



2 Photorefractive interferometers for ultrasonic measurements on paper

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8 1. Introduction

9 Photorefractive interferometers have been employed
10 for the detection of ultrasound in metals and composites
11 since 1991 [1-4]. Instances of laser-generated ultrasound
12 and laser-based detection in paper were reported in 1996
13 [5]. More recently, bismuth silicon oxide (BSO) photo-
14 refractive interferometers were adapted to detect ultra-
15 sound in paper [6]. In this article we discuss BSO and
16 GaAs photorefractive detection of ultrasound on dif-
17 ferent paper grades and present the resulting waveforms.
18 Compared to contact piezoelectric transducer meth-
19 ods, laser interferometry offers significant advantages.
20 One of these is that it is a noncontact technique. This is
21 especially important for on-line application to light-
22 weight papers which could be marked or damaged by
23 contact transducers. Broadband ultrasonic laser gener-
24 ation matched with the broadband sensitivity of laser
25 interferometers is another benefit. This is important for
26 obtaining narrow pulses in nondispersive time-of-flight
27 determinations and for measuring the phase velocity of
28 dispersive modes over a wide frequency band. Also, laser
29 ultrasonic techniques provide a measure of bending
30 stiffness through the analysis of low frequency A_0 waves.

31 2. Detection of ultrasonic waves in paper

32 From a mechanical point of view, paper is a very
33 anisotropic medium. It is roughly twice as stiff along the
34 direction of its manufacture (or machine) direction
35 (MD) than along the cross machine direction (CD), and
36 it is two orders of magnitude less stiff in the thickness
37 direction than it is in the in-plane directions. At fre-
38 quencies below 1 MHz, the thickness is generally much

less than the out-of-plane bulk mode wavelengths, and 39
low-order Lamb waves propagate naturally. Because of 40
the fibrous structure of paper [7] (about 40 μm diameter 41
fiber), high frequency ultrasonic waves (<1 MHz) are 42
greatly attenuated by Rayleigh scattering. Thus, paper 43
ultrasound analyses are essentially limited to the first 44
order symmetric Lamb wave (S_0) and the first order 45
antisymmetric Lamb wave (A_0). 46

An A_0 wave at low frequencies mainly generates dis- 47
placements perpendicular to the surface of the web. On 48
the other hand, S_0 waves produce almost exclusively in- 49
plane motions. The A_0 waves are dispersive at low fre- 50
quency, whereas the S_0 waves are nondispersive. The 51
frequency-dependent phase velocities of the first order 52
 A_0 wave are much smaller than the velocity of the first 53
order S_0 wave. As generated and detected by laser 54
methods, the amplitudes of the S_0 waves are much 55
smaller than the amplitudes of the A_0 waves [8,9]. 56

Sometimes, glossy-faced, coated papers are tested, but 57
generally we must deal with bare fiber surfaces. The ir- 58
regular character of the uncoated paper surface pro- 59
duces a major difficulty in the laser detection of 60
ultrasound. The reflected speckle pattern results from 61
the scattering of a coherent signal beam off a rough 62
surface. Because paper is such a strongly scattering 63
medium, the reflected light is diffused as well as speck- 64
led. Therefore, multiple-speckle interferometers are ex- 65
cellent candidates for paper applications. They collect 66
light from many speckles and provide better sensitivity 67
to ultrasonic displacements. 68

69 3. Photorefractive adaptive interferometers

Photorefractive [10,11] interferometers are multiple- 70
speckle interferometers with potential applicability to 71
highly scattering materials. They use a photorefractive 72
crystal to interfere the planar wavefront of a pump beam 73
with the speckled wavefront of a signal beam (beam 74

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75 back-scattered from the surface of the paper). Different
76 photorefractive techniques exist for wave mixing [11],
77 with various levels of efficiency and response times to the
78 changing speckle pattern. Listed in order of adaptation
79 speed, these are the self-pumped phase-conjugate mirror
80 (PCM) method, the double phase-conjugate mirror
81 (DPCM) technique, the four-wave mixing (FWM)
82 method [4], the two-wave mixing (TWM) technique, and
83 the photoinduced-electromotive force (photo-EMF)
84 technique.

85 In the TWM design [1,10] the pump and signal beams
86 interfere to create an index grating inside a photore-
87 fractive crystal. Ultrasonic signals modulate the phase of
88 the signal beam altering the interference between the
89 signal beam and the diffracted pump beam. This modu-
90 lates the intensity of light at a photodetector placed
91 after the crystal. The photorefractive crystal does not
92 respond fast enough to modify the diffraction pattern in
93 accordance with the ultrasonic signal. Theoretically,
94 each speckle from the signal beam is matched with a
95 speckle from the reference beam. Hence, instead of re-
96 lying on the low power of a single speckle (as does the
97 Mach-Zehnder interferometer), all of the speckles col-
98 lected by the input aperture contribute to the interfe-
99 rence signal.

100 We attempted two photorefractive interferometer
101 methods. One was a TWM technique and the other was a
102 photo-EMF method. Only the experiments with the
103 TWM technique are reported in this article. As de-
104 scribed below, we performed laser ultrasonic measure-
105 ments on paper with two different TWM
106 interferometers. In both cases, the generation of ultra-
107 sound was achieved in a noncontact way with a pulsed
108 Nd:YAG laser doubled or not at 532 nm or 1064 nm.
109 Point and line source generation shapes were formed.

110 3.1. Detection in the visible with a BSO photorefractive 111 interferometer

112 We used a bismuth silicon oxide ($\text{Bi}_{12}\text{SiO}_{20}$ or BSO)
113 crystal [2,11] as the active element for our first approach.
114 We chose BSO because of its high photorefractive gain,
115 transparency in the visible spectrum, availability of
116 green laser, uniformity of crystal production, and rea-
117 sonable cost. The wavelength of the detection laser was
118 514.8 nm.

119 Figs. 1 and 2 detail the design of the BSO photore-
120 fractive interferometer. The beam coming from the de-
121 tection laser was split into two beams (incident and
122 pump), having orthogonal polarizations using a first $\lambda/2$
123 plate and a polarizing beamsplitter. This allowed the
124 ratio of the power of the incident beam over the power
125 of the pump beam to be adjusted. The incident beam
126 was horizontally polarized before passing through the
127 second polarizing beamsplitter, and through the $\lambda/4$
128 plate. Then, it was focused onto the paper sample into

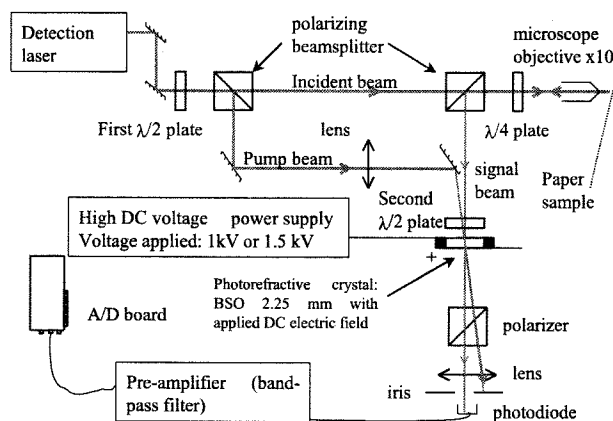


Fig. 1. Schematic of photorefractive interferometer using a BSO crystal with a DC applied voltage.

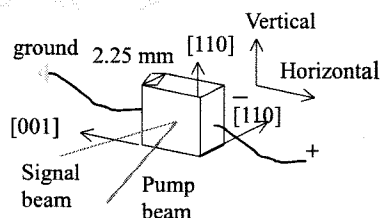


Fig. 2. Orientation of the axis of the BSO crystal in the photorefractive two-wave mixing interferometer.

the shape of a circular spot by the microscope objective. 129
In order to detect A_0 and S_0 waves simultaneously with a 130
single objective, the angle between the incident/reflected 131
beam and the perpendicular to the surface of the paper 132
was set to 40° . The back-scattered light from the paper 133
was collected by the same objective. After going through 134
the $\lambda/4$ plate a second time, the speckles having a ver- 135
tical polarization were reflected at an angle of 90° by the 136
polarizing beamsplitter to provide the signal beam. 137

The pump beam was reflected by a mirror and focused 138
by a lens having a short focal length (38 mm) onto the 139
edge of the second mirror. After the mirror, the beam 140
was sufficiently expanded to illuminate the whole input 141
surface of the photorefractive crystal. This was neces- 142
sary because otherwise the high voltage applied to the 143
sides of the crystal would concentrate the electric field 144
into the areas not impinged by the pump beam. 145

The orientations of the crystallographic axis of the 146
crystal are shown in Fig. 2. The signal and pump beams 147
were in the horizontal plane and the photorefractive 148
grating vector was along [001]. The dimensions of the 149
crystal were $10\text{ mm} \times 10\text{ mm} \times 2.25\text{ mm}$. The thickness 150
was 2.25 mm, optimized for placing the polarization of 151
the signal and reference beams at 90° to each other at 152
the output of the crystal. 153

The pump and signal beams had their polarizations 154
rotated by a second $\lambda/2$ plate before entering the crystal. 155

156 Because of the high coefficient of optical activity of BSO
 157 crystal ($38^\circ/\text{mm}$ at 515 nm), the polarization had to be
 158 rotated in order to optimize the sensitivity of the inter-
 159 ferometer to the ultrasonic phase shift. The angle be-
 160 tween the two beams was between 2° and 5° , which is
 161 appropriate for two-wave mixing when a high voltage is
 162 applied to the crystal.

163 The two beams (pump and signal) interfere in the
 164 crystal and create an index grating which diffracts the
 165 pump beam into a reference beam in the direction of the
 166 signal beam. Since the two beams did not have the same
 167 polarization at the output of the crystal, the polarizer
 168 after the crystal was oriented to decrease the power of
 169 the signal beam relative to the reference beam. A lens
 170 was used to focus the two beams (reference and signal)
 171 onto the sensitive surface of the photodiode. An iris
 172 prevented the nondiffracted light coming from the pump
 173 beam to add noise onto the photodiode. The iris also
 174 blocked the parasitic light pulse at 1064 nm coming
 175 from the generation laser.

176 The reference and signal beams interfered on the
 177 photodiode, and the voltage from the photodiode was
 178 sent to a preamplifier having a bandwidth of 13 kHz–6
 179 MHz to remove its low frequency components. The
 180 signal was digitized at 10^7 samples per second using a 8-
 181 bit acquisition/digitization board. The A/D board was
 182 driven by a software developed at IPST using LabView
 183 5.0.

184 The generation part of this first setup was classical in
 185 laser ultrasonic experiments. The energy of the Q-swit-
 186 ched Nd:YAG laser at 1064 nm could be adjusted be-
 187 tween 0 and 413 mJ per pulse thanks to the variable
 188 attenuator. The full width at half maximum (FWHM) of
 189 the laser pulse was 6 ± 1 ns.

190 3.2. Results with BSO interferometer

191 All results were obtained in a temperature and hu-
 192 midity controlled environment. Relevant parameters
 193 concerning the samples are presented in Table 1.

194 Fig. 3 represents a laser-generated waveform on 26-lb
 195 linerboard. The dispersive A_0 wave is clearly visible but
 196 the S_0 wave amplitude is too small to be detected. In the
 197 captions, HV stands for the high voltage applied across
 198 the width of the crystal (1 cm). The energy per pulse for
 199 the generation laser at 1064 nm is also provided.

200 Fig. 4 shows a waveform obtained on drawing paper
 201 which exhibits both A_0 and S_0 waves. Most of the

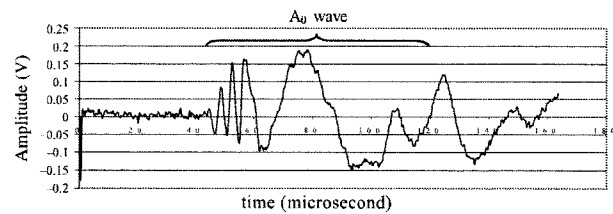


Fig. 3. 26-lb linerboard: displacement averaged four times with a generation–detection distance of 20 mm along MD, HV = 1.5 kV, 3.43 mJ/pulse.

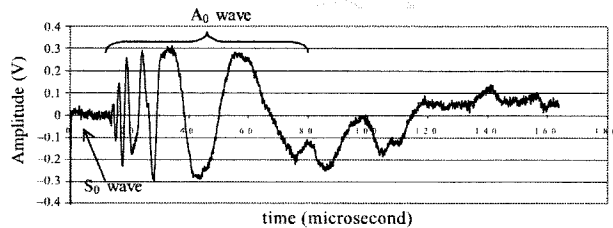


Fig. 4. Art (drawing) paper: displacement averaged three times with generation–detection distance of 10 mm along MD, HV = 1.5 kV, 0.65 mJ/pulse.

202 measurements with this setup were made using an ab-
 203 lation mode for generation to obtain high amplitude
 204 signals. This was not satisfying for two reasons: first, the
 205 strong ablation mode damages the paper and generates
 206 waveforms of varying shapes; second, the strength of the
 207 acoustic source varies significantly with the number of
 208 shots consecutively made at the same spot. Therefore,
 209 efforts were made to increase the interferometer sensi-
 210 tivity and to reduce the damage to the paper by de-
 211 creasing the power density of the generation beam.

212 3.3. Detection in the infrared with a GaAs photorefractive
 213 interferometer

214 The schematic of the GaAs interferometer is pre-
 215 sented in Fig. 5.

216 As in the case of the BSO crystal, we used the TWM
 217 method. However, no high voltage is applied to the
 218 crystal this time. This interferometer is easier to operate
 219 since GaAs is not optically active and there is need to
 220 adjust the incoming polarization.

221 The wavelength of the detection laser was 1064 nm.
 222 The incident power onto the paper was 138 mW and the
 223 power of the pump beam just before impinging the

Table 1
 Thickness and grammage of paper grades investigated

Paper grade	Newsprint	Art paper	Copy paper	Sack	26-lb linerboard	42-lb linerboard	69-lb linerboard
Thickness (μm)	64	63	91	109	189	276	453
Grammage (g/m^2)	44	58	80	87	128	205	336

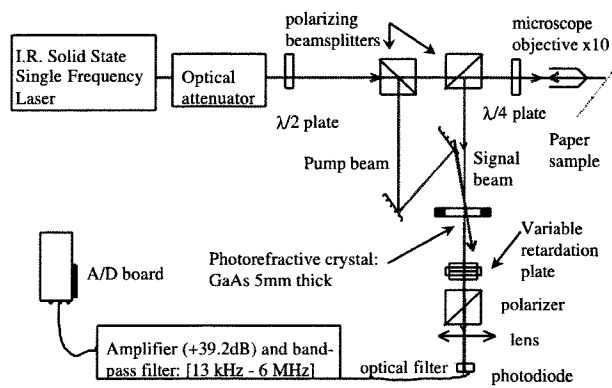


Fig. 5. Schematic of photorefractive interferometer using a GaAs crystal without applied voltage.

224 GaAs crystal was 95 mW. The power into the signal
225 beam (scattered light collected by the microscope ob-
226 jective) was typically 1.7 mW.

227 The detection beam was incident at 45° to the normal
228 to the paper surface. A line source was used for line
229 generation. It was 25 mm long, 0.5 mm wide at its edges,
230 and 1.0 mm wide at its center. Energy per pulse ranged
231 from 49 to 72 mJ depending on the paper grade.

232 Measurements were obtained for laser generated
233 waves traveling along the MD and the CD of the paper
234 samples with generation-detection distances varying
235 from 2 mm to 40 mm.

236 Figs. 6–14 present the waveforms obtained with the
237 TWM GaAs interferometer: displacement (arbitrary
238 units) as a function of time on various paper grades. The
239 ratio of amplitudes of A_0 and S_0 waveforms varies from
240 one paper to another but both waves are always present.

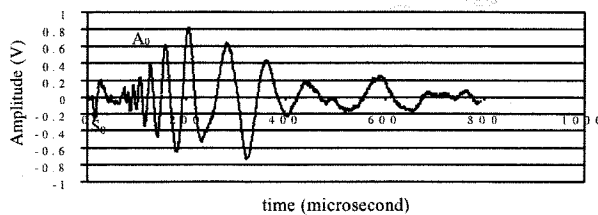


Fig. 6. Newsprint, 20 mm generation/detection distance, along CD, 56 mJ, single shot.

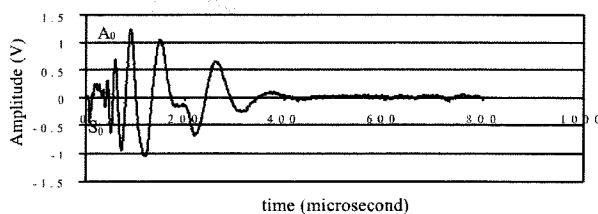


Fig. 7. Newsprint, 10 mm distance, along CD, 56 mJ, single shot.

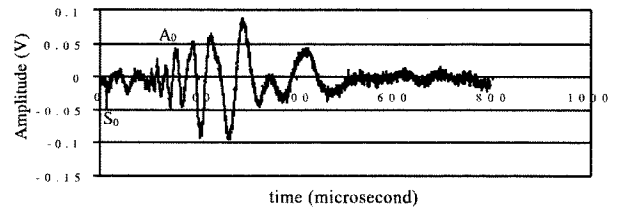


Fig. 8. Copy paper, 40 mm distance, along MD, 53 mJ, averaged ten times.

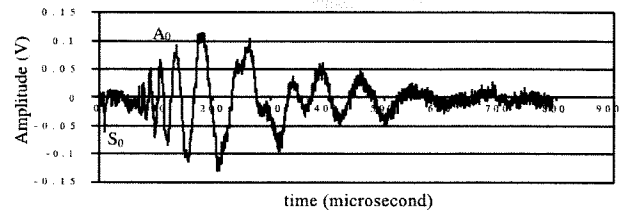


Fig. 9. Copy paper, 30 mm distance, along MD, 53 mJ, averaged four times.

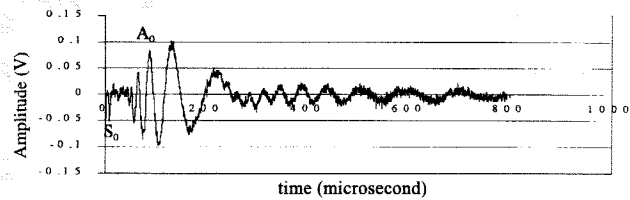


Fig. 10. Copy paper, 20 mm distance, along MD, 53 mJ, averaged ten times.

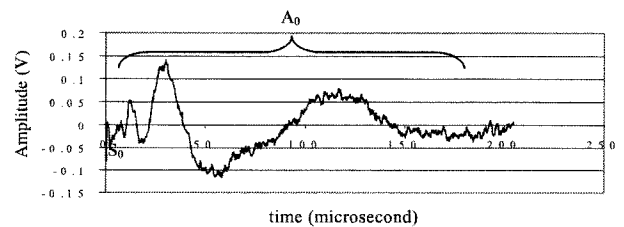


Fig. 11. Copy paper, 5 mm distance, along MD, 53 mJ, averaged four times.

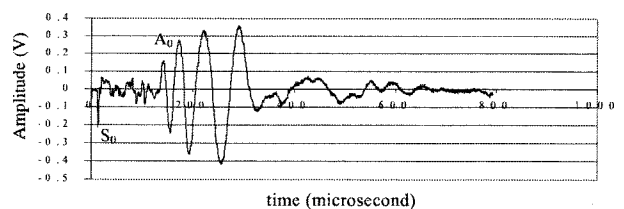


Fig. 12. Sack paper, 40 mm distance, along MD, 52 mJ, averaged four times.

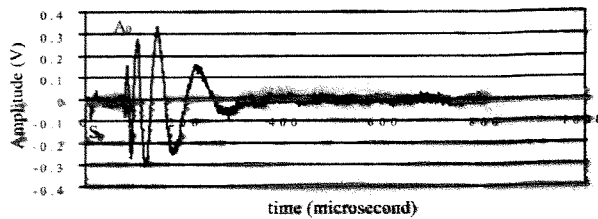


Fig. 13. 42-lb linerboard, 40 mm distance, along MD, 50 mJ, single shot.

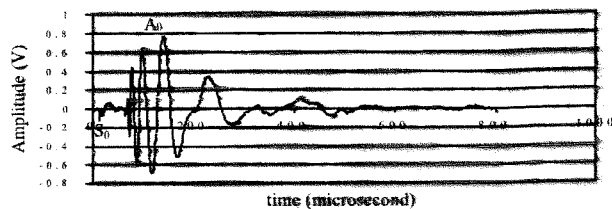


Fig. 14. 69-lb linerboard, 30 mm distance, along CD, 50 mJ, averaged four times.

241 4. Conclusions

242 Results of laser generation and interferometric detection of ultrasound on various static paper samples were presented. Seven very different paper grades were investigated. On all paper grades, the dispersive nature of the A_0 Lamb wave is clearly demonstrated.

247 A photorefractive interferometer using a GaAs crystal detected both A_0 and S_0 Lamb waves in single shot mode for the generation laser without leaving visible marks on the paper. Unlike single speckle interferometer implementations, the optimizations of the photorefractive interferometers were found to be insensitive to the orientation of the paper surface. The versatility of the interferometers was demonstrated by their optical and mechanical adaptability to very different paper grades.

256 The sensitivity of both interferometers could be improved using anti-reflection coated crystals, smaller f-number optics, and a photodiode with less noise. Since the semiconductor type crystals, such as GaAs, InP:Fe, or CdTe:V, have significantly shorter response times than BSO crystals, they should be preferred for TWM applications to a moving paper web. These crystals are able to adapt to the rapidly changing speckle pattern of a paper web impinged by a laser beam. The results presented in this paper argue that photorefractive interferometers hold promise for the mechanical charac-

terization of paper in the laboratory and on-line on a paper machine.

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