

Frequency-division-multiplexed polarimetric fiber laser current-sensor array

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We demonstrate a novel frequency-domain-multiplexing technique for implementing polarimetric fiber laser current sensors. Each sensor operates at a different polarization-mode beat frequency that is modulated in response to applied electric current. A bank of bandpass filters can be used to separate signals from different sensors. A simple frequency-demodulation technique based on a phase-locked loop is used for signal processing. © 1999 Optical Society of America

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Fiber-optic current sensors have been developed that have advantages such as immunity from electromagnetic interference, remote sensing and multiplexing capability, enhanced sensitivity, wide dynamic range, and low cost. Most of the sensors developed so far have been based on a passive polarimetric sensor configuration with optical intensity output. Inherent difficulties of this scheme, however, include instabilities owing to the residual birefringence of the sensing fibers and lead-fiber sensitivity to external perturbations. A number of different methods have been developed to overcome these problems,¹⁻⁵ but these methods have increased the complexity of optical configuration and electronic signal processing. Recently a different approach to current sensing based on a fiber laser was demonstrated.^{6,7} The laser output consists of two polarization modes whose frequency separation is a function of applied current. The polarimetric fiber laser current sensor has the potential advantages of frequency encoding, immunity to intensity fluctuations, and freedom from lead-fiber sensitivity, which are difficult to achieve with passive polarimetric current sensors.

In this Letter we show that polarimetric fiber laser sensors can be efficiently multiplexed by use of the frequency-division-multiplexing (FDM) technique. Although a number of multiplexing techniques have been developed for fiber sensors in general, to our knowledge multiplexed current sensors have not been demonstrated. Multiplexing capability is important for remote monitoring of multiple sensing elements with reduced component costs and ease of electro-optic interfacing.

As reported in Ref. 6, the polarimetric fiber laser current sensor employs a gain medium, a saturable absorber, an output fiber Bragg grating (FBG) mirror,

and a Faraday rotating mirror (FRM), as shown in Fig. 1. The FRM comprises a planar mirror and a 45° Faraday rotator. The laser is configured and arranged in such a way that the output consists of only two oscillating modes that are mutually orthogonal in their states of polarization and have different optical frequencies. The frequency difference is half of the free spectral range of the cavity, independently of the fiber birefringence. The unique characteristics of the sensor originate from the fact that the FRM acts as a conjugate mirror for the polarization state and also from the spatial hole-burning effect in the gain medium and the saturable absorber. The eigenstates of polarization at the output FBG mirror are circularly polarized independently of the fiber cavity birefringence, assuming that the FBG is polarization independent.

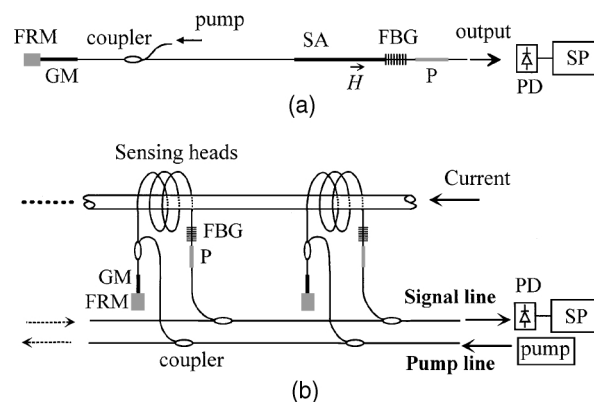


Fig. 1. Schematic of (a) a polarimetric fiber laser current sensor and (b) a current-sensor array: GM's, gain media; SA, saturable absorber; P's, polarizers; PD's, photodetectors; SP's, signal processors; H , magnetic field.

Therefore, if the fiber section that is adjacent to the FBG does not have linear birefringence, the states of polarization in that section are also circularly polarized. When an axial magnetic field is applied to the fiber section, the frequency difference between the two lasing polarization modes changes because of the nonreciprocal Faraday effect. Sending the laser output through a linear polarizer produces a beat note on the detector. We monitor the polarization-mode beat (PMB) frequency (f_p) to measure the applied current that produces the axial magnetic field. The PMB frequency change Δf_p that is due to the applied current is⁶

$$\Delta f_p \cong (2\alpha_F/\pi)f_{\text{FSR}}$$

when $\alpha_F \ll 1$, α_F is a nonreciprocal circular birefringence induced by the Faraday effect, and f_{FSR} is the free spectral range of the laser cavity. When an ac is applied, the output beat signal is frequency modulated (FM) near a carrier frequency determined by the laser cavity length. By use of a FM demodulation technique based on phase-lock loop (PLL) circuits, we can measure the electric current.⁷

By use of the unique frequency output of the sensor, multiplexing of many fiber laser sensors in the frequency domain can be realized, as shown in Fig. 1(b). Each sensor is designed to have a different cavity length and therefore operates at its designated carrier beat frequency, which can easily be isolated by use of a bandpass filter. The output signals from all the sensors are delivered through a single return bus to a receiver that is followed by a FM demodulation signal processor. The pump light is supplied to the gain medium in each sensor laser through an input bus line. It should be mentioned that the output laser signal does not respond to the fluctuation of the polarization of the pump light in the lead fiber. In addition, owing to the nature of the frequency-encoded output signal, the sensor array is immune to intensity and polarization fluctuations in the return fiber bus, which is of significant practical importance.

To demonstrate the FDM technique we constructed a sensor array containing two fiber laser sensors (sensors 1 and 2) as shown in Fig. 2. The two lasers operated at the same output wavelength (1549 nm), determined primarily by the FBG, but had different cavity lengths (10.5 and 7.1 m) that produced different PMB frequencies (4.8 and 7.2 MHz). Table 1 shows the experimental parameters of the fiber laser sensors. The pump light was delivered to both sensors from a single 980-nm laser diode through a tunable directional coupler and wavelength-division multiplexing couplers (980–1550 nm). In this experiment the total launched pump power for both lasers was ~ 15 mW, and we adjusted the output intensities of the two lasers to be equal by tuning the pump-power splitting ratio. Stable laser oscillation could be maintained over hours in the laboratory environment, except for occasional mode hopping for periods of a few minutes. Short sections of saturable absorbers (unpumped Er^{3+} -doped fiber) near the output FBG's in the sensors were arranged to go through a solenoid of 1528 turns (42 cm long) that generated an axial magnetic field in re-

sponse to an applied current. Polarizing fibers of 50-cm length were spliced to the FBG's. The FM outputs from the two sensors were combined by a directional coupler and directed to a photodetector through a return fiber bus. We constructed a frequency-demodulation circuit, using bandpass filters (stop-band attenuation, >45 dB; 3-dB bandwidth, <1 MHz) and PLL chips for electronic signal processing.

Figure 3 shows the rf spectrum of the photodetector output. The two main peaks represent the carrier beat signals of the sensors. The signal-to-noise ratio was better than 45 dB in the vicinity of the signals, with a noise-equivalent bandwidth of 18 kHz. The other small peaks come from residual longitudinal modes, indicating strong suppression of unwanted modes. When an ac (60-Hz line frequency) was applied to the solenoid, the slope of beat-frequency change as a function of applied current was measured to be 1.96 and 5.43 Hz/(A turn) for sensors 1 and 2, respectively. The theoretical values in an ideal situation in

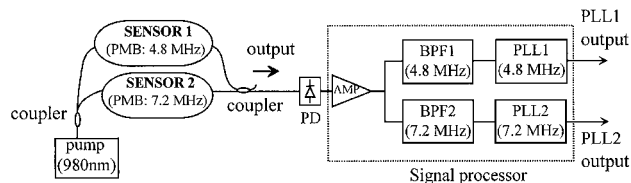


Fig. 2. Experimental setup of a current-sensor array and a signal processor: BPF1, BPF2, bandpass filters; PLL1, PLL2, phase-locked loops.

Table 1. Experimental Parameters of the Fiber Lasers

Parameter	Sensor	
	1	2
Gain medium	Er^{3+} -doped fiber; 35 cm, 2000 parts in 10^6	
Saturable absorber	Er^{3+} -doped fiber; 1.8 m, 80 parts in 10^6	
FRM	45° rotator, reflectivity 80%	
FBG mirror	1549 nm, reflectivity 91%	1549 nm, reflectivity 96%
Cavity length (m)	10.5	7.1
PMB (MHz)	4.8	7.2

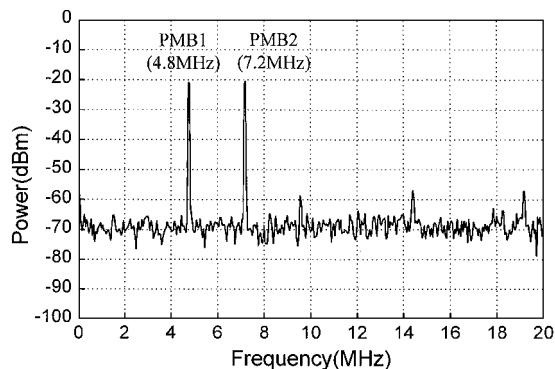


Fig. 3. rf spectrum of the photodetector output when no electrical current was applied. The noise-equivalent bandwidth is 18 kHz.

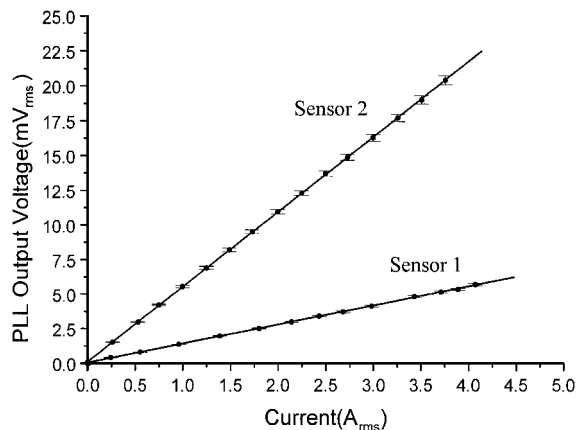


Fig. 4. Output voltage of the signal processor as a function of the magnitude of the applied current at 60 Hz.

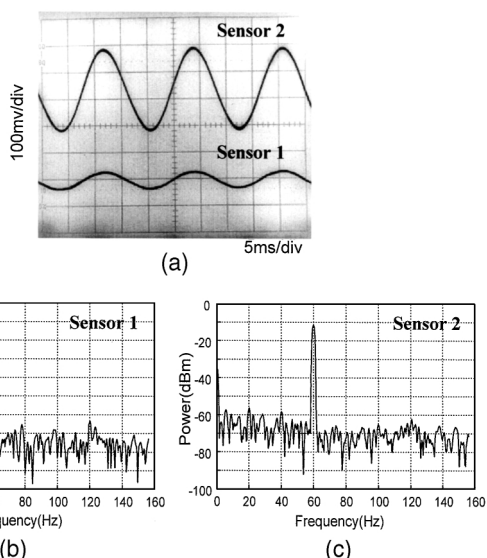


Fig. 5. Output of the PLL signal processors when an ac of $2.0 A_{rms}$ at 60 Hz was applied: (a) waveforms; (b), (c) rf spectra of the two sensors.

which it is assumed that there is no birefringence in the FBG mirror and the sensing fiber should be 4.71 and $7.07 \text{ Hz}/(A \text{ turn})$ for sensors 1 and 2, respectively. This discrepancy between theoretical and experimental values is believed to be due mainly to the birefringence in the FBG's that changed the state of polarization of light in the sensing region from circular to elliptical.⁷ The polarization dependence of the FBG mirror was not experimentally characterized in detail.

We monitored the output voltage of the PLL circuit to measure the amplitude and the waveform of the applied current. Figure 4 shows the measured response of the output voltage from each signal processor to the applied current, indicating good linearity. The scale factors for sensors 1 and 2 were 0.90 and $3.53 \mu\text{V}/(A \text{ turn})$, respectively. The scale factor varied by 1.5% when the birefringence of the laser cavity

was changed by a polarization controller. This scale-factor variation was attributed to birefringence in the FBG and the fiber in the sensing regions. Figure 5(a) shows the output of each PLL circuit as seen through an oscilloscope when an ac of $2.0 A_{rms}$ was applied to the solenoid. Each output clearly shows the waveform of the applied current. The noise-equivalent current of the sensors as measured with a rf spectrum analyzer is shown in Figs. 5(b) and 5(c). The signal-to-noise ratios for sensors 1 and 2 were approximately 55 and 62 dB , respectively, with noise-equivalent bandwidths of 1.48 Hz . From these results we obtained noise-equivalent currents of approximately 4.51 and $2.02 (A_{rms} \text{ turn})/\text{Hz}^{1/2}$ for sensors 1 and 2, respectively. To measure cross talk between the sensors we removed one of the sensors from the solenoid, and its output was monitored while the other sensor was in operation. The cross talk was smaller than -50 dB , limited by the electronic pickup at 60 Hz in the signal processor.

In conclusion, we have demonstrated a novel current-sensor array of polarimetric fiber laser sensors, using frequency-division multiplexing. The sensor array is inherently immune to the polarization and intensity fluctuations in the lead fibers. The noise-equivalent currents were 4.51 and $2.02 (A_{rms} \text{ turn})/\text{Hz}^{1/2}$ for sensors 1 and 2, respectively, and the cross talk between the sensors was less than -50 dB . It should be mentioned that FDM scheme is also compatible with the well-known wavelength-division multiplexing technique, in which each laser operates at a different optical wavelength determined by the grating mirror. Using the FDM and WDM techniques simultaneously can greatly increase the maximum number of fiber laser sensors in an array. We believe that this technique will be of importance for practical implementation of current sensors.

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