

Tailoring ultrasonic beams with optoacoustic holography

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ABSTRACT

A combination of laser-induced ultrasound generation and ultrasonic holography for spatial control of the generated ultrasonic pulse is presented. Ultrasound is produced by absorption of laser pulses at an absorbing layer in a water tank via the optoacoustic effect. In order to produce a defined ultrasonic frequency in the MHz range, the laser pulses are harmonically time-modulated using an acousto-optic modulator (AOM). Additionally, the laser intensity is spatially controlled. This is realized with a high resolution liquid crystal spatial light modulator (LCD). A computer generated pattern is displayed at the LCD and projected by the expanded laser beam to an absorptive layer in the water tank. As a result, the emitted ultrasonic wave emerges in a predetermined way, which is an acoustical analogue to the effect of a "diffractive optical element" in laser optics. The flexible method of optical ultrasound generation and diffractive steering promises new applications in medical and technical ultrasound diagnostics.

Keywords: optoacoustics, laser-generated ultrasound, computer designed holography, diffractive optics, diffractive acoustics

1. INTRODUCTION

During the past years laser-induced generation of ultrasound has become an interesting topic of research with respect to applications in medicine¹⁻⁹ and in material sciences¹⁰⁻¹³. Laser-induced generation of ultrasound employs the optoacoustic effect, i.e. the absorption of intensity-modulated laser light creates an ultrasonic wave of a frequency given by the light modulation frequency. Our interest in laser-induced ultrasound lies in its potential for flexible beam steering control of ultrasonic waves with optical elements. In contrast to piezo-generated ultrasound the method is contact-free, i.e. the ultrasonic field can be generated and steered in an object without mechanical contact of its surface with an ultrasonic transducer. The main advantages of optoacoustic holography are the flexible (spatial and temporal) control of the generated ultrasonic waves and the option of generating and tuning ultrasonic frequencies in a wide range from kHz to MHz.

In the first part we show how to create ultrasonic beams with arbitrary frequencies using modulated laser pulses. Then we show how the generated ultrasonic beam can be spatially controlled with holographic methods. Finally, we propose an extended modulation scheme which promises optical control over both temporal and spatial properties of the ultrasonic beam. This will be an analogy to diffractive optics, i.e. a kind of "diffractive acoustics".

2. ACOUSTO-OPTIC MODULATION OF LASER-INDUCED ULTRASOUND

It is well known that the absorption of light by a gas, a liquid, or a solid body results in thermal expansion, which produces a propagating pressure wave (corresponding to a sound wave), if certain conditions are satisfied (stress confinement and thermal confinement). The conversion efficiency between optical intensity and pressure amplitude is given by the so-called Grueneisenparameter¹⁴⁻¹⁶. Since this efficiency is low for solids or liquids, typically short laser pulses (in the nanosecond range) with a correspondingly high peak power are used, which produce a short ultrasonic pulse with a broad frequency bandwidth.

In our case, however, we want to generate ultrasonic pulses with a narrow frequency distribution in order to obtain sufficient temporal coherence for "ultrasound holography" applications. Thus we use a laser system which provides

pulses in the 10 μs range, which have enough peak power for producing ultrasonic pressure amplitudes in the medical-diagnostic power regime, but which are on the other hand long enough to be harmonically modulated (in the MHz range) for generating a defined ultrasonic frequency, i.e. several modulation cycles per laser pulse can be employed. Currently, we are able to continuously vary our generated ultrasound frequencies in the range of 500 kHz to 3 MHz, which is an important regime for medical diagnostics applications. In our experiments we use a flashlamp-pumped Ti:sapphire laser tuned to a wavelength of 780 nm, which delivers 10 μs -pulses with a maximum pulse energy of 550 mJ at a (maximum) repetition rate of 20 Hz.

Since the induced ultrasound wave follows the temporal shape of the laser pulse, it is possible to control the ultrasound frequency by intensity modulation of a light pulse with the required modulation frequency. For this purpose the laser pulse is chopped with an AOM¹⁷, which is switched on and off with a controlled frequency. The currently used AOM has a centre-frequency of 100 MHz and provides a maximum intensity modulation rate of 3 MHz.

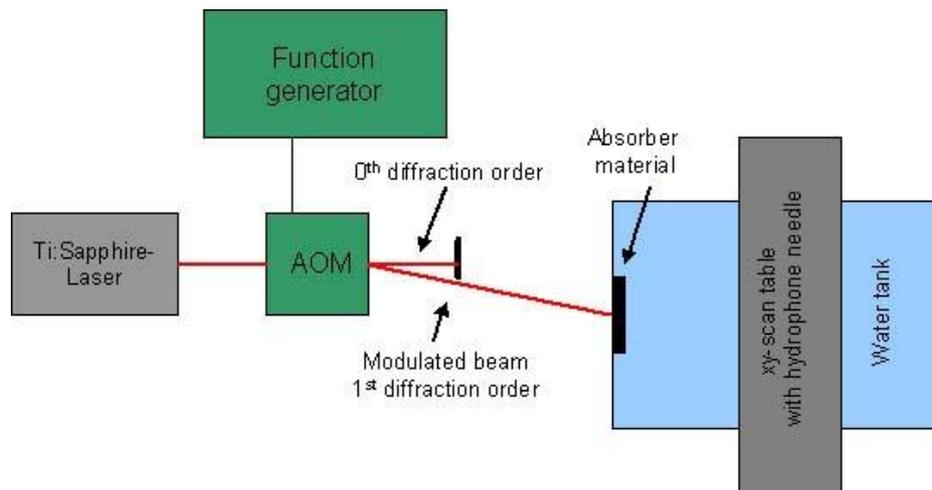


Figure 1: Experimental setup for acousto-optic intensity-modulation of the laser pulse. The diffracted beam can be switched on and off by applying an oscillating input signal to the AOM. The modulated laser pulse is converted by the optoacoustic effect at the absorbing layer in the water tank into an ultrasonic wave with a frequency corresponding to the laser modulation frequency.

Fig.1 shows a schematic drawing of the experimental set-up for optoacoustical ultrasound generation with an adjustable frequency. The 10 μs laser pulse is guided through an AOM. The first order diffracted beam is modulated by switching the AOM on and off with a frequency controlled by a function generator.

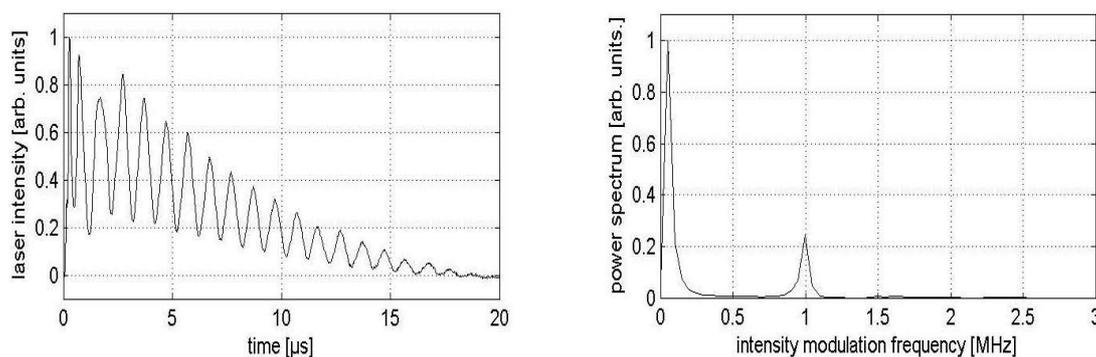


Figure 2: The modulated laser pulse (on the left) detected by a photo-diode and its corresponding power-spectrum (on the right). The frequency distribution shows a sharp peak at the laser modulation frequency of 1 MHz. The peak at lower frequencies is due to a constant offset of the signal.

An example for such a modulated laser pulse is plotted in figure 2. There the laser pulse was modulated with a frequency of 1 MHz applied at the AOM. The left part of figure 2 shows the corresponding temporal course of the laser intensity detected by a photo-diode. Due to the characteristics of our laser system, the pulse intensity starts at a high level, and then decreases slowly. On the right side of the figure the corresponding power spectrum is plotted, derived by Fourier transforming the intensity signal. As expected, the power spectrum shows a narrow peak at the AOM modulation frequency of 1 MHz.

Behind the AOM the laser pulse is expanded to a diameter of approximately 2 cm. The energy of the diffracted and modulated 10 μ s-pulse is typically adjusted to 50 mJ. The modulated light pulse is then projected to an absorbing material in the water tank (0.5 mm thick plane layer of black silicone at a glass slide - the glass side pointing to the laser beam). There, the light intensity modulation is converted via the optoacoustic effect into an ultrasound wave, which can be detected with spatial resolution by scanning a hydrophone needle¹⁸ in the water tank. The active element at the tip of the needle consists of a piezoelectric polymer (PVDF¹⁹) that converts the temporal pressure variations into a voltage signal, which is amplified and displayed on an oscilloscope. The diameter of the active PVDF element (0.4 mm) is smaller than our generated acoustical wavelength (on the order of 1.5 mm in the case of 1 MHz signals), and thus provides spatial resolution for all details of the generated ultrasonic field. The sensitivity of the hydrophone needle is about 10 mV/bar. The left part of figure 3 shows the temporal course of the resulting ultrasonic wave pressure amplitude, detected about 5 cm behind the absorption layer in the water tank.

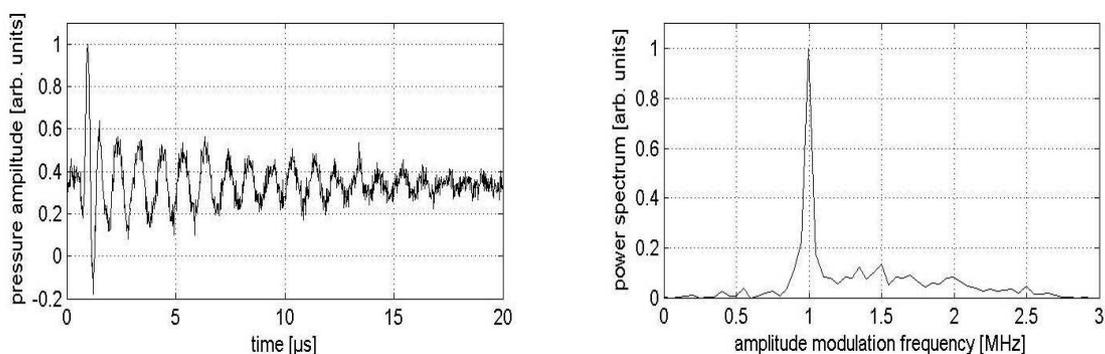


Figure 3: The modulated pressure signal (on the left) detected by a PVDF needle hydrophone and the resulting spectrum of the pressure amplitude. Clearly, the power spectrum consists dominantly of the 1 MHz contribution created by the modulated laser light.

The pressure signal has been averaged over 100 laser pulses. The resulting bandwidth of the signal around the modulation frequency of 1 MHz is about 100 kHz. Modulation frequencies of 2 MHz show similar results. However, the maximal experimentally achievable modulation frequency is currently limited by the efficiency of the AOM diffraction, which strongly decreases with higher frequencies. Nevertheless a frequency range of up to 3 MHz is currently accessible.

3. SPATIAL STEERING OF ULTRASONIC BEAMS USING PROJECTED LCD-IMAGES

So far we have shown that optical frequency control of laser-induced ultrasound is feasible, i.e. temporal control of the ultrasonic wave. In the following we additionally demonstrate spatial steering of the ultrasonic waves with optical methods. For this purpose we use a projection system which consists of a high resolution transmissive LCD²⁰ spatial light modulator, which can display computer-generated phase or amplitude holograms as a spatial polarization modulation (cf. fig.4). The modulated and linearly polarized laser beam is expanded to "overflow" the LCD. The calculated patterns are sent to the LCD display as video signals. Each pixel of the 800x600 LCD display (1 inch diagonal) rotates the incoming linearly polarized light in a range between 0 and 90 degrees, depending on the gray-level state of the pixel which is controlled by the input signal.

Behind the LCD display a polarizer acts as an analyzer and transforms the polarization modulated light field into a "normal" intensity modulated gray-level image, which is imaged sharply by a lens at the absorbing layer in the water

tank. Each "open" pixel of the LCD acts as a point source for an ultrasonic wave and the modulation phases of each "open" pixel are in phase (dark pixels always remain dark). Thus the projected picture defines the initial pressure distribution, i.e. the boundary condition for the Navier-Stokes equation which describes the spatial and temporal evolution of the laser-induced ultrasonic field. Since this equation can be approximated by a form that is of the same type as the optical wave equation⁹, all results known from optics can be applied to the pressure waves. Especially the Huygens' principle is valid for ultrasonic waves and Fresnel-Kirchhoffs diffraction theory can be used²¹⁻²⁴. A gray-level image projected with an intensity modulated laser beam to the absorbing layer acts as an acoustic analogue to a thin absorption hologram in optics. Therefore the well-known methods of computer generated holography in optics can be directly transferred to optoacoustics.

In order to demonstrate the feasibility of the method, we manipulate the ultrasonic field by projecting various fundamental diffraction patterns. Two basic examples will be shown, first the projection of absorption gratings, and second the projection of binary (i.e. "black and white") Fresnel zone-plates²⁵ to the light absorbing layer in the water tank.

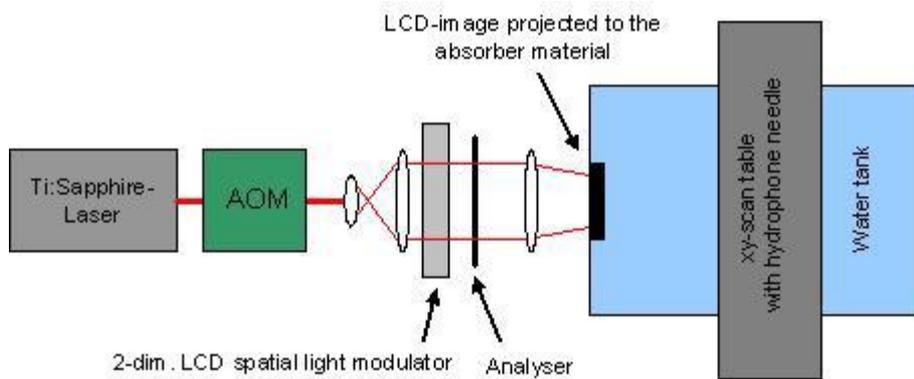


Figure 4: Experimental set-up for projecting an LCD-image to the absorber. Since the laser light is already linearly polarized only a polarization analyser behind the LCD-screen is needed to project an image to the absorbing layer within the water tank. The laser beam has to be expanded in front of the LCD for projecting the whole displayed image to the absorber.

In the case of a projected absorption grating the ultrasound wave is diffracted mainly into the first diffraction order, with a diffraction angle given by the grating equation²¹:

$$\sin(\alpha) = \frac{\lambda}{d}, \quad (1)$$

where α is the diffraction angle, λ is the wavelength of the acoustic wave in water and d is the grating constant. In our experiment we have measured the diffraction angle for various grating constants, experimentally generated by projecting different LCD stripe patterns to the sample. The maximum diffraction efficiency for absorption gratings is about 10%²² (amplitude, not intensity). According to equation (1) a plot of the grating constant d as a function of $1/\sin(\alpha)$ results in a straight line. From the slope, the wavelength of the induced sound wave in water (see figure 5) was determined. Both, the wavelength determined in this way and the ultrasonic wavelength detected with the hydrophone are in good agreement.

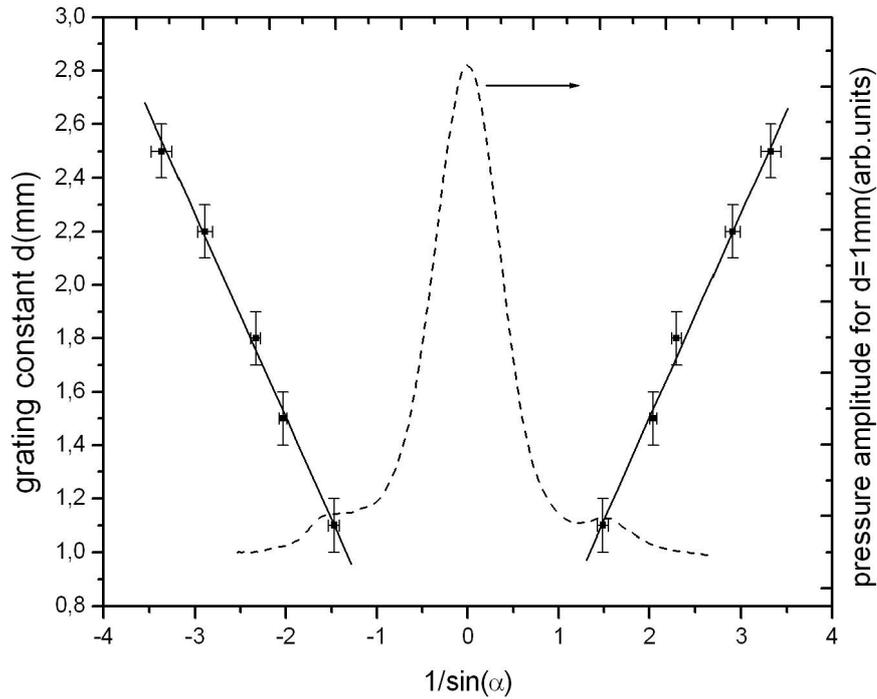


Figure 5: Position of the first diffraction order for various grating constants varied by displaying different stripe-patterns at the LCD . From the slope of the straight line the ultrasound wavelength $\lambda=0.76$ mm can be determined. As an example, one of the far-field diffraction curves (for a grating constant of 1mm) is also shown in the figure (dashed line).

In the second example we analyzed the ultrasound diffraction behaviour of a projected binary Fresnel zoneplate pattern to the sound generating material. A Fresnel zoneplate pattern consists of a concentric system of alternating black and white rings with outwardly decreasing relative distances. For a classical Fresnel zoneplate the generated ultrasound is focused at a unique distance behind the absorber, which depends on the ultrasound frequency and the size of the projected Fresnel pattern. According to Fresnel diffraction theory, the correlation between ultrasound wavelength, focal length and the various radii of the Fresnel zoneplate is²⁵ given by

$$R_n = \sqrt{n \lambda f} , \quad (2)$$

where R_n is the radius of the n^{th} zone, λ is the wavelength of the ultrasound and f is the focal length of the Fresnel zoneplate.

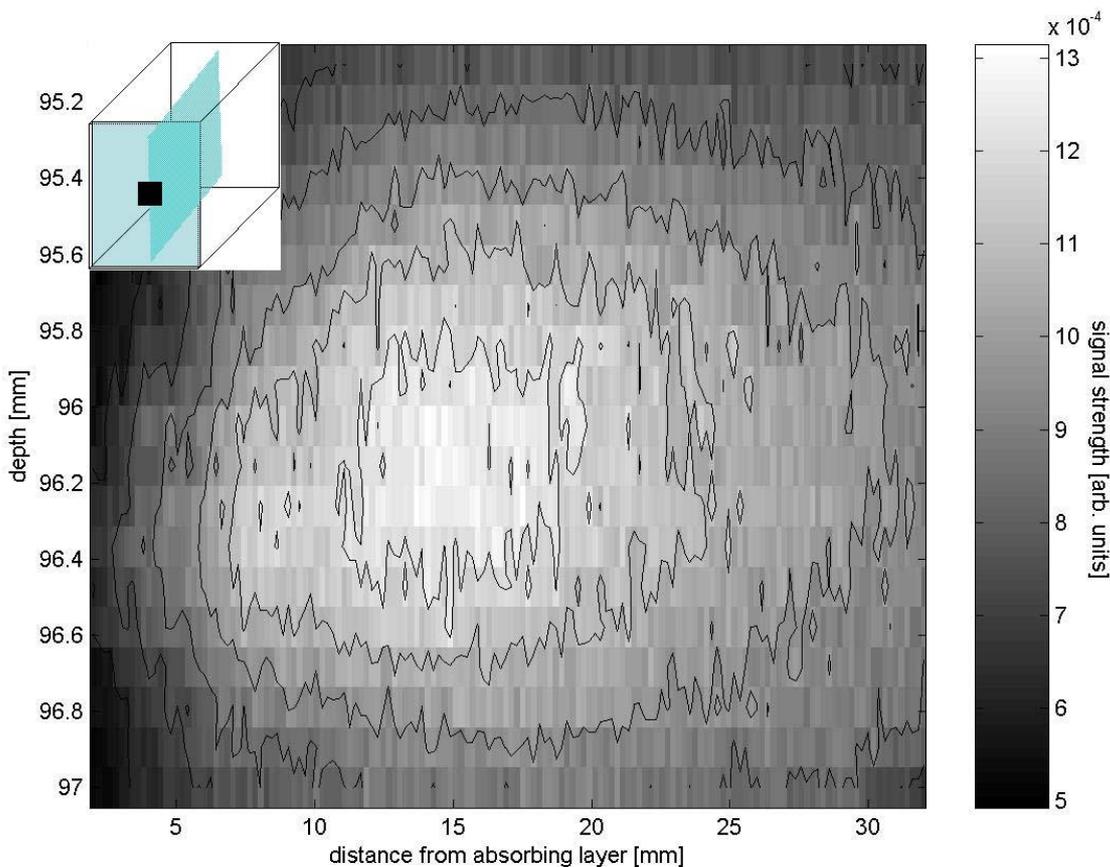


Figure 6: Scan of an optoacoustically generated focused ultrasound field. The focal point at a distance of about 15mm from the absorber was achieved by projecting a Fresnel zoneplate image displayed at the LCD to the absorber material. The insert (upper left corner) indicates the scanned plane inside the water tank, i.e. the x-axis corresponds to the distance of the hydrophone needle from the absorbing plane, whereas the y-axis corresponds to the depth in the water tank.

Figure 6 is an example of an ultrasound field focused with a binary Fresnel zoneplate projected as a LCD-image. In the experiment we projected a ring system with $R_1=4.65$ mm. The vertical axis represents the water depth in the water tank, the horizontal axis is the distance between the plane absorber and the hydrophone needle. The intensity of the ultrasound field is maximal at a distance of about 15 mm from the sound generating surface, with a FWHM of approximately 10 mm. Transverse focusing is more efficient, as expected, and yields a focus diameter (FWHM) on the order of 1 mm. The wavelength, respectively the frequency, calculated by means of equation (2) is $\lambda=1.35$ mm ($f=1.15$ MHz - the velocity of sound in water being $v=1560$ m/s), which is in good agreement with the independently measured ultrasonic frequency.

The experiments demonstrated so far clearly indicate that the basic conditions for acoustic holography are fulfilled, i.e. the diffraction behavior of ultrasound can be steered as expected by projecting computer designed patterns with a modulated laser pulse to an absorbing layer in the water tank.

4. DIFFRACTIVE ACOUSTICS WITH LASER-INDUCED ULTRASOUND

In the previous section we have demonstrated the projection of absorptive structures, which corresponds to an acoustic analogue to absorption holography. However, from classical optics it is known that absorption holography has a low efficiency, and there are disturbing contributions of other diffraction orders which bother the desired field distribution. An improvement is possible using phase holograms instead of absorption holograms, which have a much higher diffraction efficiency. The best results, however, are obtained with optical elements which go beyond holography, i.e. with diffractive optical elements. These diffractive optical elements correspond to computer calculated phase profiles, which are not symmetric (for example: saw-tooth profiles), and which cannot be obtained by classical holographic recording methods. Basic examples for such elements are blazed gratings, or Fresnel lenses with saw-tooth phase modulation profiles. These optical elements achieve for the designed wavelength 100 % diffraction efficiency in the desired order, without any disturbing side effects.

In order to obtain such diffractive optical elements, it is necessary to control the phase of each pixel of a wave emitting surface individually. In optics this is achieved by creating a spatial surface relief in a transparent material (or a spatial refractive index distribution), which results in a controlled spatial phase distribution of a transmitted plane wave. In acoustics there is an additional possibility due to the fact that the used frequencies are much lower than in optics and thus technically accessible. The acoustic amplitude can be controlled at individual positions of an ultrasound generating surface. The method is known as "phased arrays", and is used, e.g., to steer medical ultrasonic beams emitted from phased array piezo transducers.

In order to construct an optoacoustical analog to a diffractive optical element, it is necessary to control the phase of each pixel of an ultrasound emitting surface individually. For our case this means that our laser has to project a spatial pattern to the absorbing layer, where all of the pixels perform an intensity oscillation with the same frequency, but with different, controlled phases. Particularly, there are no pixels which are always dark, as in the previous experiment dealing with acoustic analogues to absorption holograms. In fact, such a modulation scheme is possible with our system. For this purpose, it is necessary to illuminate the LCD with a laser pulse which has a *continuous polarization rotation* with the desired ultrasound frequency (in contrast to the previous experiment, where the laser pulse was *intensity* modulated by the AOM). Each pixel of the LCD then additionally rotates the laser polarization in a range between 0 and 90 degrees, depending on its gray-level value. Thus, behind the LCD each pixel of the light field is still continuously rotating in its polarization (without any intensity modulation), however with a new phase which is controlled by the LCD pixel state, i.e. by the computed pattern displayed at the LCD. The transmitted laser light then passes an output polarizer, which transforms the polarization modulation into an intensity modulation. Now, each pixel performs an intensity modulation with the same frequency, but with a phase which is controlled by the LCD. Sharp imaging of this oscillating pixel structure at the absorptive layer in the water tank then produces the desired acoustic analogue to a diffractive optical element, or a phased array. In principle, such an ultrasound emitting surface can steer the ultrasonic field in any desired way, i.e. the beam can be focused to points, lines, arrays, or pre-calculated three-dimensional pressure distributions in the water tank. Furthermore, the ultrasonic field can be manipulated at video rate by projecting temporally changing LCD images to the surface. The resolution of this optical element is determined by the LCD resolution, i.e. there are 800x600 independently controllable phased elements, which is much higher than in technical applications using phased piezo arrays.

The main problem which remains to be solved in order to produce such a modulation is to create a light pulse with a continuous polarization rotation in the MHz range. For this purpose we make use of the fact that a light beam diffracted at an AOM acquires a frequency offset corresponding to the electronically controlled AOM frequency. Interferometric superposition of the light diffracted by two AOMs with different driving frequencies and with orthogonal polarization directions produces a combined light pulse which changes its polarization state with the frequency difference of the two AOM driver frequencies. In the following we present a possible method for a polarization rotation with tunable frequency which is currently being set up in our lab (figure 7).

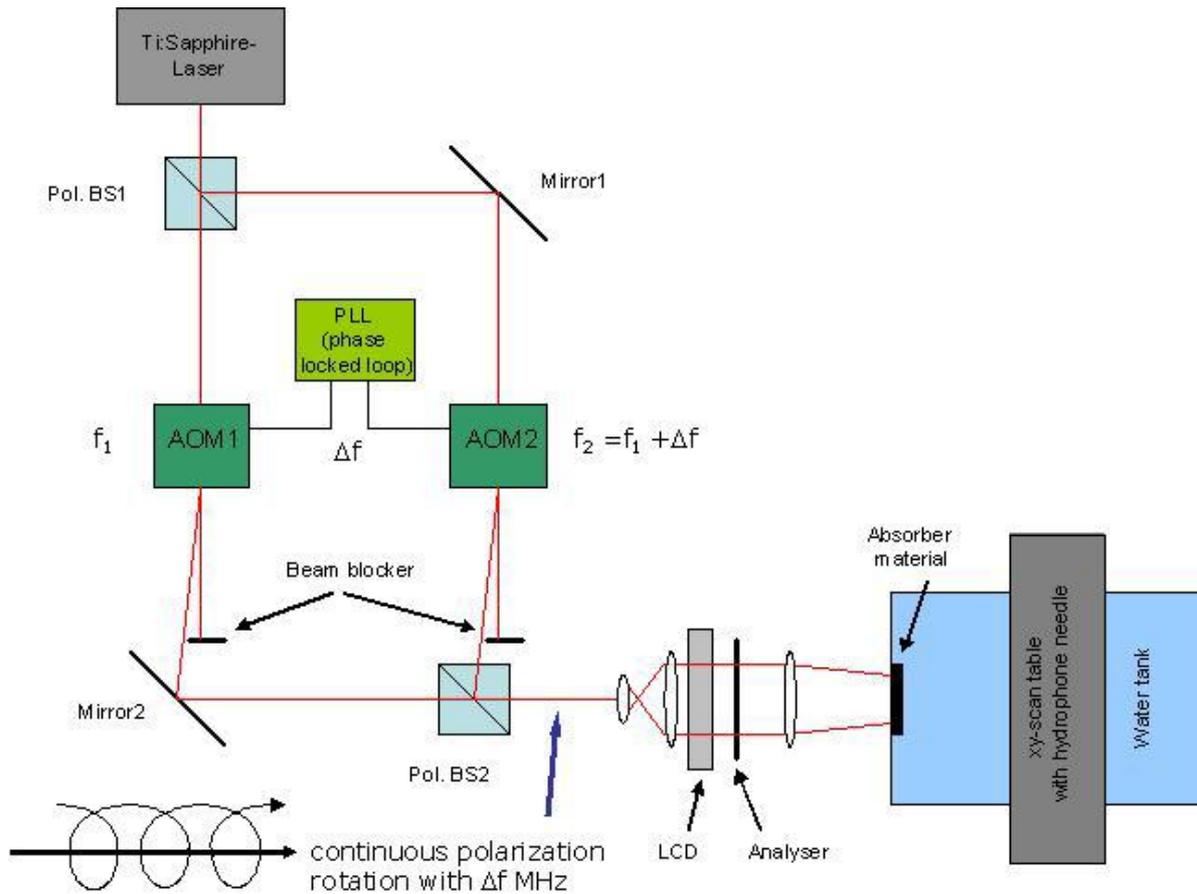


Figure 7: Experimental set-up of a Mach Zehnder interferometer to generate a continuous polarization rotation input beam for the LCD. The polarizing beam splitter (Pol. BS1) splits the incoming laser beam into two perpendicularly polarized beams. Due to the different frequency shifts of the beams diffracted off the two AOMs, their final interferometrical superposition (by Pol. BS2) results in a continuously rotating polarization. The rotation frequency corresponds to the difference of the two centre frequencies of AOM1 and AOM2.

The $10\ \mu\text{s}$ -laser pulse entering the Mach Zehnder interferometer is separated into two orthogonal linear polarizations by a first polarizing beam splitter Pol.BS1. The two beams travel through the cavity of the interferometer, each of them passing an acousto-optical modulator AOM1 or AOM2. The two centre frequencies f_1, f_2 of the two AOMs differ by the desired ultrasound frequency. To avoid frequency drifting, the AOMs have to be stabilized with phased locked loop (PLL) techniques. A second beam splitter (Pol.BS2) superposes the two beams, maintaining their different polarizations. This kind of superposition of two orthogonally polarized waves with different frequencies produces a combined beam which changes its polarization continuously with the beat frequency Δf . During a period of $1/\Delta f$ the light beam undergoes all possible polarization states, e.g. horizontally linear, clockwise circular, vertically linear, counter-clockwise circular, and then again horizontally linear. After one period it ends up in the polarization state where it started, and begins with a new cycle.

Using AOMs with tuneable centre frequency, the polarization rotation frequency can be adjusted electronically in a range from kHz to MHz, and will determine the acoustic frequency of the generated sound wave. Behind the second beam splitter (Pol.BS2) the beam is expanded and passes the LCD. From then on, the light beam is controlled as described above, i.e. each LCD pixel individually influences the polarization state of the transmitted light. Thus the LCD embosses a spatially controlled polarization rotation at the incoming plane wave front. Behind the LCD a polarizer transforms the polarization profile into a light intensity distribution. Using imaging optics, the pattern displayed at the LCD is then imaged onto the absorbing surface of an object, where the acoustic wave is generated. As a result, each

spot of the object surface is illuminated periodically with a different temporal phase depending on the state of the corresponding LCD pixel. The modulated light intensity transforms at the surface into a spatially extended pressure modulation with a controlled phase profile, which generates a sound wave. Since this is an acoustic analogue to an optical phase hologram this procedure will result in the reconstruction of a predetermined acoustic field at some distance from the surface. The predetermined ultrasonic fields are detected by our PVDF hydrophone.

The experiment is currently being set up with the modulation scheme described above. We expect that such phase holograms, and particularly computer designed diffractive holographic elements, will reach near 100 % diffraction efficiency in one predetermined order. Moreover, we expect the feasibility of generating pre-calculated, arbitrarily shaped ultrasonic field distributions in the water tank.

5. CONCLUSIONS AND OUTLOOK

We have demonstrated that the frequency of laser-induced ultrasound can be controlled with optical methods and that the emitted ultrasonic beam can be steered holographically with optical methods, too. This already allows the generation of arbitrarily shaped ultrasonic fields. Acoustic analogues to optical absorption holograms have already been realized experimentally. With the suggested new modulation technique it will also be possible to generate acoustical analogues to phase holograms and to diffractive optical elements, which promise 100% diffraction efficiency, i.e. complete control over the emitted ultrasonic field. The combination of temporal and spatial control of the ultrasonic fields allows to generate beams whose properties change with video rate, i.e. they can be scanned through the water tank or produce any desired pressure amplitude distributions. Both frequency and spatial properties can be adapted continuously to the required purposes.

As a long-term goal we intend to investigate the feasibility of an “all optical” ultrasonic investigation method, i.e. laser-induced ultrasound generation is supplemented by optical detection of the ultrasonic waves which have traveled through a material, e.g. by interferometric methods. The ultrasonic field could then be produced and detected at the surface of an investigated object. One of the advantages of this method over traditional piezoelectric ultrasound diagnostics would be the possibility of varying (or chirping) the ultrasound frequency in a huge range (kHz or MHz). As the ultrasound is generated directly at the surface of the investigated medium, the impedance matching is an inherent feature. Furthermore, once the absorbing layer is put in place, no mechanical contact to the investigated object is necessary. Therefore our method is sterile, and might be suited for remote examination of hazardous, infectious, or corrosive objects in the future.

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