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LONG ACOUSTIC BUFFER RODS WITH LOW SPURIOUS SIGNALS

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INTRODUCTION

Ultrasonic pulse-echo techniques are in widespread use for the nondestructive evaluation of materials. Since these techniques are sometimes applied in adverse conditions such as elevated temperatures and pressures [1,2], buffer rods are often necessary to avoid exposing the ultrasonic transducer to such conditions. In addition, long and small diameter buffer rods are sometimes required to probe materials inside a closure which has only tinly accessible opening. In most ultrasonic measurements employing a buffer rod, a test sample is attached to one end, and the echoes coming from the sample are analyzed to obtain ultrasonic velocity and attenuation [1,2], or to detect voids or inclusions in the test sample.

The concern with a long buffer rod is the presence of spurious signals due to the wave diffraction and the finite rod diameter. These signals always arrive later than the directly transmitted or reflected longitudinal echoes and will be referred as trailing echoes [3] throughout this paper. Such echoes are unwanted because of their possible interference with the desired signals from the sample. In our previous works, isotropic buffer rods with a notched periphery and a tapered shape [4] and anisotropic single crystal buffer rods with a collimating or focusing mechanism for a particular mode [5] were found to be able to reduce these trailing echoes.

In this paper theoretical considerations and experimental measurements of two additional types of long acoustic buffer rods with low trailing signals are presented. One is cladded glass rods with small velocity differences between core and cladding. An acoustic lens has been also fabricated at the end of a long cladded rod. Another is glass rods with graded acoustic velocity profiles across the rod diameter. The graded acoustic velocity profiles were measured by using a V(x,z) analysis with a reflection scanning acoustic microscope [6]. The diameters and lengths of these two types of buffer rods can be easily adjusted by using the standard optical fiber glass pulling technique. Here, the diameters and lengths used for the experiments range from 6 to 12 mm and a few to tens of centimeters, respectively. The acoustic frequency range of interest is between 5 to 25 MHz. Since a liquid couplant which does not support shear wave often exists between the buffer rod and the sample, only longitudinal acoustic waves are used for the illustrations.

EXPERIMENTAL SYSTEM AND ISOTROPIC BUFFER RODS

The ultrasonic system is composed of a pulser and a broadband receiver used in the pulse-echo mode in conjunction with well-damped longitudinal wave transducers. A common ultrasonic couplant between the transducer and the buffer rods was used. Many transducers with different operating frequencies and apertures were also used. Here, only representative results obtained with a 10 MHz, 6.35 mm diameter broadband transducer are given.

Figure 1a shows a common ultrasonic pulse-echo measurement arrangement which consists of an ultrasonic transducer without a buffer rod, a liquid couplant of distance d and a flat and parallel sample of thickness h. In Figs.1b and 1c the echo S_0 is the reflected longitudinal echo from the sample surface and echoes S_1, S_2, S_3 .... are the echoes traversing back and forth between the top and bottom surfaces of the sample. Figure 1c is a zoomed image of 1b. If h is known and acoustic travelling time t_h in the sample is measured, then the ultrasonic velocity v of the sample can be obtained from the relation $v = 2h/t_h$. A typical measurement is given in Fig.1b where $t_d = 2d/v_w$ is the acoustic delay time in the liquid couplant and v_w is the longitudinal velocity of the liquid couplant.

If a buffer rod is required to be used in the above measurement as shown in Figure 2a, it should not prevent the measurement of, for instance, v of the sample. However, this is not possible if a buffer rod is not chosen properly. Figure 2b shows the reflected echoes through a 109 mm long Pyrex glass rod of 10 mm diameter using the same transducer as in Fig.1. The echo B_0^0, is the first longitudinal arrival. Echoes B_0^1,, B_0^2, B_0^3, ... are the so-called trailing echoes [3] which result from the wave diffraction and finite rod diameter. The arrival time delay difference between echoes B_0^0, and B_0^1, (or B_0^1, and B_0^2,, etc.) defined as t_T was found to be [3]

$$t_T = \frac{2a/\cos\theta}{v_S} - \frac{2a\tan\theta}{v_L} \qquad (1)$$

where a is the rod radius; θ is equal to $\sin^{-1}(v_S/v_L)$; v_S and v_L are the shear and longitudinal wave velocities in the isotropic rod.

As mentioned earlier, the concern in ultrasonic measurements with long buffer rods is that the unwanted trailing echoes (B_0^1, B_0^2, B_0^3, ...) may overlap with the desired echoes S_0, S_1, S_2, ... The ratio between the energy sum of all trailing echoes over that of the first arrived longitudinal echo may be used to evaluate the degree of diffraction in the rod. In order to reduce this ratio one obvious method is to increase the diameter or shorten the length of the rod. However, in the next two sections long and thin buffer rods but with low spurious signals are proposed and discussed.

CLADDED GLASS RODS UNDER WEAK GUIDANCE CONDITIONS

Cladded rods consisting of core and cladding are preferred over uncladded rods due to their little cross-talk if cladded rods are touched one another. Weak guidance which states that the velocity of the core is slightly (< a few percent) less than that of the cladding provides low dispersion [7]. Boyd et al [8] demonstrated flexural (F_{11} mode) acoustic wave long delay lines using cladded fiber rods operated in tens of MHz. Here we give examples of applications using guided longitudinal waves in the cladded rods [9].

The details of the analysis of acoustic modes in weakly guiding cladded rods can be found in Refs.[7,9]. Let V be the normalized frequency defined as

$$V = \frac{2\pi f a}{v_{L,core}(1-\eta^2)^{1/2}} \qquad (2)$$

where

$$\eta = \frac{v_{L,core}}{v_{L,clad.}} \qquad (3)$$

If V is less than 2.405, only the lowest longitudinal mode (L_{01}) can be guided [9]. Furthermore, under weak guidance the L_{01} mode is close to a planar longitudinal wave.

Figure 3a shows the echoes (B_0^0, B_1^0, B_2^0, B_3^0, ...) traversing back and forth between the top and bottom surfaces of a 191mm long cladded glass buffer rod which consists of a core of 2.4 mm radius and a cladding of 3 mm thick as shown in Fig.3b. The measured $v_{LSAW,core}/v_{LSAW,clad.}$ is ~0.98. LSAW means leaky surface acoustic wave [6]. If we assume that η in Eqn.3 is approximately equal to $v_{LSAW,core}/v_{LSAW,clad.}$, then the V for the cladded rod

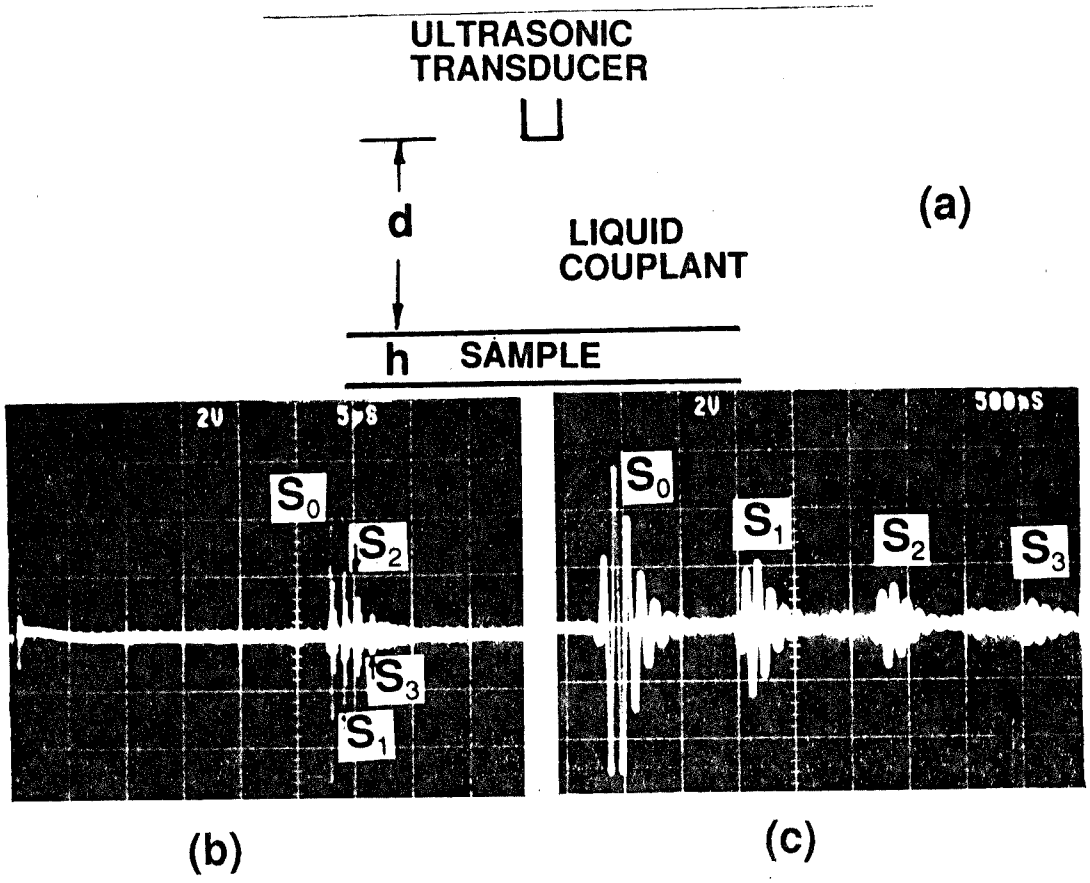

Fig.1 (a) A common ultrasonic pulse-echo measurement with a liquid couplant and a sample. (b) A typical measurement result of (a). (c) The zoomed picture of (b).

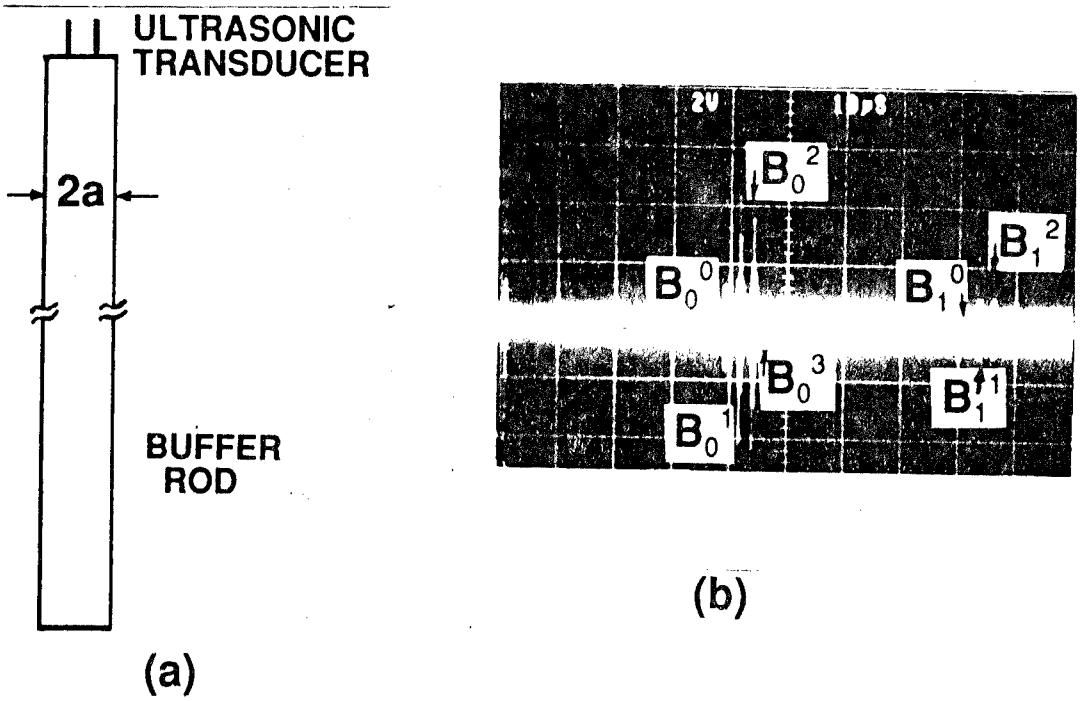

Fig.2 (a) An ultrosonic pulse-echo measurement with a buffer rod. (b) The reflected echoes through a 109 mm long Pyrex glass rod of 10 mm diameter.

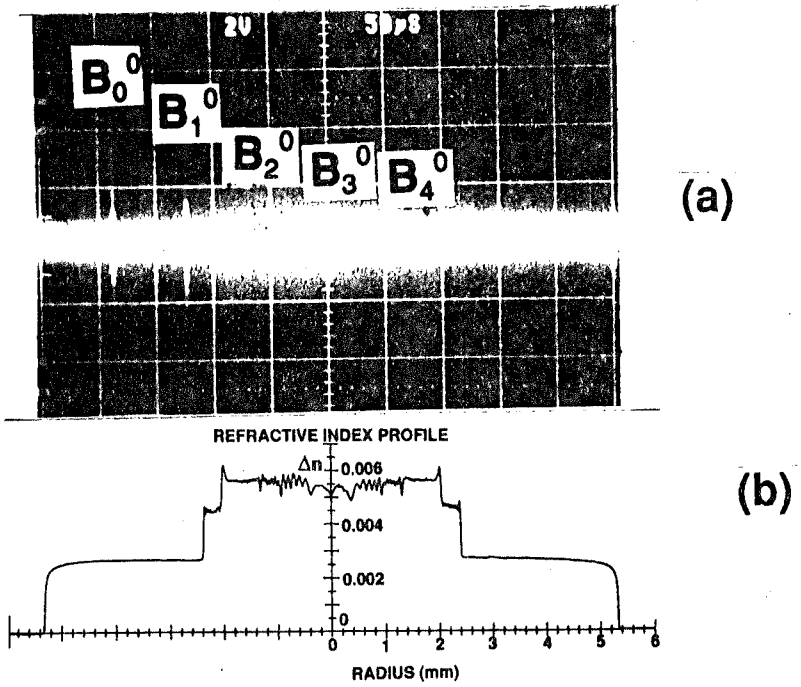

Fig.3 (a) The reflected echoes through a 191 mm weak guidance cladded glass buffer rod. (b) Optical index profile.

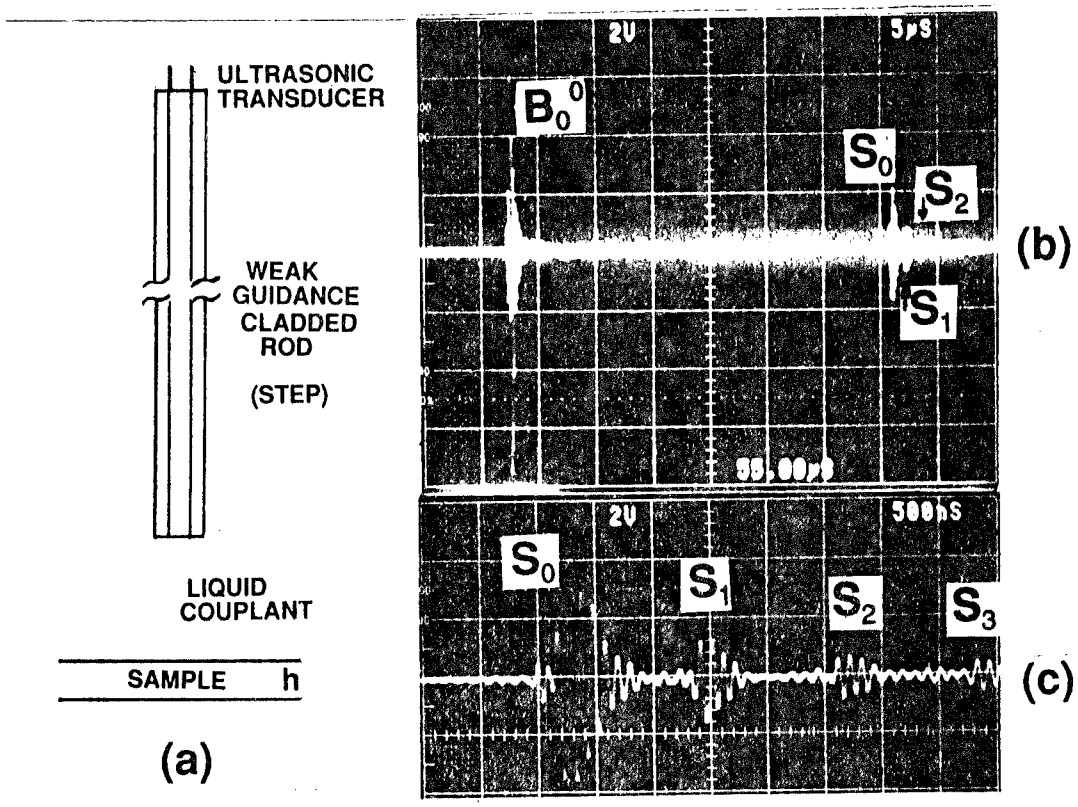

Fig.4 (a) An ultrasonic pulse-echo measurement with a cladded buffer rod in Fig.3, a liquid couplant and a sample. (b) A typical measurement result of (a). (c) The zoomed picture of (b).

used in Fig.3 is 5.3 which means that four longitudinal modes are propagating [9]. Figure 3a clearly indicates that the little trailing echoes exist even at the seventh echo at which ultrasonic total path is more than 2.6 meters. Again, the ultrasonic transducer was a 10 MHz, 6.35 mm diameter broadband transducer. It is noted that the acoustic attenuation for bulk longitudinal wave in pure fused silica is about $\alpha/f^2(x10^{-15}s^2m^{-1}) = 0.13$ which is very low.

If a liquid couplant and a sample are used as shown in Fig.4a, the first echo from the end of the buffer rod, B_0^0, and the echoes (S_0, S_1, S_2, ...) from the sample will be as shown in Fig.4b. Because Figure 4c which is a zoomed picture of Fig.4b is almost identical to Fig.1c obtained without a buffer rod, we conclude that the weak guidance cladded buffer rod is an excellent candidate for long buffer rod applications.

We have also fabricated a spherical concave lens of 9.5 mm diameter at the end of the buffer rod as shown in Fig.5a. The received echoes at the focus for the setup shown in Fig.5a are given in Fig.5b. When the sample is displaced along the rod axis direction, the amplitude variation shown in Fig.5c of the first echo, S_0^f, from the sample surface clearly indicates the focusing behavior.

GLASS RODS WITH RADIALLY GRADED ACOUSTIC WAVE VELOCITY PROFILES

Glass rods having a graded index of refraction along the radial direction are commonly used in optical lens design. They are referred to as graded-index (GRIN) lenses [10] or SELFOC rods [11]. The parameters that define the index distribution provide valuable new degrees of freedom for designers of optical imaging systems [10]. In our previous work on the acoustic characterization of doped fused silica optical fibers fabricated by the modified chemical vapor deposition method, we have demonstrated that such fibers having step or graded refractive index profiles also exhibit step or graded leaky surface acoustic velocity variations respectively [6,12]. In this section, we show that glass rods having radially graded acoustic velocity profiles can be also used as long acoustic buffer rods with low spurious signals.

The techniques to fabricate such GRIN lenses or SELFOC fibers are ion exchange, chemical vapor deposition, sol-gel, etc. They are commercially available. Based on our previous work [13] analogy exists between weakly guiding optical and acoustic fibers. It is expected that rods having graded acoustic velocity profile in the radial direction possess similar "focusing" behavior existed as in counterpart optical GRIN lens. It means that diffraction in such buffer rods exists to a lesser extent.

Since both bulk shear (S) and longitudinal (L) acoustic waves are present in an isotropic glass rod, in contrast to optical waves for which only the S wave exists, acoustic profiles of GRIN rods should be evaluated for both S and L waves. However, it appears that there has been no report about such measurement. In our previous work [6], we found that v_{LSAW} could be measured using the V(z) analysis of a reflection scanning acoustic microscope (SAM). It is well known that transverse components play a major influence on v_{LSAW}; therefore, we expect that the profile of S wave is close to that of v_{LSAW}. Furthermore, because the velocity of the surface skimming compressional wave in an isotropic material is nearly the same as that of L wave, velocity profile of leaky surface skimming compressional waves, v_{LSSCW}, (which can be measured by a SAM [15]) is expected to be close to that of L wave in GRIN rod. In our study we have measured v_{LSAW} and v_{LSSCW} profiles and found that GRIN rods also have graded v_{LSAW} and v_{LSSCW} profiles.

Figures 6a and 6b show the reflected echoes through a 67 mm long Pyrex glass rod of 10 mm diameter and a 67 mm long GRIN rod of 5.4 mm diameter, respectively using the same transducer as in Fig.1. The optical refractive index profile of this GRIN rod is given in Figure 6c and the measured $v_{LSAW,center}/v_{LSAW,edge}$ is 0.86 which means strong guidance. It is noted that for this GRIN rod higher refractive index means lower acoustic wave velocity. From Figs. 6a and 6b it is obvious that GRIN rod with even thinner rod radius offers less spurious signals. It also shows that less wave diffraction exists in GRIN rod.

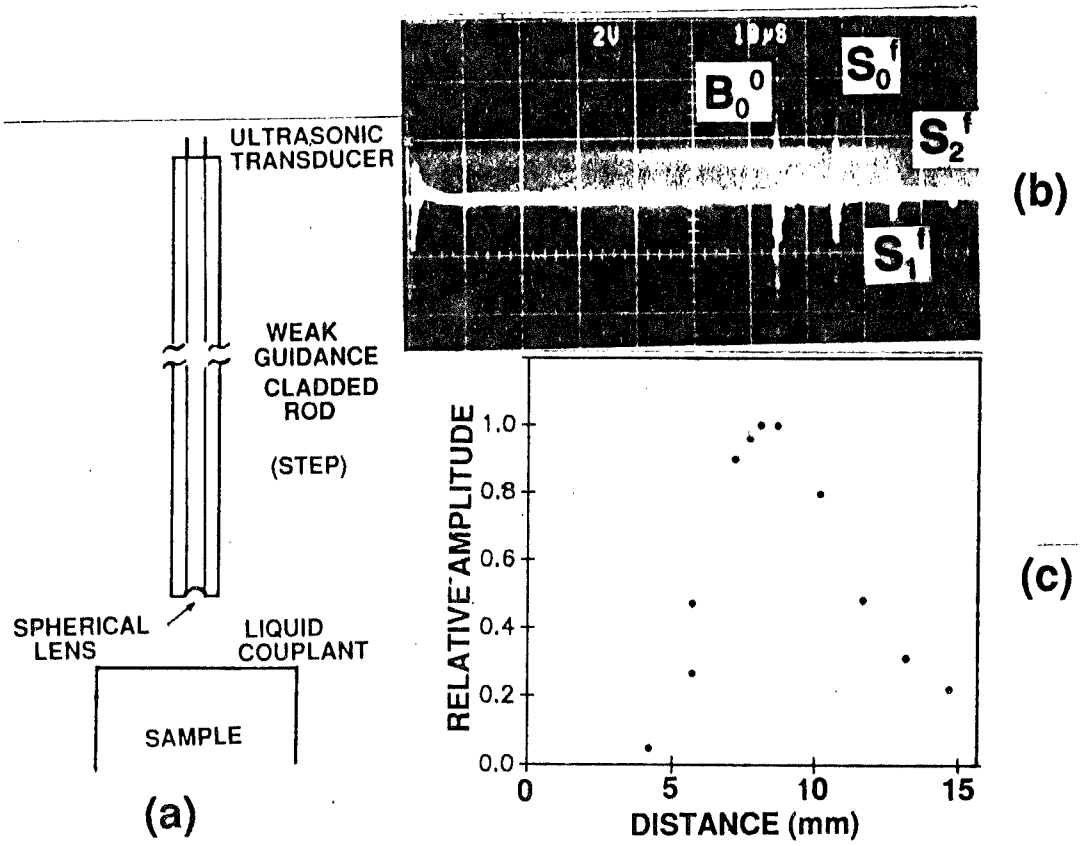

Fig.5 (a) A spherical lens fabricated at the end of the cladded rod. (b) The received echoes when a flat sample is located at the focal point. (c) The axial amplitude variation for the received signal near the focus.

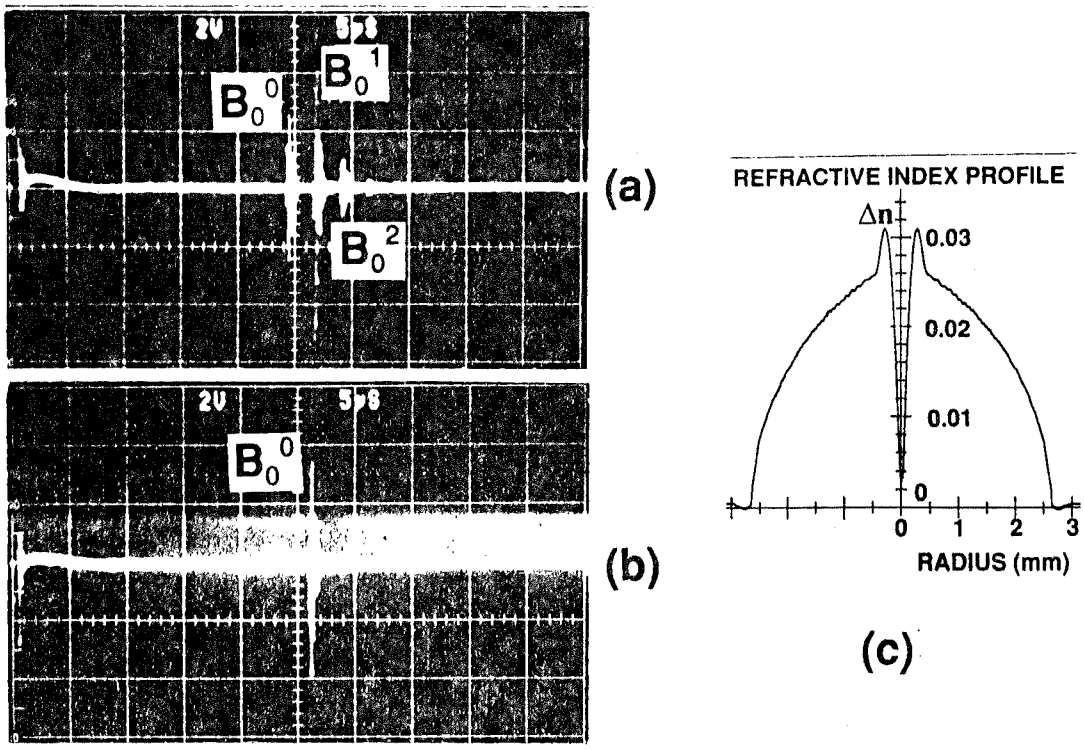

Fig.6 The reflected echoes through a 67 mm long (a) Pyrex glass and (b) GRIN rod. (c) Optical index profile of GRIN rod in (b).

CLADDED GLASS RODS HAVING A CORE WITH RADIALLY GRADED ACOUSTIC WAVE VELOCITY PROFILES

Equation (2) indicates that a higher value of V of a cladded acoustic rod means a larger number (N) of propagation modes inside the core, and also higher pulse dispersion for a broadband acoustic pulse. During nondestructive evaluation of materials we often require higher frequency operation which leads to higher value of V and N. In counterpart optical fiber system, in order to reduce the modal dispersion cladded glass fibers having a core with radially graded refractive index profile are used [11]. We expect a similar behavior for cladded acoustic rods.

Figures 7a and 8a show the echoes (B_0^0, B_1^0, B_2^0, B_3^0, ...) traversing back and forth between the top and bottom surfaces of two 350mm long cladded glass buffer rods which consist of a core of ~ 2.4 mm radius and a cladding of 2.5 mm thick. The variations of the index for these two rods are step and graded as shown in Figs.7b and 8b, respectively. The measured $v_{LSAW,center}/v_{LSAW,clad.} \sim 0.93$. The zoomed pictures of B_0^0 and B_1^0 are given in Figs.7c and 8c, and 7d and 8d, respectively. It is noted that the total acoustic travel distances for B_0^0 and B_1^0 are 0.7 and 1.4 meters, repectively. By comparing them we conclude that for multimode acoustic propagation the cladded rod with a core having graded velocity profile has less dispersion and also low spurious signal.

CONCLUSIONS

Theoretical considerations and experimental measurements of two types of long acoustic buffer rods with low spurious signals have been presented. One is cladded glass rods with small velocity differences between core and cladding. An acoustic lens has been also fabricated at the end of a cladded rod. Another is glass rods with graded acoustic velocity profiles across the rod (no cladding) or core (for cladded rods) diameter. Multimode cladded acoustic buffer rods having graded velocity profiles have low pulse dispersion and also low spurious signal.

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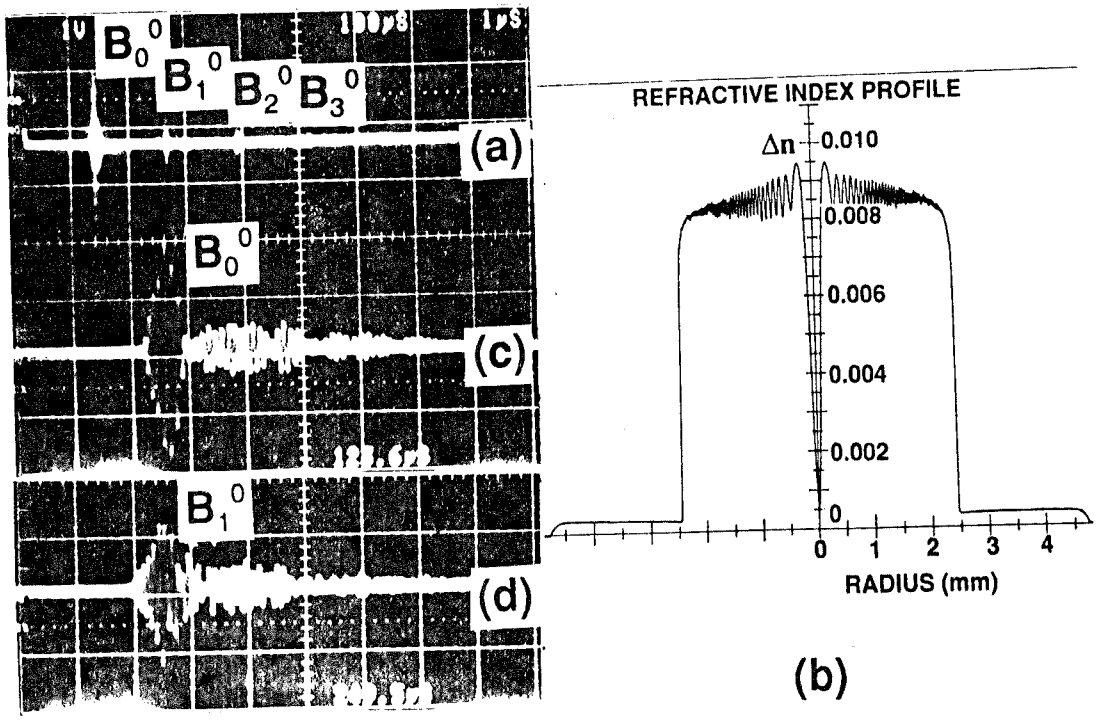

Fig.7 (a) The reflected echoes through a 350 mm long cladded glass rod with a step index profile shown in (b). (c) and (d) are zoomed pictures near B_0^0 and B_1^0 respectively.

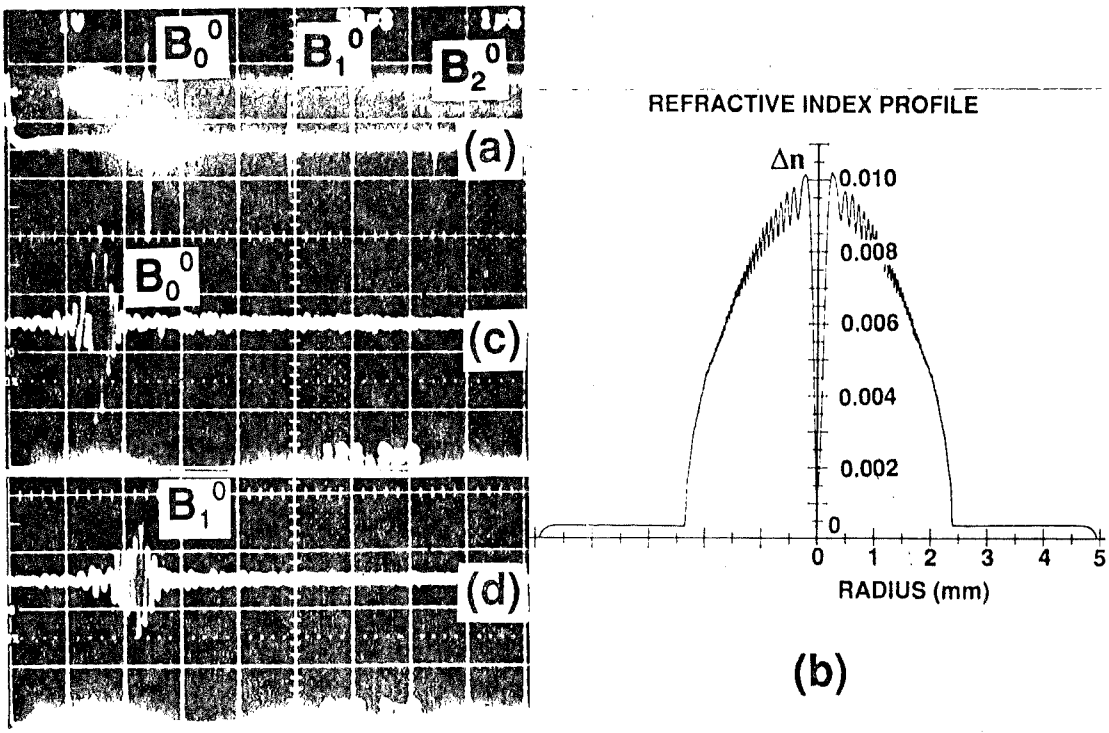

Fig.8 (a) The reflected echoes through a 350 mm long cladded glass rod with a graded index profile shown in (b). (c) and (d) are zoomed pictures near B_0^0 and B_1^0, respectively.