Lead Sensitivity in White Light Fiber Optic Interferometry

R. R. Gauthier, N. Dahi, and F. Farahi

Physics Department, University of North Carolina at Charlotte, Charlotte, N.C. 28223

Abstract

Interferometric systems consisting of two tandem interferometers using white light have been used as the basis of remote sensing systems. Generally, no regard has been given to the effect of externally induced polarization changes in the fiber linking the interferometers. It is shown here both theoretically and experimentally that both phase and amplitude of the interference signal at the output of the system is significantly affected by externally induced birefringence in the fiber link. In some systems this may cause total fading of signal.

1. Introduction

Fiber optic interferometric sensors have been shown to offer the most accuracy in optical fiber metrology. White light interferometry is an attractive technique, since it can be used for absolute measurement [1], and can be readily applied to multiplexed systems [2]. Remote configurations for fiber optic interferometric sensors have been studied [1-3] which use a balanced system of two tandem interferometers, where an arm of one of the interferometers is used as the sensor.

It has been found that noise caused by fluctuations in the states of polarization in the interfering beams - the so-called "polarization-induced fading", is a limiting factor in many arrangements. The problem is attributed to either variation in input polarization [4] or fluctuation in the arms of the sensor [5].

It has been a common belief that any external effect (such as stress) on the input lead to an interferometer will not affect the phase of the output. There has been some evidence [5] to show that this is not so. In this paper it will be shown that perturbations of the fiber link in a two-interferometer tandem system critically affect both the output phase and visibility, theoretically using the Jones calculus, and also experimentally.

2. Theoretical Analysis

A simple system is shown in Figure 1, consisting of two unbalanced interferometers linked by a single mode fiber. An optical element is placed in each arm of the interferometers. We can represent the fiber by a Jones matrix $F$, and likewise for optical elements $A$ through $D$.

![Figure 1. Balanced dual interferometer system with polarization controlling elements A through D. Each path imbalanced interferometer is identical, producing a balanced system.](image)

With an input of arbitrarily polarized white light, the system is considered balanced to within the coherence length of the light so that two of the possible paths produce interference. The two electric field components that interfere are then found from the application of the appropriate Jones matrices of the optical elements for the paths as,

$$E'_1 = C^2 FA^2 E_1,$$  \hspace{1cm} (1)

$$E'_2 = D^2 FB^2 E_2,$$  \hspace{1cm} (2)

where $E_1$ and $E_2$ are the original field components from the first splitter. The total electric field $E'$ is the sum of Eqs. (1) and (2), and the intensity of the interference is given as,
\[ S' = E\dagger E', \]  

where \( \dagger \) denotes the complex conjugate transpose, with the electric fields treated as column matrices. Thus in general, there are terms in the expression for the output intensity that depend on the fiber and the four optical elements,

\[ S' = E_2\dagger B\dagger F\dagger D\dagger C^2FA^2E_1 + E_1\dagger A\dagger F\dagger C^2D^2FR^2E_2 \]

(4)

The fiber can be treated as a general elliptical retarder as,

\[ F = \frac{1}{\sqrt{f_{21}}} \begin{bmatrix} f_{11} & f_{21} \\ -f_{21} & f_{11} \end{bmatrix}, \]

(5)

where \( f = f_{11}f_{21}^* - f_{21}f_{11}^* \), and fiber losses are ignored. Now if the polarization control is ignored, or if elements A through D are treated as unity, then equation (4) simplifies to,

\[ S' = E_2\dagger E_1 + E_1\dagger E_2, \]

(6)

since \( F \) is a unitary matrix. Thus the intensity will vary sinusoidally with the difference in phase between \( E_1 \) and \( E_2 \), with no output dependency on the properties of the fiber.

If only optical elements A and/or B are considered, perturbations of the fiber will not affect the output. But if we consider only the element D, with the symbol \( D \) accounting for the net effect of D (\( D = D^2 \)), equation (4) simplifies to,

\[ S' = 2E_1\dagger F\dagger MFE_1, \]

(7)

where \( M = D\dagger + D \). Equal splitting ratio is considered for the beam splitters, and no net differential phase between the electric fields has been assumed so that \( E_1 \) equals \( E_2 \). If the simplifying assumption that the off-diagonal elements of \( D \) satisfy \( d_{12} = -d_{21}^* \), then \( M \) becomes diagonal, and we obtain the simplest case for which perturbations of the fiber will affect the output,

\[ S' = \frac{2}{f} \left[ (f_{11}^*m_{11}f_{11} + f_{21}^*m_{22}f_{21}) E_x^2 
+ (f_{21}^*m_{22}f_{21} - f_{11}^*m_{11}f_{21}^*) 
+ f_{11}m_{22}f_{21} - f_{21}m_{11}f_{11} \right] E_yE_x 
+ (f_{21}^*m_{11}f_{21} + f_{11}^*m_{22}f_{21}) E_y^2 \]

(8)

If we make a second assumption that \( d_{11} = d_{22} \), then the element D becomes an elliptical retarder, and the dependence on the fiber vanishes. Thus if D is a polarizer or absorber, the output will be affected by perturbations of the fiber.

Now a combination of elements A and D is considered, this time allowing A and D to be elliptical retarders similar to the form in Eq. (5). If we make the simplifying assumptions that \( a_{21} = -a_{21}^* \) and \( d_{21} = -d_{21}^* \), then Eq. (4) simplifies to,

\[ S' = \frac{2E_1^2}{f\sqrt{ad}} \left[ f_{11}^*f_{11} \left( d_{11}^*a_{11} + d_{11}a_{11}^* \right) 
+ f_{21}^*f_{21} \left( d_{11}a_{11} + d_{11}^*a_{11} \right) 
+ d_{21}a_{11} \left( f_{21}^* - f_{11}^* + f_{21} - f_{11} \right) \right] \]

(9)

It can be shown that the output intensity will depend on perturbations of the fiber matrix if either,

\[ d_{11} \neq d_{11}^*, \quad \text{and} \quad a_{11} \neq a_{11}^*, \]  

(10a,b)

or the conditions,

\[ d_{21} \neq d_{21}^*, \quad \text{and} \quad a_{21} \neq a_{21}^*, \]  

(11a,b)

are met, meaning that either the diagonal elements of \( A \) and \( D \) must not be equal, or the off-diagonal elements must not be zero.

3. Experimental Results

The experimental setup used is shown in Figure 2. The input light was linearly polarized from a broad-band source. The second interferometer is an all-fiber Mach-Zehnder configuration.

**Figure 2.** Schematic of experimental arrangement used to test fiber lead dependence of output interference.

PZT1 was modulated to create a pseudo-heterodyne carrier by sweeping the interferometer over one fringe. PZT3 was then used as a signal, and PZT2 was used to periodically induce birefringence in the fiber link. The half-wave plate was used for further control of the polarization state of light prior to the fiber link.
With the standard definition of visibility given by,
\[ V = \frac{I_{\text{max}} - I_{\text{min}}}{I_{\text{max}} + I_{\text{min}}} \]  \hspace{1cm} (12)

Figure 3 shows two sets of data taken of the visibility of the output arising from the modulation of PZT1 versus the rotation angle of the half-wave plate.

![Figure 3](image)

**Figure 3.** Two trials of data for the visibility of the output versus the rotation angle of the half-wave plate.

The two sets of data represented in Figure 3 correspond to two different arbitrary polarization states in the second arm of the fiber interferometer. The data reveals that the visibility changes by about 100% when the polarization control is rotated by 30 degrees.

When PZT3 is used as a signal on top of the carrier frequency provided by the mirror modulation from PZT1, a modulation of the fiber via PZT2 will show up as an additional sideband.

![Figure 4](image)

**Figure 4.** Spectrum of the output of the experimental configuration showing carrier and two sets of sidebands produced by PZT2 and PZT3.

Figure 4 shows a large peak near 11.1 kHz from the carrier frequency induced by PZT1. Modulation by the signal from PZT3 at 700 Hz then produces the outermost sidebands. If PZT2 is then modulated at about 100 Hz, a second set of sidebands is produced. The sidebands produced by modulating the fiber are of the same character as the signal, and can easily be the same order amplitude as the signal.

### 4. Conclusions

From the theoretical discussion we see that polarization control is critical in determining how prone the output will be to perturbations in the fiber. There may therefore be problems in configurations which do not use polarization-preserving fiber links, or other types of polarization control.

Experimentally it was demonstrated that the polarization control in the linking fiber can dramatically affect the visibility. When the arm of the fiber interferometer is used as a sensor, noise in the form of modulations of the fiber at frequencies near that of the signal can cause a complete fading of the signal.

Since the critical areas of control affecting the lead sensitivity are in the arms of the second interferometer, strategies to cancel polarization changes such as using phase-conjugate mirrors or Farady rotators might be employed there.

### References


