SPECIFICATIONS OF AN ULTRASONIC RECEIVER BASED ON TWO-WAVE MIXING IN PHOTOREFRACTIVE GALLIUM ARSENIDE IMPLEMENTED IN A LASER-ULTRASONIC SYSTEM

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INTRODUCTION

Optical techniques for ultrasonic measurements present several advantages over conventional piezoelectric methods. First, they are remote sensing techniques and can be, for example, used for the inspection of materials at elevated temperature or products moving on a production line. Secondly, surfaces of complex shape can be easily probed since these techniques work with scattered light. For specific applications, these advantages compensate the usually lower sensitivity of optical techniques.

The basic scheme of optical detection of ultrasound consists of three successive steps: the ultrasonics-to-optics, the optical phase-to-intensity and the optical intensity-to-electric signal conversions. The ultrasonics-to-optics conversion is produced by the surface motion associated with the ultrasonic wave which induces a phase change on the light beam scattered by the surface. Since optical detectors are not sensitive to phase variations but to intensity variations, an optical phase-to-intensity conversion is required and is usually performed by an interferometric technique. The resulting modulated light beam is then converted by an optical detector in a time-varying electrical signal, representative of the surface ultrasonic motion.

In order to be used for inspection of materials on a production line or more generally in an industrial environment, the optical detection system should meet several criteria that have been reviewed [1]. In summary, the device should work with speckle beams scattered by a rough surface and should have a large étendue or throughput to gather a large fraction of the scattered light. In practice, since the amount of light collected at a distance from the scattering surface is low, illumination by a high power...
laser is preferable. Since in practice, this laser has to be pulsed, the system should be fast enough to operate in this pulse regime. Furthermore, the device should not be too sensitive to ambient vibrations and thermal drift. Finally, as expected for a measuring device, the sensitivity should be adequate for the intended application.

SPECKLE INSENSITIVE INTERFEROMETERS

Among the few passive interferometric techniques available for ultrasound detection[1], the one based on the use of a confocal Fabry-Perot (FP) was recognized as the most appropriate for operation in an industrial environment [2]. Active interferometric approaches have also been recently considered and an interferometer based on two-wave mixing (TWM) in photorefractive crystal was proposed and tested in a BaTiO₃ crystal [3]. In spite of comparable or even better results than the FP regarding the operation with speckle beam, étendue and sensitivity, it appears that the response time of BaTiO₃ is too slow to meet the requirements for industrial operation. This slow response time makes the device too sensitive to ambient vibrations. Clearly, a faster response time is required, which is found in photorefractive semiconductors.

The characteristics of a TWM interferometer in an undoped semi-insulating photorefractive GaAs crystal were recently reported [4]. The diffusion of charge carriers was the mechanism responsible for the photorefractive effect since no electric field was applied to the crystal. From measurements performed with a low power cw laser, a comparison of the FP and TWM devices was performed. It appeared that the sensitivity of the photorefractive system is about 2.5 times lower than the maximum sensitivity of the Fabry-Perot operated in the transmission mode. For frequency lower than 2 MHz, however the sensitivity of the photorefractive device is higher. The étendue of the photorefractive system was verified to be at least equal to that of the Fabry-Perot. It should also be noted that the GaAs TWM device has the advantage of not requiring any stabilization circuitry to compensate ambient vibrations or thermal drift [4]. The device is also more compact and could be possibly of lower cost.

In this paper, we are presenting the results obtained by inserting the GaAs photorefractive device in a complete laser generation and detection system. The GaAs device was also replaced by a Fabry-Perot system previously used, thus allowing direct comparison between the two detection schemes.

EXPERIMENTAL SETUP

The scheme of the experimental setup is sketched in figure 1. The ultrasonic generation laser is a TEA CO₂ laser with a pulse duration of about 120 ns and an energy of 100 mJ per pulse. The detection laser is a Nd:YAG laser which delivers about 1 kW peak power in a 50 μs long pulse. The detection beam is transmitted through a multimode optical fiber and directed colinearly with the CO₂ beam onto the surface of the sample. The spot size is about 4 mm. The sample is a 13 mm thick carbon-epoxy material. It is white-painted to increase both generation efficiency and light scattering. The light scattered by
the surface is collected by lenses and transmitted to the Fabry-Perot or to the two-wave mixing interferometer by a second optical fiber. The confocal Fabry-Perot is one meter long with two 85% reflectivity mirrors. The TWM device is based on anisotropic two-wave mixing in the diffusion regime in a GaAs crystal and a differential configuration, as previously described, is used [4]. Both input and output faces of the crystal are anti-reflection coated at 1.064 μm. To optimize the signal-to-noise ratio, which is a function of the ratio of the photorefractive gain to absorption [4], a crystal length of 10 mm is used. The pump beam for two-wave mixing is obtained by taking off a small fraction of the energy at the output of the high power detection laser. The buildup time of the grating can be tuned from 1 to 10 μs or more by varying the pump power level. It should be noted that the use of a differential detection scheme permits a strong reduction of the noise coming from the amplitude fluctuations of the laser. The overall detection bandwidth is limited by electronic filters from 0.1 MHz to 12 MHz.

COMPARATIVE PERFORMANCES OF THE TWO DETECTION SYSTEMS

From the experiments we performed, it is not possible to readily evaluate the absolute sensitivity of each detection system, however, their sensitivities can be precisely compared.

The two systems which were actually used present a few differences, besides the ones which are intrinsic to their operation, and which should be taken into account to
make a fair comparison. There was in particular a difference in the transmission of the coupling optics, originating from the presence in one system of a few uncoated elements. The quantum efficiency of the detectors and the electronic gain were also different. The results presented below take these differences into account and are appropriately normalized. Plotted in this form, the results simulate conditions where all the optical elements were properly anti-reflection coated and where identical detectors and amplifiers were used. Since the photorefractive system uses polarized light, the utilization of a polarizer ahead of the system results into the loss of about half of the signal intensity when using a multimode optical fiber for light transmission. The confocal Fabry-Perot does not have such a requirement. We did not take this loss into account in the case of the photorefractive, since the lost light can be used by a second photorefractive device, thus eliminating this penalty (however this will make the system more complex and expensive).

We present first the results obtained on the sample mentioned earlier. In figure 2, we show the signal given by the two detection devices in exactly the same experimental conditions and with proper normalization. The curves were obtained after averaging over 100 consecutive shots. The scattered light injected in each device was 12 mW.

The first point to notice is the difference of amplitude of the first echo seen by the systems, which readily demonstrates the higher sensitivity of the Fabry-Perot device. The shape of the echoes is also different and a more careful inspection indicates that the

![Figure 2. Ultrasonic signal obtained on a white-painted 13 mm thick composite plate. Upper part, the signal obtained with the Fabry-Perot interferometer; lower part, the signal obtained in the same conditions with the photorefractive two-wave mixing interferometer.](image-url)
bandwidth of the photorefractive system is larger, leading to the detection of lower
frequencies (below 2 MHz). Since ultrasonic attenuation increases with frequency, the
decay of the echoes is more severe in the case of the Fabry-Perot. The frequency
contents of the echoes shift also towards lower frequencies as the ultrasonic pulse
propagates through the material. Consequently, as can be seen, the second echo and the
subsequent ones appear larger with the photorefractive system.

More quantitative information can be obtained by frequency analysis. Figure 3
shows the Fourier transform of the first echo detected by each system. The characteristics
of these spectra are determined by those of the source pulse (which in this case follows
closely the laser pulse shape [5]), the material, the frequency response of the devices and
electronic filtering (high frequency cutoff set at 12 MHz by an analog filter).

Figure 3 shows that the peak detectivity of the Fabry-Perot is more than twice the
plateau of the photorefractive receiver and that for frequencies lower than 2 MHz, the
photorefractive device is more sensitive.

If we want to compare the two signal-to-noise ratios, we have to determine the
noise level in each case. We found experimentally that the noise is of photonic nature.
We measured 2.0X10^{-4} V (rms) at the output of the detectors of the photorefractive
system (for the two detectors mounted in a differential scheme) and 3.0X10^{-4} V (rms) at
the output of the detector after the Fabry-Perot. Theoretically, the rms noise level can be
determined from the following relation:

![Figure 3. Frequency spectrum of the first echo measured by the two interferometers. F-P, Fabry-Perot; TWM, photorefractive two-wave mixing; dashed lines, theoretical frequency responses of the two detecting devices.](image-url)
\[ \sqrt{\langle \delta v \rangle^2} = \eta R_v \sqrt{\frac{2h\nu B W_0}{\eta}}, \]  

where \( R_v \) is the responsivity of the detector (in V/W), \( h \) is the Planck constant, \( \nu \) is the optical frequency, \( B \) is the electronic bandwidth, \( W_0 \) is the power incident on the detector and \( \eta \) is the quantum efficiency. Using this formula, we calculated a photonic noise level of 1.7\( \times 10^{-4} \) V for the photorefractive system and 2.5\( \times 10^{-4} \) V for the Fabry-Perot, in good agreement with the measured values.

Using the data of figure 3 and the value of the noise levels, we can now compare the sensitivities of the two systems. We find that the maximum sensitivity of the Fabry-Perot (i.e. at 5 MHz) is about 2.5 times higher than the one of the photorefractive device based on a GaAs crystal. This value agrees very well with the previously calculated value, as well with the one measured with lower and continuous wave laser illumination.

SENSITIVITY OF THE TWO-WAVE MIXING DETECTION SCHEME TO VIBRATIONS AND DOPPLER SHIFT

Ambient vibrations and thermal drifts are known to change the optical paths and alignment of the beams in any interferometric setup (Michelson, Fabry-Perot). These effects can be strongly reduced by a well designed rigid setup, but in practice, active stabilization is needed to ensure operation of the device at the proper point. This is not needed for a photorefractive device and in particular for the one we have developed based on two-wave mixing in GaAs. The hologram formed inside the crystal adapts itself in few microseconds to the slow motion of the interference pattern induced by vibrations. The fast response time ensures that the phases of the signal beam and of the diffracted reference beam are dynamically locked. The system is then essentially insensitive to ambient vibrations and temperature fluctuations.

Nevertheless, problems can arise when the surface displacement is much larger than a wavelength, for example in the case of very strong vibrations or when probing an object in motion in the direction of the line-of-sight. In this case, according to the well known Doppler effect, the signal beam acquires an optical frequency shift proportional to the velocity of the sample. As a consequence of this frequency shift between the pump and the signal beams, there is a constant displacement of the interference pattern with a velocity proportional to the shift. As the shift is increased, the hologram formation mechanism is not able to follow the moving interference pattern, which eventually results into a wash-out of the hologram and a loss of the demodulated signal.

We investigated this effect with a sample mounted on a vibration shaker for two different response times of the crystal. The results are presented in figure 4, where we plot the loss of sensitivity for response times of 1 and 10 µs versus the velocity of the sample in the direction of the line-of-sight. Obviously, the loss of sensitivity is more
severe with a slower response time. We measure a loss of sensitivity of 50% for a sample velocity of only 0.03 m/s ($\Delta f=54$ kHz) and a response time of 10 $\mu$s for a sample velocity of 0.18 m/s ($\Delta f=360$ kHz) and a response time of 1 $\mu$s. The reduction of the sensitivity can then be partially counterbalanced by decreasing the response time of the crystal.

CONCLUSION

In conclusion, we have integrated our novel photorefractive ultrasonic receiver based on two-wave mixing in GaAs in a complete laser generation and detection system. The performances of this system were compared to those of the confocal Fabry-Perot previously used. The results obtained, for the GaAs system and for its comparative performance, are consistent with our theoretical estimates and previous measurements made at lower and continuous laser power. Even though the sensitivity of the Fabry-Perot is still superior to the photorefractive system, the Fabry-Perot can be advantageously replaced by the GaAs system for operation at low frequencies, required in cases such as the inspection of thick composites or coarse microstructure materials.

We have also explored the effect of the motion of the sample in the direction of the line-of-sight. We have observed a reduction of sensitivity, which can be minimized by a faster response time of the crystal.

REFERENCES
