ULTRASONIC SENSORS

The subject of ultrasonic sensors deals principally with (1) the application of ultrasonic devices to measure physical parameters (either material or field related) and (2) the application of various technologies to excite and measure the behavior of ultrasonic and/or acoustic fields in matter. In the latter case, almost invariably, detecting and processing ultrasonic fields is to determine the physical properties of the acoustically conducting medium or interfaces with other adjacent media to image objects, flaws or other artifacts, measure strength, stiffness, ductility, any other material property that can be imagined, and even, by appropriate coupling mechanisms, static and dynamic electromagnetic properties. Such sensors are used in commercial manufacturing (materials processing, formation, extrusion, joining, robotics, etc.), structural reliability and maintainability (nondestructive evaluation), security (perimeter intrusion), safety, and the military (sonar).

Inevitably, we are ultimately led back to case (1) for our final objectives, whereas case (2) is responsible for extensive academic, industrial and governmental research and engineering development of materials, devices, signal processing methods and products based thereon to facilitate measurement, quality, and process control.

It would be most convenient to organize a scheme for the subject of ultrasonic sensors into a suitable matrix of parameters. However, this field is too complex, multidimensional and, given the pace of technology, continuously growing to represent so simply. Ref. 1 proposes an organizational scheme for sensors to which the reader is directed. A review of acoustic sensors is also presented in Ref. 2.

For discussion it is convenient to distinguish two basic types of ultrasonic sensors: those based on *bulk acoustic wave* (BAW) excitation and those based on *surface acoustic waves* (SAWs). Sensors based on related modes of propagation, for example, surface skimming bulk acoustic waves (SSBAWs) and shallow bulk acoustic waves (SBAWs), are thought of as hybrids or intermediate variants of the two basic types, though this might be an oversimplification. We will familiarize the reader with the technology of ultrasonic sensors by examining a selection of bulk and surface acoustic wave sensor devices and their application to numerous problems.

BULK ACOUSTIC WAVE SENSORS

A variety of bulk acoustic wave devices have been engineered to detect or quantitatively measure the presence and/or concentration of gaseous and liquid media in direct contact with the acoustic device. The device most often consists of a single or multiple of transducers that excite an ultrasonic wave and detect the effect of the adjacent medium.

The use of ultrasonic devices as environmentally sensitive frequency control elements in oscillator circuits is a well developed method (see *frequency control*). The process is conceptually simple, somewhat more complicated in implementation, and uses bulk, surface, layer, and suspended beam and diaphragm structures. The frequency-controlling element can be a resonant or delay-line structure.

In single transducer devices, the most common method of sensing is to measure the reflectance admittance matrix response (S_{11}) of the transducer as the adjacent medium changes. Typically, the loss factor of the transducer increases with the viscosity of the medium. A variant method for this characteristic is to incorporate the transducer as a frequency-control element in an oscillator circuit. Referenced to air at standard temperature and pressure (STP) or vacuum or to a standard liquid, the oscillator characteristic frequency and circuit Q factor typically drop. Furthermore, an additional level of sophistication can be added to the sensor design by coating the exposed substrate with a selectively absorbing material, so that change in oscillator characteristics is affected by only one substance.

The most common example in commercial use is the vacuum deposition crystal thickness monitor used in thermal and electron beam deposition stations. It consists typically of a quartz crystal oscillator circuit where the quartz disk is usually mounted at the same distance from the source as the target substrate (Fig. 1). The frequency shift induced by the mass loading is multiplied by a coefficient particular to the material being deposited, which yields the thickness change in angstroms (or nanometers). When the accumulated mass detunes the oscillator frequency and Q beyond acceptable limits of linearity, it is customary to discard the crystal sensor or return it to the manufacturer for refurbishing. It is also possible to recycle the crystals directly by etching off the deposited materials, taking care to leave the base electrode layer intact.

The Vacuum Deposition Crystal Thickness Monitor

Oil Viscosity/Quality Sensor. A piezoelectric disk, in the form of an AT-cut quartz resonator operating at its fundamental shear mode as the frequency control element of a dedicated electronic circuit, is described in Ref. 3. The sensor can differentiate between different grades of oil and the degradation of oil viscosity by contamination and dilution from water, ethylene glycol, and gasoline. Figure 2 presents the qualitative features of the sensor. One surface of the quartz disk resonator is in contact with the oil which loads the surface because of viscosity and density, whereas the other contacts air, which has a smaller effect.

Elements of An Ultrasonic Resonating Oil Viscosity Sensor

The lumped-equivalent circuit for the resonator is shown in Fig. 3. The motional circuit elements, R_1, C_1, and L_1 may vary

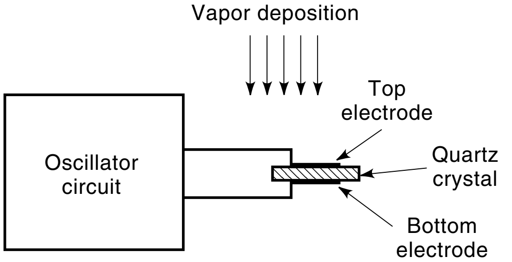

Figure 1. The crystal thickness monitor is a quartz crystal disk that is the frequency-controlling element in an oscillator circuit. The driving circuit is external to the vacuum system. A typical commercial crystal has a nominal operating frequency of 5 MHz. Mass loading due to vapor deposition in a high vacuum chamber shifts the resonant frequency of the crystal. The frequency shift is converted into an equivalent thickness, depending on scaling constants for different materials.

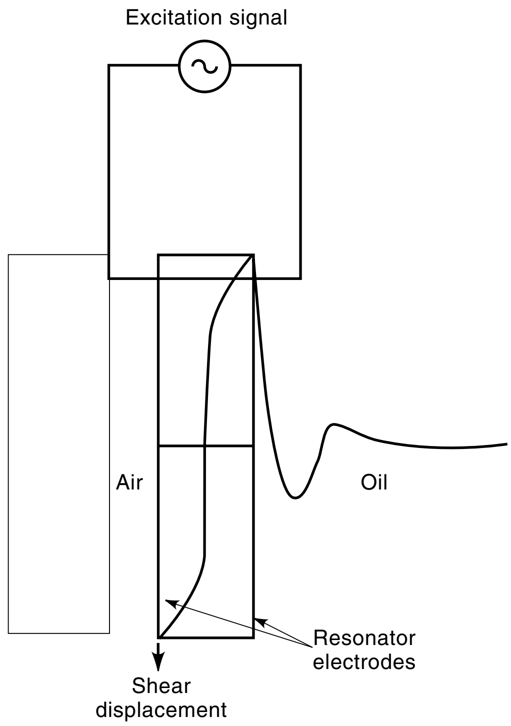

Figure 2. An adaptation of the crystal thickness monitor to measure changes in automotive oil viscosity. A shear-mode AT quartz crystal is in contact with the oil. The mechanical coupling to the oil affects the electromechanical characteristics of the sensor.

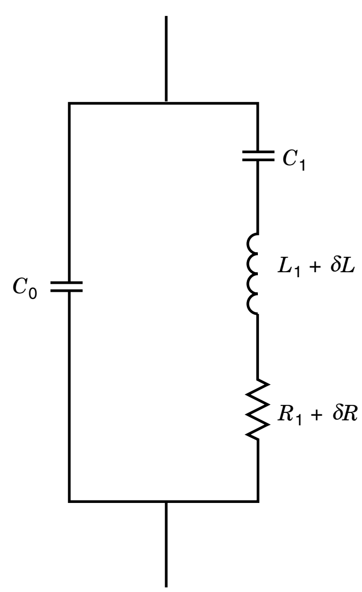

Figure 3. The lumped-element equivalent circuit of the ultrasonic resonator oil viscosity sensor. C_0 is the equivalent static capacitance. The remaining elements are the motional capacitance C_1, inductance L_1, and resistance R_1. The electromechanical coupling between the crystal sensor and the oil is characterized by changes in the motional inductance δL and resistance δR.

to represent the viscous loading which shifts the resonant frequency and alters the quality factor (Q) of the resonator. Degradation changes the viscoelastic properties of the oil with consequent effect on the electrical properties of the resonator, principally the motional inductance and resistance. A voltage-controlled oscillator (VCO) circuit design uses both amplitude and phase information relative to a reference crystal. An attractive feature of this sensor is the ability to locate all electronic components, apart from the sensor, remote from the harsh environment of the engine crankcase. The resonant frequency and Q are both sensitive to temperature, and a technique has not yet been devised which separates and identifies the different contributions to sensor shift due to temperature and contamination from that of water, ethylene glycol, gasoline, or other additives. Similar work has been reported by others (see Ref. 4).

Equivalent Circuit of An Ultrasonic Resonator Oil Viscosity Sensor

Infrared Sensor. The quartz resonator can be adapted for sensitivity to temperature and infrared radiation. Ref. 5 describes the enhanced infrared absorption of a quartz AC-cut disk microresonator (i.e., operating at 160 MHz fundamental frequency, and therefore quite small) enhanced to 51% by depositing a 100 Å coating of titanium on the surface of the microresonator. The microresonator crystal was 10 μm thick and had an area of $500 \times 500\ \mu m^2$. Smaller size and mass increases response time, and smaller thickness raises resonant frequency, increasing the frequency coefficient of temperature. The AC-cut was chosen to produce a significant coefficient with acceptable linearity over the useful range. A detectivity D^* of 8×10^7 cmHz$^{0.5}$/W, and a time constant of 100 ms to 170 ms was reported. As a prototype device, this is not yet competitive in performance with the best commercial IR sensors, but theoretical predictions based on known properties of quartz resonators, design tradeoffs, and improved processing imply that superior sensors are possible.

SURFACE ACOUSTIC WAVE SENSORS

The application of SAW to sensing has yielded a variety of devices. Very often the key property exploited is the change in phase delay due to an imposed external effect or the attenuation resulting from vapor or liquid contact with the device surface between transmitting and receiving transducers. For SAW resonators, the effect is generally more spectacular because of much higher quality (Q) factor and steeper phase slope of such devices. Several examples illustrate the range of applications.

Accelerometer. Measurement of acceleration typically involves a proof mass that loads a mechanical structure under acceleration and produces an electrically measurable output proportional to the acceleration. One SAW device that demonstrates this principle is shown in Fig. 4. The SAW device in the figure is the control element of a delay-line oscillator, mounted as a cantilever to a base mass (assumed infinite). Acceleration along the axis indicated produces a force on the proof mass attached to the end of the delay line. A detailed modeling of the distributed mass of the delay line is taken into account. The shear strain induced on the surface of the

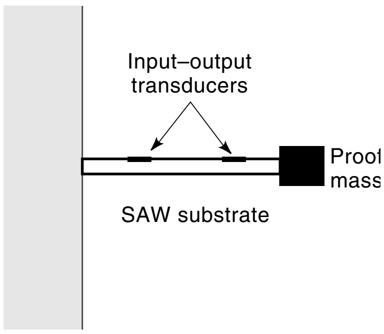

Figure 4. Representation of accelerometer based on SAW delay-line cantilever. The proof mass deforms the beam, inducing tension along the surfaces of the SAW substrate parallel to the propagative direction.

SAW substrate produces a change in SAW velocity and time delay.

Cantilever Beam SAW Accelerometer

A simplified description of the oscillator circuit is shown in Fig. 5. Because the time delay τ of the substrate is the principal determinant of the loop time in the circuit and the frequency of the oscillator is determined primarily by the inverse of the loop delay ($f = n/\tau$, where n is an integer), and because of the operating frequency of SAW interdigital tranducers, the shearing force on the cantilever produces a change in the propagative time caused by longitudinal strain in the plane of the substrate parallel to the direction of SAW propagation. The delay time is affected by the physical change in path length and the strain-induced shift in the elastic stiffness of the medium. If the velocity is assumed constant, then to first order the change in time delay is linear in the surface strain. Thus, if the SAW substrate is deformed by a transverse cantilever force, as shown, the oscillator frequency shifts down if the time delay increases, and shifts up in the reverse case. All this must occur within the pass bandwidth of the transducers.

SAW Delay-Line Oscillator Accelerometer Circuit

It is quite possible that acceleration parallel to the SAW propagative direction will induce a similar change in frequency, corresponding to a longitudinal sensitivity. Clearly, the choices of SAW substrate material, propagative direction and dimensions (particularly thickness) play a role in determining the sensitivity to multiple axis loading, and proper choice of parameters can limit the undesirable errors that can arise.

The frequency shift must be calibrated for given a given acceleration induced upon the proof mass. The calibration can be fitted to the following generic function (6):

$$f = k_0 + k_1F_t + k_2F_1 + k_3F_tF_1$$

where k_0 is the fundamental frequency of the SAW oscillator under zero load, k_1 and k_2 are the sensitivities to transverse (cantilever) load and longitudinal load, respectively, and k_3 represents the higher order (nonlinear) response. DiNatale et al. (6) report that the longitudinal sensitivity is about one-fortieth the transverse sensitivity to load, or about 2%. The nonlinear term is about six orders of magnitude smaller than the transverse sensitivity.

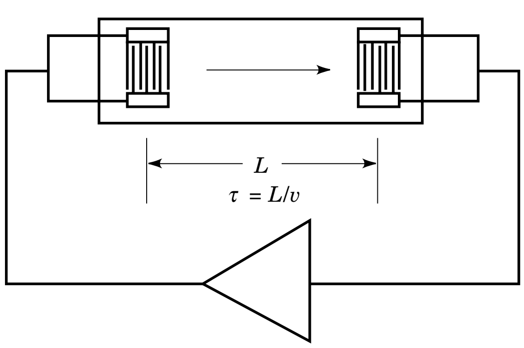

Figure 5. The delay-line transducers have a characteristic frequency pass bandwidth that coincides with the oscillator frequency. An amplifier compensates for losses and returns the signal to the delay line. The measured frequency indicates the strain induced in the SAW substrate by the load mass under accelerating force.

SAW Chemical Sensors. If the path between the transmitting and receiving transducers is coated with a thin film that is chemically selective, the SAW delay time changes with the acoustic impedance and velocity of the surface wave, and the frequency, Q, and amplitude of a delay-line oscillator shifts. All three of these measurable parameters can be exploited to obtain a measure of vapor concentration. A SAW humidity sensor has been demonstrated which uses two SAW delay-line oscillators. A hygroscopic film of cellulose acetate is deposited in one path, and the other path serves as a reference, as shown in Fig. 6 (7). A shift in the frequency difference between the two oscillators is linear in the range of 10% humidity to 70% relative humidity. Both the sensor and reference oscillator showed frequency shifts, but the differential shift over the 10% to 70% relative humidity range was 5 kHz at an operating frequency of 30 MHz. In addition, the temperature coefficient of delay, which for the chosen substrate $LiNbO_3$ is

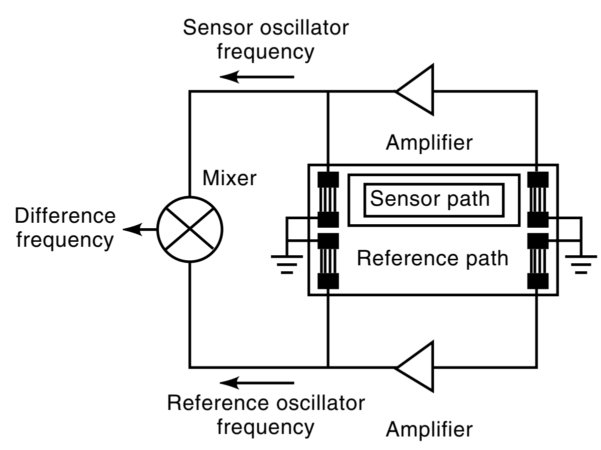

Figure 6. A SAW chemical sensor based on a dual delay-line oscillator. Two SAW paths on the same substrate, one sensitive to humidity via an absorptive surface coating and one uncoated reference path, produce different oscillator frequencies. A mixer generates the difference frequency, which is proportional to the change in SAW velocity produced by absorption in the sensor path of the substrate. Because both paths have nearly the same response to temperature, the difference frequency output subtracts or nulls out its effect.

93 ppm, has no nominal effect on the sensor output because the frequencies are subtracted, a technique called common-mode rejection.

Dual Delay-Line SAW Oscillator Chemical Sensor

SAW Resonator Sensors. The sensitivity of the SAW sensor is dramatically enhanced when the interaction length is increased or the operational frequency is increased. This is equivalent to increasing the phase slope of the SAW device. The most effective way to accomplish this is to substitute a SAW resonator for a delay line implemented with an appropriate oscillator circuit. The lumped-element equivalent circuit model of the SAW single-pole resonator is a series RLC circuit of motional loss, inductance, and capacitance in parallel with a capacitor corresponding to the static capacitance of the interdigital transducer—identical, in fact to the simple model for bulk wave crystals. The resonant frequency is defined by the LC product of the motional elements, and the device Q-factor by $\omega L/R$. At resonance the impedance drops and the phase slope is steepest, setting the operational frequency at or near the point of zero phase (external reactances can shift this point somewhat). With a high Q-factor—the equivalent of the SAW wave reflecting across the device many times, thus increasing the effective path length—the interaction with external phenomena is thus scaled approximately by the Q-factor relative to a simple delay line, and therefore is much more sensitive. Design choices are made in the frequency, device substrate thickness and acceleration range to optimize sensitivity and/or determine dynamic range.

Similarly, chemical sensors are fabricated on SAW resonator devices in which deposited films selectively adsorb chemical species from the vapor or liquid phase, shifting the frequency and Q, as the mass loading of the substrate shifts the resonance frequency. A distinct advantage of the SAW resonator over delay-line devices is that the higher Q-factor leads to a lower noise level and cleaner frequency signal. In addition, the photolithographic process enables SAW devices to reach higher operational frequencies than is possible with bulk acoustic wave sensor devices.

Moriizumi et al. (8) have reported that sensitivity is superior to bulk resonator methods (quartz crystal microbalance—QCM) provided the SAW frequency is four times higher than the QCM device frequency. This is easily accomplished on SAW substrates because crystal fragility limits QCM to about 60 MHz. The device is implemented with four SAW resonators, one as a reference and the other three coated with films of different selective absorptivity. This results in a three-frequency shift signature that is suggested as a precursor to developing smart chemical sensors—an electronic nose.

FIBER OPTIC SENSORS

Fiber optics are used to detect ultrasonic waves in the growing field of smart materials and smart structures. As generally implemented, optical fibers are embedded within the structural material or bonded to the surface of the structure of interest. For internally embedded sensors, the application is most typically to composites, such as graphite/epoxy, where the material processes involve temperatures that do not damage the fibers. Furthermore, the dimensions of the material structure, that is ply thickness, must be such that the array of embedded fibers does not compromise the structural integrity or material strength so that the reliability and lifetime of the structure are compromised.

Fiber optic sensors are implemented in structures to detect vibrations in a multitude of ways. First, there is the classification of fiber sensors as extrinsic or intrinsic. Extrinsic sensors are those which generally rely on an external structural feature—which may sometimes involve a nonfiber component as the sensor element—to induce change in the optical signal. Intrinsic sensors invoke a fundamental property of the fiber in contact with the environment of concern to detect changes in some physically observable parameter. Discussion here is limited to a few examples of fiber sensors applied to ultrasound detection.

For a first example of ultrasound detection using optical fibers, refer to Fig. 7, which is a simplified representation of an interferometric detector of longitudinal strain waves. An optical source, typically a laser diode (ld) or light-emitting diode (led), illuminates the fiber core. The optical signal propa-

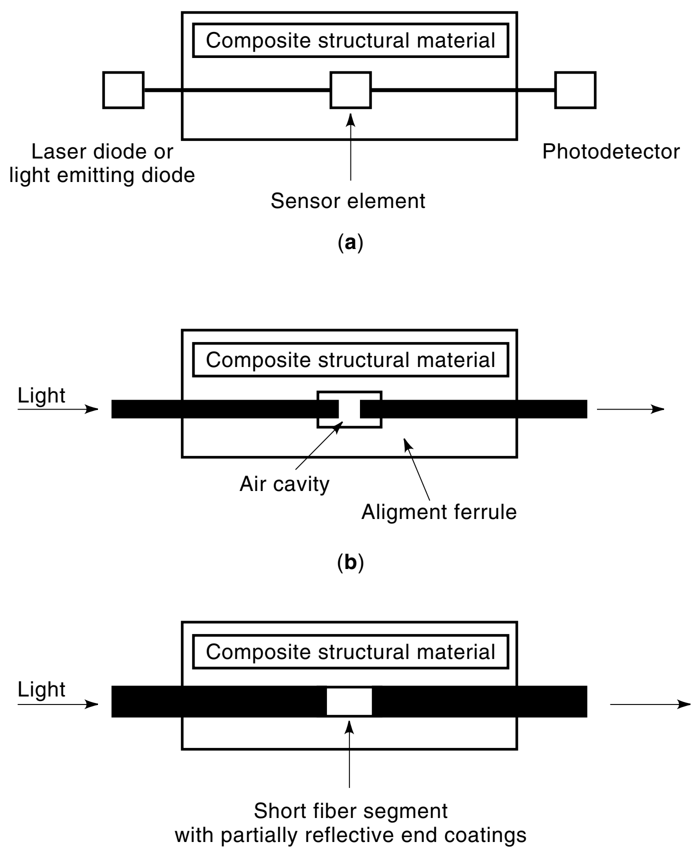

Figure 7. (a) Fiber optic strain and vibration sensor based on a miniature Fabry–Perot interferometric cavity embedded in a composite structural material. An ultrasonic wave with displacement amplitude parallel to the optical fiber axis produces a modulation of the cavity length, resulting in modulation of the light transmitted through the cavity. (b) The cavity can be formed by a hollow ferrule that holds and aligns the fiber. The ferrule lengths modulates with the strain field that sweeps by, producing interferometric modulation of the optical signal. (c) The cavity is formed by a short segment of optical fiber that is coated at each end with a partially reflecting layer, producing a microcavity.

gates through the fiber embedded in the structure or material. The fiber has a small cavity sensor element spliced into the fiber before it is embedded in the material. Figure 7(b) shows one of two concepts for implementing this element. The embedded fiber is cleaved and inserted in a ferrule that maintains the collinear alignment of the fiber cores, but which has an elastic stiffness equal to or less than that of the encapsulating environment, and is mechanically bonded in contact with the medium. Thus, any elastic strain or thermal expansion of the surrounding medium is transmitted to the cavity formed by the air gap in Fig. 7(b). In Figure 7(c), the cavity is formed when the fiber is cleaved. Partially reflecting coatings may be applied by vacuum deposition techniques, and a small fiber segment spliced one fiber, for example, the fiber is connected to the optical source, and the resulting combined structure is spliced to the second fiber that leads to the detector. In this latter case, the fiber may be directly embedded in a composite or cured material, but the resulting sensor segment is fragile and requires extreme care in handling.

Fiber Optic Interferometric Sensor

The resulting structure of either design forms a Fabry–Perot cavity, and the signal transmitted displays interferometric intensity modulation. The depth of modulation depends on the length of the cavity relative to the coherent length of the optical source and the reflectivity of the fiber faces that form the cavity, that is, the fineness of the cavity.

If the reflectivity of interface at each fiber that defines the cavity is defined as α, the transmitted signal has a power intensity that varies as

$$P(d) = (1-\alpha^2)^2[1+\alpha^2\cos(2kd)]^2$$

where $k = 2\pi/\lambda$, is the wave number of the light and λ is the wavelength.

Typically, the cavity is on the order of 100 μm to 300 μm, and the wavelength ranges from 850 nm to 1550 nm. Generally speaking, 1300 nm single-mode fiber is quite common and economical, which determines the choice of optical source. Figure 8 is an example of the modulation that may be expected with the air-gap cavity of Fig. FO-2a, where the reflection coefficient is $\alpha = 0.2$ (i.e., the reflected power is 4% at each interface), and the wave length is 1.5 μm.

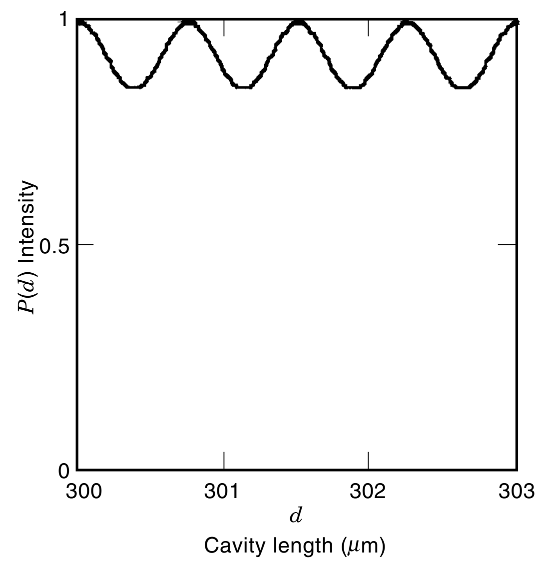

Figure 8. Predicted modulation of the optical transmission of a fiber sensor where the cavity is an air gap 300 μm long. $\alpha = 0.2$ corresponds to an air-glass relative index of refraction $n = 1.5$ and a reflectance amplitude $r = \alpha^2 = 0.04$.

Fiber Optic Strain Sensor Transmission Versus Longitudinal Air-Cavity Strain, $\alpha = 0.2$

Figure 9 is an example of the transmission modulation whose coatings enable the interface reflection coefficient to be chosen at will, for example, $\alpha = 0.5$.

Fiber Optic Strain Sensor Transmission Versus Longitudinal Fiber Cavity Strain, $\alpha = 0.5$

Optical fiber Bragg gratings are a relatively recent development particularly well suited to sensor applications.When the fiber core is doped with germanium, coherent interference of two external beams intersecting at an angle produces a strong electric field standing wave pattern (hologram) in the region crossing the fiber. This induces ionic migration that remains as a fixed periodic modulation of the waveguide index unless bleached by a similarly intense field or high temperature. The period of the pattern can cause efficient and very narrow bandwidth reflection of optical waves guided within the fiber because of the large number of grating lines produced in the hologram. If a fiber embedded in a material is strained by a modulating ultrasonic field, as described earlier, the peak of the reflectance band is similarly modulated as the period of the grating is strained by the wave. The period is controlled by the angle at which the beams interfere. Typically, the wave number corresponding to the period of the grating is chosen as twice that of the wave number of the propagating optical

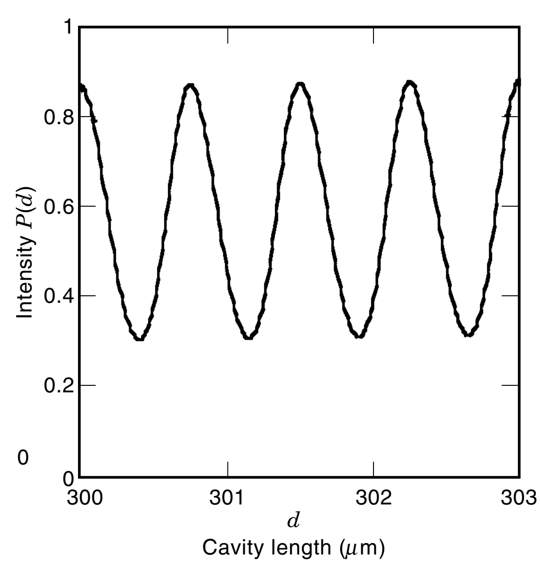

Figure 9. Predicted modulation of the optical transmission of a fiber sensor where the cavity is a glass fiber segment ($n = 1.5$) 450 μm long. A partially reflective coating, corresponding to $\alpha = 0.5$ results in deeper intensity modulation. Choosing the segment length or optical wavelength to bias the transmission signal at maximum slope results in maximum sensitivity to optical wavelength and in maximum sensitivity to small amplitude ultrasonic waves.

wave, so that the coupled mode is the wave traveling backward in the fiber toward the optical source. By suitable mixing and filtering of the source and reflected optical waves, it is possible to detect the ultrasonic wave. The assumption is made that the period of the ultrasonic wave is substantially larger than the extent of the grating region in the fiber.

The commercial production of fibers with grating regions periodically deposited along the fiber as the fiber is drawn from the melt is now common, and the production of in-line fiber sensors for strain and temperature measurement is becoming practical using Bragg fibers. Using pulsed optical techniques, it is possible to measure static strain and temperature. With broadband led sources (20 nm to 50 nm), distributed gratings, and spectral analyzers or homodyne mixing, it is possible to measure ultrasonic velocity and frequency.

LASER DETECTION OF ACOUSTIC WAVES

When ultrasonic waves reach the surface of a material, the surface vibration can be detected with coherent laser illumination. When the light scattered from the sample surface is combined with a portion of the source beam in a confocal Fabry–Perot interferometer, the combined signal replicates the ultrasonic wave. The illuminating laser light must have a long coherent length compared to the optical paths of the system and a wavelength that is considerably shorter.

ROBOTICS

Several ultrasonic devices have been devised for robotic navigation, motion control, and tactile sensing and manipulation. Navigation devices consist mainly of pulse-echo techniques similar to radar. One transducer can serve as both source and detector, or two elements can be nearly colocated.

A coarsely imaged map of the terrain in front of a navigating mobile robot or manipulator is generated by interpreting the time-of-flight data obtained as a single transducer scans the environment or as an array of transducers sequentially fires to obtain the same information with less mechanical scanning and more distributed electronic processing. Multiple reflections degrade the signal quality. Range decreases sharply with increasing frequency because of frequency-dependent attenuation. Specular reflection prevent reflected waves from returning to the receiver, so that longer wavelength and lower frequency are more advantageous and less sensitive to surface details. On the other hand, low frequency pulses reduce the ranging resolution.

THERMOCOUPLES

Conventional thermocouples sense temperature change due to temperature-sensitive relative shifts in the surface work functions at the junction of two metals or semiconductors. The sensing element, a thermopile, is limited to low-frequency response, however, because of thermal conductivity and specific heat properties typical of the materials and design, so that direct response to ultrasonic thermoelastic heating is zero order, that is, average energy flux at best. Response time is a function of mass, specific heat, and thermal conductivity of the metals. In addition, the sensitivity of the wire leads to interference from external static or electromagnetic sources. Electric shielding, when required, often complicates the packaging and responsivity of the device.

Ultrasonic devices that function as temperature sensors, and therefore, in effect, as thermocouples, are those in which some operational parameter (velocity/time delay, attenuation, oscillator frequency, etc.) is altered by a change in the temperature of the surrounding environment.

Bulk acoustic wave versions of such devices are typically oscillator circuits in which the frequency-controlling element (usually quartz) is in contact with the environment through appropriate thermal contacting packaging. What is particularly relevant is that the cut of crystal must be chosen to produce a nonzero shift in resonant frequency with temperature, whereas in standard frequency control applications, crystal orientation and cut are selected to minimize such sensitivity. Furthermore, it is highly desirable to obtain a linear shift with frequency, whereas it is quite common to find quadratic or higher order frequency dependence on temperature in quartz oscillator crystals. Compensation techniques, such as the use of two crystals in close proximity, simultaneously oscillating at slightly different frequencies, or the selection of quartz crystal cuts which produce simultaneous multiple resonance with different quadratic temperature coefficients, have been demonstrated and employed.

Surface acoustic wave devices relying on cuts of lithium niobate or tantalum niobate single crystals with large linear thermal coefficients of delay are quite common. It is a relatively straightforward process to conceive of time-delay or phase-slope-dependent means of sensing temperature. The most straightforward approach is a delay-line oscillator in which the phase-slope-controlling element is the temperature-sensitive SAW delay line. Changes in temperature alter the time delay and thus the frequency corresponding to the constructive standing wave supported by the feedback circuit. A positive coefficient of delay means that fractional time delay increases with temperature, that is, velocity decreases, and oscillator frequency therefore drops as circulation time in the oscillator feedback loop increases.

In practice, it is important to take packaging into account, so that thermally induced stresses in the packaging are not transmitted to the frequency-control element, where stress coefficients of delay are likely to corrupt the information content of the observed frequency output. This is no simple matter because good thermal conductivity generally requires firm mechanical contact.

Common-mode rejection of stress or other undesirable effects are achieved by employing two delay lines that have slightly different frequency (by designing the interdigital transducer period) but the same stress coefficients of delay. The frequency shift of each device is scaled by the absolute frequency of oscillation. Then the difference in output frequencies are quite linear in temperature, but independent of stress, which is the same for two identically mounted devices. This comes at the cost of doubling the component content of the device, adding a mixer, and the consequent effect on cost.

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