Polarization alignment of polarization maintaining fiber using coherent detection

Roman C. Gutierrez

Jet Propulsion Laboratory, California Institute of Technology,
4800 Oak Grove Dr., Pasadena> CA911 09

ABSTRACT

A new method of polarization alignment into PM fiber based on electronic coherent detection is presented. The electric field resulting from interference between the polarization eigenmodes of a PM fiber at a linear polarizer when the light coupled into the fiber is amplitude modulated is solved for. The results of polarization alignment experiments using a current modulated laser diode are compared with the theory. Even though current modulation of a laser diode produces a complicated electric field, it is shown that the measurements made in the experiments agree well with the simple model.
The new method is used to align the input to a PM fiber coupler with a polarization extinction ratio (PER) of 25 dB (limited by coupler crosstalk) and to align into a 1 km long PM fiber with a PER of 20 dB (limited by fiber crosstalk).

Keywords: polarization alignment, polarization maintaining (PM) fiber, fusion splicing, amplitude modulation, interference

1, 1NTROI>.UCTION

The development of high birefringence polarization maintaining (PM) fibers has brought many new possibilities to the field of fiber optics [3]. Duc to the essential elimination of crosstalk between eigenpolarizations inside the fiber, phase information can be transmitted over long distances inside a PM fiber. Coherent communications as well as fiber optic sensors rely on accurate phase information being carried by the intensity modulation of light inside a fiber optic line. in the case of the fiber optic gyroscope, PM fiber will allow rotation rate measurement sensitivities of less than 0.01 degrees/hour [4].

When both polarization eigenmodes are excited with monochromatic light at the input of a high birefringence PM fiber, the state of polarization changes along the length of the fiber. The polarization at the output depends on the accumulative phase difference between the two modes. Changes in temperature, stress, and bending of the fiber change the birefringence of the fiber so that the state of polarization at the output of the fiber is unstable [5,6,11]. If only onc polarization eigenmode is excited, the state of polarization will be unchanged along the fiber. Therefore, in order to use high birefringence polarization maintaining (PM) fiber, a method of accurately launching linearly polarized light into just one of the fiber axes is ncccssary [8,9,10], This paper presents a simple new method to do this.

2. DIRECT AND C()I IERENT DETECTION

In an unmarked PM fiber, it is difficult to visually make polarization alignments. For panda fiber, for example, the stress rods arc not easily visible under a microscope, even when white light is coupled into the fiber. It is usually preferable to align by making a measurement at the output of the PM fiber that will be a function of the input alignment.

When linearly polarized light (CW) is coupled into the PM fiber, the output polarization can be analyzed at the output of the PM fiber with a linear polarizer. If the output polarization is stable and highly elliptical, i.e. close to linear, the input is well aligned. This method is commonly used in the industry to align the polarization of a laser with the axes of a PM fiber. The fiber is usually heated to measure the stability of the output polarization, and the polarization extinction ratio is measured to determine the ellipticity of the output polarization. This method, although extensively used, has a lot of problems. For long lengths of fiber, the output polarization is usually so unstable that measuring the extinction ratio becomes impossible. Even a short piece of PM fiber, for which the output polarization is more stable, the method is very time consuming, requiring many iterations of trial and error before achieving reasonably good alignment.

When the light that is coupled into the PM fiber is amplitude modulated, coherent detection can be used to measure the extinction ratio. This modification to the polarization alignment method described above reduces the noise in the analyzed output considerably. Still, many iterations are required until the input and output polarizers are in line with the axes of the PM fiber.

When using coherent detection, not only the amplitude of the modulation is known, but also the phase. This paper will show the great advantages of using the phase measurement of coherent detection to make polarization alignments. It will be shown that the iterative process of polarization alignment is eliminated, and that, in addition, the alignment accuracy is increased dramatically.

3. THEORY

When linearly polarized light is launched into a PM fiber, the state of polarization is decomposed into a sum of the two polarization eigenmodes of the PM fiber. These two eigenmodes are nearly perfect linearly polarized along the two orthogonal axes of the PM fiber. Due to either form birefringence (e.g. elliptical core PM fiber) or stress birefringence (e.g. Panda PM fiber), the two polarization eigenmodes propagate through the fiber at different velocities. It is precisely this velocity mismatch, which is large enough to not be compensated by random birefringence, that forbids coupling between the two polarization eigenmodes. At the output of the PM fiber, the two polarization eigenmodes are forced to interfere by a linear polarizer.

When the light is amplitude modulated, the effect of the velocity mismatch between the two polarization eigenmodes on the amplitude and phase of the modulation is not directly evident. The problem will be analyzed using Jones calculus. In Jones calculus, the light is represented by two dimensional complex Vector. Therefore, the effect on both the phase and the amplitude of the electric field are calculated simultaneousl y.

Figure 1 illustrates the problem we want to analyze. The figure shows a stress birefringent fiber., The lightly shaded regions are the stress rods which provide a linear stress field across the core of the fiber (shaded darker). The axes of the fiber are then along the line connecting the stress rods and orthogonal to it. Linearly polarized modulated light is launched into a high birefringence PM fiber at an angle θ

with respect to one of the axes. At the output, an analyzer is placed at an angle ϕ with respect to the PM fiber axes. The output phase and the output intensity are the two functions of ϕ that need to be derived.

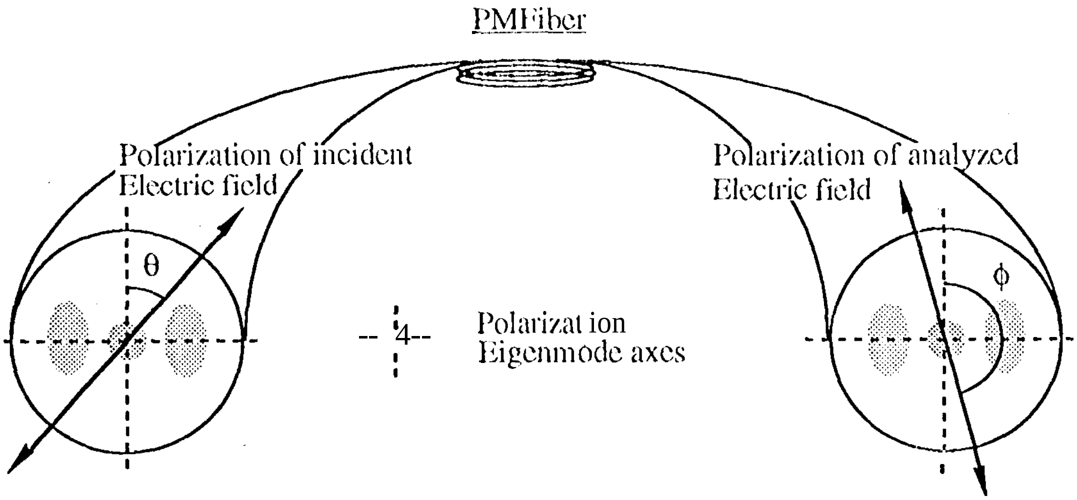


Fig. 1 Diagram of the input polarization angle and the output analyzing angle.

A theoretical treatment of high birefringence polarization maintaining fiber can be easily performed by assuming that the two eigenmodes propagating inside the fiber arc exactly linearly polarized and orthogonal. If these assumptions arc made, basic geometrical arguments can give formulas for the intensity and phase of a modulated signal propagating through a polarization maintaining fiber.

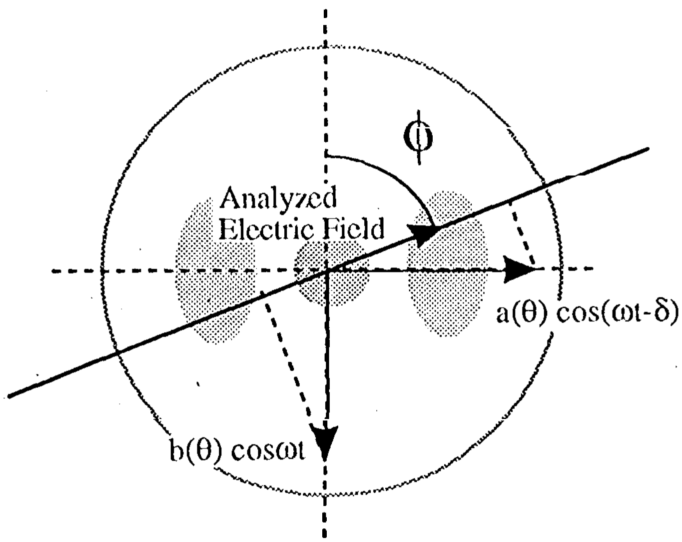


Fig. 2 Projection of the two polarization eigenmodes on the analyzer.

Figure 2 shows the projection of the two modes onto a polarizer. Since the two modes have different phase velocities, the waves carried in the two modes build up a relative phase shift δ between them.

$$\delta(\omega) = \omega \frac{(n_s - n_f)}{c} \cdot \ell \qquad (1)$$

where,

n_s = index of refraction of the slower mode

n_f = index of refraction of the faster mmic

ℓ = length of the PM fiber

Equation (1) assumes zero dispersion. For a small modulation frequency, the group velocity is approximately [7],

$$v_g = \frac{d\omega}{dk}$$

Since, $\omega = k \cdot v_p$,

$$v_g = v_p + k \cdot \frac{dv_p}{dk}$$

In a nondispersive medium, the phase velocity is independent of the wavelength of light, so,

$$\frac{dv_p}{dk} = 0$$

V* = .v_p

Therefore, in nondispersive media, the phase velocity is equal to the group velocity, anti equation (1) is valid.

Since Jone's calculus [1] provides a general method for treating this sort of problem, it will be used to derive an equation for the light intensity at the output side of the system in figure 2. The electric field of the light is represented by a vector with two components. The two components are orthogonal to each other and to the direction of propagation: Each component has information about the amplitude and the phase of the light polarized in that direction,

When the light propagates through a length of PM fiber, the components of the polarization along the birefringent axes of the fiber build up a relative phase between them. Therefore, the output polarization of a PM fiber is related to the input polarization by the following matrix multiplication.

$$\vec{E}_{out} = \exp\left(-i\frac{\Delta(\omega)}{2}\right) \cdot \begin{pmatrix} \exp\left(-i\frac{\delta(\omega)}{2}\right) & 0 \\ 0 & \exp\left(i\frac{\delta(\omega)}{2}\right) \end{pmatrix} \cdot \vec{E}_{in} \qquad (2)$$

where,

$$\Lambda(\omega) = \omega \cdot \frac{(n_s + n_f)}{c} \cdot \ell$$

Equation (2) can bc rewritten as,

$$\vec{E}_{out} = \exp\left(i\,\frac{\delta(\omega) - \Lambda(\omega)}{2}\right) \cdot \begin{bmatrix} \exp(-i\delta(\omega)) & 0 \\ 0 & 1 \end{bmatrix} \cdot \vec{E}_{in} \tag{3}$$

Since phase is a relative measurement, the common phase term in equation (3) can bc ignored,

$$\vec{E}_{out} = \begin{pmatrix} \exp(-i\delta(\omega)) & 0 \\ 0 & 1 \end{pmatrix} \cdot \vec{E}_{in} \tag{4}$$

Both the output and input electric field vectors are represented in the coordinate system of the birefringence axes of the PM fiber. The rotation matrix and tbc matrix multiplication in equation (4) can bc used together to generate a relation between the input and output intensity vectors when they arc not represented in the coordinate system of the birefringence axes of the PM fiber.

Referring back to figure 2, the intensity at the output of the analyzer is given by the following expression:

$$\vec{E}_{out} = \begin{pmatrix} 1 & 0 \\ 0 & 0 \end{pmatrix} \cdot \begin{pmatrix} \cos\phi & \sin\phi \\ -\sin\phi & \cos\phi \end{pmatrix} \cdot \begin{bmatrix} \exp(-i\delta(\omega)) & 0 \\ 0 & 1 \end{bmatrix} \cdot \begin{pmatrix} \cos\theta & \sin\theta \\ -\sin\theta & \cos\theta \end{pmatrix} \cdot \vec{E}_{in} \tag{5}$$

where ϕ is the angle between the analyzer and one of the axes of the PM fiber, and θ is the angle between the input polarization and the same axis of the PM fiber.

If the input is linearly polarized and modulated at frequency $\omega_m = \omega_1 - \omega_2$, where ω_1 and ω_2 arc on both sides of the frequency of the optical carrier, the electric field vector can be written as

$$\begin{aligned} \vec{E}_{in} &= \begin{pmatrix} 0 \\ E_{in} \end{pmatrix} \cdot \left[\exp(i\omega_1 t) + \exp(i\omega_2 t)\right] \\ &= \begin{pmatrix} 0 \\ 1 \end{pmatrix} \cdot E_{in} \left[\exp(i\omega_1 t) + \exp(i\omega_2 t)\right] \end{aligned} \tag{6}$$

By substituting equation (6) into equation (5) and simplifying,

$$\vec{E}_{out} = \begin{pmatrix} \sin\theta \cdot \cos\phi \cdot \exp(-i\delta(\omega)) + \cos\theta \cdot \sin\phi \\ 0 \end{pmatrix} \cdot E_{in}\left[\exp(i\omega_1 t) + \exp(i\omega_2 t)\right] \tag{7}$$

Therefore,

$$E_{out} = \mathrm{Re}\left\{E_{in}\left[\sin\theta\cdot\cos\phi\cdot\exp(-i\delta(\omega)) + \cos\theta\cdot\sin\phi\right]\cdot\left[\exp(i\omega_1 t) + \exp(i\omega_2 t)\right]\right\}$$
$$= E_{in}\left\{\sin\theta\cdot\cos\phi\cdot\left[\cos(\omega_1 t - \delta_1) + \cos(\omega_2 t - \delta_2)\right] + \cos\theta\cdot\sin\phi\cdot\left[\cos\omega_1 t + \cos\omega_2 t\right]\right\}$$

Using a trigonometric identity,

$$E_{out} = 2E_{in}\left\{\begin{array}{c}\sin\theta\cdot\cos\phi\cdot\cos\frac{1}{2}\left[(\omega_1+\omega_2)t-(\delta_1+\delta_2)\right]\cdot\cos\frac{1}{2}\left[(\omega_1-\omega_2)t-(\delta_1-\delta_2)\right]+ \\ +\cos\theta\cdot\sin\phi\cdot\cos\frac{1}{2}(\omega_1+\omega_2)t\cdot\cos\frac{1}{2}(\omega_1-\omega_2)t\end{array}\right\} \quad (8)$$

where, $\delta_i = \delta(\omega_i)$; $i = 1,2$.

The output intensity is given by the square of equation (8). ignoring fast varying terms, an expression for the irradiance is,

$$I_{out} = 4E_{in}^2\left[\begin{array}{c}\sin^2\theta\cdot\cos^2\phi\cdot\cos^2\frac{1}{2}(\omega_m t-\delta_m)+\cos^2\theta\cdot\sin^2\phi\cdot\cos^2\frac{1}{2}\omega_m t+ \\ +2\cdot\sin\theta\cdot\cos\theta\cdot\sin\phi\cdot\cos\phi\cdot\cos\frac{1}{2}\omega_m t\cdot\cos\frac{1}{2}(\omega_m t-\delta_m)\cos\Delta\end{array}\right] \quad (9)$$

where,

$\omega_m = \omega_1 - \omega_2$ = frequency of modulation

δ_m =31 – δ_2 = envelope phase delay

$\Delta = \frac{(\delta_1+\delta_2)}{2}$ –average optical phase delay

If equation (9) is equated to a sinusoid of amplitude A and phase Γ:

$$1_{out} = A\cdot\cos^2\frac{1}{2}(\omega_m t - r) \quad (10)$$

Equating sines and cosines on both sides of equation (1 O), wc get:

$$A\cdot\sin\Gamma = \sin^2\theta\cdot\cos^2\phi\cdot\sin\delta_m + 2\sin\theta\cdot\cos\theta\cdot\sin\phi\cdot\cos\phi\cdot\sin\frac{\delta_m}{2}\cdot\cos\Delta \quad \text{(ha)}$$

$$A\cdot\cos\Gamma = \cos^2\theta\cdot\sin^2\phi + \cos^2\phi\cdot\sin^2\theta\cdot\cos\delta_m +- \quad \text{(11b)}$$
$$+2\sin\theta\cdot\cos\theta\cdot\sin\phi\cdot\cos\phi\cdot\cos\frac{\delta_m}{2}\cdot\cos\Delta$$

Dividing equations (11a) and (11b), we get an expression for the phase:

$$r = \tan^{-1}\left[\frac{\sin\delta + 2\tan\phi\cdot\cot\theta\cdot\sin\frac{\delta_m}{2}\cdot\cos\Delta}{\tan^2\phi\cdot\cot^2\theta + \cos\delta_m + 2\tan\phi\cdot\cot\theta\cdot\cos\frac{\delta_m}{2}\cdot\cos\Delta}\right] \tag{12}$$

Squaring equations (11a) and (11b) and then adding them, and assuming that $\delta << 1$, we get an expression for the amplitude:

$$A = a^2\cdot\cos^2\phi\cdot\cos\delta_m + b^2\cdot\sin^2\phi + 2ab\cdot\sin\phi\cdot\cos\phi\cdot\cos\frac{\delta_m}{2}\cdot\cos\Delta \tag{13}$$

where, $a = \sin\theta$ and $b = \cos\theta$.

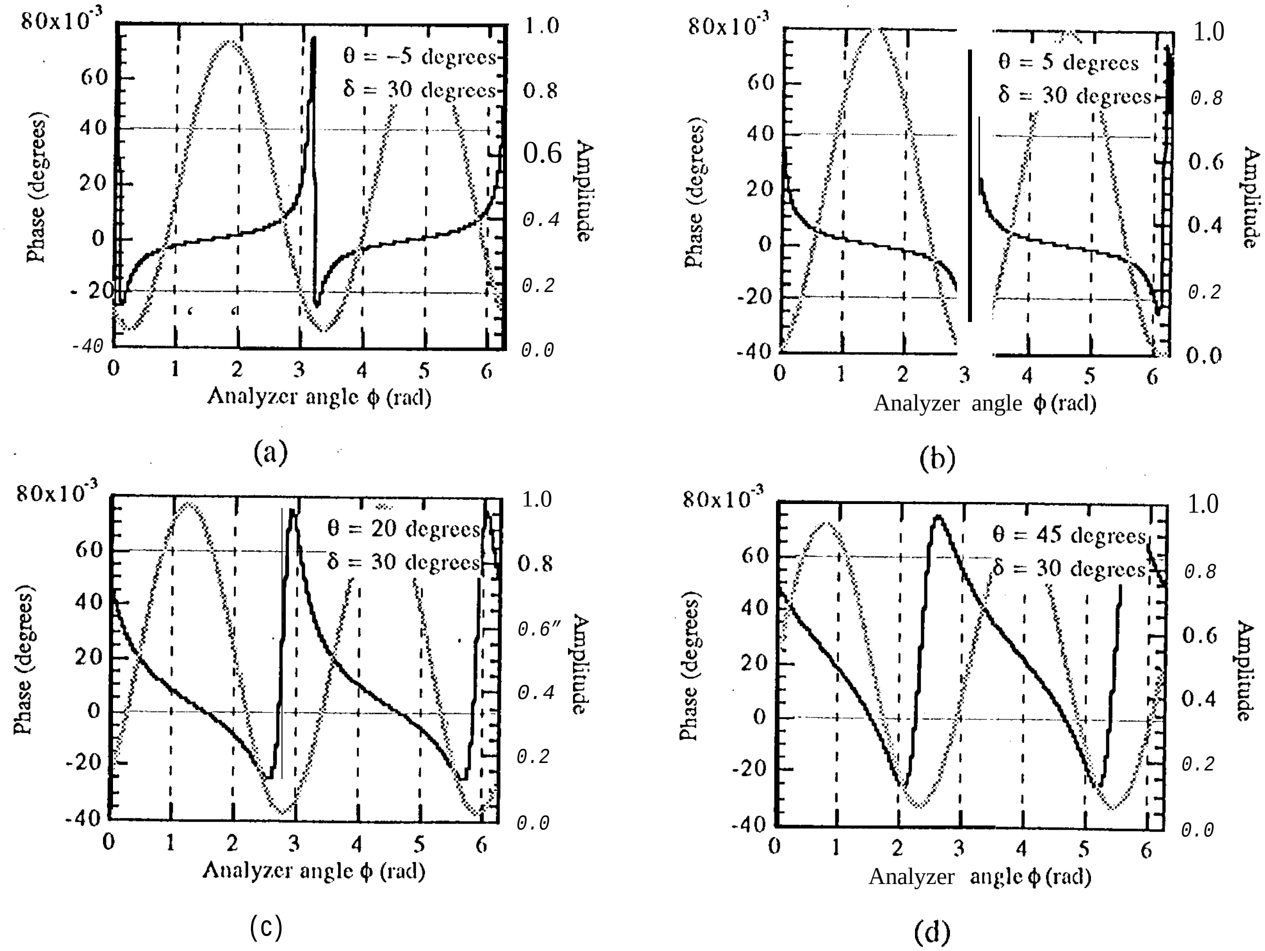


Fig. 3 Plots of phase (black) and amplitude (gray) as a function of the analyzer angle (ϕ) for an optical phase delay (δ) of 30 degrees and different input polarization angles (θ).

The functions in equations (12) and (13) arc shown in figures 3 and 4.

Figure 3 shows the change in the phase curve shape as a function of alignment accuracy. θ is the input polarization angle and δ is the optical phase delay between the two polarization eigenmodes. Two main observations of great significance for polarization alignment should be pointed out. The width of the phase peaks decreases as θ decreases, and the symmetry of the peaks flips around at θ = 0. It is then possible to use the width of the phase peaks as a measure of the misalignment. Figure 3 d shows a nearly sinusoidal phase curve indicating that the polarization is highly misaligned. Figures 3 a and 3 b have sharp phase curves indicating that the input polarization is nearly aligned with one of the axes. in addition, when the curve flips, the point of perfect alignment has been passed. Comparing figure 3 a with figure 3 b, we can see how the curve flips.

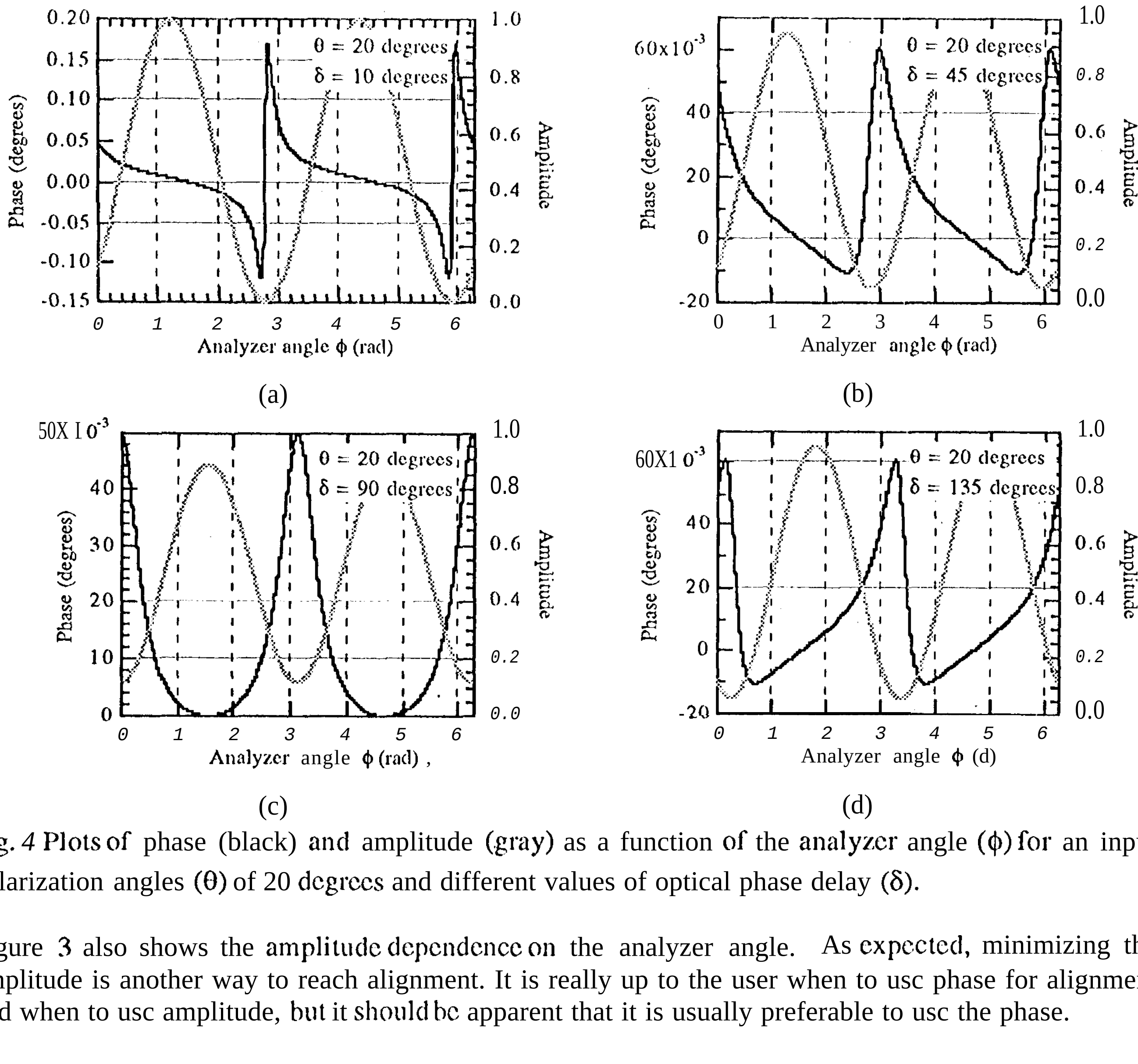


Fig. 4 Plots of phase (black) and amplitude (gray) as a function of the analyzer angle (ϕ) for an input polarization angles (θ) of 20 degrees and different values of optical phase delay (δ).

Figure 3 also shows the amplitude dependence on the analyzer angle. As expected, minimizing the amplitude is another way to reach alignment. It is really up to the user when to use phase for alignment and when to use amplitude, but it should be apparent that it is usually preferable to use the phase.

Figure 4 shows the dependence on the optical phase. Again, θ is the input polarization angle and δ is the optical phase delay between the two polarization eigenmodes.. As shown in figures 4 a and 4 b, the peak to peak variation in phase increases as the optical phase decreases. The curves are symmetric for an optical phase of 90 degrees (see figure 4 c), and the phase curves also flip around this point (as they did at $\theta = 0$). The high sensitivity on optical phase. may be of some use in some other applications, but it is really an undesirable effect for polarization alignment. Notice that it also affects the amplitude. This is really a manifestation of the change in polarization at the output of a PM fiber as the optical phase delay of the two polarization eigenmodes changes. A possible solution to this problem would be to dither the optical phase with, for example, a modulated piezoelectric crystal in physical contact with the fiber. As will be seen in the experimental section of this paper, the optical phase in a long piece of PM fiber changes randomly sufficiently fast to result in what looks like an integration of the optical phase.

4. EXPERIMENT SETUP

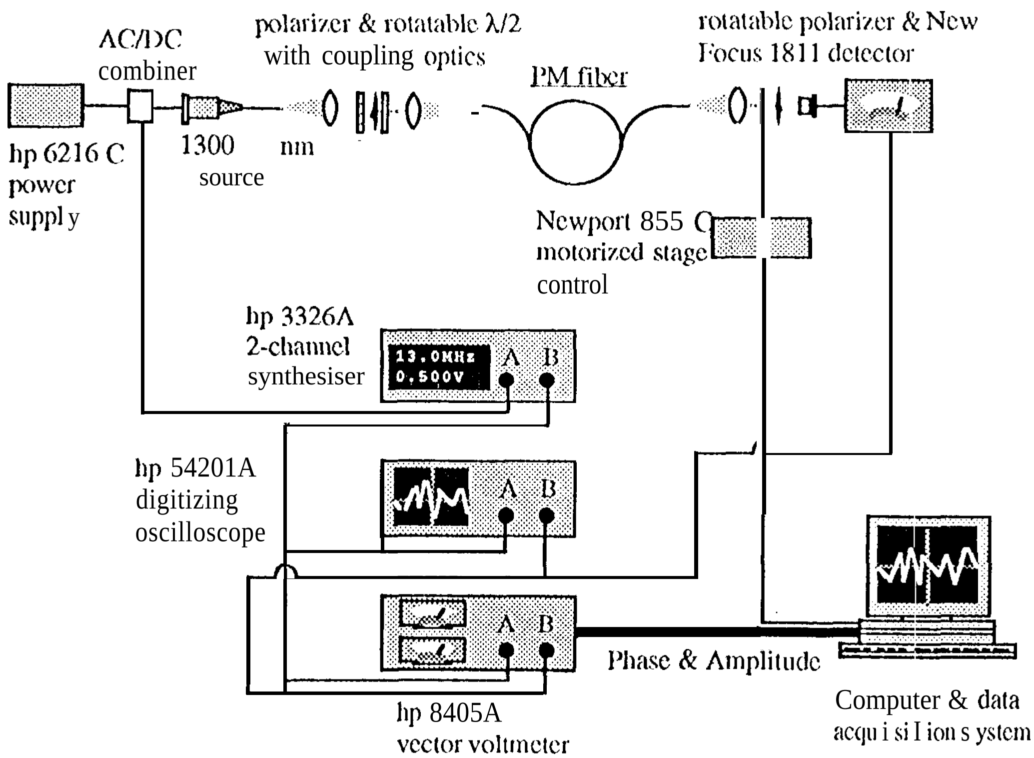


Fig. 5 Diagram of the experimental, setup for coherent detection polarization alignment.

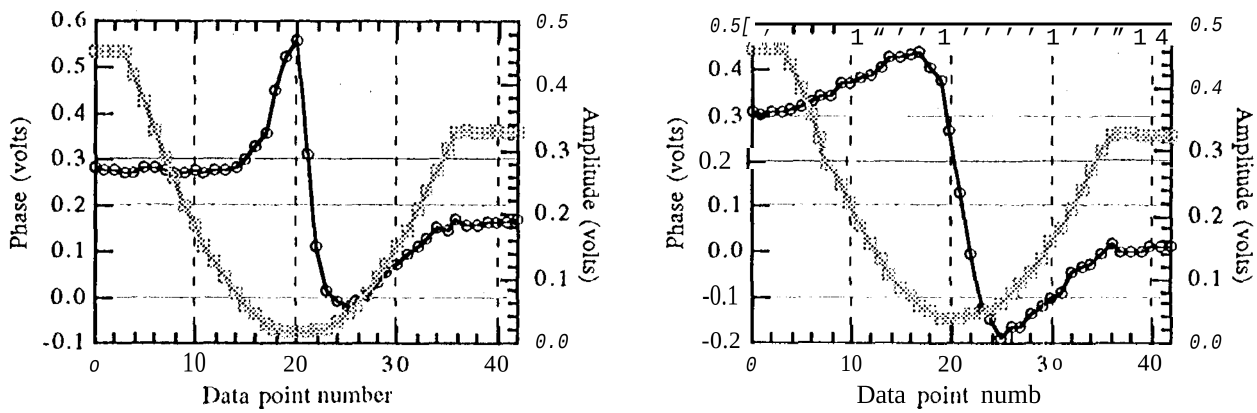
The setup used to gather the data is shown on figure 5. A pigtailed current modulated multimode laser diode at 1300 nm was used for the experiments. The output was collimated and passed through a polarizer, a half wave plate, and coupled into a PM fiber pigtail. The $\lambda/2$ (half-wave) plate was used to rotate the linear polarization launched into the fiber. The output from the PM fiber was collimated and analyzed by means of a linear polarizer on a motorized rotation stage. The angular position of the polarizer was controlled by the computer through the motorized rotation stage control electronics. The intensity of the light was then detected with a 100 MHz bandwidth detector. The "goal" is then to rotate the λ/2 plate until a single polarization eigenmode of the PM fiber is excited. A series of electronic instruments are used to help determine when the "goal" is achieved.

The instruments needed for coherent detection are a signal generator (to modulate the laser and provide a reference signal for phase measurements) and a vector voltmeter or other electronic coherent detector to measure the amplitude of the optical power meter output and the phase with respect to the reference signal. A two channel signal synthesizer was used to provide sinusoids of different amplitude (but same frequency) to the laser and to the vector voltmeter.

In addition, an oscilloscope is used to view the input and output waveforms, and a computer records the amplitude and phase of the output waveform as a function of the analyzer angle. Initially, a chart recorder was used to record the data, but the switch to a computer data acquisition system using Labview was welcome.

5. EXPERIMENTAL RESULTS

Several experiments have been done to verify the theoretical predictions. It has been found that the observations agree well with the theory, but only qualitatively. In the experiments, a current modulated multimode semiconductor laser diode was used as a modulated light source. The output form this laser is a combination of intensity modulation and frequency modulation of all the longitudinal modes of the laser. An accurate theoretical analysis would need to include all these effects, and would therefore involve series of Bessel functions. While such an analysis would be necessary to accurately predict the experimental results, the basic treatment presented in this paper is sufficient to determine the shape of the phase and amplitude curves used for alignment.



(a) (b)

Fig.6 Phase (black) and amplitude (gray) for a 68 degree change in analyzer angle for an input alignment angle of (a) 1 degree (b) 9 degrees.

The first experiment was done on a short piece of PM fiber (about 2 meters long). The modulation frequency was 20 MHz. This experiment was clone before the theory was worked out, and it was very surprising to see that the phase of the modulation depended on the position of the input and output polarization so strongly. Variations of several degrees in the phase measurement were observed! This is surprising since the phase difference between the two polarization eigenmodes for a 2 meter long PM fiber is in the order of 2000 optical wavelengths (for a 1 mm beat length) or a mere 0.05 degrees at a 20 MHz modulation frequency. The large variations in phase, as was shown in the theory, are a result of the interference between the two polarization eigenmodes. The interference causes the phase at the modulation frequency to depend on the optical phase. Since the optical phase is strongly dependent on the position of the input and output polarization, the interference results in large variations in the phase of the modulation.

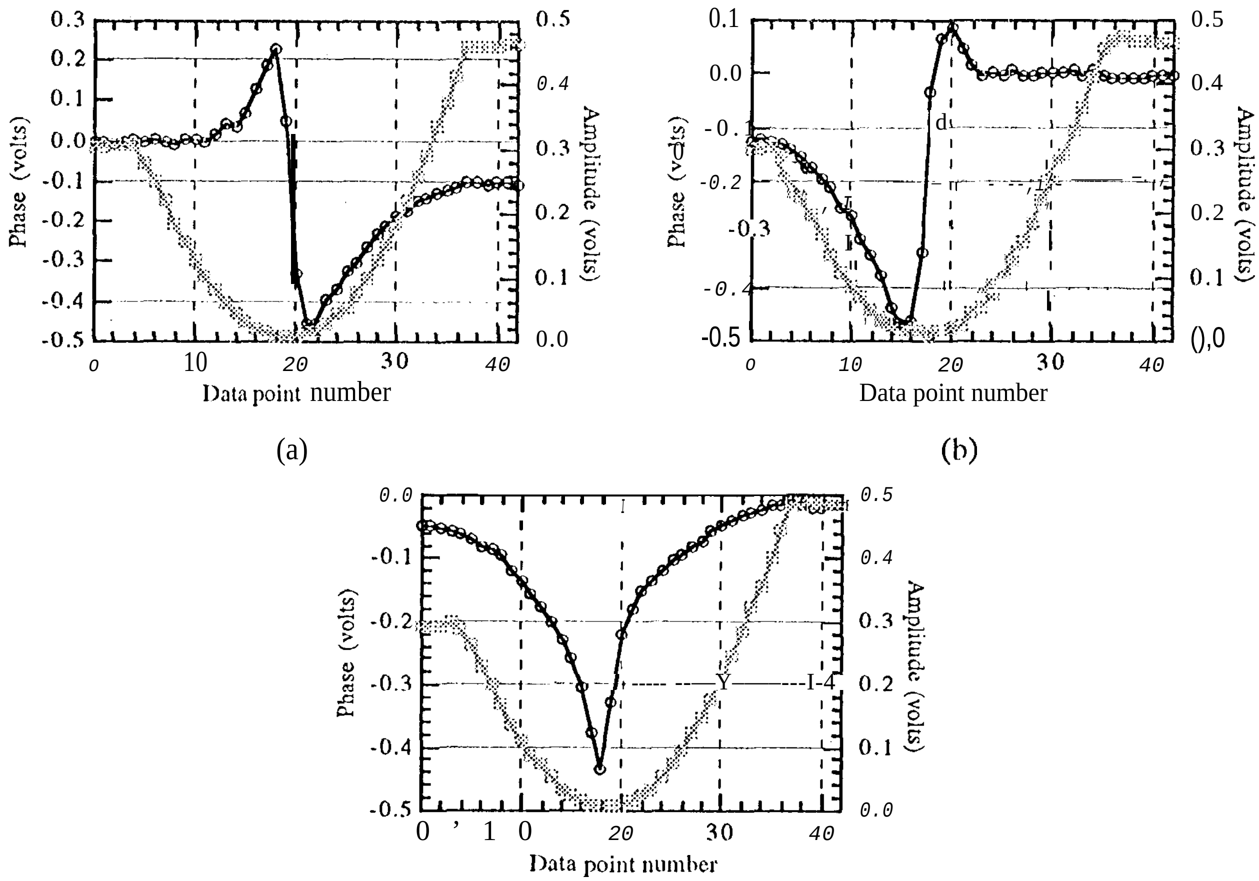


Fig. 7 Phase (black) and amplitude (gray) for a 68 degree change in analyzer angle for an input alignment angle of a few degrees and different optical phase (drift).

In the second experiment, the polarization was aligned into one of the PM fibers of a variable ratio PM fiber coupler. A polarization extinction ratio of 25 dB was measured after completing the alignment. The coupler, made by Canadian Instrumentation and Research Limited, is a polished PM fiber evanescent coupler with transverse micrometer positioning to adjust the coupling ratio [thesis by Dalgren]. To the polarization alignment setup, it is just like a piece of PM fiber. The optical length between the input and the output was approximately 10 meters. The width of the phase peaks was minimized in order to align the polarization. The alignment takes only a few minutes, since a single measurement gets you really close to alignment right away. Once the polarization is almost aligned, the amplitude was used to fine tune the alignment. The amplitude has the advantage that it is a single measurement that can be obtained immediately without having to wait for a scan of the analyzer angle.

Figures 6 and 7 show some of the measurements made. The analyzer angle is changed 68 degrees in these plots. The phase is in volts--1 volt corresponds to 10 degrees. The amplitude is also in volts, but the absolute measurement is not important, since it depends on the laser power used, the detector sensitivity etc.

Figure 6a shows the change in the width of the phase peaks as the input angle is changed from 1 degree to 9 degrees. The width increases as the input polarization is misaligned. This is in agreement with the theory. It can also be seen, as is shown in the theory, that the minimum amplitude corresponds to the sharp change in phase, and that the minimum amplitude increases as the input is misaligned. The flat regions in the amplitude and phase seen in figures 6 and 7 correspond to before and after the analyzer angle was changed. The larger difference in phase between the flat regions in figure 6 b is a nice way to see that the phase peaks are wider than in figure 6 a.

Figure 7 shows the change in the shape of the phase peaks as the optical phase drifts around. If these figures are compared with the theory, figure 7 c probably corresponds to a 90 degree optical phase difference, while figures 7 a and 7 b probably have optical phases equally separated from 90 degrees but on opposite sides (since the curves have flipped).

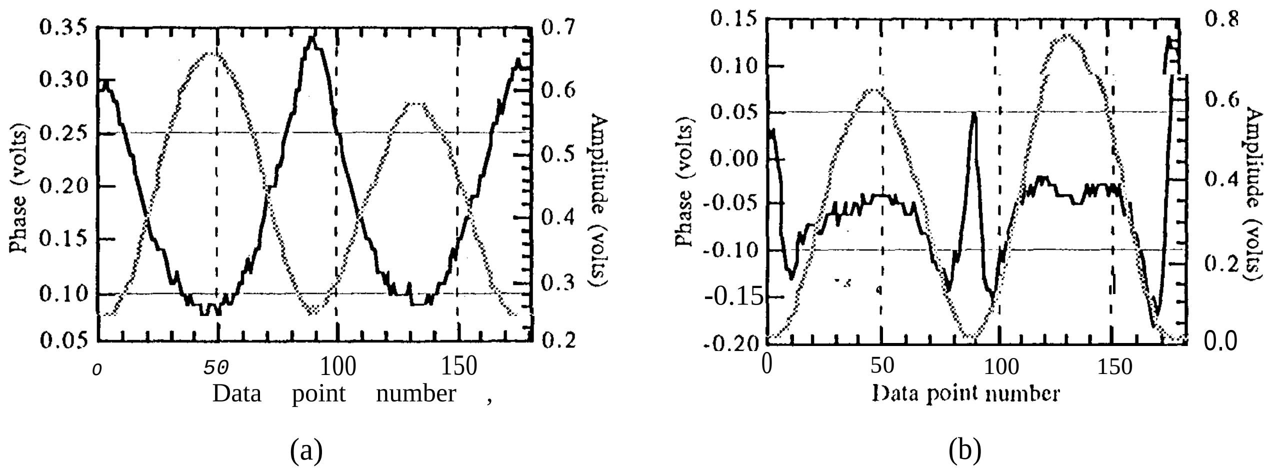


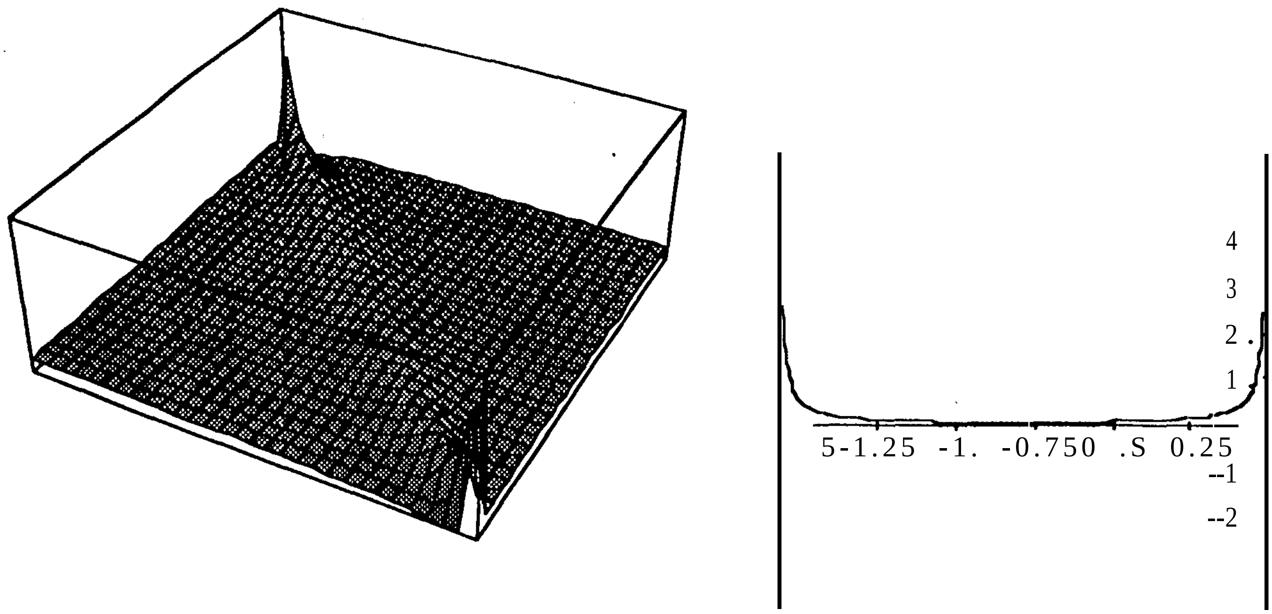
Fig. 8 Phase (black) and amplitude (gray) for a 360 degree change in analyzer angle for an input alignment angle of (a) 20 degrees and (b) 2 degrees.

The purpose of the third experiment was to see if the same method can be used to align polarization into a very long PM fiber. In this experiment, a 1 km long PM fiber was used. A polarization extinction ratio of 20 dB was achieved by minimizing the phase vs. analyzer angle peaks. A sample of the data is shown in figure 8. The shape of the phase curves did not drift as for shorter pieces of PM fiber, but the peak to peak phase variation did. It is suspected that a 1 km long PM fiber is sufficiently long to integrate over the optical phase. The difference in peak to peak amplitude seen in figure 8 is attributed to beam steering by the rotating analyzer.

6. ALIGNMENT METHODS

The alignment method used in the polarization alignment experiments described in this paper was to minimize the width of the phase vs. analyzer angle peaks. Since the width of the peaks gives you an immediate estimate of the input alignment, it is an especially useful method to get close to alignment with a single measurement. Once the input alignment is within a couple of degrees, minimizing the amplitude is a more practical alignment method since an immediate value is available, while the phase requires a scan by the analyzer.

To solve the problem of having to visually determine the width of a phase vs. analyzer angle peak, the derivative of this curve could be measured by changing the analyzer angle by a very small amount. As the Mathematica 3-D figure 9 a shows, the derivative of the phase peaks sharply when the input is aligned. The vertical axis shows the relative magnitude of the derivative, and the two horizontal axes are the input angle (θ) and the analyzer angle (ϕ). The left corner is $(0, \phi) = (0, 0)$, and the right corner is $(\theta, \phi) = (90, 90)$ degrees. A method of alignment would be to change the analyzer angle to maximize the derivative of the phase. This would position the input polarization and output analyzer angle such that $\theta = 90 - \phi$, i.e. orthogonal to each other. Then, if the input is rotated by the same amount as the output (but in opposite directions), the crest of the phase derivative (shown in figure 9 b) can be followed until a maximum is reached at the point of perfect alignment.



(a) (b)

Fig. 9 (a) 3-D plot of the phase derivative (vertical axis) as a function of input polarization angle and output analyzer angle (horizontal axes). (b) Relative magnitude of the phase derivative along the crest in (a).

7. CONCLUSION

This paper has described how electronic coherent detection can be used to align polarization in PM fibers. A theoretical model using Jones calculus agrees very wc]] with experimental measurements. The theoretical model was then used to develop a method of polarization alignment which was used experimentally to align polarization into a PM fiber coupler and a 1 km long PM fiber.

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