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Time Domain Referencing in Intensity Modulation Fiber Optic Sensing System

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Time domain referencing in intensity modulation fiber optic sensing systems

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Abstract

Intensity modulation sensors are classified depending on the way in which the reference and signal channels are separated: in space, wavelength (frequency), or time demains. To implement the time domain referencing different types of fiber optic (FO) loops have been used. A pulse of short duration sent into the loop results in a series of pulses of different amplitudes. The information about the measured parameter is retrieved from the relative amplitudes of pulses in the same train.

Introduction

During the past several years FO sensors have become intensively employed in measuring systems.[1,2] Among these sensors a large group is formed by intensity modulating sensors. A wide variety of these sensors has been developed to measure diverse parameters. All these sensors require distinguishable channels for reference and information carrying signals. Thus the sensing system could be conveniently classified by the method used to separate the reference and signal channels. The possible methods are spatial separation, wavelength (frequency) separation, and separation in time.

In this paper the separation of channels in the time domain is discussed and principles of construction of a FO sensing system employing the time domain referencing are outlined.

Principle of operation

In time separation (Time Multiplexing) method the channels are separated in the time domain within the same fiber. A light pulse of short duration is launched into a fiber-optic loop. If the pulse duration is much less than transit time of this pulse in the FO loop, a train of pulses of different amplitudes will be observed.

Two fundamental types of FO loop described in the literature are Fabry-Perot type loops[3,4] and recirculating loops.[5,6] They differ by the number of passes through the loop that each initial light pulse experiences before emerging to produce the secondary pulse. Other configurations of FO loops also can be constructed depending on the application and requirements. Schematics of different configurations of FO loops are shown in Figure 1.

Fabry-Perot type loop

A piece of fiber placed between two partially reflecting mirrors M1 and M2 forms a Fabry-Perot type loop. (See Figure 1(a)) A light pulse of a properly chosen duration launched into such a loop gives a series of pulses of different power in the transmission and reflection modes.[7] The period of the emerging pulses in one train is twice longer then their transit time in the fiber between the mirrors.

Assuming that the loop is lossless, the expression for power of the N-th emerging pulse is

for the transmission mode:

$$I_N = I_0 T_1 T_2 \, (R_1 R_2)^{N-1}, \tag{1}$$

for the reflection mode:

$$I_N = \begin{cases} I_0 R_1 & \text{for } N = 1 \\ I_0 R_1^{N-2} R_2^{N-1} T_1^2 & \text{for } N > 1 \end{cases} \tag{2}$$

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where I_0 is the power of the initial pulse, I_N is the power of the N-th emerging pulse, and R_1, T_1, R_2, T_2 are the reflection and transmission coefficients of mirrors M1 and M2 respectively. The ratio of power of any two pulses in the same train is independent of the power of the initial pulse I_0.

To represent a real sensing system a modulating parameter must be introduced into Equations (1) and (2). Depending on the configuration of the sensing system and the nature of the measurement this modulating parameter accounts for the power losses or the transmission coefficient for a light beam propagating along the fiber between the mirrors, the coupling losses on the mirror-fiber interfaces, or varying parameters of the mirrors.

Schematic examples of Fabry-Perot type FO loops for different applications are presented in Figure 2. The corresponding modulating parameters and accompanying expressions for the power of the pulses in one train are given in Table 1.

Recirculating loop

Typically a recirculating FO loop is built using a 2x2 coupler with one of the output ports connected to the unused input. The 2x2 coupler can employ either a bulk optical component (beam splitting mirror or cube) or be all fiber optic. In such a FO loop the pulse period within one train is equal to the transit time of the initial pulse in the loop.

An example of a recirculating FO loop with a beam splitting cube is shown in Figure 1(b). Let R and T to be the reflection and transmission coefficients for the cube. If we neglect backscattering and unwanted light coupling and assume that the FO loop is lossless, then the power of emerging pulses in one train is given by

$$I_N = \begin{cases} I_0 R_1 & \text{for } N = 1 \\ I_0 T^2 R^{N-2} & \text{for } N > 1 \end{cases} \tag{3}$$

If we introduct the splitting ratio K and transmission coefficient α as new parameters of the coupler:

$$K = T/R \tag{4}$$

and

$$\alpha = R + T \tag{5}$$

then Equation (3) could be written as:

$$I_N = \begin{cases} I_0 \dfrac{\alpha}{1 + K} & \text{for } N = 1 \\ I_0 K^2 \left(\dfrac{\alpha}{1 + K}\right)^N & \text{for } N > 1 \end{cases} \tag{6}$$

The power ratio of the first two pulses is

$$\frac{I_2}{I_1} = K^2 \frac{\alpha}{1 + K} \tag{7}$$

Equations (6) and (7) can also be used to describe an all fiber optic recirculating loop (Figure 1(c)). A sensor incorporated in the recirculating loop modifies these equations, and the expressions become:

$$I_N = \begin{cases} I_0 \dfrac{\alpha}{1 + K} & \text{for } N = 1 \\ I_0 K^2 \left(\dfrac{\alpha}{1 + K}\right)^N \gamma^{N-1} & \text{for } N > 1 \end{cases} \tag{8}$$

and

$$\frac{I_2}{I_1} = K^2 \frac{\alpha}{1 + K} \gamma \tag{9}$$

where γ is the transmission of the loop.

Experimental results

An all fiber recirculating loop has been constructed and tested with a microbend incorporated in the loop.[8] The microbend acts as a pressure sensor by generating a power loss dependent on the disturbance. The all fiber recirculating loop has also been used as a thermometer.[9] The temperature sensing in this system is based on the temperature dependent absorption of a piece of Nd^{+3} doped glass fused in the loop. The experimentally obtained ratio of the first two pulses as a function of temperature is given in Figure 3. In both cases the experimental data have closely followed either the theoretically predicted function or those obtained by other authors using different techniques.

Unfortunately the entire FO loop acts as a sensor, so special precautions should be taken in designing the loop. In order to neutralize the effect of disturbances on the actual sensor the loop should be as short as possible. From this point of view the Fabry-Perot type loop has an advantage. Shorter loops require initial pulses of shorter duration. Therefore, if nanosecond pulses are required, laser diodes must be used because light emitting diodes have a limited modulating capability.

Components used to construct the loop also play an important role in the stability of the loop. The couplers in the recirculating loops shall be modally insensitive. Thus, change in the modal power distribution in the fiber due to mechanical perturbations would not lead to a change in the coupler parameters. In that respect the all fiber couplers are disadvantageous.

In general, the decision about what type of loop to employ and components to use comes from the initial requirements for the sensing system, its purpose, accuracy, and repeatability, as well as from the sensor itself.

Acknowledgments

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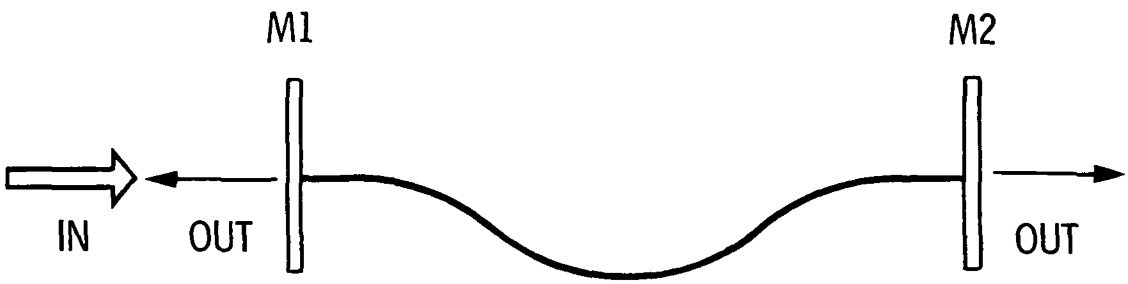
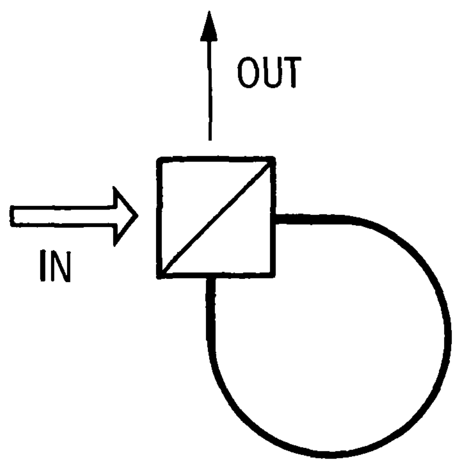
Table 1. - Expressions for the power of the N-th pulse for examples presented in Figure 2

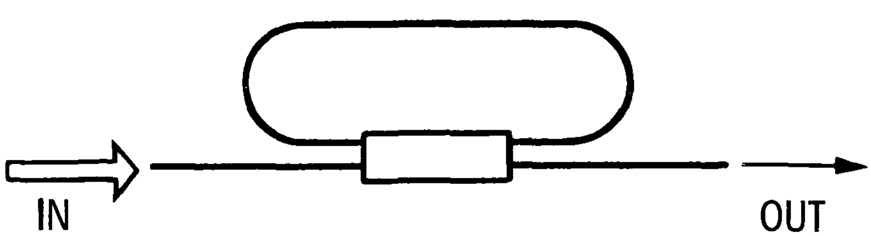
Figure 2(a)	Measurement	Pressure P
	Modulating parameter	$\gamma = f(P)$ Transmission of the FO loop
	Reflection mode	$I_N = \begin{cases} I_0 R_1 & \text{for } N = 1 \\ I_0\ T_1^2 R_1^{N-2} R_2^{N-1}\ \gamma^{2(N-1)} & \text{for } N > 1 \end{cases}$
	Transmission mode	$I_N = I_0 T_1 T_2 (R_1 R_2)^{N-1} \gamma^{2N-1}$
Figure 2(b)	Measurement	Displacement L
	Modulating parameter	$\beta = f(L)$ Coupling coefficient on mirror-fiber interface
	Reflection mode	$I_N = \begin{cases} I_0 R_1 & \text{for } N = 1 \\ I_0\ T_1^2 R_1^{N-2} R_2^{N-1}\ \beta^{N-1} & \text{for } N > 1 \end{cases}$



(a) Fabry-Perot type loop.

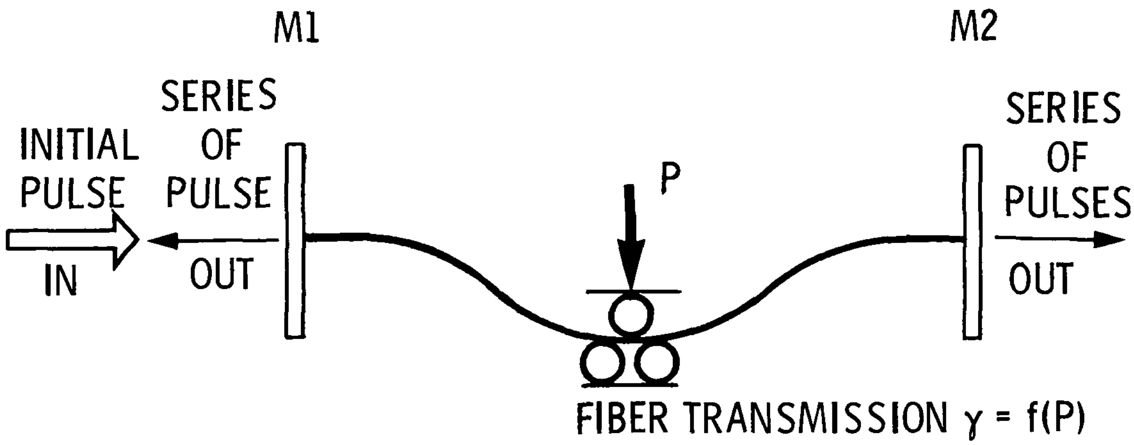


(b) Recirculating loop with a beam splitting cube.

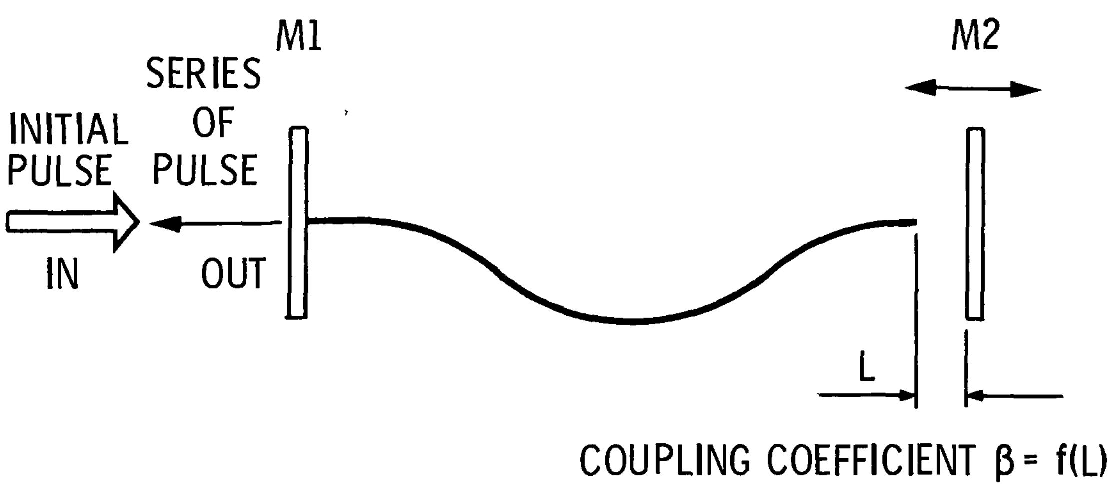


(c) Recirculating loop with a 2x2 fiber coupler.

Figure 1. - Schematics of different configurations of FO.



(a) A pressure sensing FO loop with a microbend.



(b) A FO loop for displacement measurement.

Figure 2. - Schematic examples of Fabry-Perot type FO loops.

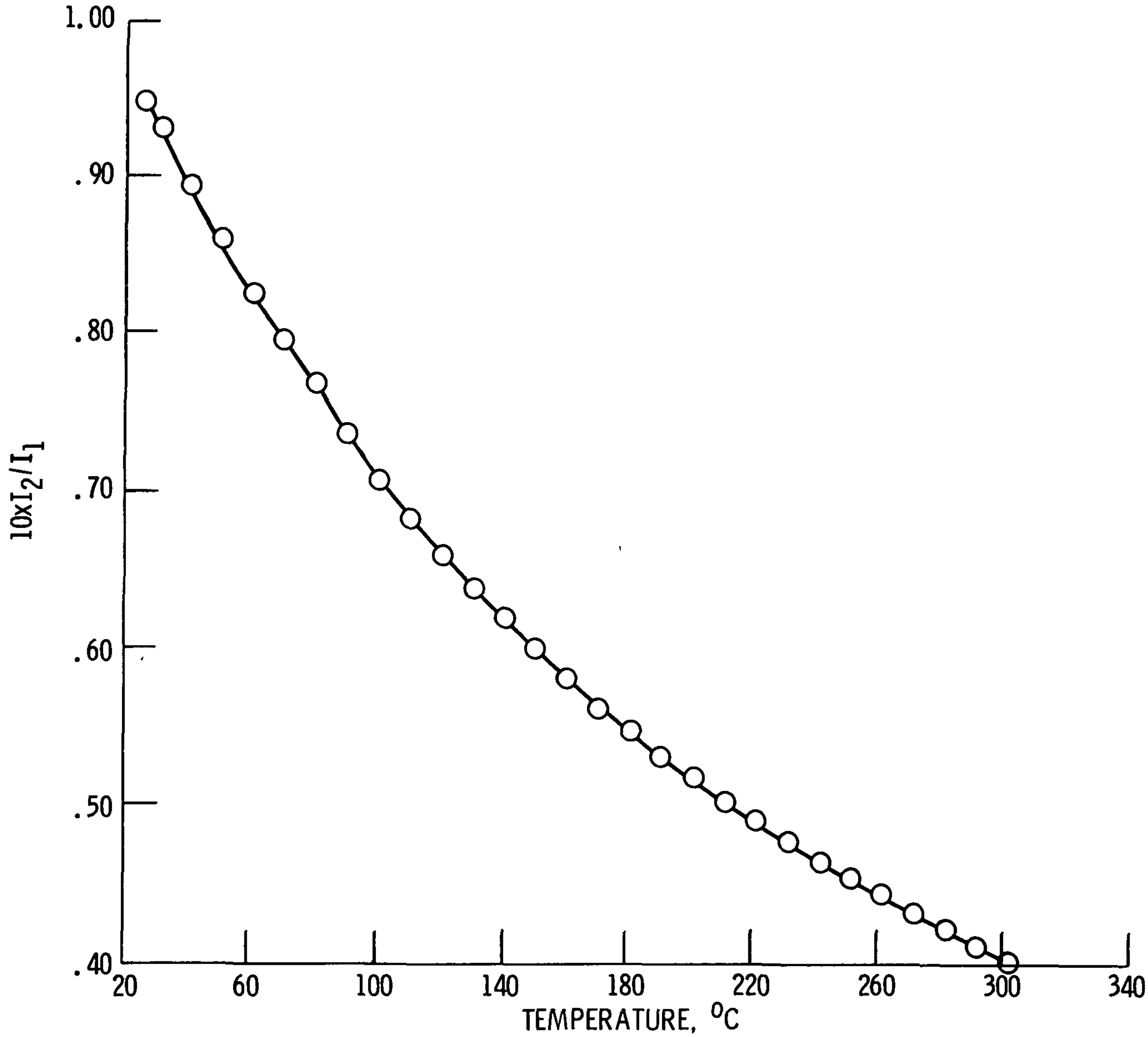


Figure 3. - Experimentally obtained power ratio I_2/I_1 as a function of temperature using Nd^{+3} doped glass as a temperature sensor.

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