Experimental investigation of a photorefractive ring phase modulation amplifier

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EXPERIMENTAL INVESTIGATION OF A PHOTOREFRACTIVE RING PHASE MODULATION AMPLIFIER

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Abstract :

We present the experimental investigation of a photorefractive ring phase modulation amplifier, that is not resonant and that can work with distorted beams. We show that with this geometry an amplification by a factor 5 of a phase modulation signal is possible. We also show that this strong amplification is alleviated by the presence of losses in the ring. These losses lead to a real gain in signal to noise ratio of a factor 3, that nevertheless expresses that with such a system the photon noise limit of laser ultrasonics system can be overpassed. The losses are also responsible for the strong sensitivity of the system to the vibrations, which puts a strong limitation of the ring amplifier.

1. Introduction

The development of the laser ultrasonic technique has increased the demand for detection scheme that are both sensitive and can work with highly deformed speckled beams. Different systems based on dynamic wavefront adaptation in photorefractive crystals have been studied and characterized [1 - 6]. All these systems meet the necessary requirements concerning the étendue and the possibility to work with speckled beams. With these speckle structures, they reach the sensitivity obtained by other optical techniques (homodyne or heterodyne detection) with plane waves [7]. Nevertheless, all these optical techniques suffer from reduced sensitivity if compared to piezoelectric transducers : they are all limited by the photon noise.

A solution to overcome this limit is to amplify the phase modulation by multiple pass on the phase shifting structure. For example, in the case of ultrasonic signals, the tested surface can be the back mirror of a Fabry-Perot interferometer. At resonance, the photons are stocked in the cavity which results in multiple passing on the vibrating surface, enhancing the total phase shift seen by the wave. This technique works well but requires very tough conditions on the quality and the positioning of the surface to be tested. It should be a highly reflective and flat (or eventually spherical) surface to have a high finesse of the Fabry Perot. It should be very exactly positioned for the cavity to be at resonance. Under these conditions high amplifications of the signal can be obtained. Unfortunately, most of the time, the surfaces tested with the laser ultrasonic techniques are rough low reflectivity surfaces, with a position that can vary in the range of some millimeters. The use of such Fabry Perot cavity is thus unrealistic.

Recently, a new kind of cavity was proposed [8]. In this cavity, based on a photorefractive crystal, some of the requirements on the quality of the surface are alleviated. This is because the cavity being no more resonant, its length is no more a condition for the amplification of the phase modulation. As a consequence such an amplification system could increase the sensitivity of laser ultrasonic systems, keeping their advantages such as the possibility to have a non contact measurement system.

In this paper we will describe the experimental implementation of such a photorefractive ring amplifier. Its performances will be evaluated and compared to the theoretical expectations. Some of its limits will be finally discussed.

2. The photorefractive ring amplifier: Principle

The ring geometry used for the amplification of the phase modulation [8] was first used as a real time programmable ring for image storage [9]. The principle of this ring can be seen in figure 1. A beam, with power density I_i, is sent on a photorefractive crystal. After transmission through the crystal, it is returned back to the crystal, as beam I_d with a set of mirrors in a ring geometry. The crystal orientation is such that there is energy transfer through two beam coupling from I_d towards I_i. So when sent on the crystal, I_i generates I_d and writes with it a photorefractive grating on which I_d diffracts. Through energy transfer the power of I_d is increased, leading to a reinforcement of the grating, until a steady state regime is reached. In this steady state regime, we have increased the power of I_d through beam coupling. We have then an accumulation of energy in the ring, all the more that the photorefractive gain is high. This accumulation of energy corresponds to photons that are trapped in the ring and thus make several turns in the ring. Then if a phase modulation $\varphi(t)$ is introduced in the ring, as illustrated by the electrooptic modulator (EOM) in figure 1, the photons see several time this phase modulation leading to an amplification of the phase modulation. The exit beam carries an amplified phase modulation that can be detected through classical techniques like a photorefractive beam mixer [1 - 3, 5, 6]. Moreover, except during a short transient behavior, all the energy put at the entrance is transferred to the exit of the ring if there is no loss in the cavity.

One problem with this principle is that, as the photons make several turns in the cavity, they see several times the different cavity losses (absorption, diffusion, ...). The energy transmitted through the cavity will decrease all the more that the photorefractive gain (i.e. the number of turns) will be high. This will cause a reduction of the efficiency of the system, as the device that will demodulate the phase modulation has its sensitivity that depends on the energy of the carrying beam. So a very low loss crystal and cavity will be necessary for the system to work. These losses will also make the system extremely sensitive to low frequency vibrations as will be seen in the following.

3. The energy accumulation in the ring : Comparison of experiment and theory

The first point that we will conduct in the experiment is to underscore the energy accumulation in the ring and compare it to the theory. This point is important as the whole phenomenon of phase modulation amplification is based on the capacity of the ring to trap the photons and to make them go several times through the phase modulation element. We are here only interested in the steady state regime.

The source is a single longitudinal mode frequency doubled Nd:YAG laser emitting at λ=532nm. Its total power is about 80mW. For the experiment, we use a $BaTiO_3$ crystal of 0.36cm thickness, with antireflection (AR) coatings, and with a crystallographic cut (i.e. the c axis in the plane of incidence and perpendicular to the normal of the coated faces). The beams I_i and I_d were incident on the crystal with angles of 32° and 57° respectively, in order to maximize the photorefractive gain [10], that we measure to be around $\Gamma = -9cm^{-1}$ (the minus sign comes from the sign of the energy transfer and indicates energy transfer from the probe beam I_d towards the pump beam I_i). With these large angles the efficiency of the AR coating is reduced especially for I_d. We measure a reflection coefficient of 2.7% for I_d and 0.3% for I_i with extraordinary polarizations (with close values for ordinary polarizations). We also measure an absorption coefficient α=0.18cm^{-1} for this crystal at this wavelength.

For the theoretical treatment we consider a beam I_0 incident on the crystal. This beam gives the beam $I_i(0)$ at the entrance of the crystal but inside it (we have $I_i(0)=T_i\ I_0$, with T_i the transmission factor of the first interface). This beam is transmitted through the crystal to give $I_i(d)$, just before the exit face, and is sent back on the crystal by the ring as beam $I_d(0)$, just after the entrance face, with an intensity transmission T. Transmission T thus includes the transmissions on the exit and entrance interfaces and the transmission of the different elements of the ring. Its value is T= 0.88. $I_d(0)$ is transmitted through the crystal to form $I_d(d)$. This beam exits from the crystal to form I_F (we have $I_F=T_d\ I_d(d)$, with T_d the transmission of the exit interface), and is finally sent on the phase demodulation device. All the beams $I_i(x)$ and $I_d(x)$ are taken inside the crystal.

A simple calculation [9] gives the energy accumulated in the ring as well as the energy at the output of the cavity. We have (supposing small angles inside the crystal) :

$$I_d(0) = T\,I_i(d) = I_i(0)\frac{K}{2\,e^{\Gamma d}} \quad \text{and} \quad I_d(d) = I_i(0)\frac{K^2}{4T\,e^{\Gamma d}} \tag{1}$$

with $K = \left[-\left(1 - T\,e^{-\alpha d}\right) + \sqrt{\left(1 - T\,e^{-\alpha d}\right)^2 + 4\,T\,e^{-\alpha d}\,e^{\Gamma d}}\right]$

In the lossless case ($T\,e^{-\alpha d} = 1$), we have $K = 2e^{\frac{\Gamma d}{2}}$ which gives $I_d(0) = I_i(0)e^{-\frac{\Gamma d}{2}}$ and $I_d(d) = I_i(0)$, the energy accumulation is simply given by the factor $e^{-\frac{\Gamma d}{2}}$. The presence of losses reduces the energy accumulated in the ring, but also decreases the energy that goes out of the ring. This last point will be the main limitation of the performances of the ring for the amplification of the phase modulation as, as it is well known, the signal to noise ratio of phase demodulation systems depends on intensity of the demodulated beam.

Experimentally we measure both the energy accumulation in the cavity (i.e. $I_d(0)$) and the decrease of the output intensity (i.e. $I_d(d)$). For $I_d(d)$ we put the detector at the output of the ring. For $I_d(0)$ we used the reflection of the beam at the first interface of the crystal (that can be easily separated from the reflection of the same beam on the second interface). So we can monitor $I_d(0)$ without introducing new losses in the ring. For both beams we monitor the variation of intensity with time when the beams are put on in the ring. The results are shown in figure 2. We can see the temporal evolution of both beam intensities until the steady state regime. Before the beams are put on, there is no grating in the crystal and thus $\Gamma=0$, we can thus measure $I_d(0)_{\Gamma=0}$, whereas, at steady state, we measure $I_d(0)_{\Gamma\neq 0}$ (with the same measure for $I_d(d)$). From these curves we deduce that $I_d(0)$ is amplified by a factor $\frac{I_d(0)_{\Gamma\neq 0}}{I_d(0)_{\Gamma=0}} = 3.2 \pm 0.3$, whereas $I_d(d)$ is decreased by a factor $\frac{I_d(d)_{\Gamma=0}}{I_d(d)_{\Gamma\neq 0}} = 1.9 \pm 0.2$.

Once noted that when $\Gamma=0$, we have $K = 2T\,e^{-\alpha d}$, we can easily compare the experimental values with the theoretical ones. We have :

$$\frac{I_d(0)_{\Gamma\neq 0}}{I_d(0)_{\Gamma=0}} = \frac{\left[-\left(1 - T\,e^{-\alpha d}\right) + \sqrt{\left(1 - T\,e^{-\alpha d}\right)^2 + 4\,T\,e^{-\alpha d}\,e^{\Gamma d}}\right]}{2\,T\,e^{-\alpha d}\,e^{\Gamma d}} \tag{2a}$$

and

$$\frac{I_d(d)_{\Gamma=0}}{I_d(d)_{\Gamma\neq 0}} = \frac{1}{4e^{2\alpha d}\, e^{\Gamma d}\left[-\left(1-T e^{-\alpha d}\right)+\sqrt{\left(1-T e^{-\alpha d}\right)^2+4T e^{-\alpha d}\, e^{\Gamma d}}\right]^2} \tag{2b}$$

With the experimental values T=0.88, $e^{-\alpha d}$=0.935 and $e^{-\Gamma d}$=26, we calculate $\frac{I_d(0)_{\Gamma\neq 0}}{I_d(0)_{\Gamma=0}} = 3.5$ and $\frac{I_d(d)_{\Gamma=0}}{I_d(d)_{\Gamma\neq 0}} = 2.1$, which corresponds to the experimental results.

So we observe an accumulation of energy in the ring that corresponds to the expected value. This energy accumulation is accompanied with a decrease of the energy that goes out of the cavity. This loss of energy will limit the performances of the ring as will be seen in the following. We will now study the phase modulation amplification brought by this energy accumulation.

4. The phase modulation amplification : Comparison of experiment and theory

The ring acts as a phase modulation amplifier. We will now analyze its amplification ability by measuring the phase modulation of the beam $I_d(d)$ at the output of the ring. For this phase demodulation we use a photorefractive beam mixer, made with a photorefractive crystal with an applied DC electric field, as previously implemented [3, 5 - 7]. Because of the wavelength sensitivity range of the $BaTiO_3$ crystal used in the ring, the photorefractive beam mixer has to operate in the visible (here at 532nm). Then a $Bi_{12}SiO_{20}$ crystal is used (Fig. 3). In this study, we will compare the signal given by the photorefractive beam mixer with the ring either working or not. For simulating a not working ring, we put in the ring, just before the crystal, an half wave plate (HW2 in Fig. 3), that turns the polarization of $I_d(0)$. When $I_d(0)$ is extraordinary polarized, the ring works. When $I_d(0)$ is ordinary polarized, it is crossed polarized with $I_i(0)$, and no photorefractive grating can be written. A simple rotation of the wave plate allows the measurement of the phase modulation amplification without changing anything in the set-up.

The phase modulation is given by a Pockels cell (EOM) introduced in the cavity. This Pockels cell gives a sinusoidal phase modulation with a RMS amplitude of 1.7mrad at frequency 100kHz.This phase modulation amplitude would correspond to a displacement of one of the mirror of the cavity of about 0.1nm.

4.1 Theoretical treatment

A. Phase modulation amplification

Once a steady state regime is obtained, the system can be seen as a steady state volume grating on which beams diffract in the Bragg regime. Using the method described in Ref.[8] but taking into account the crystal absorption and the losses of the ring, we obtain the optical field amplitudes E_i and E_d of the different beams at the exit of the crystal :

$$\begin{cases} E_i(d) = e^{-\frac{\alpha d}{2}} E_i(0)\sqrt{1-\eta} + e^{-\frac{\alpha d}{2}} E_d(0) e^{-i\varphi_0}\sqrt{\eta} \\ E_d(d) = -e^{-\frac{\alpha d}{2}} E_i(0) e^{i\varphi_0}\sqrt{\eta} + e^{-\frac{\alpha d}{2}} E_d(0)\sqrt{1-\eta} \end{cases} \quad (3)$$

with $\sqrt{\eta} = \sqrt{T e^{-\alpha d}}\left(\frac{1-e^{\frac{\Gamma d}{2}}}{1+\frac{K}{2}}\right)$ and $K = \left[-\left(1-T e^{-\alpha d}\right) + \sqrt{\left(1-T e^{-\alpha d}\right)^2 + 4 T e^{-\alpha d} e^{\Gamma d}}\right]$

where the absorption losses in the crystal are taken into account. φ_0 is the phase shift introduced by the transfer through the ring between $E_i(d)$ and $E_d(0)$.

Once the ring is in its steady state regime, a low amplitude phase modulation $\varphi(t)$ ($\varphi(t) \ll \pi/2$) is introduced in the ring. This phase modulation is introduced in the transfer expression of the ring :

$$E_d(0) = \sqrt{T}\, e^{i\varphi_0}\, e^{i\varphi(t)} E_i(d) \quad (4)$$

This transfer relation introduced in the system allows to calculate the amplitude $E_d(d)$ at the output of the crystal. We have :

$$E_d(d) = E_i(0) e^{i\varphi_0} e^{-\frac{\alpha d}{2}}\left[-\sqrt{\eta} + \frac{\sqrt{T}\, e^{-\frac{\alpha d}{2}}(1-\eta) e^{i\varphi(t)}}{1-\sqrt{T}\sqrt{\eta}\, e^{-\frac{\alpha d}{2}} e^{i\varphi(t)}}\right] \quad (5)$$

If now, we use the fact that the phase modulation is very small ($\varphi(t) \ll \pi/2$), i.e. $e^{i\varphi(t)} = 1 + i\varphi(t)$ and $\cos(\varphi(t)) = 1$, the previous equation can be rewritten :

$$E_d(d) = E_i(0) e^{i\varphi_0}\, Y\left[1 + i X \varphi(t)\right] \quad (6)$$

with $X = e^{-\frac{\Gamma d}{2}}$ and $Y = \frac{K e^{-\frac{\Gamma d}{2}}}{2\sqrt{T}}$

If we now suppose that the amplification is low enough to assure that ($X\varphi(t) \ll \pi/2$) we will have :

$$E_d(d) = E_i(0) e^{i\varphi_0}\, Y e^{i X \varphi(t)} \quad (7)$$

indicating the amplification of the phase modulation by a factor X, whereas the intensity of the output beam intensity decreases by a factor Y^2 as seen previously (eq.1). One remarkable point is that the amplification of the phase modulation is not at all influenced by the losses in the cavity and depends on the photorefractive gain only.

B. Signal to noise ratio amplification

Now to estimate the true performances of the system we have to include the phase detection system and to remind that this is the initial intensity I_0 that has to be taken into account. The phase detection system receives a beam of amplitude :

$$E_F = E_0 \sqrt{T_i T_d}\, e^{i\varphi_0}\, Y\, e^{iX\varphi(t)} \tag{8}$$

The detection system we use here, is a photorefractive beam mixer, but the following treatment is independent of the type of detection scheme used. Consider that the photorefractive crystal of the beam mixer has an amplitude gain $\gamma = \gamma' + i\gamma''$, a thickness x and an absorption α'. When a beam of amplitude $E_s(0,t) = E_s(0,0)e^{i\phi(t)}$ (with $\phi(t) << \pi/2$) is sent on such a crystal, we measure at the output [11]:

$$I_s(x,t) = I_s(0,0)e^{-\alpha' x}\left[e^{2\gamma' x} + 2\,e^{\gamma' x}\sin(\gamma'' x)\phi(t)\right] \tag{9}$$

With our previous notations, we have $E_s(0,0) = E_0\sqrt{T_i T_d}\, e^{i\varphi_0}\, Y$ and $\phi(t) = X\varphi(t)$. Thus, on the detector, we will have :

$$I_s(x,t) = I_0\, T_i\, T_d\, Y^2\, e^{-\alpha' x}\left[e^{2\gamma' x} + 2e^{\gamma' x}\sin(\gamma'' x)\, X\varphi(t)\right] \tag{10}$$

From this, we can establish the signal to noise ratio for the whole system (phase amplifier and demodulator) [6]:

$$SNR_{Ring} = \sqrt{\frac{2\eta_d I_0}{h\nu\,\Delta f}}\sqrt{T_i T_d}\, X\, Y\, \varphi(t)\, e^{-\frac{\alpha' x}{2}}\sin(\gamma'' x) \tag{11}$$

in which η_d is the quantum efficiency of the detector, $h\nu$ is the photon energy, and Δf is the measurement frequency bandwidth.

This result has to be compared to the signal to noise ratio obtained with the same phase demodulation system used with the same target without going through the amplification ring but with the same incident intensity. This corresponds to a reference signal to noise ratio :

$$SNR_{Ref} = \sqrt{\frac{2\eta_d I_0}{h\nu\,\Delta f}}\,\varphi(t)\, e^{-\frac{\alpha' x}{2}}\sin(\gamma'' x) \tag{12}$$

Comparing equations (11) and (12), we define the gain in signal to noise ratio that can be written :

$$G_R = X\,Y\sqrt{T_i\,T_d} \tag{13}$$

which gives :

$$G_R = \frac{e^{-\Gamma d}}{2\sqrt{T}}\sqrt{T_i T_d}\left[-\left(1 - T\,e^{-\alpha d}\right) + \sqrt{\left(1 - T\,e^{-\alpha d}\right)^2 + 4\,T\,e^{-\alpha d}\,e^{\Gamma d}}\right] \tag{14}$$

This gain in signal to noise ratio, as expected, depends only on the parameters of the ring and is independent of the characteristics of the phase demodulation system.

4.2 Experimental study

A. Phase modulation amplification

The demodulation photorefractive beam mixer uses a $Bi_{12}SiO_{20}$ crystal of thickness 7mm having an absorption $\alpha' = 0.86cm^{-1}$. We applied on this crystal a DC voltage of 3kV (which corresponds to a field of about $4kV.cm^{-1}$). Under these conditions we measure, using the demodulation of the known phase modulation signal and equation (9) [6, 11], the amplitude of the amplitude gain $\gamma = \gamma' + i\gamma''$ with $\gamma' \approx 0.04cm^{-1}$ and $\gamma'' \approx 0.3cm^{-1}$.

To compare more easily the signal with and without the ring active, a neutral filter is put at the output, when the ring is inactive (crossed polarization and $\Gamma=0$), to compensate for the energy loss that occurs when the ring becomes active. The half wave plate at the output of the ring (HW3, Fig.3) is here to turn the polarization when we go from the crossed polarization geometry ($\Gamma=0$) to the parallel polarization geometry ($\Gamma\neq0$), i.e. to maintain a constant state of polarization for the beam entering the photorefractive beam mixer.

The measured signal has a DC part and an AC part that is the demodulated phase modulation signal (eq.10). With an inactive ring, ($\Gamma=0$) we measure a DC signal $V_0=8.2\pm0.1V$ and an AC modulated part $\delta V_{RMS}=8.3\pm0.2mV$. With the active ring ($\Gamma\neq0$), we measure a DC signal $V_0=8.2\pm0.5V$ and an AC modulated part $\delta V_{RMS}=42\pm2.7mV$. These results are shown in figure 4. As the DC level is the same for the two cases, the curves show directly the amplification X of the phase modulation due to the amplification ring.

As the phase modulation $\Delta\varphi$ is proportional to the ratio $\delta V_{RMS}/V_0$ (eq.10) with the same proportionality coefficient in both cases ($\Gamma=0$ and $\Gamma\neq0$), we have :

$$X_{exp} = \frac{\Delta\varphi_{(\Gamma\neq 0)}}{\Delta\varphi_{(\Gamma=0)}} = \frac{\left(\delta V_{RMS}/V_0\right)_{(\Gamma\neq 0)}}{\left(\delta V_{RMS}/V_0\right)_{(\Gamma=0)}} = 5 \pm 0.8$$

This value corresponds well to the theoretical value $X_{th} = e^{-\frac{\Gamma d}{2}} = 5$.

We also measure the influence of the losses in the ring on this amplification of the phase modulation. For this, we introduce in the ring a variable neutral filter of transmission T_{NF}.

For T_{NF}=0.91, we measure with the inactive ring (Γ=0) : V_0=8.06±0.08V and an AC modulated part δV_{RMS}=8.3±0.17mV. With the active ring (Γ≠0) we get : V_0=6.7±0.4V and an AC modulated part δV_{RMS}=33±2.1mV. From this, we deduce $X_{exp} = 4.7 \pm 0.8$.

For T_{NF}=0.84, we measure with the inactive ring (Γ=0) : V_0=7.5±0.1V and an AC modulated part δV_{RMS}=8±0.2mV while with the active ring (Γ≠0) we obtain : V_0=5.2±0.3V and an AC modulated part δV_{RMS}=25±1.6mV. We deduce $X_{exp} = 4.5 \pm 0.7$.

From these results, we see that the phase modulation amplification does not depend, within the experimental errors, on the losses in the ring. We also see that the decrease of the DC signal is much stronger when the ring is active, which confirms the theoretical results on the influence of losses on the ring performances.

B. Gain in signal to noise ratio

We have now all the experimental parameters to evaluate the performances of the ring and to calculate the gain in signal to noise ratio G_R brought by the phase amplification ring. If we remember that the transmissions of the faces are close to one we have $\sqrt{T_i T_d} = 1$ and the value of G_R is given by the product XY. We have measured in the first part of the study a loss at the output of the ring : $\frac{I_d(d)_{\Gamma\neq 0}}{I_d(d)_{\Gamma=0}} = \frac{1}{1.9}$. As Y^2 can be written as $Y^2 = \frac{I_d(d)_{\Gamma\neq 0}}{I_d(d)_{\Gamma=0}} \times \frac{I_d(d)_{\Gamma=0}}{I_i(0)}$ with $\frac{I_d(d)_{\Gamma=0}}{I_i(0)} = T\,e^{-2\alpha d}$, we deduce Y=0.58±0.03. In the same time we have measure a phase modulation amplification X=5±0.8.

So, from these results, we deduce the gain in signal to noise ratio provided by the ring G_R=2.9±0.6**.** It is the amplification of the signal to noise ratio that is obtained in comparison with the one that would be obtained with the same incident power sent directly on the same target but without passing through the ring and its different losses. This gain in signal to noise ratio corresponds to the one that can be expected from the theoretical model (eq.14) with the experimental parameters : G_R=3.1. This value is also not optimum due to the low value of the photorefractive gain in the crystal used (Fig. 5). With a better crystal we will reach a high gain limit value of $G_{R\,lim} = \frac{\sqrt{T}\, e^{-\alpha d}}{\left(1 - Te^{-\alpha d}\right)}$, which value is 4.95. So we have the confirmation that the ring can be used to amplify the phase modulation. The gain in signal to noise ratio is modest and very dependent on the losses in the ring but it exists and is noticeable. Nevertheless, one point does not appear in this study, and we will discuss it now, this is the sensitivity of the system to external vibrations that is brought by the presence of the losses.

C. Vibration sensitivity of the ring

This vibration sensitivity is directly induced by the working principle of the amplification ring. Indeed, in its normal working mode the induced grating is $\pi/2$ phase shifted from the illumination grating which causes the energy transfer responsible for the energy accumulation in the ring. Now a low frequency vibration (but high enough frequency compared to the frequency response of the photorefractive crystal, i.e. some tenths of Hertz), will be characterized by a high amplitude phase shift that will displace the illumination grating relatively to the index grating, that remains stationary. The optimum condition for energy transfer will be no more fulfilled and some energy will be expelled from the ring, leading to an increase of the energy at the output, increase that will be totally random as the vibration that induces it. In the same time the phase modulation signal will be linearly demodulated by the photorefractive crystal of the ring that will act as a photorefractive beam mixer (as the phase shift between the illumination and the index gratings is no more $\pi/2$, it is equivalent to a complex photorefractive gain γ). The main problem with this phenomenon, which is not detrimental by essence, is the fact that the vibrations are generally completely random and uncontrollable, and thus unexploitable.

This influence of the vibrations can be easily described theoretically. For this we go back to equation (5), that describes the beam amplitude at the output of the crystal. We can rewrite it as :

$$E_d(d) = E_i(0)e^{i\varphi_0}\, e^{-\alpha d}\sqrt{T}\left[\frac{-\left(1-e^{\frac{\Gamma d}{2}}\right)+\left(1+\frac{K}{2}\right)e^{i\varphi(t)}}{\left(1+\frac{K}{2}\right)-T\,e^{-\alpha d}\left(1-e^{\frac{\Gamma d}{2}}\right)e^{i\varphi(t)}}\right] \qquad (15)$$

with $\varphi(t) = \varphi_s + \Delta\varphi(t)$, φ_s being the phase shift given by the vibration (that is supposed to be rapid enough not to erase the index grating) and $\Delta\varphi(t)$ the phase modulation to be measured with $\Delta\varphi(t) << \pi / 2$. In these conditions we have :

$$\cos\varphi(t) = \cos\varphi_s - \Delta\varphi(t)\sin\varphi_s \qquad (16)$$

And, if we calculate the energy at the output of the ring, we can write it as :

$$I_d(d) = I_i(0)\left[A - B\Delta\varphi(t)\right] \qquad (17)$$

with $A = e^{-\alpha d} + \frac{\left(T\,e^{-\alpha d}-1\right)}{2Te^{\Gamma d}}\frac{K}{\left[1+C\left(1-\cos\varphi_s\right)\right]}$ and $B = \frac{\left(Te^{-\alpha d}-1\right)}{2T\,e^{\Gamma d}}\frac{K\,C\sin\varphi_s}{\left[1+C\left(1-\cos\varphi_s\right)\right]^2}$

where $C = \left(\frac{K^2}{2T\,e^{-\alpha d}\,e^{\Gamma d}}\right)\frac{\left(1-e^{\frac{\Gamma d}{2}}\right)\left(1+\frac{K}{2}\right)}{\left(e^{\frac{\Gamma d}{2}}+\frac{K}{2}\right)^2}$

We find on these expressions the different interesting points we discussed previously. First A increases when φ_s changes from 0, indicating the energy increases at the output of the ring. Second there is a phase demodulation as B is different from zero when φ_s departs from 0. Another remarkable point, that also appears on the expressions, is that this effect totally disappears when there is no losses in the ring : we have A=1 and B=0 when $T\,e^{-\alpha d} = 1$.

We think that this sensitivity to the low frequency vibrations is the main limitation of the use of the amplification ring. The solutions would be to increase the rapidity of the crystal used in the ring without losing in amplification, i.e. keeping a low absorption value and a high two wave mixing photorefractive gain. Thus the optimization of such a system seems to be quite difficult.

5. <u>Conclusion</u>

We have presented the experimental investigation of a photorefractive ring phase modulation amplifier proposed in Ref. [8]. The main results of this study is that such a system can allow for the amplification of a phase modulated signal, such as an ultrasonic vibration signal, by a factor that can be as high as a factor 5. We also show that this amplification should be tempered by the increased losses that occur due to the amplification of the losses that occurs in the ring. These losses strongly reduce the amplification of the signal to noise ratio brought by the ring. By limiting at maximum these losses we obtain an amplification of this signal to noise ratio by a factor 3. This amplification is sufficient to allow the break of the photon noise limit of laser ultrasonic system, and can make them more competitive compared to classical piezoelectric systems. The properties of the system keep all the advantages of the optical techniques, which are the possibility to be non contact with a good depth of field. Due to the properties of the photorefractive effect it is possible ~~The possibility~~ to work with rough surfaces, if used with detection systems like the photorefractive beam mixer. This will be a great amelioration if compared to passive interferometers that are used in the same way, like Fabry Perot interferometers. Nevertheless we have shown that this result is acquired only in the case where losses remain low, i.e. on highly reflecting surfaces and if all the scattered light can be recovered and reinjected in the ring. The study also show a strong limitation of the system which is its extreme sensitivity to vibrations, because of the cavity losses. Nevertheless this sensitivity is also partly due to the slowness of the crystal used in this demonstration. The use of faster photorefractive crystals can allow to overpass this limitations, if this enhanced rapidity is not obtained at the detriment of the efficiency or the absorption. Another solution to prevent this vibration sensitivity could be the use of an active stabilization of the ring to compensate for the vibrations.

This study also shows a good adequacy of the experimental results to the theoretical model. The work will be continued towards the study of new geometry, like the reflection grating geometry, and to the development of dynamical models that can describe the frequency response of such a system.

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Figure Captions :

Figure 1 : Schematic representation of the phase modulation amplification ring. The phase modulation is simulated by an electrooptic modulator (EOM).

Figure 2 : Temporal evolution of the intensity of the beam inside the ring $I_d(0)$ and at its output $I_d(d)$. When the beam is put on there is no grating inside the crystal. The intensity are normalized to their values without grating.

Figure 3 : Experimental set-up with both the amplification ring and the photorefractive beam mixer for phase demodulation. HW_i are half wave plates. L_i are lenses. PBS is a polarization beamsplitter. NF is a neutral filter used to compensate for the increased signal when the amplification ring doesn't work.

Figure 4 : AC part of the demodulated signal with the ring operating (solid line) and with the non working ring (dashed line), showing the amplification brought by the amplification ring. Both curves corresponds to the same value of the DC part of the signal.

Figure 5 : Calculated gain in signal to noise ratio of the ring G_R as a function of the photorefractive gain $(-\Gamma)$, showing the saturation of the amplification at high gain due to the losses of the ring. We use for the calculation the experimental values α=0.18cm^{-1}, T=0.88 and a crystal thickness of 0.36cm. The experimental data (■) is placed on the curve for comparison.

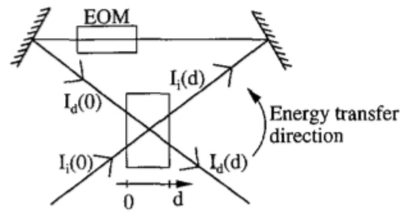

Figure 1

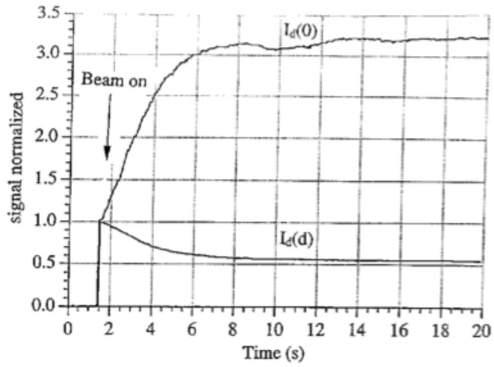

Figure 2

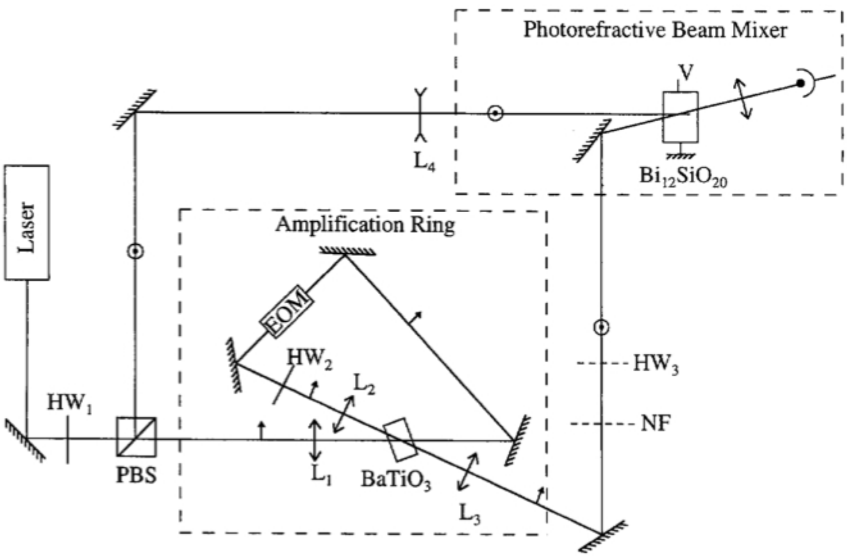

Figure 3

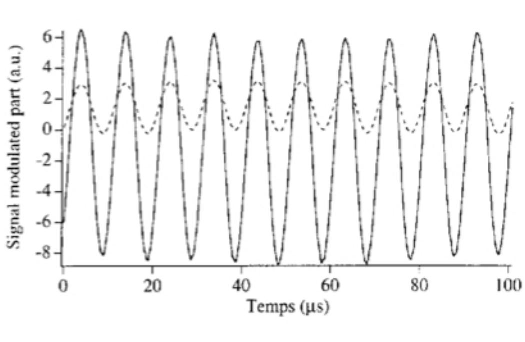

Figure 4

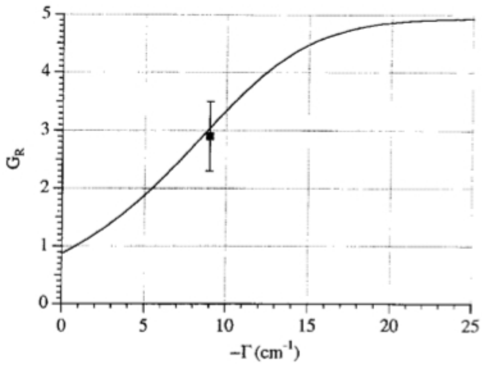

Figure 5