Optical Bragg imaging of acoustic fields after reflection

Nico F. Declercq[a)]
Georgia Institute of Technology, George W. Woodruff School of Mechanical Engineering, UMI Georgia Tech — CNRS 2958, Georgia Tech Lorraine, Laboratory for Ultrasonic Nondestructive Evaluation, 2 rue Marconi, 57070 Metz, France

Michael S. McPherson
Department of Physics and Astronomy, Western Kentucky University, 1906 College Heights Boulevard No. 11077, Bowling Green, Kentucky 42101

Mack A. Breazeale
National Center for Physical Acoustics, 1 Coliseum Drive, University, Mississippi 38677

Alem A. Teklu
Department of Physics and Astronomy, College of Charleston, 101 Hollings Science Center, 58 Coming Street, Charleston, South Carolina 29424

(Received 11 July 2009; revised 31 March 2010; accepted 6 April 2010)

Bragg diffraction of x-rays occurs when the rays interact with a crystalline lattice at the appropriate angle. Bragg diffraction of *visible* light occurs when the light interacts at the Bragg angle with an ultrasonic field of the appropriate frequency. (The spacing between acoustic condensations and rarefactions acts like the planes in an atomic lattice.) If a beam of light is Bragg diffracted by an ultrasonic beam that previously has passed through an object, an image of the structure of the object is made visible in the diffraction field of the optical beam since there is a one-to-one mapping of the ultrasonic field onto the diffraction order. In many acoustic Bragg imaging applications, the sound field must pass through the object which is to be imaged. Ultrasonic attenuation at the very high acoustic frequencies needed for Bragg imaging (typically ~25–30 MHz) severely limits the nondestructive testing (NDT) applications of traditional acoustic Bragg imaging. In this paper, a reflection-based application of acoustic Bragg imaging is discussed which may have useful industrial and biomedical NDT applications.
 [DOI: 10.1121/1.3419772]

PACS number(s): 43.35.Sx, 43.20.El, 43.20.Fn [RR] Pages: 3466–3469

I. INTRODUCTION

Recently, there has been renewed interest in the development of possible acousto-optic techniques for biomedical imaging applications.[1] The first experimental investigations of the interaction of light with ultrasound were made in the first half of the last century.[2] Of particular interest were observations that the wavefronts of an ultrasonic beam in a transparent medium such as water or CCl_4 can act like the slits in a transmission diffraction grating and diffract light. Raman and Nath[3–6] developed the theoretical framework that explained the mechanisms by which light can be ultrasonically diffracted. At low ultrasonic frequencies (in the range from 1–15 MHz) the condensations of the acoustical wave act like planes in a crystal lattice. Figure 1 shows a diagram of typical Bragg diffraction of x-rays in a crystal lattice compared to its acoustic analog. Phariseau[7] further developed the theory of Raman and Nath to include calculations of light intensities in the Bragg diffraction orders.

A new means of utilizing Bragg diffraction for imaging was developed by Korpel[8–10] who showed that the first Bragg diffraction orders contain an image of the ultrasonic wavefront which diffracted the light. Korpel demonstrated that an object placed in the ultrasonic field is imaged in the Bragg diffraction order; he also developed a theoretical analysis of this effect which treated the process as analogous to parametric mixing. He showed that there is a one-to-one mapping of the ultrasonic wavefront onto the first diffraction order.[8–10]

Van Den Abeele *et al.*[11] showed that there are additional mappings of the acoustic field to the higher diffraction order (with 2 images present in the 2nd order, 3 images in the 3rd, etc.). Na and Breazeale[12] extended the work of Korpel to explore NDT applications of acoustic Bragg imaging. No matter if transmitted or reflected sound is considered, the sound beam contains an image of the object as it is directly disturbed by it. This can be represented by an appropriate plane wave spectrum containing that information as well. The focused light beam contains a Bragg angle for each of those acoustic plane waves and hence, as thoroughly described in Ref. 11, there is a mapping between the optical spectrum and the acoustic spectrum, this mapping occurs in phase and amplitude and hence an optical image is formed of the acoustic beam and therefore also the object.

Until now reflected ultrasonic waves have never been exploited for Bragg imaging of objects.

[a)]Author to whom correspondence should be addressed. Electronic mail: nico.declercq@me.gatech.edu

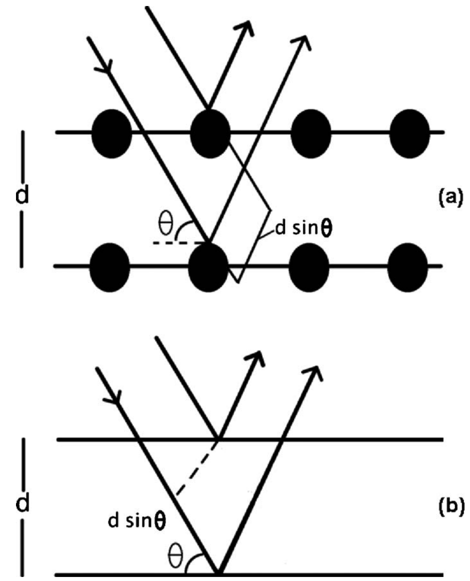

FIG. 1. Interference condition leading to Bragg diffraction in a crystal lattice and in an acoustic standing wave.

Typical frequencies needed for acoustic Bragg imaging fall in the range from 25–30 MHz. At lower frequencies we would work in the Raman-Nath regime, which does not generate optimum images as in the Bragg regime. The Bragg regime involves strong interaction between light and sound, hence improving the imaging possibility. The acousto-optic regime[13] (Raman-Nath or Bragg), is determined by the mechanical properties of the acoustic medium, by the interaction length and by the color of light that is used. For red light in water (from a He Ne laser), 25–30 MHz forms the right conditions for Bragg imaging. This creates practical problems which previously have inhibited widespread use of acoustic Bragg imaging as a tool for nondestructive testing (NDT) applications. These problems include a very high attenuation of the sound as it passes through the object, which causes an image of the general contour of the object form as an acoustical shadow. This has limited the applications of Bragg imaging to objects that were either thin enough for the sound to pass though or situations where only information about the general contour of the object is desired. In this paper, we present a new approach to acoustic Bragg imaging whereby the acoustic beam is reflected from the object to be imaged rather than directed through it. By using a reflected acoustic beam rather than a transmitted one, surface features (and perhaps those just under the surface) of an object of arbitrary thickness can be imaged.

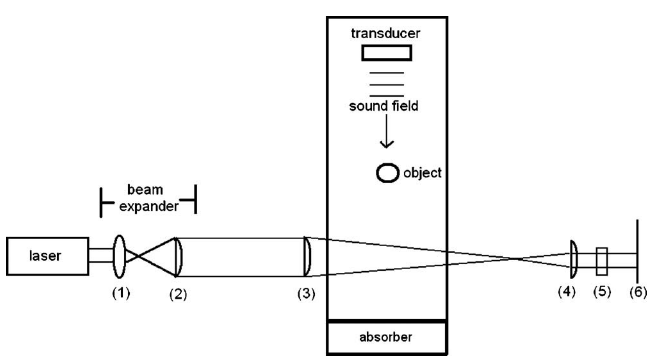

FIG. 2. Experimental setup used in the traditional acoustic Bragg diffraction experiment.

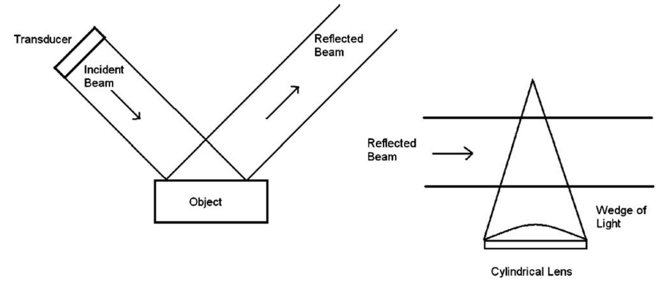

FIG. 3. Bragg imaging from a reflected acoustic beam.

II. EXPERIMENTAL SETUP

Figure 2 shows the experimental setup used in the traditional acoustic Bragg diffraction experiment (which uses transmission of the sound through the object). As seen in the figure, laser light is first incident on a diverging spherical lens (1). The light is arranged to diverge from the focal point of a second lens (2) in order to produce collimated light. The collimated light is incident on lens (3), a cylindrical lens which focuses the light into a wedge, the geometry that gives the best image; this light wedge assures that some portion of the light is incident at the Bragg angle.

Lens 3 is placed just before a water (or some other transparent liquid) filled tank in which the diffraction occurs. In the tank, a transducer generates an acoustic signal which travels down the length of the tank and is incident on an absorber. The object to be imaged is placed in the tank at a position where the sound must pass through it before the sound interacts with the optical beam.

After passing through the tank, the light is focused by the cylindrical lenses (4) and (5) which are oriented with their respective axes 90° apart. Two different cylindrical lenses [(4) and (5)] compensate for the foreshortening of the light along one direction, which causes differing along the two axes. Item (6) can be a projection screen or a camera.

The arrangement described above is for transmission-mode acoustic Bragg imaging; the sound interacts with the object by passing through it, and then the light interacts with the sound field to produce an image of the object. In order to achieve acoustic Bragg imaging from a reflected acoustic

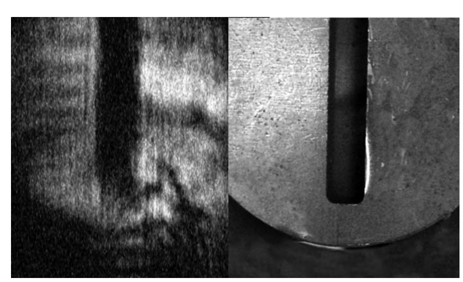

FIG. 4. Bragg image (left) and photographs image (right) of a 4 mm wide slit in a circular brass disk of 2 mm thickness. The disk is placed on a damping material to make sure only reflection from the brass disk is possible. The slit and the disk edge are clearly visible on the Bragg image.

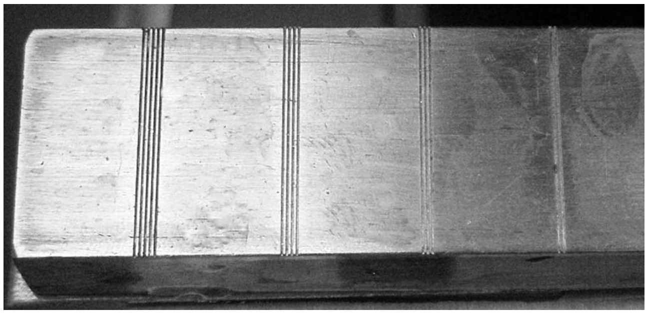

FIG. 5. Photographic picture of a brass sample with rectangular grooves engraved of 0.0254 cm deep and wide. The grooves are organized in sets of 2, 3, 4 and 5 grooves

beam, one must modify the placement of the transducer and object. For reflection-based acoustic Bragg imaging, the optical system is identical to that used in the transmission-based experiment. Figure 3 shows the configuration of the transducer/object system that is needed for reflection-mode Bragg imaging.

III. RESULTS

To gain a better understanding of the possibilities presented by reflection-mode Bragg imaging, three different types of reflector were used. Figure 4 shows a reflection mode Bragg image of a metal disk with a cavity cut down the center in the form of a large slit (the actual disk is also shown in the figure). In Fig. 4, the Bragg image (left) and photographs image (right) of a 4 mm wide slit in a circular brass disk of 2 mm thickness is shown. The frequency of the acoustic wave was 30 MHz, and the light was from a helium neon laser. The disk is placed on a damping material to make sure only reflection from the brass disk is possible. The slit and the disk edge are clearly visible on the Bragg image.

Figure 5 shows a photograph of a brass bar upon which varying numbers of rectangular grooves have been ruled in order to evaluate the response of reflection-mode Bragg imaging to multiple grooves. The grooves are 0.0254 cm deep and wide. The grooves are organized in sets of 2, 3, 4 and 5 lines.

Figure 6 shows reflection-mode Bragg images of the different sets of grooves. Bragg images of the sets of 2, 4 and 5 grooves are shown. For each set of grooves there is always a line structure visible possessing white lines which corresponds to the periodic groove structure shown. Lines are clear in the center of the structure and are more difficult to distinguish and count on the edges of the structure.

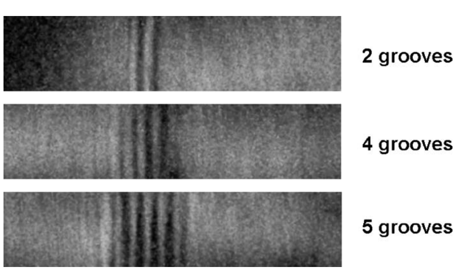

FIG. 6. Bragg images of the sets of 2, 4 and 5 grooves as shown in Fig. 2.

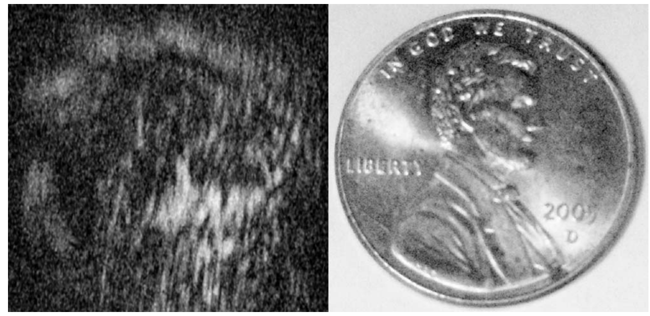

FIG. 7. Bragg image of a coin.

Figure 7 shows a coin (United States 1-cent coin) and its corresponding reflection-mode Bragg image. The contour of the portrait is somewhat visible in the Bragg image, but the image is not as clear. Evidently, the variation of height in the portrait embossed on the coin does not provide sufficient depth for clear Bragg imaging.

IV. CONCLUDING REMARKS

The advantages and limitations of Bragg imaging on reflection have been explored. Traditional transmission-mode Bragg imaging is often limited by the acoustic attenuation of the sound as it passes through the sample. This limits the possible applications of acoustic Bragg imaging for NDT applications. A new, reflection-mode method of acoustic Bragg imaging has been demonstrated. Since the sound does not penetrate into the sample, the thickness of the sample is not a limiting factor. So while reflection-mode Bragg imaging is limited to the imaging of surface features of a sample, it can be used with samples where transmission-mode Bragg imaging would fail. The most obvious advantage is that Bragg imaging on reflection can be used in situations where sharp edges are prominent. When thin grooves are present, the effects resulting from acoustical diffraction are noticeable. It is less able to delineate images when the surface roughness presents a variation less than one acoustical wavelength. With a more optimized imaging system, possible applications of Bragg imaging to NDT or biomedical applications may be possible. Additionally the clarity of images obtained by the proposed technique will depend on the reflectivity properties of the envisaged objects. The better an object reflects acoustic waves, the more likely a clear image is possible.

ACKNOWLEDGMENT

The authors are grateful to the “Conseil Regional de Lorraine” (France) for financial support.

[1]T. W. Murray and R. A. Roy, “Illuminating sound: Imaging tissue optical properties with ultrasound,” Echoes **16**, 1–3 (2006).
[2]P. Debye, and F. W. Sears, “On the scattering of light by supersonic waves,” Proc. Nat. Acad. Sci., Wash. **18**, 409–414 (1932).
[3]C. V. Raman and N. S. N. Nath, “The diffraction of light by high frequency sound waves: Part I,” Proc. Indiana Acad. Sci. **2**, 406–412 (1935).
[4]C. V. Raman and N. S. N. Nath, “The diffraction of light by high frequency sound waves: Part II,” Proc. Indiana Acad. Sci. **2**, 413–420 (1935).
[5]C. V. Raman and N. S. N. Nath, “The diffraction of light by high frequency sound waves: Part III: Doppler effect and coherence phenomena,” Proc. Indiana Acad. Sci. **3**, 75–84 (1936).

[6]C. V. Raman and N. S. N. Nath, "The diffraction of light by high frequency sound waves: Part IV: Generalised theory," Proc. Indiana Acad. Sci. **3**, 119–125 (1936).
[7]P. Phariseau, "On the diffraction of light by supersonic progressive supersonic waves," Proc. Indiana Acad. Sci. **44A**, 165–170 (1956).
[8]A. Korpel, "Visualization of cross section of a sound beam by Bragg diffraction of light," Appl. Phys. Lett. **9**, 425–427 (1966).
[9]A. Korpel, *Proceedings of the Second International Symposium on Acoustical Holography* (Plenum, London, England, 1970), pp. 69–86.
[10]A. Korpel, *Acousto-Optics*, 2nd ed. (Dekker, New York, 1997), pp. 21–22 and 206–279.
[11]K. Van Den Abeele, M. A. Breazeale, O. Leroy, and J. K. Na, "Strong interaction of arbitrary fields of sound and light—Application to higher order Bragg imaging," J. Appl. Phys. **75**, 84–95 (1994).
[12]J. K. Na, M. A. Breazeale, and O. Leroy, "Ultrasonic Bragg imaging of flaws," J. Acoust. Soc. Am. **81**, S43 (1987).
[13]M. G. Moharam and L. Young, "Criterion for Bragg and Raman-Nath diffraction regimes," Appl. Opt. **17**, 1757–1759 (1978).