Detection scheme of coherence-multiplexed sensor signals using an optical loop with a frequency shifter: sensitivity enhancement

Detection Scheme of Coherence-Multiplexed Sensor Signals Using an Optical Loop with a Frequency Shifter: Sensitivity Enhancement

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***Abstract*— A sensitivity enhancing scheme in a coherence-multiplexed sensor system using an optical loop with a frequency shifter is described. In order to enhance sensitivities of the multiplexed sensors, an erbium-doped fiber amplifier is introduced into the optical loop, which compensates for loop loss. The sensitivities can be experimentally enhanced by optical amplification in the fiber amplifier and, consequently, we can successfully multiplex four sensors.**

I. INTRODUCTION

MULTIPLEXING fiber-optic sensors is an attractive technology because it will save cost due to reduction in the number of light sources, photodetectors, and fiber transmission lines. Three different types of the multiplexing schemes have been investigated: time division multiplexing [1], [2]; frequency division multiplexing [3]–[5]; and coherence multiplexing [6]–[8]. The coherence-multiplexed sensor system is composed of a light source, a set of sensing interferometers whose optical path differences (OPD's) are different each other, and a corresponding set of receiving interferometers. The OPD of each receiving interferometer must match that of one of the sensing interferometers. The sensing and receiving interferometers are arranged in tandem and are illuminated by a CW light source whose coherence length is much shorter than any OPD of the interferometers. The sensor signal imprinted on the light in one of the sensing interferometers can be recovered only by the corresponding receiving interferometer due to the low coherence nature of the light source. In this system, $2n$ interferometers (n sensing and n receiving interferometers) and n photodetectors are required for multiplexing n sensors, and consequently the optical system becomes considerably large.

We have proposed a detection scheme for coherence-multiplexed sensor signals by using an optical loop with a frequency shifter [9]. In the system, the OPD's of sensing interferometers are adjusted to integer multiples of the loop length of the optical loop. The sensor signals are multiplexed in the frequency domain, appearing at the integer multiple of the working frequency of the frequency shifter in the optical loop. The sensitivities of the sensors and the number of sensors to be multiplexed are dominated by loop loss of the optical loop, and the loop loss must be reduced or compensated to enhance the sensitivities of the sensors and to increase the number of sensors to be multiplexed.

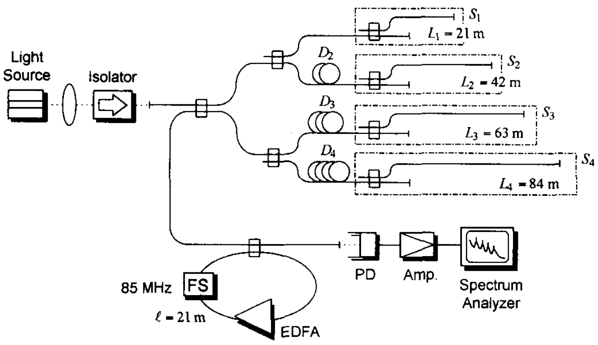

Fig. 1. Experimental setup of a sensitivity enhanced coherence-multiplexed sensor system using an optical loop with a frequency shifter.

In this paper, we demonstrate a sensitivity enhancing scheme in this system by using an erbium-doped fiber amplifier (EDFA). An EDFA is introduced into the optical loop to compensate for the loop loss. The sensitivities can be experimentally enhanced by optical amplification in the EDFA and, consequently, we can successfully multiplex four sensors.

II. PRINCIPLE

The experimental setup is shown in Fig. 1, in which four Michelson-type interferometric sensors are arranged in parallel. This system consists of a low-coherence light source, four sensing interferometers $S_1 \sim S_4$, an optical loop with a frequency shifter (FS) working at f Hz, and a photodetector (PD). The optical path differences (OPD's) of S_1, S_2, S_3, and S_4 are denoted by L_1, L_2, L_3, and L_4, respectively, and the loop length of the optical loop is denoted by ℓ. It is essential that the OPD L_k is chosen as $L_k = k \times \ell$, and the loop length ℓ is chosen to be much longer than the coherence length of the light source.

The principle of the system is as follows. If we consider the interferometer S_1 and the optical loop together, then the beam passing through a long path of S_1 and recirculating i times in the loop can interfere with the beam passing through a short path of S_1 and recirculating $(i + 1)$ times in the loop. Since the latter beam is more frequency-shifted by f Hz than the former, the interference signal, that is,

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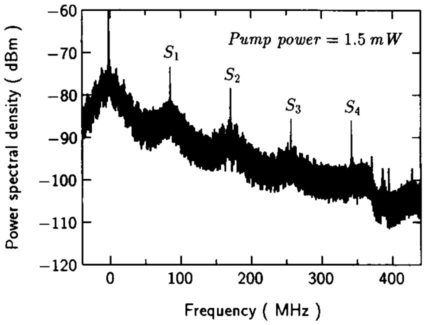


Fig. 2. An example of the detected multiplexed spectrum.

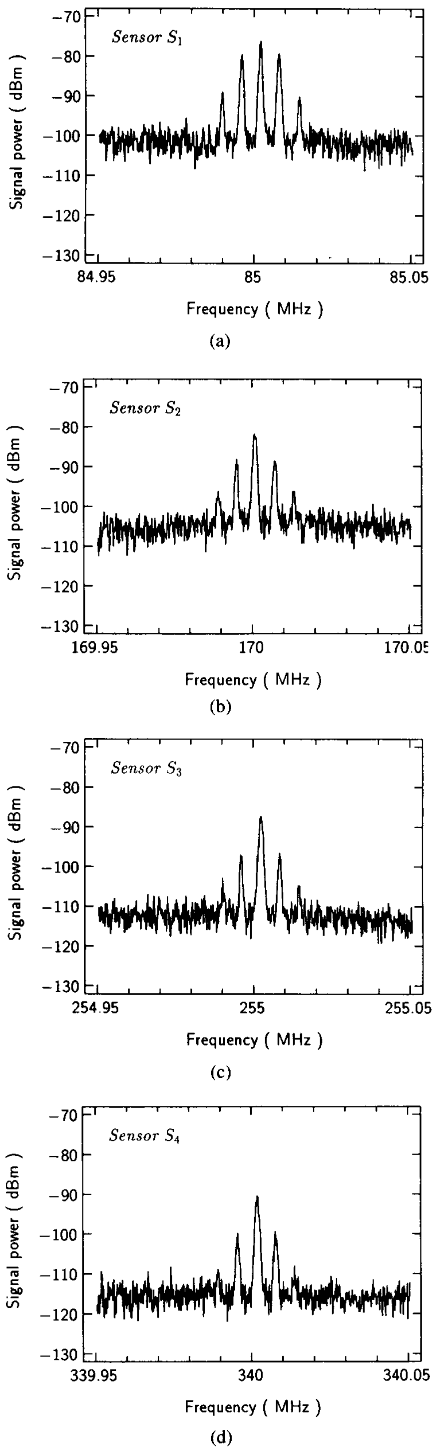
the sensor signal, appears around f Hz. Similarly, the sensor signal of S_k appears around $(k \times f)$ Hz. Therefore, all sensor signals of the array are multiplexed in the frequency domain and can be detected separately by using electric bandpass filters. In this method, n sensing interferometers and only a set of the optical loop and a photodetector are required for multiplexing n sensors. The numbers of the interferometers and the photodetectors are considerably reduced compared to the conventional coherence multiplexed system where $2n$ interferometers and n photodetectors are required.

In multiplexed sensor systems, crosstalk between sensors is a serious problem and must be avoided. In this system, crosstalk can be easily avoided by inserting optical delay lines (length = D_2, D_3, D_4) in front of each sensing interferometer, as shown in Fig. 1, because any crosstalk appears in a higher frequency region than the intended signal frequency range.

III. EXPERIMENTS

In our experiments, the light source used was a DFB laser emitting at 1.53 μm (Hitachi HL-1541), whose coherence length is about 15 m. In this paper, the coherence length is defined as the OPD of the two-beam interferometer where insignificant interference occurs. As acousto-optic modulator (AOM: HOYA AF-150) was used as the frequency shifter, which was driven at 85 MHz. The insertion loss of the AOM was 8 dB, and the total loop loss including losses at connectors and fusion splices was 8.7 dB. The length of the optical loop was 21 m, and hence the OPD's of S_1, S_2, S_3, and S_4 were adjusted as $L_1 = 21$ m, $L_2 = 42$ m, $L_3 = 63$ m, and $L_4 = 84$ m, respectively. The excess loss and the coupling coefficient of the fiber coupler in the optical loop were 1 dB and 50%, respectively. The optical delay lines were inserted in front of S_2, S_3, and S_4 to avoid crosstalk, whose lengths were $D_2 = 63$ m, $D_3 = 140$ m, and $D_4 = 230$ m, respectively. The optical power at the input port of the optical loop was about 10 μW. When an EDFA was not introduced into the optical loop, we were able to multiplex only two sensors (S_1 and S_2), and their sensitivities were about 0.5 mrad/$\sqrt{\text{Hz}}$. The cause of restricted number of sensors is large loop loss of the optical loop. The loop loss must be reduced or compensated for by an optical amplifier to increase the number of sensors to be multiplexed.

In order to compensate for the loop loss, a 16-m EDFA was introduced into the optical loop. Er^{3+} concentration of the EDFA is 500 ppm, and A1 is codoped in the core of the EDFA. The EDFA was pumped by a 0.98 μm semiconductor laser. The loop length of the optical loop and the OPD's of



(a)

(b)

(c)

(d)

Fig. 3. Examples of the detailed signal spectrum. (a) Detailed spectrum of S_1. (b) Detailed spectrum of S_2. (c) Detailed spectrum of S_3. (d) Detailed spectrum of S_4.

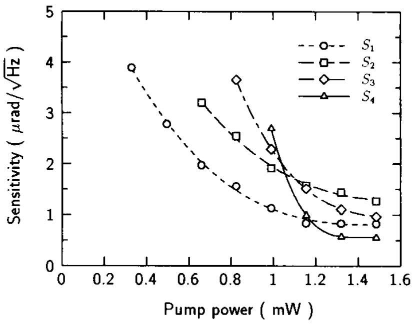


Fig. 4. Measured sensitivities of the sensors against the pump power.

S_1, S_2, S_3, and S_4 were $\ell = 21$ m, $L_1 = 21$ m, $L_2 = 42$ m, $L_3 = 63$ m, and $L_4 = 84$ m, respectively. The optical power at the input port of the optical loop was about 10 μW. In this condition, the optical loop lased around 1.55 μm when the pump power was above 1.5 mW; therefore, the pump power was adjusted to below 1.5 mW throughout the experiment.

Fig. 2 shows an example of the experimental results. The pump power to the EDFA was 1.5 mW. Four sensor signals are clearly observed. Their frequencies are 85 MHz, 170 MHz, 255 MHz, and 340 MHz, corresponding to the sensor signals of S_1, S_2, S_3, and S_4, respectively. The increases of noise level around 0 MHz, 85 MHz, 170 MHz, 255 MHz, and 340 MHz are due to the interferometric conversion of the phase noise of the DFB laser into the intensity noise, and the spectrum around each frequency indicates the spectral profile of the DFB laser. If we use a low-coherence light source such as a superluminescent diode or a multilongitudinal mode semiconductor laser instead of the DFB laser, a flat noise floor can be achieved. The detailed spectra of the sensor signals of S_1, S_2, S_3, and S_4 are shown in Fig. 3. In the experiment, S_1, S_2, S_3, and S_4 were sinusoidally phase-modulated at 5 kHz, 5.5 kHz, 6 kHz, and 6.5 kHz, respectively. The bandwidth of the spectrum analyzer was 1 kHz. Good phase-modulated signals are obtained.

Fig. 4 shows the sensitivities of $S_1 \sim S_4$ against the pump power. The sensitivities are found to be enhanced with increasing pump power. It is also found that the sensitivities are almost constant for pump powers above 1.3 mW. This is due to gain saturation of the EDFA at the signal wavelength (1.53 μm), which is caused by amplified spontaneous emission of the EDFA. If we introduce an optical wavelength filter into the optical loop so as to select only the signal wavelength, more enhanced sensitivities may be achieved.

IV. CONCLUSION

We have demonstrated a sensitivity enhancing scheme in a coherence-multiplexed sensor system using an optical loop with a frequency shifter. In order to enhance sensitivities of the multiplexed sensors, an erbium-doped fiber amplifier was introduced into the optical loop, which compensates for the loop loss. It was experimentally confirmed that the sensitivities of the four-sensor multiplexing configuration can be successfully enhanced by optical amplification in the fiber amplifier.

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