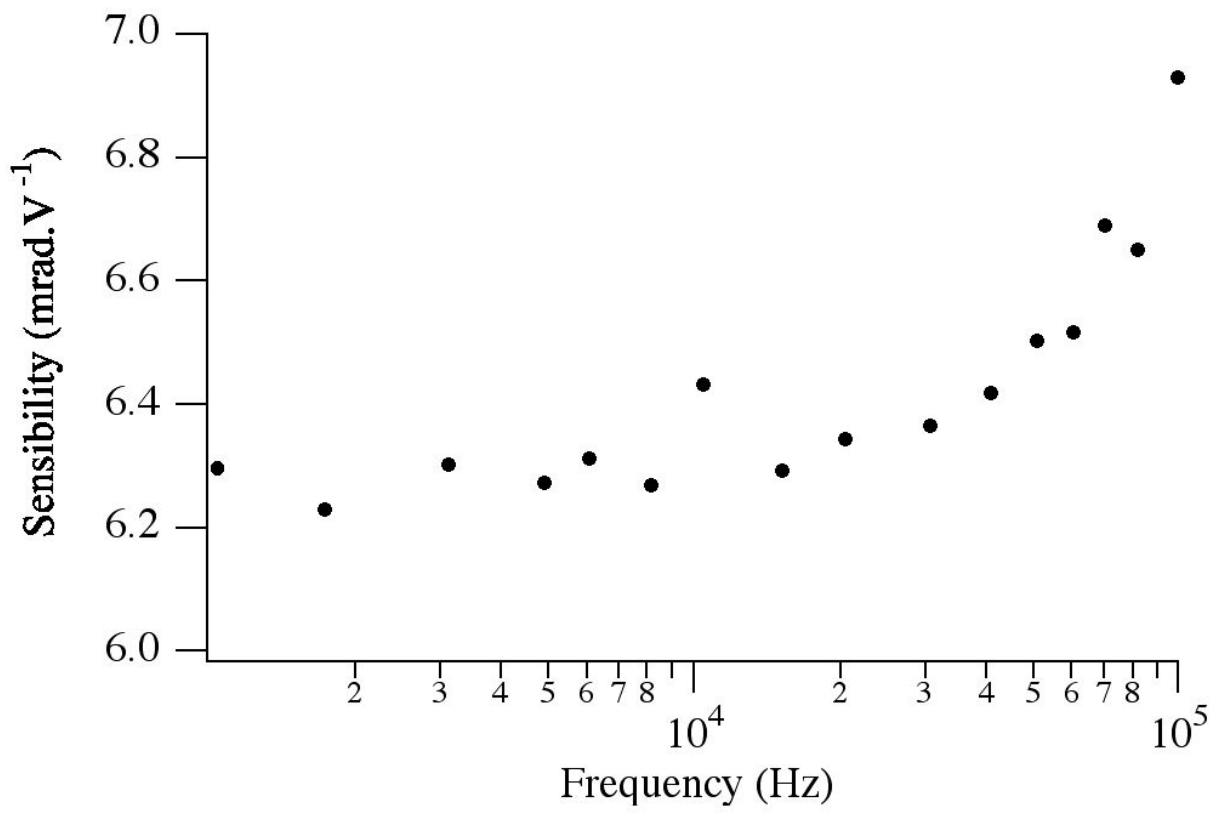


Figure 5 : Delaye et al.