## Final Report:

# LOW COST DISTRIBUTED SENSING FOR GAS PIPELINES

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## Summary

The goal of this program was to examine the feasibility of developing acoustic sensor arrays using ordinary communications-grade optical fiber, to be used for health monitoring of gas pipelines. Continuous monitoring of acoustic propagation in pipelines has some advantages for location and diagnosis of structural integrity problems. For physical security issues, such as strikes or deliberate tampering, continuous monitoring is not of real interest since the technique cannot identify a problem before it happens. However, health monitoring and inspection of a large number of "non-piggable" pipelines, particularly for gas transmission in metropolitan areas, remains an industry need which could potentially be addressed by acoustic sensor arrays.

Two alternatives were investigated in this program. The first alternative was predicated on using a single, unaltered fiber, many kilometers in length. This method relied on the principle of stress-induced coupling between optical spatial modes in the fiber. These different spatial modes travel through the fiber with different velocities, and thus by using correlation or interferometric techniques, a phase shift or time delay could be tuned to select signals from particular locations along the fiber where acoustic disturbances would then change the amplitude of the received signal. This approach proved to be unworkable due to the practicalities of achieving efficient mode coupling for typical acoustic events, and due to the lower than expected difference in propagation constants between the different modes.

The second alternative considered was to use a network of sensor nodes along the pipeline, or an array of individual sensors tapped into a single fiber and interrogated using standard optical fiber communication techniques of time division multiplexing (TDM) or wavelength division multiplexing (WDM). This alternative also proved unworkable for cost and technical reasons.

Due to the low technical feasibility of both approaches considered and based on feedback from industry and DOE sources that the difficulties with acoustic inspection might be unworkable in spite of the sensor technology, we opted not to pursue a Phase II program.

## Activities and Findings

*1. Technical Overview*

As noted above, the sensing principle we planned to exploit is based on spatial modal interference in ordinary fiber. In a standard singlemode communications fiber such as SMF-28, wavelengths shorter than the cutoff wavelength will propagate in more than one spatial mode (for example, SMF-28 supports $LP_{01}$, $LP_{11}$, $LP_{21}$, and $LP_{02}$ at a wavelength of 633 nm, as indicated in Fig. 1). Since these modes have different mode field diameters and propagate with different group velocities, it is possible to discriminate between them interferometrically. When the fiber is squeezed or pulled, the applied stress induces coupling between different modes which, after propagating down a length of fiber, have a relative phase delay determined by the distance over which they have propagated (i.e. the location where the event occurred). Mathematically, the two

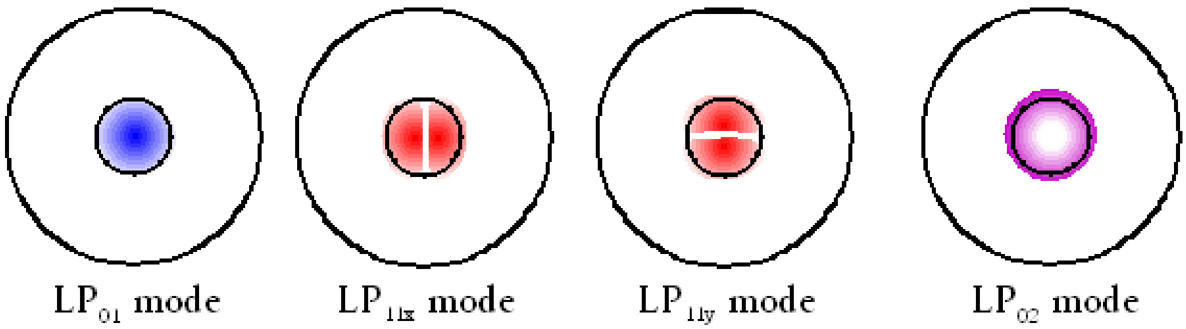


**Figure 1. Illustration of low order spatial modes in optical fiber.**

spatial modes will have two different propagation constants ($\beta_1$ and $\beta_2$) so that the phase difference between two coherent wavefronts after propagating a length $L$ down the fiber will be

$$\Delta\phi = (\beta_1 - \beta_2)L = L\Delta\beta .$$

Thus, standard communications fiber (e.g. SMF-28) can be used as the sensor fiber. It is preferable to use this fiber since the cost is very low (due to economies of scale in the communications business). While multimode (MM) fibers do exist at communications wavelengths (1310 and 1550 nm), these fibers allow many modes to propagate at these operating wavelengths (typically 50-100 modes). For reasons discussed below pertaining to controlling the spatial asymmetry of the mode pattern in the fiber, it is desirable in our approach to use fiber that permits only a few modes (i.e., 2 or 3) to propagate. Two mode fiber (TMF) for use at 1550 or 1310 nm does not exist, so our investigations were restricted to the shortwave region between 800 and 1000 nm.

In this regime, the relative time delay (due to modal dispersion) between load points spaced at 1 m is on the order of picoseconds, so that processing this information in the time domain would require THz clock rates. It is thus necessary to process the phase shift between modes directly. One way to do this is to interfere the modes with each other; since all modes in the fiber originate from the same source, they are temporally coherent (within a given coherence length determined by the coherence of the source). One can show that the periodicity, $\Lambda$, of the beats is [1]

$$\Lambda = \frac{\pi\Phi}{2}\frac{M}{m\sqrt{\Delta}} ,$$

where $\Phi$ is the effective mode field diameter in the fiber core, $M$ is the total number of modes, $m$ is the mode index and $\Delta$ is the ratio of the core-clad index difference to the core index. In this case, we have $\Phi = 8.2\ \mu m$, $M = 4$, $m = 2$, and $\Delta = 3.6 \times 10^{-3}$. This periodicity will manifest itself in the orientation of the $LP_{01}$-$LP_{11}$ interference pattern (the lobes will "rotate"), and thus a device which is sensitive to the orientation of these modes will be able to convert this spatial information into an amplitude change.

In earlier work, IPITEK's Passive Component Engineering Group developed and prototyped an optical fiber device based on a fiber optic pre-tapered asymmetric mode coupler (AMC), as shown schematically in Fig. 2. The concept behind this AMC device was that by pre-tapering one fiber to induce a preference for a given mode (e.g., $LP_{01}$), we could construct a device whose outputs would vary based on the relative optical intensity in the different spatial modes.

We had also observed behavior which appeared to support this thesis, as indicated in the pictures at the bottom of Fig. 2, which show two images from the two output legs of an AMC device when attached in series to TMF. The image on the right, consisting of two lobes, was at first thought to be the result of selective coupling of only the higher order mode into the larger fiber, but it was later found to be the interference pattern produced by roughly equal proportions

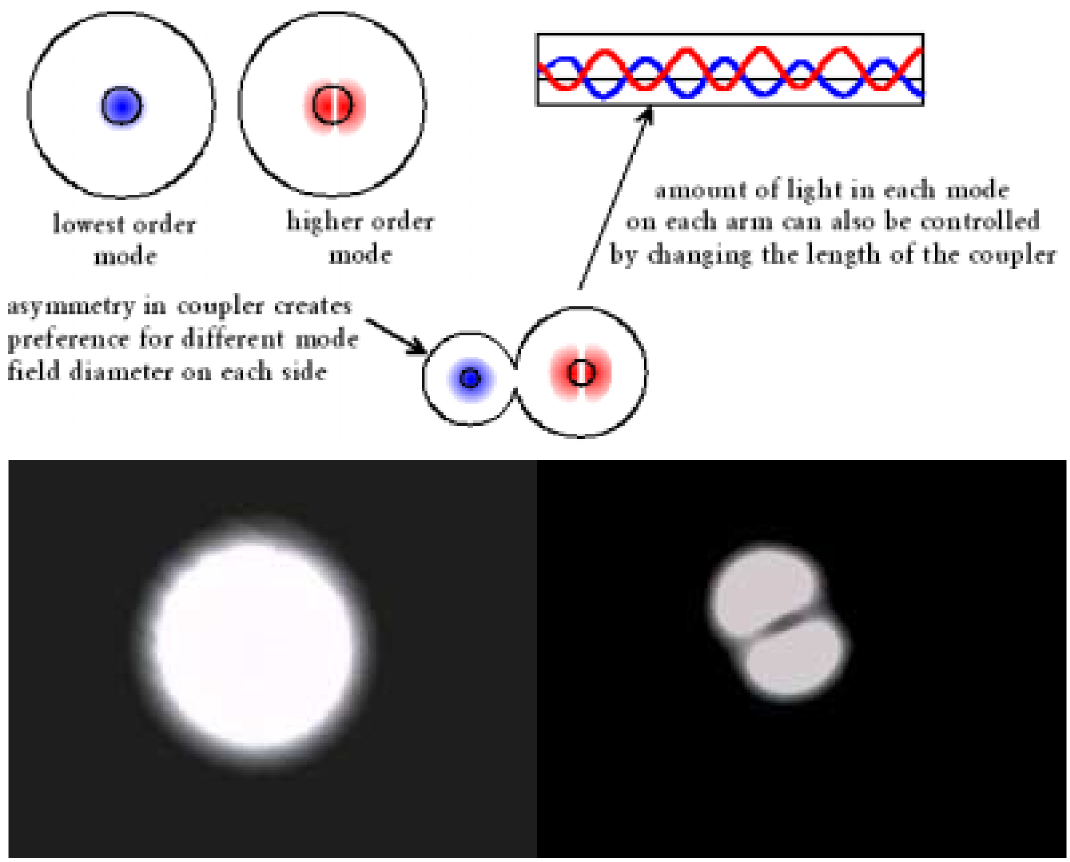


**Figure 2. Top: Asymmetric mode coupler (AMC) concept. Bottom: Images of spatial modes separated by AMC.** The left picture is primarily the fundamental mode $LP_{01}$, but may have some $LP_{11}$ components. The right picture was originally identified as the higher $LP_{11}$ mode, but is in fact more likely the interference of $LP_{01}$ and $LP_{11}$.

of the lower and higher modes.

*2. Single fiber sensor array*

The discovery about the function of the AMC device led us to re-examine the mode coupling hypothesis. In fact, we found that a more plausible explanation was that the larger arm of the AMC was in fact just attenuating the $LP_{01}$ mode (the brightest part of the signal) and allowing the interference between $LP_{01}$ and $LP_{11}$ to be seen in the second leg. Further experiments showed that it was unlikely that any measurable direct coupling between the $LP_{01}$ and $LP_{11}$ modes was occurring but that the changes induced by stress on the fiber were more likely evidenced by coupling between the degenerate $LP_{11}$ modes.

Even though the AMC device did not work the way we originally thought, there was still some potential to use this device to make a long-telemetry array, since there was indeed a preferential separation of modes between the two sides of the AMC. In order to extract location information directly, the intermodal delay would have to be relatively large. Our measurements showed that the $LP_{01}$-$LP_{11}$ intermodal group delay was less than the expected value of 2 ps/m, which indicates that the degenerate $LP_{11}$ intermodal group delay, which should be orders of magnitude smaller, would be nearly negligible.

We thus shifted the focus of our effort to looking at other means to extracting the information indirectly, such as using multiple wavelengths or other modulation schemes. The basic problem with the short intermodal delay is that the periodicity of any interference between the modes will be very short and thus signals from points on the fiber at the period of the modal delay will be impossible to tell apart. In order to break this periodic degeneracy, some means of adding a longer periodicity is required.

The first approach we examined was standard low coherence interferometry. In this technique, white light is input to the fiber and any modal delay can then be read out by introducing a delay on the order of the coherence length at the other end. This concept is shown in Fig. 3.

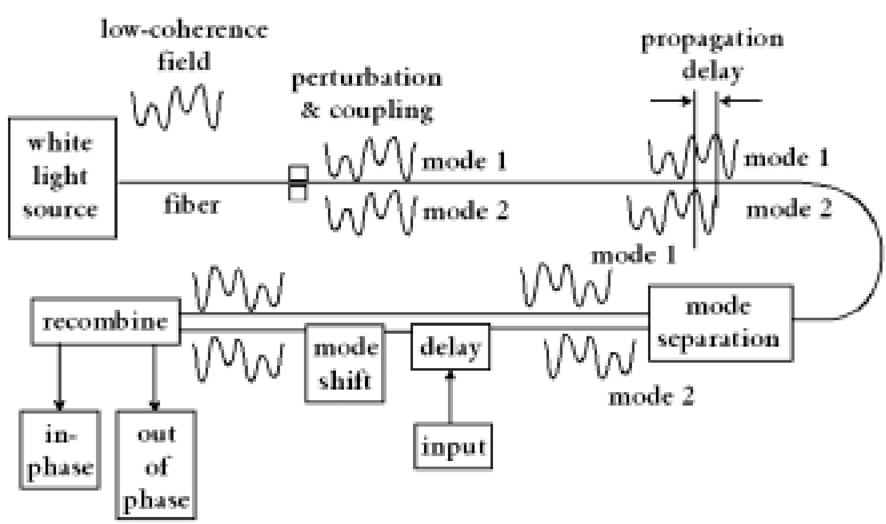


**Figure 3. Low coherence interferometry setup & concept.**

Though the white light input to the fiber has very low coherence, when it is split into different modes by a physical perturbation on the fiber, those two modes are coherent with each other. Delay is introduced as they propagate down the fiber, so that an interferometer can be used to program delays that correspond to different lengths down the fiber (points on the array). When the two modes are recombined, a stronger and sharp constructive interference signal will be observed only when the delay input to the interferometer matches the delay in the other leg, introduced by propagation. Since the intermodal delays are less than picoseconds/meter, a total delay of 600 ps (commercially available in a fiber coupled package) could potentially be used to scan kilometers of fiber.

However, our results using a commercial low coherence interferometry system showed that either the physical perturbation does induce enough coupling between high order modes or the intermodal delay between the high order modes is small enough to yield insignificant results. We also found no significant correlation between applied load on the fiber at different locations and a shift in the interferometer output as a function of delay. We did measure intensity oscillation along the fiber due to intermodal interference, but the period of this oscillation was 0.5 mm (in excellent agreement with the theory). We therefore concluded that this approach would not be viable for the long-distance pipeline application.

We also considered using multiple wavelengths to add dispersion to the system and thus break the degeneracy described above. We were able to discern some dispersion in the periodicity as a function of wavelength by measuring the spatial loading dependence of the combined output of two wavelengths at the same time. However, the effect of dispersion was simply to increase the periodicity (of the envelope function) to about 3 mm, still well short of the required characteristic length for pipeline applications.

### *3. Multi-sensor array*

We found that under single point loading, the fiber was quite sensitive to transverse forces, leading us to believe that a very sensitive gauge could be made to sense vibration (with an appropriate transducer). We thus directed the remaining part of our study to devising schemes by which numerous point sensors could be multiplexed onto a single telemetry fiber.

The two extant methods for doing this are TDM and WDM, as noted above. The WDM array (Fig. 4) would require either wavelength selective couplers (called WDM couplers) or selective

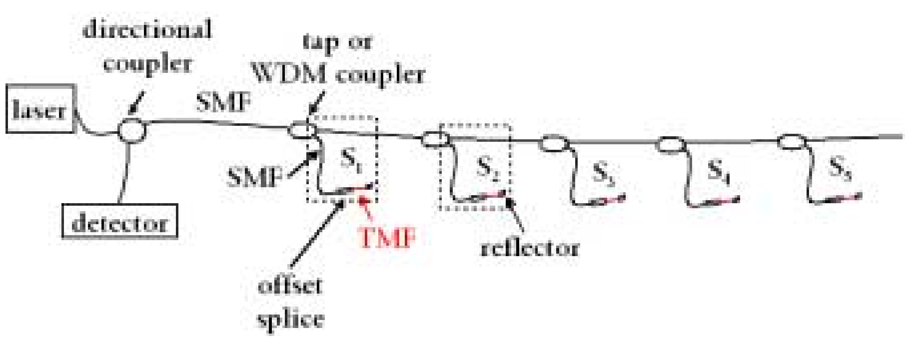


**Figure 4. WDM/TDM sensor array concept.**

reflectors at the ends of the sensor fibers. Both of these options are quite costly (more than $300 per point) so we focused our analysis on the TDM approach.

A TDM array requires tap couplers and broadband reflectors, both of which can be inexpensive (less than $20). The defining constraint in the TDM case is the temporal restriction on the excitation pulses. A typical short pulse of 10 ns will be 2 m long in standard optical fiber, which would allow points to be spaced a minimum of 2 m apart. This spatial constraint should be more than adequate for pipeline sections 30 m or more in length.

By pulsing the sensor array periodically, a sampled measure of the acoustic disturbance along the array can be obtained. This concept is illustrated in Fig. 5 . Obviously, the overall sampling rate for any given point in the TDM scheme will be limited by the most distant point in the array. For a 1 km array with 100 sensing points (10 m spacing) at 10 ns pulse duration, the maximum repetition rate for output pulses will thus be 5 μs. Allowing some time budget to delineate signals and allow for data processing, the maximum sampling rate for any point on the array will be approximately 100 kHz. This also should be more than adequate to resolve anomalies in acoustic propagation in the line due to damage or degradation of the pipe. Finally, the power division of the signal is of concern when this type of multiplexing is used, but our calculations show that one can expect less than 0.1% shot noise using a 30 mW laser source with –60 dBm or better relative intensity noise (in band).

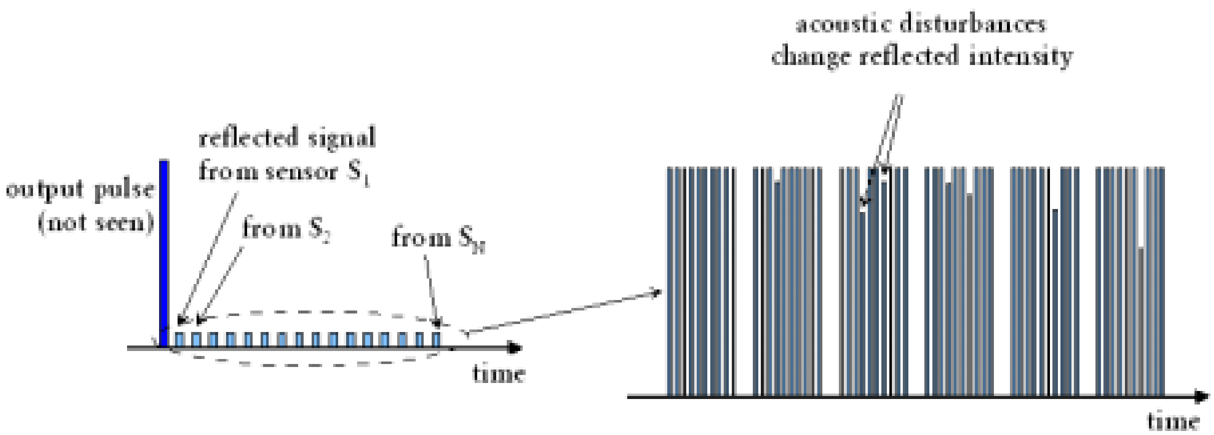


**Figure 5. TDM signal processing.**

While the technical constraints to this approach are feasible, the cost is prohibitive. Our experiments in Phase I were performed with specialty singlemode fiber, with a cutoff wavelength below 850 nm. While this fiber is not fundamentally different from standard communications fiber, it also does not benefit from the same economies of scale. Where as SMF-28 can be as low as $0.10/meter, the SM fiber required for this work is typically $7-10/meter at best. Thus, the fiber expense alone for a 1 km section of pipeline would be somewhat less than $10,000. Since this fiber is needed for telemetry of the signals, longer pipelines would incur proportionately larger expense, even without adding more sensors. The feedback we obtained in Phase I concerning costs indicated that a total price tag of less than $10,000 would be plausible for a complete system.

The last option considered was to network individual pipe sections, as shown in Fig. 6. In this scheme, multiple individual fibers would be routed to sensor points on a pipeline section to sense discrete points, and then all the signals would be collected and processed by a single electronic node on the pipe. Different sections could be networked together in a fashion analogous to a local network of computers. This approach would also allow for more independent local processing of data obtained from individual sections of pipe, and could provide a better means to accommodate pipe joints. However, the cost again proved to be prohibitive, since the nodes most likely cannot be made for a price of less than $300 including fiber and sensors.

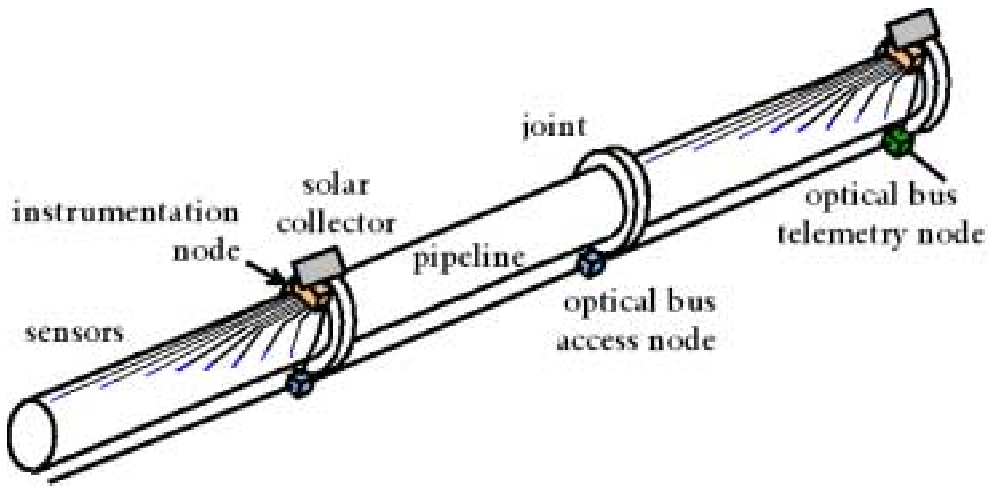


**Figure 6. Multi-sensor pipeline network concept.**

## Conclusion

The concept of sensing using intermodal interference remains valid, though untenable for applications involving long telemetry distances such as gas pipelines. Other multiplexing alternatives such as TDM or WDM arrays, including several types not discussed here such as Bragg gratings, are likely to be cost prohibitive for some time in the future. Thus, while the infrastructure need remains acute, the solution to pipeline health monitoring is not likely to be found using optical fiber sensors alone. However, a combination of approaches or "hot spot" monitoring of specific locations, potentially using some of the approaches described above, may prove a useful addition to the repertoire of tools available for pipeline health monitoring.

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[1] J. Berthold et al, *J. Lightwave Tech.* **5**, 870 (1987).