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FIBRE-OPTIC RING RESONATOR HYDROPHONE

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1. INTRODUCTION

Several types of fibre optic acoustic sensors have been proposed and demonstrated[1-4]. The single mode interferometric type is potentially the most sensitive. Interferometer configurations suitable for acoustic detection are the Mach-Zehnder[4], the Fabry-Perot[5,6], and the ring-resonator[7], all of which have relative advantages and disadvantages. The Mach-Zehnder can operate with a low coherence source and utilize long lengths of sensor fibre, but requires an acoustically de-sensitized reference arm and two fibre couplers, leading to complex underwater designs. The single-cavity Fabry-Perot[6] is the simplest configuration but its high back reflectance toward the laser diode tends to destabilize the source, thus requiring some means of isolation, a difficult complication. Cielo[5] has proposed a double-cavity Fabry-Perot system which relaxes significantly the coherence requirements, allowing the use of long lengths of fibre for better sensitivity. The single-cavity ring resonator exhibits very low back reflectance and can offer high sensitivity if used with a highly coherent and stable source such as a single mode He/Ne laser. It can be separated from the electronics by long lengths of connecting lead fibre which is inherently insensitive to environmental noise. The sensing fibre length, however, is limited by the source coherence and stability. Again, a double cavity ring resonator system can be devised that will relax the coherence requirements of the source and allow very high sensitivity.

The hydrophone described in this paper uses a single cavity ring-resonator with a single mode laser diode as a source. While the coherence length of the source is not adequate to allow a high sensitivity, experience gained from this work is applicable to both single- and double-cavity sensors, the laser diode being ideally suited for the latter. A key component that allows successful field operation of the ring-resonator hydrophone is a low-loss directional coupler that has very good temperature stability and very low back reflectance to the laser diode source.

2. SYSTEM DESCRIPTION

A schematic diagram of the system is shown in Fig. 1. The sensor resonator is made of single mode (SM) fibre. Light is guided to the sensor by means of a polarization preserving (PP) fibre, and then back to the detector by the SM fibre with no additional splices. The servo electronics adjusts the laser current, and hence its wavelength, to keep the interferometer at a point of "resonance". More detailed descriptions of the components follow:

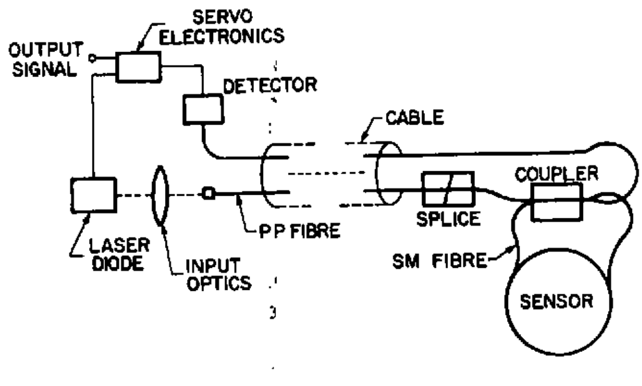

Figure 1. Schematic diagram of the ring resonator hydrophone system.

a. Source

The source is a thermocooler-stabilized Mitsubishi ML-3101 laser diode (3mW, 8050 Å) operating at around 19mA. The bandwidth was measured on a scanning Fabry-Perot interferometer to be 50 MHz (10^{-3} Å). The wavelength of the main mode can be continuously modulated through the injection current at an approximate change rate 0.15Å/mA, and over a current range of more than 1 mA. Light from the diode is linearly polarized.

b. Input Optics

For efficient coupling into the fibre, the input optics comprise a high numerical aperture collimator, a cylindrical telescope that converts the elliptical beam cross section into circular, and a focusing lens that matches the fibre numerical aperture. The fibre end is polished at an angle of 6° relative to its axis and is oriented so that the incident beam, after refraction, travels along the fibre axis. In this way light reflected from the air-glass interface misses the focusing lens and does not contribute to diode feedback, an important consideration in laser diode stability. The output fibre end is also polished at an oblique angle to avoid back reflections.

c. Link Fibre and Cable

The PP fibre used was ITT 1605 approximately 10 m long. It is housed, together with the return fibre in a hand-made cable consisting of a 1/4" ID reinforced neoprene tube with an additional steel strength member. The splice between SM and PP fibres is a butt-coupling of the two fibres, each bonded in a glass capillary tube, polished at an angle of 6°, and permanently cemented together with epoxy.

d. Resonator

A fibre optic ring resonator is a length of SM fibre with its two ends joined by a low loss directional coupler, so that light can propagate continuously around the fibre loop. When monochromatic light is injected at the coupler, and its wavelength is adjusted so that it re-enforces the wave travelling in the loop, then the intensity can reach much higher levels than the injected light. Those discrete wavelengths where this re-enforcement occurs are the resonances of the loop or ring resonator. The sharpness or "finesse" of the resonance depends on fibre loss, coupler loss, and coupling coefficient, and is discussed in detail by Stokes et al.[8] Resonances in the loop correspond to sharp dips in the output port of the coupler.

In the present system the resonator is a 50 cm long SM fibre fabricated by a technique similar to that described by Stokes et al[8] (i.e., polished blocks) but with one essential difference: the coupler halves are optically contacted with no index-matching oil between them. After adjustment for optimum resonance, the two halves are cemented and sealed hermetically. Elimination of the index-matching oil and careful cementing has led to an essentially temperature-independent coupler. The resonator length of 50 cm is the maximum that can be used to advantage, considering the bandwidth of the laser diode.

e. Hydrophone

The hydrophone sensor element is a hollow, end-capped cylinder made of PVC plastic around which the jacketed SM fibre resonator is wrapped under tension. This makes the sensor fibre weakly birefringent so that a propagating light wave, that is polarized parallel (or perpendicular) to the cylinder axis, tends to maintain its polarization. However, due to the weak birefringence and the short fibre leads to the coupler, there can be some change in the state of polarization. Consequences of this will be discussed later.

The 3.8 cm-diameter PVC cylinder was made with a diameter-to-wall thickness ratio of 75 so as to achieve a reasonable sensitivity from the rather short 50 cm sensor fibre. The cylinder and coupler were mounted in a metal framework onto which the lead cable was attached.

f. Electronic System

The electronic system receives the light output signal from the detector and applies the injection current to the laser diode. Figure 2 shows a plot of ring resonator output intensity as a function of resonator length in wavelengths. N is a large number near 1 million for the 50 cm resonator length. Each negative peak represents a resonance of the ring resonator and the servo electronics adjusts the injection current to maintain the laser wavelength at one of these peaks: a small carrier current modulation at 50 kHz is applied as shown, with enough amplitude to bring the peak points A and A' near the maximum fringe slope (dashed curve). Two sample-and-hold circuits register these levels and their outputs are fed to a difference amplifier. If an acoustic signal changes the length of the resonator (solid curve) so the peak signals are at B and B', the difference signal is used to change the diode drive current, and hence its wavelength, until the difference is nulled. This change in current, after removing the D.C. component and the 50 kHz carrier, represents the desired acoustic output signal.

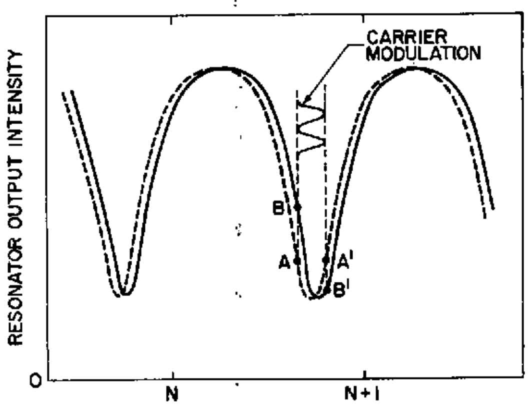

Figure 2. Ring resonator output intensity as a function of the optical length of the resonator in wavelengths. The quarter wave length offset in resonance peaks is due to the $\pi/2$ phase shift introduced by the coupler.[8]

3. EXPERIMENTAL RESULTS

When a modulation is applied to the laser diode current, with the servo loop open, the resonator acts like a scanning interferometer. Figures 3a and 3b show the optical output with a sinusoidal modulation. In 3a the two polarization modes are clearly separated, while in 3b the input fibre is rotated so that one mode predominates. The theoretical output intensity from a ring resonator at a resonance is zero[8], but perfectly polarized, monochromatic light is assumed. The non-zero output exhibited here is attributed largely to small changes in the state of polarization because of the weak birefringence of the resonator loop, as mentioned in Section 2(e) above.

The maximum finesse measured with this resonator was 5 which is not far from the maximum observable limit of 8 for the diode bandwidth. No attempt was made to further optimize the resonator, as an increase in finesse was accompanied by increase in noise, which is probably inherent to the diode.

Despite very careful polarization alignment, the PP fibre was found to be very sensitive to environmental perturbations, producing substantial intensity noise as well as having poor polarization preservation. Splicing difficulties are the cause for this behaviour: the PP fibre has a smaller core than the SM and in addition, its cladding is acting as a waveguide because it is surrounded by lower index glass. It is then likely that cladding light from the PP fibre finds its way into the SM. As the PP core size is only 3.4 µm it is very difficult to ensure that only core light is

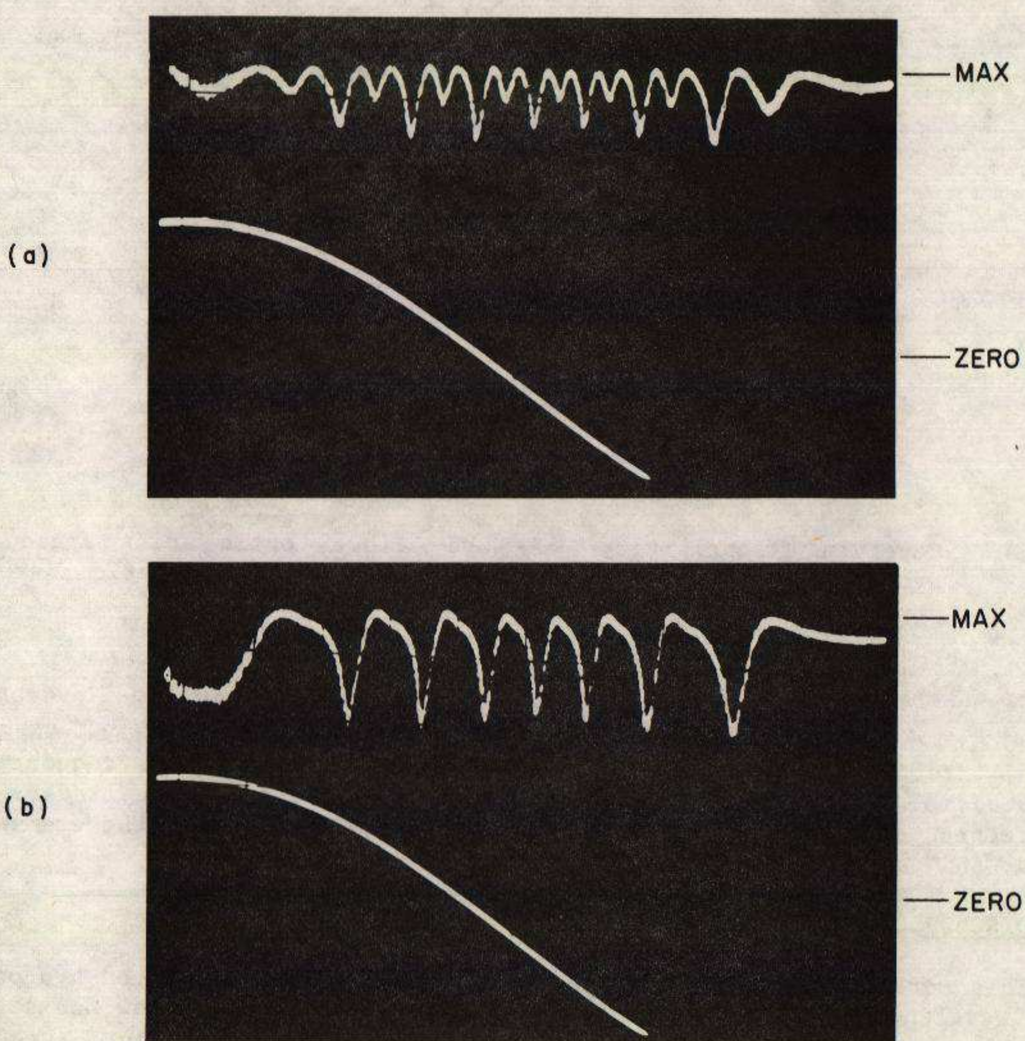

Figure 3. Observed ring resonator output with a sine wave modulation of laser diode current. A portion of the sine wave is shown by the lower trace in each photograph. The two polarization modes are clearly separated in (a). The input fibre has been rotated in (b) so that one polarization mode predominates. The zero intensity level relating to upper trace is shown at the edge of each photo.

launched into it. This explanation is supported by the fact that the noise was found to be critically dependent on the input optics adjustment. Selection of a PP fibre that does not have a guiding cladding should eliminate this problem. As the signal recovery system rejects intensity noise to some extent, these effects were more clearly seen in the open loop state and did not drastically affect the closed loop operation.

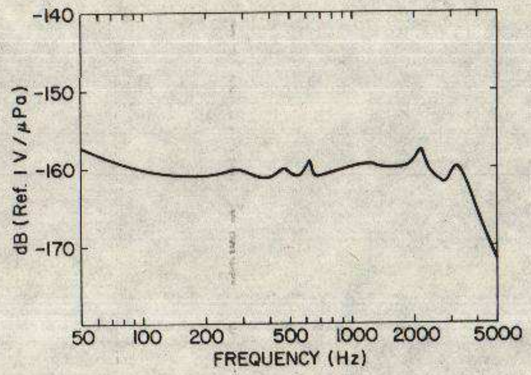

Figure 4. Receiving sensitivity of the fibre optic ring resonator hydrophone measured by a noise technique in an acoustic tank at a depth of 2 metres.

Figure 4 shows a plot of receiving sensitivity of the hydrophone measured in an acoustic tank by a noise method.[10] The drop-off at 4 kHz is due to internal low-pass filtering and the rise at low frequency is attributed to the rate dependent stiffness of the PVC plastic cylinder. The small resonance peaks are likely due to the framework in which the element is mounted, and can be eliminated by more careful mechanical design.

4. DISCUSSION AND OUTLOOK

This work has demonstrated the operation of a ring resonator hydrophone with a wavelength-modulated, single mode laser diode source. Low backscatter and temperature stability of the resonator have been major areas of development. The noise caused by the PP fibre can be reduced with the use of a fibre that has a larger core and does not support cladding modes. Also, by making the resonator from PP fibre, the problems of splicing and polarization alignment are eliminated. However, the limiting component of the present system remains the laser diode, whose coherence and stability do not allow high sensitivity. A single mode, frequency-modulated He/Ne laser, or special laser diode source would permit the use of longer resonators.

A double cavity system also seems to offer the means of increased sensitivity. Cielo's double-cavity Fabry-Perot system[5], in which the first cavity is piezoelectrically modulated, would require modification, as the ring resonator output is similar to the Fabry-Perot reflectance rather than transmittance. It may be adequate in this respect to have a tap in the first resonator loop (local cavity), the tap output being used to feed the sensing cavity. A simpler servo system would also result from modulation of a piezoelectric voltage instead of the laser diode current. Matching the two cavity lengths is required for optimum signal; the length difference must be less than the coherence length of the source and is also dependent on the resonator finesse. A single mode laser diode offers adequate coherence length for comfortable length matching.

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