Reduction of semiconductor laser diode phase and amplitude noise in interferometric fiber optic sensors

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An optical configuration employing two conventional Michelson interferometers and a fiber Fabry–Perot interferometer connected in parallel is used to demonstrate the principle of common mode rejection of both the amplitude and frequency noise of a semiconductor laser. Common mode noise rejection is maximized when the outputs of the two interferometers with matched path imbalance, fringe visibility and amplitude are differentially combined. One interferometer is used as a reference, and the other as a sensing interferometer. The fiber Fabry–Perot interferometer is used as the sensing interferometer and is demonstrated as a miniature acoustic sensing element.

I. Introduction

Semiconductor laser diodes offer considerable advantages over gas lasers for illuminating fiber optic interferometric sensors. Compared to gas lasers they are much smaller, more robust and cheaper. In addition they also have the major advantage that their frequency is dependent on the injection current[1] and therefore electronic processing systems can be based on frequency modulation.

To process an interferometric signal, it is necessary to be able to control the phase between the reference arm and signal arm of the interferometer. This can be achieved either by varying the optical path length of either arm, e.g., by stretching the fiber, or by varying the frequency of the source.

For remote point sensing an all fiber Fabry–Perot interferometer has been demonstrated.[2,3] To fully utilize the point sensing capability of such a sensor, it is generally inappropriate to incorporate a fiber stretcher owing to the associated increase in the size of the sensing element and the requirement for an active element in the measurement region. Instead it is more advantageous to rely on frequency modulation of the laser source for the signal processing. This generally necessitates the use of a semiconductor laser.

An alternative technique based on white light interferometry has been demonstrated which permits the use of a passive sensing element and therefore true point sensing capability while using a fixed frequency source.[4] The output of one sensing interferometer is used to illuminate a second interferometer of matched path imbalance. Processing is performed by controlling a PZT mounted mirror in the second interferometer so that the overall path imbalance of the two interferometers is held at the first quadrature point.[5] The present major limitation of white light interferometry is the difficulty of coupling sufficient power into a single mode fiber and therefore the signal to noise ratio is at present limited by photodetector noise.

Using semiconductor laser diodes provides us with the opportunity of dispensing with active elements required for varying the optical path length and permits the extremely small remote sensors to be manufactured. However, semiconductor laser diodes exhibit both frequency and amplitude fluctuations which both contribute to the overall noise in the inteferometric sensor. In conjunction with an unbalanced interferometer, frequency noise is transduced to phase noise.

The principal method for reducing either amplitude or frequency fluctuation noise is to stabilize the laser.[6–8] In the case of amplitude noise a signal derived from a photodetector monitoring the optical power is fed back to the laser injection current so that the optical power is maintained constant. As an alternative to current modulation, the temperature of the laser can be controlled.[9] To stabilize the frequency of the laser a second cavity (for example, a Fabry–Perot etalon) is used to obtain an interferometric output dependent on the fluctuation of the mean lasing frequency. This

signal is then used to control the injection current so that frequency fluctuations are minimized. Although either the intensity or frequency of the laser can be controlled by varying either the injection current or temperature of the laser, these are not independent variables and in practice it proves difficult to stabilize both the intensity and frequency of the laser simultaneously. Generally the frequency of the laser is stabilized by locking to an external cavity and the amplitude noise is compensated in the receiver by using a signal from a photodetector measuring only the amplitude of the source.

This paper describes a novel configuration in which both the amplitude and phase noise can be compensated by matching the measuring interferometer to a reference interferometer. The signal from each interferometer is then simultaneously affected by both phase and amplitude noise and the differential intensity output of the two interferometers demonstrates a significant improvement in the signal-to-noise ratio. The advantages and disadvantages of this method compared to frequency locking of the laser are discussed.

II. Theory

The irradiance of the output from a two beam interferometer illuminated by a noise-free source can be written as

$$I_1 = A_1[1 + k_1 \cos\psi_1],$$

where ψ_1 is the phase difference between the interferometer arms, k_1 is the visibility, and A_1 is a constant. It is instructive to consider the situation in which the interferometer is nominally held at quadrature, but with a time dependent phase signal, $\phi_1(t)$, superimposed so that $\psi_1 = \phi_1(t) + 2m\pi - (\pi/2)$, where m is an integer. We may hence write

$$I_1 = A_1[1 + k_1 \sin\phi_1(t)]. \tag{1}$$

In the presence of both amplitude and frequency noise of the semiconductor laser source

$$I_1 = A_1[1 + \Delta A(t)]\{1 + k_1 \sin[\phi_1(t) + \Delta\phi_1(t)]\}, \tag{2}$$

where $\Delta A(t)$ expresses the amplitude fluctuations and $\Delta\phi_1(t)$ is the phase noise arising from the frequency fluctuations of the laser which is given by

$$\Delta\phi_1(t) = \frac{2\pi l_1 n_1 \Delta\nu(t)}{c}, \tag{3}$$

where $\Delta\nu(t)$ is the fluctuation in laser frequency, l_1 is the path imbalance of the interferometer, n_1 the refractive index, and c is the speed of light in vacuo.

Similarly for the reference interferometer

$$I_2 = A_2[1 + \Delta A(t)]\{1 + k_2 \sin[\Delta\phi_2(t)]\}, \tag{4}$$

where $\Delta\phi_2(t)$ is given by

$$\Delta\phi_2(t) = \frac{2\pi l_2 n_2 \Delta\nu(t)}{c}. \tag{5}$$

Provided each interferometer is held at quadrature, the path imbalance ($n_1 l_1$ and $n_2 l_2$), amplitude (A_1 and

A_2) and visibility (k_1 and k_2) of each interferometer are made equal, we can then subtract the photodetector outputs of the signal and reference interferometers giving

$$\begin{aligned} I_1 - I_2 = Ak[1 + \Delta A(t)] \\ \times \{\sin[\phi_1(t) + \Delta\phi(t)] - \sin[\Delta\phi(t)]\}, \end{aligned} \tag{6}$$

where

$$\Delta\phi_1(t) = \Delta\phi_2(t) = \Delta\phi(t), \tag{7}$$

$$A_1 = A_2 = A. \tag{8}$$

Since $\Delta\phi(t)$ is generally $\ll 1$ and we are interested in methods to detect signal levels of a similar magnitude to the phase noise

$$\sin(\phi_1(t) + \Delta\phi(t)) = \phi_1(t) + \Delta\phi(t), \tag{9}$$

$$\sin[\Delta\phi(t)] = \Delta\phi(t). \tag{10}$$

Hence Eq. (6) becomes $I_1 - I_2 = Ak(1 + \Delta A(t))\phi_1(t)$ so that the signal-to-noise ratio arising from amplitude noise is simply $1/\Delta A(t)$, and is independent of the magnitude of the signal. Because $\Delta A(t)$ is small, we may approximate the result by

$$I_1 - I_2 = Ak\phi_1(t). \tag{11}$$

That is the phase and amplitude noise can both be subtracted from a signal interferometer by using a matched reference interferometer.

This approximation does not simply neglect amplitude noise; instead the product of amplitude noise and the signal i.e. $\Delta A(t)\phi_1(t)$ in comparison to the signal $\phi_1(t)$ is neglected. In view of the fact that we are principally interested in detecting small signals this is not a restricting assumption. Amplitude noise is normally a problem with a single interferometer because of the D.C. term in the transfer function of a two beam interferometer. Using our subtraction technique this term is cancelled as well as the phase noise arising from laser frequency jitter.

III. Experimental

The optical configuration used in these experiments is shown in Fig. 1. It consists of three interferometers; two conventional bulk optic Michelson interferometers and a fiber Fabry–Perot interferometer. Only two interferometers are actually required for stabilization, but it is convenient to use three to make intercomparisons. The fiber Fabry–Perot was manufactured in the laboratory by cleaving a single-mode fiber inside a close fitting capillary tube.[2] The two portions of fiber are secured with adhesive to the capillary tube to provide a stable reflective splice. The interferometers are illuminated by a 5-mW semiconductor laser, with a nominal wavelength of 780 nm (Hitachi HL 7801). The beam is first amplitude divided by a beam splitter. One portion is used to illuminate the fiber Fabry–Perot interferometer and the remaining light is divided by a second beam splitter to illuminate each of the Michelson interferometers.
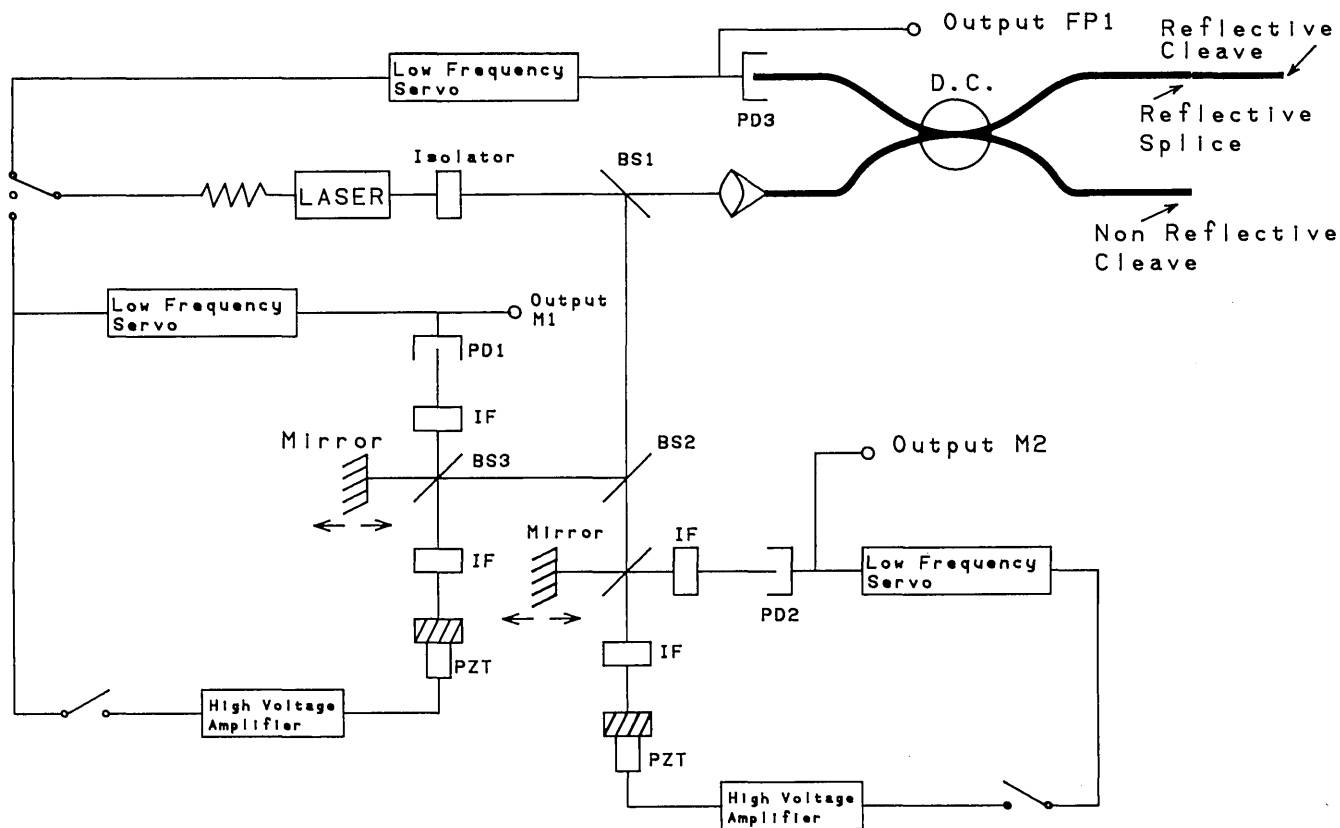
Fig. 1.   Optical configuration used to demonstrate common mode noise reduction of both amplitude and frequency noise of a semiconductor laser diode.

In the case of the fiber Fabry–Perot the light is further amplitude divided at a fusion type bi-directional coupler.   One output of the directional coupler leads to the fiber Fabry–Perot.   The second output is terminated by a nonreflective cleave and coated with index matching gel to avoid unwanted reflections. The interferogram of the fiber Fabry–Perot is detected at the fourth port of the bi-directional coupler.

One mirror of each of the Michelson interferometers is mounted on a PZT transducer to permit the optical path imbalance to be varied by a few microns and hence locked at the quadrature position using a low frequency servo.   The second mirror of each interferometer is mounted on a mechanical translation stage to allow the two Michelsons to be adjusted to the same optical path imbalance as the fiber Fabry–Perot interferometers.

To accurately match the path imbalance of all three interferometers, the injection current of the semiconductor is modulated with a sawtooth waveform, frequency 2 kHz, of sufficient amplitude to drive the fiber Fabry–Perot interferometer over precisely one fringe as judged by inspecting and maximizing the fundamental 2-kHz frequency while simultaneously minimizing the 4-kHz harmonic.   The Michelson interferometers are also adjusted until they too are each being driven over one fringe.   The accuracy of this adjustment is better than 100 μm, or 0.05% of the overall optical path imbalance of 203 mm.

Having thus ensured all three interferometers were of similar optical path imbalance, the principle of common mode rejection of both amplitude and phase noise was first demonstrated using the two Michelson interferometers, for two situations.   In the first case, both Michelsons are locked at quadrature by controlling the position of their PZTs to maintain the intensity output from each interferometer at a value equal to the mean of the maximum and minimum value of the corresponding interferogram.   The frequency bandwidth of each servo is $\sim$5Hz.   As the output intensity of the interferometer at quadrature is dependent on the source intensity, a reference intensity is derived directly from the source using an additional photodiode (not shown).

The optical receivers are reverse biased photodiode operated in a transimpedance mode so that the voltage output is linear with optical power.

In the second case one Michelson is locked again by controlling the position of its PZT mounted mirror and the laser frequency is locked to the second Michelson to give a quadrature output by using a low frequency servo (5-Hz bandwidth) to control its injection current.

Prior to recording the frequency spectra of each interferogram, each interferometer is adjusted using neutral density filters and polarization analysers so that both their visibilities and amplitudes are matched.   Frequency spectra are then obtained for each interferometer and for the differential output of

the two interferometers using a differential amplifier with common mode rejection of 55 dB.

The principle of common mode rejection of both amplitude and phase noise was then demonstrated using one Michelson interferometer and the fiber Fabry–Perot interferometer. The visibility of the fiber Fabry–Perot interferometer is found to be 87% which is greater than that achieved with the conventional Michelson. In order for both amplitude and phase noise to be simultaneously rejected, it is important that each interferometer has the same visibility. A portion of light is therefore launched into a fiber and directed via a delay line, to avoid unwanted interference, onto the photodetector recording the fiber Fabry–Perot interferogram, thus reducing the visibility. By varying the efficiency of the launch into the delay line, the visibility of the fiber Fabry–Perot is matched to the value obtained with the Michelson interferometer, which is 43%.

Although the initial visibility of the fiber Fabry–Perot is high the amplitude of the signal is of an order of magnitude lower than that of the Michelson. The output of the photodetector used to measure the fiber Fabry–Perot interferogram is therefore amplified by a factor of 10. With this additional amplification the voltage ouput representing the fringe amplitude of the two interferometers can be accurately matched using neutral density filters.

The laser is then locked by controlling its input current thus maintaining the Fabry–Perot interferometric output at quadrature; the Michelson is locked by controlling the PZT mounted mirror and the frequency spectra are recorded for each interferometer and also the differential output.

In addition, the fiber Fabry–Perot interferometer was demonstrated as a miniature acoustic sensing element. The frequency spectrum at the differential output of the two interferometers is obtained with the fiber sensing element exposed to an acoustic sound field of 95 dB(A) in an acoustically shielded enclosure.

IV. Results

The results of the first series of experiments, in which both Michelson interferometers are locked at their quadrature positions by actively controlling the two PZT mounted mirrors, are shown in Figs. 2(a) and (b). Figure 2(a) is of the frequency spectrum of just one interferometer and Fig. 2(b) is of the frequency spectrum of the differential outputs of each interferometer. The servo bandwidth is so low that the region of the spectrum within the bandwidth is unobservable in all the spectra shown.

The visibility and fringe amplitude (difference between maximum and minimum) of each Michelson interferometer equalled 43% and 4.2 volts. The mean optical power corresponding to 4.9 volts is estimated to be approximately 9.8 μW, taking the photodetector sensitivity to be 0.5 A/W.

For a single inteferometer of several centimeters path imbalance, the predominant noise source is due to a laser frequency jitter seen as phase noise in the
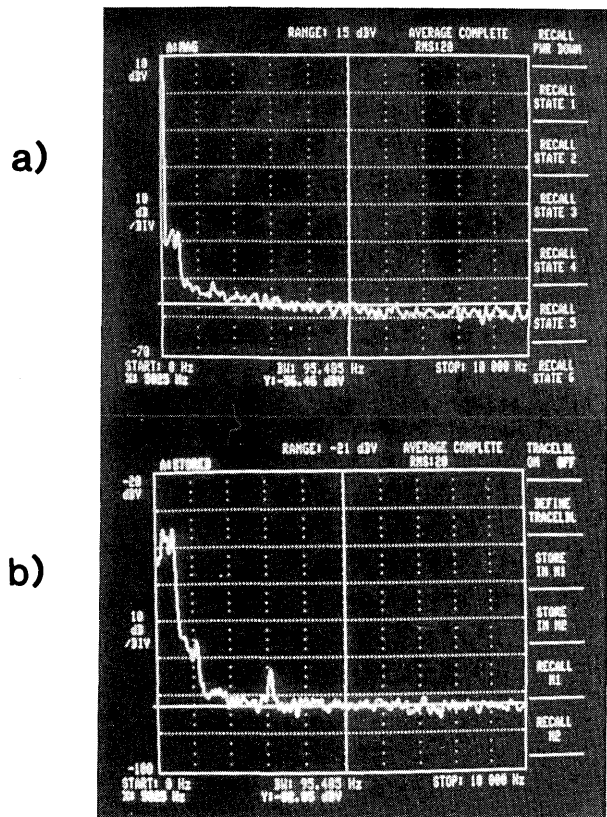

a)

b)

Fig. 2. (a) Frequency spectrum of a single Michelson interferometer locked at quadrature by active path length tuning. Fringe amplitude = 3 dB(V). (b) Differential frequency spectrum of two matched Michelson interferometers both locked at quadrature by active path length tuning. Resonant peak of one PZT is discernable.

interferometer output. The phase noise is proportional to the path imbalance of the interferometer; for comparison it is appropriate to normalize our noise figures by dividing by the path imbalance. The amplitude of one fringe equals 3 dB(V), [OdB(V) = 1 volt], so taking 5 kHz as our observation frequency, and a bandwidth of 95 Hz, we obtain a reduction in noise floor from −56 db(V) to −83 db(V) or normalized and in terms of radians and, 570 n radians/mm $\sqrt{\text{Hz}}$ (rms) to 25 n radians/mm $\sqrt{\text{Hz}}$.

One PZT has a resonance at approximately 3 kHz. It is discernable only in the differential output with the lower noise floor, demonstrating the increased sensitivity of the system.

Similarly, with one Michelson locked to the quadrature position by controlling the laser inspection current, the noise floor equals −56 dB(V) compared to the differential output of the two interferometers which equals −79 dB(V), see Figure 3. The output of the two Michelson interferometers increases slightly; the visibility remains at 43%, but the fringe amplitude equals 4.3V or 4 dB(V). The noise floors correspond to 505 n Radians/mm $\sqrt{\text{Hz}}$ for the output of single interferometer and 36 n Radians/mm $\sqrt{\text{Hz}}$ for the differential output of the two interferometers respectively. The optical power is approximately equal to 10.1 μW (see Fig. 3).
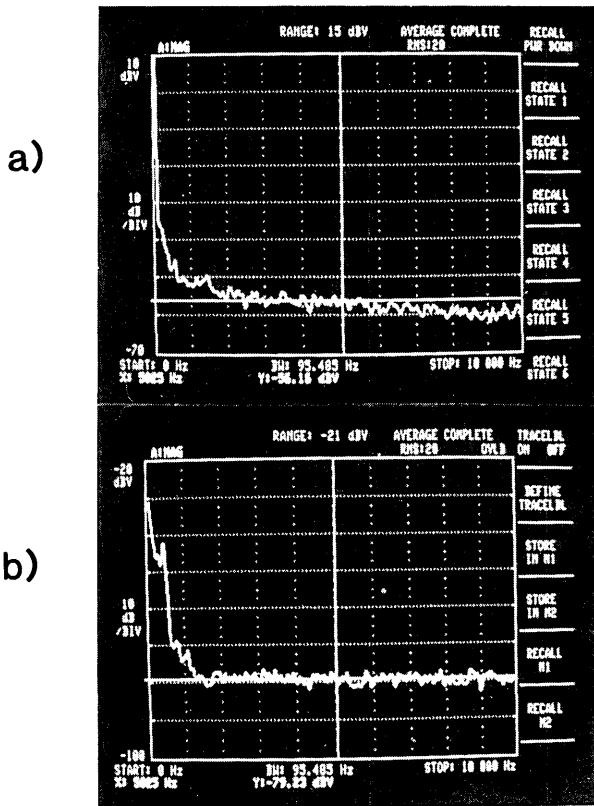
a)

b)

Fig. 3. (a) Frequency spectrum of a single Michelson interferometer locked at quadrature by active wavelength tuning. Fringe amplitude = 4 dB(V). (b) Differential frequency spectrum of two matched Michelson interferometers one locked using active wavelength tuning, the other locked using active phase tracking.

a)

b)

Fig. 4. (a) Frequency spectrum of fiber Fabry–Perot interferometer, when subject to an acoustic signal of 95 dB(A), locked by active wavelength tuning. The signal induced by the acoustic wave is not detectable. Fringe amplitude equalled = 10 dB(V). (b) Differential frequency spectrum of the fiber Fabry–Perot interferometer locked by active wavelength tuning and matched Michelson interferometer locked using active phase tracking. Presence of same acoustic signal is clearly discernable.

Finally, the spectrum of the fiber Fabry–Perot and Michelson interferometer are shown in Figs. 4(a) and (b). The visibility of the Fabry–Perot interferometer is initially 87% but is reduced to equal the Michelson interferometer value of 43%; the mean optical power of the fiber Fabry–Perot equals 0.2 μW. The noise floor of the sensing fiber Fabry–Perot is reduced from −67 dB(V) to −83 dB(V). The fringe amplitude equals −10 dB(V) and so these figures correspond to noise levels of 714 n Radians/mm√Hz and 113 n Radians/mm√Hz respectively.

Figure 4(b) also shows the signal obtained when the fiber is exposed to the acoustic sound field of 95 dB(V) just below the noise floor of the fiber Fabry–Perot interferometer and is therefore only visible when the noise floor was reduced, by taking the differential output of the two interferometers.

V. Discussion

The principle of noise cancellation of semiconductor laser diode phase and amplitude noise is demonstrated by electronically subtracting the photo-detector current from two interferometers each held at their quadrature points. This is demonstrated first using two conventional Michelson interferometers with both interferometers locked at quadrature by controlling the PZT mounted mirrors in one arm of each interferome-
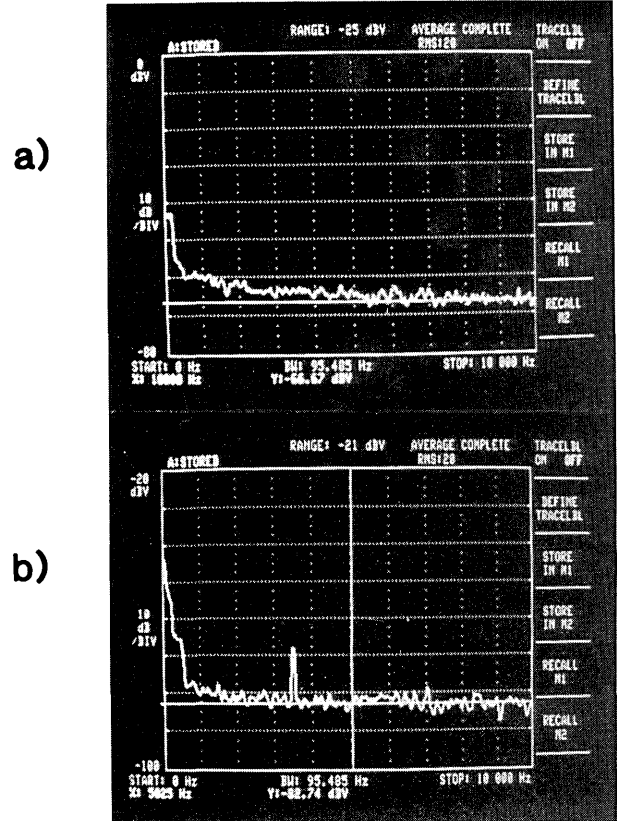
ter, and then by locking one of the interferometers by controlling the laser injection current. Both methods lead to similar noise reductions of 27 and 23 dB(V) at an observation frequency of 5 kHz. The degree to which the noise floor can be reduced is critically dependent on matching the amplitude, visibility and path length of each interferometer as well as locking both interferometers at precisely their respective quadrature points. For improved noise reduction each of these parameters would therefore have to be more closely controlled. In our final demonstration using the Fabry–Perot interferometer as an acoustic sensor, the noise floor is limited by the photodetector noise floor.

Although our noise cancellation is demonstrated by electronic subtraction it is feasible to perform this subtraction optically by locking the second interferometer to the quadrature point 180° out of phase to the first measuring interferometer, and then adding their outputs on to the face of a photodetector. A delay greater than the coherence length of the source is required to avoid unwanted interference of the two signals. The advantage of this refinement lies in dispens-

ing with the differential amplifier which can be a limiting factor in maximizing the common mode noise reduction as a result of introducing its own noise and can also limit the frequency response of the system.

The performance realized in our experiments is limited by the relatively low optical power coupled into the fiber interferometer. The launched power is limited by the onset of optical feedback into the laser cavity. We use a simple optical isolator between the laser and fiber, comprising a polarizer and quarterwave plate. However, the isolator has limited efficiency, so it is necessary to misalign the launching optics to reduce the feedback to an acceptable level, but with a concomitant reduction in launched power. Suitable use of a Faraday isolator would be more effective, and would allow higher powers to be coupled into the fibers.

VI. Conclusions

The widespread use of semiconductor lasers for fiber optic sensors is limited by their inherent problem of amplitude and frequency fluctuations leading to noise on the interferometric output. The phase noise arising from frequency fluctuations is less easily compensated for than amplitude noise and is also proportional to the path imbalance of the interferometer. This limits the use of laser diodes to interferometers with path imbalances of a few centimeters for micro radian resolution.

Successful stabilization of a laser using an external cavity is governed by the electronics of the locking servo. In practice the amplifier, photodetector, and laser all contribute to the overall phase delay of the locking servo and therefore limit the overall gain that can be achieved while avoiding the instability of the control loop. Since the gain determines the reduction of phase noise, this limits the noise level that can be achieved. Even when the laser is locked, the phase noise is still proportional to the path imbalance of the interferometer, thus setting an upper limit to the path imbalance which can be employed usefully.

In theory our differential technique overcomes this problem, provided a second reference interferometer can always be built to match the sensing interferometer. We have demonstrated the reduction of phase and amplitude noise using a second reference interferometer using two conventional interferometers and hybrid system incorporating a fiber Fabry–Perot and a conventional Michelson. The theoretical limitation is only that of the stability of the reference cavity and photodetector shot noise.

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