Multiplexed fiber-optic sensors using a dual-slope frequency-modulated source

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We propose and demonstrate a multiplexed fiber-optic sensor system using a dual-slope (triangular) frequency-modulated laser source. The restrictions in the selection of beat frequencies of the multiplexed sensors in previous studies that employed ramp modulation wave forms are eliminated.

Interferometers based on a laser diode frequency modulated by a ramp wave form have been demonstrated by several groups.[1–4] In the application of this technique to fiber sensor systems, there is the additional advantage that one does not need another phase-modulation device in the sensing loop. This technique has also been used for multiplexing fiber sensor systems by Giles *et al.*[1] and Sakai *et al.*[5,6] They selected different path-length differences in each interferometer such that distinct beat frequencies corresponding to the individual sensors were generated. These beat frequencies could then be separated by bandpass filters. The optical phase information was extracted from the phase of the beat frequencies. A novel method that combines the time-division-multiplexing scheme and the ramp modulation technique has also been developed by Farahi *et al.*[7,8] and Santos *et al.*[9]

For multiplexing fiber sensors, the ramp technique imposes certain restrictions on the system: (1) The beat frequencies must be an integral multiple of the frequency of ramp wave form. Furthermore, certain selection rules must also be satisfied to eliminate the cross-modulation effect, as discussed by Sakai *et al.*[5,6] (2) The fast flyback portion of the ramp wave form may induce noise in the phase measurement, as discussed by Economou *et al.*[4] In this Letter we propose a novel method to eliminate the limitations of the ramp technique in multiplexed sensor systems. Our approach employs a triangular wave form, which can be considered as a dual-slope ramp signal with fixed time delay, to modulate the laser-diode source followed by time-division gating.

The operation principle of our method is shown in Fig. 1. If the injection current of the single-mode laser diode is modulated by a triangular wave form, the instantaneous frequency of the laser diode will also be modulated. As a result, the optical phase delay of the interferometer is scanned. If the path imbalance of each interferometer is set separately, we should observe distinct beat frequencies corresponding to each interferometer. A phase offset with opposite sign will also be present between the half-periods of the triangular wave form. This is illustrated in Figs. 1(b) and 1(c) for a multiplexed system of two interferometers as an example. The output signal of the multiplexed interferometric sensors can be expressed as

$$I_+(t) = I_1\cos(\omega_1 t + \phi_1) + I_2\cos(\omega_2 t + \phi_2) + \ldots, \quad -T/2 < t < 0, \quad (1)$$

$$I_-(t) = I_1\cos(\omega_1 t - \phi_1) + I_2\cos(\omega_2 t - \phi_2) + \ldots, \quad 0 < t < +T/2, \quad (2)$$

where $\omega_1, \omega_2 \ldots$ are beat frequencies that depend on the sweep rate of the triangular wave form and the path imbalance of each interferometer, and $\phi_1, \phi_2 \ldots$ are the optical phase delays induced by variation in the optical path length. The output signals I_+ and I_- can be separated by analog switching. The pair of output signals, corresponding to the individual sensor with a phase term of opposite sign at the same beat frequency, are then demodulated by a set of phase-locked-loop (PLL)-type bandpass filters. For simplicity, let us consider two fiber sensors only, as shown in Fig. 2. These demodulated signals can be expressed as

$$S_1(\omega_1) = I_1\cos(\omega_1 t + \phi_1) \quad \text{at the output of PLL1,} \quad (3a)$$

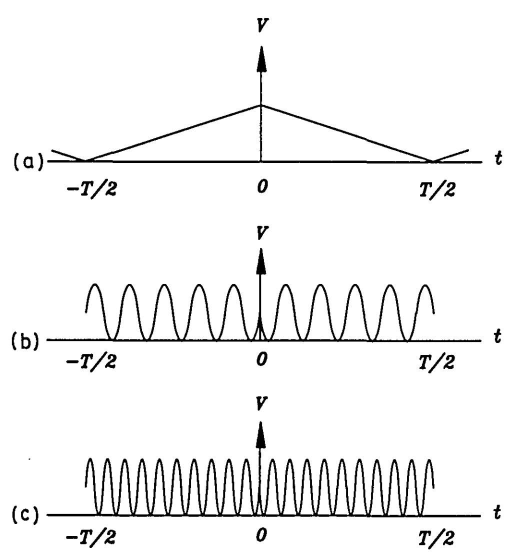

Fig. 1. (a) Triangular wave form applied to the laser diode for frequency modulation. (b), (c) The output signals for two interferometers with different path imbalances. The total output signal of the system is (a) × [(b) + (c)].

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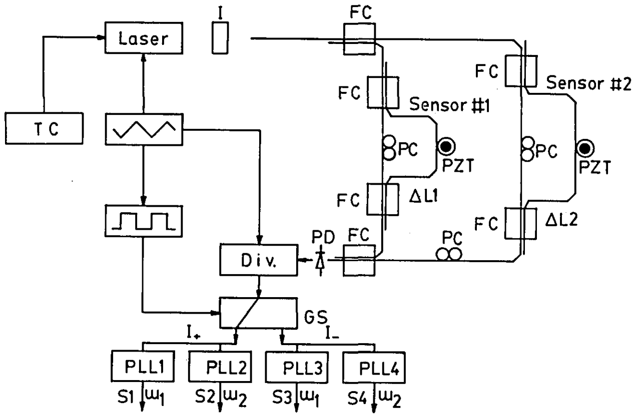

Fig. 2. Experimental setup for two multiplexed Mach–Zehnder sensors that uses a laser diode frequency modulated by a triangular wave form. Div., division circuit; TC, temperature controller; FC's, fiber couplers; PZT's, piezoelectric transducers; PLL's, phase-locked-loop filters; PC, polarization controller; ω_1 and ω_2, beat frequencies corresponding to sensor #1 and sensor #2; GS, gate-switching circuit; PD, photodiode; ΔL1, ΔL2, optical path-length differences of the two sensors.

$$S_2(\omega_2) = I_2 \cos(\omega_2 t + \phi_2) \quad \text{at the output of PLL2,} \quad (3b)$$

$$S_3(\omega_1) = I_1 \cos(\omega_1 t + \phi_1) \quad \text{at the output of PLL3,} \quad (3c)$$

$$S_4(\omega_2) = I_2 \cos(\omega_2 t + \phi_2) \quad \text{at the output of PLL4.} \quad (3d)$$

It is clear that the following can be achieved by this approach:

(1) The employment of the temporally symmetric triangular wave form automatically eliminates the wideband noise generated during the fast flyback portion of the ramp wave form.

(2) The sensor's information at the PLL outputs can be simultaneously demodulated by measuring either the frequencies of S_1 (or S_2) or the phase difference between the pair of signals S_1 and S_3 (or S_2 and S_4). The measurement of phase signals ϕ_1 or ϕ_2 is not influenced by the period of the triangular wave form, since these are measured at the common beat frequencies. The beat frequencies thus can be chosen arbitrarily.

(3) The phase signal can be measured with the sensitivity of $2\phi_1$ and $2\phi_2$ by comparing the signals $S_1(\omega_1)$ and $S_3(\omega_1)$ [or $S_2(\omega_2)$ and $S_4(\omega_2)$]. The common-mode noise in the phase measurement is also eliminated. In the ramping technique, the sensitivity is only ϕ_1 or ϕ_2.

To demonstrate this approach, we performed an experiment using the optical and electrical system shown in Fig. 2. Two Mach–Zehnder interferometers were connected in parallel. A single-mode laser diode (Hitachi HLP-1400, $\lambda = 0.83\ \mu$m) was used as the light source. Its bias current and temperature were stabilized such that the fluctuations were less than 1 μA and 0.01°C, respectively. The path-length differences of the interferometers were chosen to be 10 and 25 cm, respectively. For simplicity in signal detection, the cross term in the interference signal due to the two Mach–Zehnder sensors was eliminated by choosing the lengths of the connecting fibers between the interferometers to exceed the coherence length of the laser diode, e.g., 100 m in this experiment. The optical frequency of the laser diode was current modulated by means of a periodic triangular wave form of 4 kHz. The amplitude of the modulation signal can be adjusted such that the beat frequencies of the two interferometers were 10 and 25 kHz, respectively. The modulation signal at 4 kHz can be removed by a PLL-type tracking circuit. The outputs of the two interferometers were combined in a fiber coupler and detected by an ac-coupled photodetector. The output signal of the amplifier for the photodiode was divided into the triangular modulation wave form to reduce the amplitude-modulated portion of the output signal. This signal was then gated by an analog switch. Each half-period of the gated signal was fed into separate channels sequentially. The beat frequencies were then demodulated by the four PLL-type bandpass filters, of which the center frequencies were set at 10 or 25 kHz and the bandwidth was 2 kHz.

Two sinusoidal path length modulation signals at 1

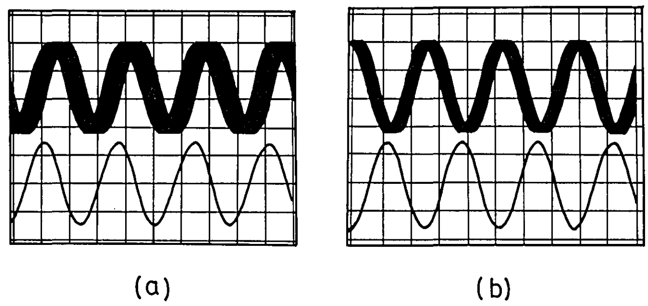

Fig. 3. Output signals of the four PLL circuits with different beat signals under the condition that sinusoidal path-length modulation signals at 1 kHz with different amplitudes were applied to the piezoelectric transducers. (a) The output signals $S_1(\omega_1)$ (lower trace) and $S_3(\omega_1)$ (upper trace) for sensor #1 with a beat frequency of 10 kHz. The amplitude of the sinusoidal signal is 2.7 V. (b) The output signals $S_2(\omega_2)$ (lower trace) and $S_4(\omega_2)$ (upper trace) for sensor #2 with a beat frequency of 25 kHz. The amplitude of the sinusoidal signal is 1.0 V.

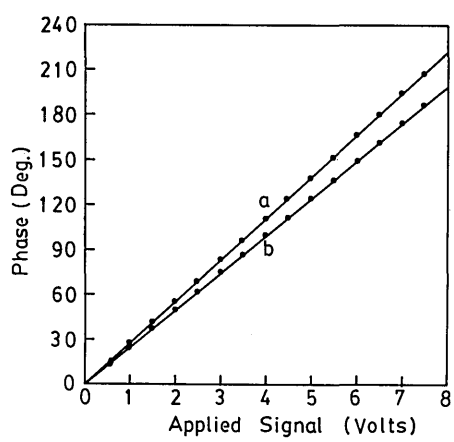

Fig. 4. Detected phase signal of sensor #1 (curve a) and sensor #2 (curve b) as a function of the amplitude of the modulation signal at 1 kHz.

kHz with different amplitudes were applied to the fiber-coiled piezoelectric transducers in the two Mach–Zehnder interferometers. One pair of output signals of sensor #1, $S_1(\omega_1)$ and $S_3(\omega_1)$, is shown in Fig. 3(a). The amplitude of the applied sinusoidal signal was 2.7 V. The other pair of output signals of sensor #2, $S_2(\omega_2)$ and $S_4(\omega_2)$, is shown in Fig. 3(b). The amplitude of the applied sinusoidal signal was 1.0 V. Excellent phase-modulation signals were obtained at the different carrier frequencies, ω_1 and ω_2. Note that the carrier frequencies in our experiment have been selected arbitrarily. These were not integral multiples of the frequency of the triangular wave form. The scale factors of the two interferometers have also been measured by applying a 1-kHz sinusoidal signal with different amplitudes to the fiber-coiled piezoelectric transducer in the two interferometers. Good linearities of the detected phases of the two sensor systems as a function of the amplitudes of the applied signals are shown in Fig. 4.

In summary, we have proposed and demonstrated a multiplexed fiber-optic sensor system in which the laser diode was modulated by a dual-slope ramp (triangular) wave form. This approach eliminated the restrictions imposed on the selection of beat frequencies in previous studies that employed ramp-type modulation wave forms.

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