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We present an improved version of the classical heterodyne interferometer for ultrasound detection, which includes a double phase conjugate mirror (DPCM) in the detection arm. The DPCM performs wave front adaptation to plane wave of the speckled beam scattered by the rough surface of the sample. The performances of the system are analyzed regarding the transmission (≈30%) and fidelity (≈70%) of the phase conjugation and the response time and étendue of the device. An example of application to the detection of laser generated ultrasound is also presented.

Ultrasonic excitation of a solid sample (optically opaque) can be detected by directing a laser beam at one of its surfaces. Surface motion causes a transient phase shift upon the scattered light, which has to be demodulated into an intensity variation prior to its detection by a photodetector. Classical reference beam interferometry (homodyne or heterodyne) is a well-known technique for performing this demodulation and is characterized by a broad detection bandwidth, but is essentially limited (antenna theorem, Ref. 1) to the detection of one speckle, when used on rough surfaces. In order to circumvent this limitation (i.e., in order to increase the étendue of the interferometer), two different approaches for adapting the signal and reference wave fronts have been considered. The first approach proceeds by creating a reference beam that matched the wave front of the signal beam. This can be done by using a Fabry–Pérot (FP)[2] which is a self-reference interferometer and means that the reference beam is generated by the signal beam. It can also be done by using two-wave mixing (TWM) in a photorefractive crystal.[3,4] In this case, the reference beam is created by the diffraction of a plane wave pump beam by the hologram written by both pump and signal beams. Alternatively, the signal beam wave front can be adapted to the reference wave front, which requires, since the reference beam can usually be approximated by a plane wave, the transformation of the speckled beam to a beam with a plane wave front. Devices using externally pumped[5] or self-pumped phase conjugate mirrors[6] have been reported. These schemes require two reflections on the sample surface which strongly limit the sensitivity when the surface is absorbing. The double phase conjugate mirror (DPCM) is a speckle to plane wave front converter when one of the two beams creating the mirror is a plane wave.[7] A DPCM was previously used in a heterodyne scheme to produce a wide field of view interferometer[8] for remote sensing. It has also been used in a homodyne interferometer for ultrasound detection.[9]

In this letter we present the main characteristics of a heterodyne interferometer with a DPCM for ultrasound detection. We also present an example of the application of the device to the detection of laser generated ultrasound.

The configuration of the device is shown in Fig. 1. The laser is a single mode argon ion laser operating at 514 nm. An acousto-optic modulator (AOM) driven at 40 MHz is used for both splitting the laser beam and producing a 40 MHz frequency offset between the two beams. The direct frequency unshifted beam is again split in two variable parts, using a half-wave plate and a polarization beam splitter. One part, labeled P_1, is sent to the photorefractive $BaTiO_3$ crystal where DPCM action occurs. The other part is the reference beam of the heterodyne interferometer. The deflected frequency shifted beam is coupled onto the surface in ultrasonic motion using a large core multimode fiber [MMF, numerical aperture (NA)=0.22, core diameter (Φ)=200 μm]. Scattered light is then collected by the same fiber. The beam being

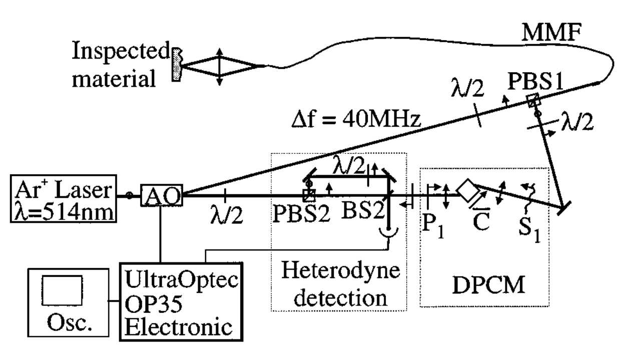

FIG. 1. Experimental setup. PBS: polarizing beam splitter; BS2: beam splitter; λ/2: half-wave plate; MMF: multimode optical fiber; Osc.: oscilloscope.

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entirely depolarized by the transfer through the fiber, we use a polarizing beam splitter (PBS1) to extract the vertical component. Then, a half-wave plate rotates the polarization by 90° which results in a horizontally polarized speckled beam, labeled S_1, is sent to the photorefractive crystal. The DPCM produces two phase conjugate beams counterpropagating with respect to the incident beams with the following properties: (1) each generated wave front is an exact replica of its counterpropagating brother, (2) the two generated beams acquire the temporal phase modulation of the copropagating incident beam. For our purpose, the interesting point is that the beam which counterpropagates along the beam P_1 is a plane wave with the transient phase variation of beam S_1, (3) the two incident beams should be incoherent in order to prevent the formation of reflection gratings, which is realized in our setup by using beams with a large frequency offset. In summary, the experimental setup is that of a classical heterodyne interferometer[11] having in its signal beam path a wave front converter provided by the DPCM. Two parameters are important in order to characterize the performance of the DPCM in this case.[10] The first one is its transmission (T_{DPCM}), which indicates the fraction of the incident speckled beam power that is transferred to the phase conjugate plane wave. The second one is the conjugation fidelity (CF) that indicates the proportion of the transmitted beam that is truly the phase conjugate of the second beam pump incident on the DPCM. This parameter affects the mixing efficiency of the heterodyne detection.[11] A perfect DPCM should have unitary transmission and a conjugation fidelity of 1, which means that the DPCM would be, in this case, a purely transparent wave front adapter.

In a first series of experiments, an electro-optic modulator was inserted in the pathway of the signal ahead of the fiber to produce a sinusoidal phase modulation of variable amplitude and frequency. Demodulation of the phase modulated rf signal was provided by a commercial demodulation unit with a bandwidth of 35 MHz.[12] We used a barium titanate ($BaTiO_3$) crystal with input faces cut perpendicularly to the $\vec{c}$ axis. The two p-polarized incident counterpropagating pump beams, S_1 and P_1, made a small angle (≈20° outside the crystal). The bisector of the two beams was at an angle with respect to the $\vec{c}$ axis (≈40° outside the crystal) in order to make use of the high r_{42} coefficient of the electro-optic tensor of the barium titanate (see Fig. 1). To maximize the transmittivity of the DPCM we used P_1 and S_1 of approximately equal power,[13] which means that the optimum power to be used for P_1 is determined by the amount of light collected from the inspected material. The two beams were slightly focused to increase the energy density and to optimize beam overlap inside the crystal. Concerning the power used for the reference beam (i.e., the local oscillator), this power should be chosen much higher than the power of the phase conjugate beam, which is the usual condition to get high sensitivity in heterodyne detection.[1]

We first measured the DPCM transmission T_{DPCM} and found a value between 25% and 30%. Since the losses from reflection and absorption contribute to a transmission of the crystal of about 40%, it means that almost 75% of the transmitted beam is diffracted in the phase conjugate direction. The second parameter we measured is the conjugation fidelity. Usually, a plane wave pumped DPCM leads to very poor phase conjugation fidelity because of conical diffraction.[14] In our setup this drawback is eliminated since one pump beam is a speckled beam, and therefore good quality of the phase conjugation is expected. The heterodyne rf signal is given by $I = I_S + I_R + 2CF\sqrt{I_S I_R}\cos\Delta\omega t$, where I_S is the signal power, I_R is the reference power, and $\Delta\omega$ is the offset angular frequency, and CF is the conjugation fidelity that is equivalent to the mixing efficiency integral of the two waves.[11] By measuring the modulation depth of the 40 MHz signal output, we deduced a value of the CF around 0.6 and 0.8, which indicates a good fidelity of the phase conjugation. We can remark that the same measurement conducted with a mirror replacing the DPCM gives about the same value. This indicates that CF is not far from one.

Using the calibration factor of the rf phase demodulator we derived the minimum detectable displacement (displacement detection limit) $\delta_{\mathrm{rms}} = 0.41$ Å, δ_{rms} is defined as the rms displacement which gives a rms signal equal to the rms noise. This value is close to the theoretical detection limit, which is evaluated to be about 0.24 Å, by using the formula giving the sensitivity of heterodyne detection[1] and the values of the experimental parameters applicable to our setup. If we normalize, as it is usual, the detection limit to unitary detection bandwidth and unitary collected power (the measurement bandwidth is 15.5 MHz in our case and the power of the signal incident on the DPCM of 1.7 mW), we obtain the normalized sensitivity: $\delta_{l\mathrm{rms}} = 4.3\times10^{-6}$ Å $\sqrt{\mathrm{W/Hz}}$. This value takes into account not only the losses of the DPCM (reflection, absorption, DPCM transmission, and conjugation fidelity), but also some avoidable losses of the setup, due in particular, to a nonoptimized beam splitter (BS2) that samples the conjugate beam, nonoptimized reference beam power, and some uncoated optics. We have also characterized our DPCM with regard to its response time by monitoring the build up of the phase conjugate beam. These data show the known kinetics of the DPCM,[10] i.e., a first part with no output which corresponds to the establishment of the multiple beam-fanning gratings, then a fast rising part corresponding to the construction of the phase conjugate grating to the detriment of all the others. The total build up time is around 5 s which is quite rapid taking into account the low power of the two pump beams S_1 and P_1 (1.9 and 3.7 mW, respectively). We have also verified, using a mirror mounted on a piezoelectric pusher, that the DPCM was not affected by the Doppler effect induced by high amplitude motion of the sample (several microns at frequencies of a few hundreds of Hz). The étendue of the device is at least equal to that of the used optical fiber (NA=0.22, $\Phi = 200\ \mu$m) which corresponds to an étendue of 5×10^{-3} mm^2 sr. We have also performed measurements with a larger core fiber (NA=0.36, $\Phi = 1$ mm, and étendue of 0.4 mm^2 sr) and obtained reduced performance, T_{DPCM} being around 8% and CF around 0.3. This could be attributed to the smaller value of the power density inside the crystal due to the higher fiber étendue. The power density was in this case insufficient to saturate the

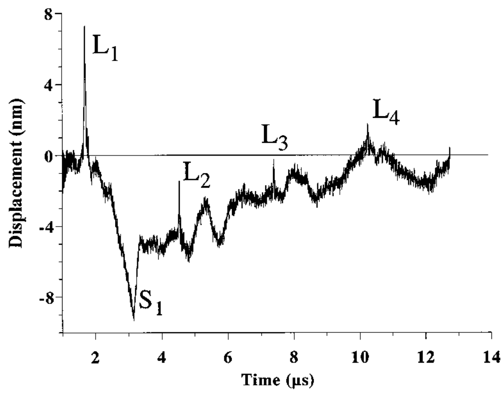

FIG. 2. Ultrasonic displacement induced by a Nd–YAG laser pulse on an aluminum plate. The pulse is sent on the plate at time $t=0$, at epicenter on its opposite face. We can readily identify the longitudinal wave arrival (L) with its various echoes, as well as the shear wave arrival (S).

photorefractive gain, leading to smaller gain and then smaller efficiency and fidelity.[15] Nevertheless, our system's étendue is limited by the multimode fiber rather than that of classical heterodyne receivers.

Figure 2 shows the ultrasonic data obtained on an aluminum plate with a thickness of about 9 mm. The ultrasonic wave was generated on the opposite side via ablation by a Nd:YAG laser. The observed wave form is typical of laser generated ultrasound in this regime, showing the arrival of the longitudinal wave, of the shear wave and their echoes.

How do the characteristics of this interferometer compare with other interferometers designed for ultrasonic measurements? The system we have presented has a major advantage over the conventional heterodyne interferometer by its large étendue. This means, in particular, that the beam does not have to be focused onto the surface of the sample to a near-diffraction limited spot, and that it is possible to detect ultrasound field averaged over a much larger area. Large étendue means also that the beam could be coupled to and from the surface with a multimode large core fiber allowing remote operation of the system. Note that the system presented here has the same detection bandwidth as the classical heterodyne interferometer, this bandwidth being limited on one side by the AOM frequency shift and on the other side by the low-frequency cutoff of the phase demodulation. Being heterodyne in nature it is also readily calibrated. All the improvements brought by the DPCM are kept when a homodyne configuration is used.[9] The differences between these two systems using a DPCM are the same as the ones between conventional heterodyne and homodyne interferometers.[1] It should be noted that, since the two pump beams of the DPCM have to be incoherent or frequency shifted to prevent the formation of reflection gratings, these beams are readily available in the heterodyne system. The homodyne scheme actually needs an additional frequency shifter to satisfy this requirement.[9]

A limitation of our device is linked to the response time of the DPCM that could nevertheless be improved, at least theoretically, by the use of more rapid crystals like photorefractive semiconductors or improved $BaTiO_3$ crystals. Compared to other wide field of view interferometers, like the FP or the TWM,[4] it suffers from its slow turn-on time. This turn-on time, which is linked to the conjugate beam build up time, is adversely affected by the low light level collected from the scattering surface. Furthermore, the proper operation of this system requires that the speckle pattern be constant during the build up time, so there will be major limitations for the inspection of products on a production line or any moving products. One advantage of the DPCM system over the TWM one is that it is not sensitive to Doppler shift induced by low-frequency and large amplitude motions perpendicular to the surface of the inspected sample, as far as those do not change the speckle pattern.

We have described an étendue widened heterodyne ultrasonic receiver based on the clean-up of the speckled beam by a double phase conjugate mirror. We illustrated its use by detecting laser generated ultrasound on a rough surface aluminum plate with good sensitivity. The key element of this system, the DPCM was characterized regarding its phase conjugate transmission (≈30%) and fidelity (≈0.7). The étendue of our system was shown to be limited by the étendue of the multimode fiber used for light collection. The turn on time of the system was determined by the DPCM build up time and evaluated to ≈5 s, which limits its use to stationary conditions over such a time. In spite of this limitation, the other advantages mentioned above should make this system very useful for many applications.

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