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P32 Quadrature Polarization-State Delivery Through Optical Fiber For Polarimetric Sensors

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Abstract

Single-ended, active control of the output polarization state of a polarization-maintaining fiber is demonstrated. Normal eigenstate plus controlled quadrature outputs together allow stable phase demodulation and fringe counting in polarimetric fiber sensors.

Introduction

Polarimetric optical fiber sensors measure the retardation of a birefringent optical element by injecting an optical signal of known state of polarization (SOP) and measuring the fraction of light I_t transmitted through an output polarizer. Many ingenious signal processing schemes have been proposed[1] to circumvent the fundamental problem of this class of sensors; the sensor transfer function is periodic, resulting in signal fading and directional ambiguity if the measurand drives the sensor over more than one fringe. To our knowledge, the signal recovery scheme described here is novel. It is of wide applicability and solves the above problems through the sequential generation of quadrature states.

Signal processing schemes previously proposed fall broadly into three categories: (a) heterodyne or pseudo-heterodyne, (b) active homodyne and (c) passive homodyne methods. The first category uses source frequency modulation to generate an output even in the absence of a change in the measurand[2]. Variations of the measurand then produce an instantaneous phase change which is recovered by standard FM demodulation techniques.

Active homodyne schemes rely on locking the phase to a particular point of the sensor transfer function using a low-frequency servo loop. High sensitivity operation is restricted to the linear portion of the sinusoidal transfer function and ambiguity results if phase changes occur which move the operating point more than one fringe.

In the passive homodyne technique the optical configuration itself produces two separate outputs which are in phase quadrature. The availability of two quadrature outputs allows the elimination of signal fading and the determination of direction in a fringe counting system. Such schemes are simple yet capable of excellent sensitivity[3].

The remote polarization state control scheme proposed here is applicable to this third category of signal processing, and may be termed 'sequential passive homodyne'. It works by sequentially delivering two pairs of SOPs through polarization-maintaining (PM) optical fiber to a sensor head at a remote location. These are not only the <u>orthogonal</u> (π phase difference) states transmitted unchanged along the fiber eigen-axes, but additionally two states in phase <u>quadrature</u> ($\pm\pi/2$ phase difference). The controlled state pair is locked using an active control loop modulating the fiber birefringence Γ_f by heating a small section of fiber.

In this work the actively-controlled states leaving the fiber are left- and right-circular states. Controlled and normal states may of course be transformed into any other pair of output quadrature states using a suitable retarder.

Experiment

Figure 1 shows the experimental configuration. The SOP of light from a linearly polarized HeNe (633nm wavelength) laser was rotated using a bulk half-wave-plate and injected into the fiber (10m, PM, beat length $\approx$1mm) at -45° to the H-axis (H,V designate the fiber axes). The fiber was cabled in plastic sleeving and both ends were polished at 15° to the axis to reduce disturbing reflections. At the output of the fiber the light was collimated and projected through a bulk quarter-wave-plate (QWP) at 22.5° and a normally oriented, 50% dielectric reflector. This *Primary Output* would be used as input to the polarimetric sensor.

Light reflected by the dielectric reflector travelled back through the QWP and fiber to be split off in a 50% pellicle beamsplitter oriented at $< 10°$ angle of incidence. This *Control Output* SOP was analyzed using a 5° deviation Wollaston prism and two photodetectors D_H, D_V. The prism was oriented to resolve the H,V intensities.

In order to effect a SOP-control loop, the difference between the electrical outputs corresponding to the two detected intensities was amplified, normalized to the total intensity, integrated and used to drive a heater in contact with 150mm of bare fiber. This was close to the input end, but could be placed anywhere convenient. The fiber-heater was formed by dip-coating the fiber in conductive silver paint. The heater resistance was 40-200Ω in different constructions. The heater allowed a fiber differential retardation (Γ_f) of $>6\pi$ radians and a phase slew rate $\approx$100 rad/s.

In the absence of closed-loop control, the Primary Output state wandered randomly with stress and temperature variations in the cabled fiber, as is expected with non-eigenstate transmission. Closing the control loop forced the output state to a stable, linear state at -22.5° to the fiber output eigenstates, independent of modest thermal perturbations to the fiber. Phase variations of less than 2° remained. With larger variations in fiber birefringence Γ_f the range of the control loop would be exceeded, and lock lost.

Theoretical Treatment

In order to describe the loop operation we use the Jones calculus[4]. For a linear input state at -45° to the fiber axes the Jones vector is $J_{input} = (E_H : E_V) = 1/\sqrt{2} \cdot (1:-1)$. The corresponding Control Output state is $J_{control} = 1/2 \cdot (1 - e^{i\Gamma f} : 1 + e^{-i\Gamma f})$. As the fiber retardation Γ_f varies from $0\text{-}2\pi$ with environmental temperature variations both $J_{primary}$ and $J_{control}$ vary, with $J_{control}$ being in the same SOP for only two values of Γ_f ($\pi/2$, $3\pi/2$). This is in stark contrast to the case if the retarder QWP is not present. Then the Control Output is of the form $J_{control} = 1/\sqrt{2} \cdot (e^{-2i\Gamma f} : 1)$, the $2\Gamma_f$ term causing the SOP to repeat itself continuously for values Γ_f and $\Gamma_f + n\pi$ where n is an integer. The double-angle characteristic would mean that while Control Output stabilization would function, the Primary Output would be ambiguous, taking on one of two possible orthogonal states.

We may better visualize the control scheme's operation using the well-known Poincaré sphere[5] representation of polarization states (Figure 2). On the sphere are shown two loci of SOPs. With the QWP in place the Primary Output state varies with $\Gamma_f=0\text{-}2\pi$ along a great circle through the points (-135°,45°), (135°,0°), (45°,-45°), (-45°,0°), where angles are sphere angles. The locus of states at the Control Output given above is wrapped into a figure-of-eight centred on P and touching the eigenstates H,V. The control loop forces the detected H and V intensities to be equal and the Control SOP to be P. To determine which of the two branches of the locus of states passing through P at ±45° (corresponding to different primary output states at (135°,0°) and (-45°,0°)) is stable we must also know the electronic phase of the control loop. On the figure-of-eight locus P is passed with increasing retardation Γ_f in the directions shown by the arrows. If we assume that an increase in the error control variable $\epsilon=(I_H-I_V)/(I_H+I_V)$ increases Γ_f, then only the "North-West" branch is stable (Primary Output (-45°,0°)). Hence no state ambiguity exists. If the amplifier phase is reversed then the "North-East" branch is selected, with a flip of the Primary Output state to (135°,0°). Errors in angular placement of the QWP cause little change in the Control Output locus. The figure-of-eight lobes simply expand towards Q or contract to a smaller locus near P. Hence the loop is very insensitive to such errors.

Note further that any state on the PLQR great circle can be coupled in to the fiber. The control loop forces an identical output state (-45°,0°) independent of the input state. It is not even necessary to change the position of the analyzing Wollaston prism. Of course, input H,V eigenstates can also be delivered, giving Primary Output states at (45°,45°), (-135°,-45°) on the sphere. These are in quadrature (90° on sphere) to the controlled states. Limited continuous control over most of the Primary Output locus can be achieved by offsetting ϵ before passing to the servo amplifier.

Application to Polarimetric Sensors

By way of example we apply the technique to the determination of the retardation of a birefringent element of known angular orientation. This is depicted in the 'Remote Sensing Head' of Figure 2. One possible configuration is as follows: An eighth-wave-plate oriented through SS' is used to rotate the Primary Output locus to the equatorial plane. Then the normal fiber eigenstates enter the sensing crystal as R,L-circular states. The sensing crystal is then oriented at 45° on the sphere. Variation of the unknown retardation θ then causes rotation of the transmitted state along a great circle through RSLS'. A polarizer at S allows the sequential measurement of two intensities $I_{t1}=A\cdot\cos^2(\theta/2)$ and $I_{t2}=A\cdot\cos^2(\theta/2+\pi/4)$, where A is the unknown peak intensity and θ the unknown phase. The state analysis and transmission to the sensor evaluation system can occur using a single- or multi-mode fiber. θ may be determined from $\theta=2\cdot\tan^{-1}(1\text{-}\surd 2I_{t2}/I_{t1})$ independent of A. Endless phase determination for $\theta>>2\pi$ is simply effected by applying I_{t1}, I_{t2} to in-phase and quadrature inputs of an electronic up/down counter.

Summary

A technique for feedback-controlled delivery of non-eigenstates through polarization-maintaining fiber has been described. The output state is monitored in reflection through the same fiber, and controlled by a single fiber retardation variable. The ability to simply deliver two passive and two actively controlled states at 90° on the Poincaré sphere is sufficient for many applications in remote ellipsometry or requiring quadrature detection. Faster SOP control would be possible using semiconductor diode sources via current-induced wavelength shifts, fiber-stretchers or electro-optic devices.

References

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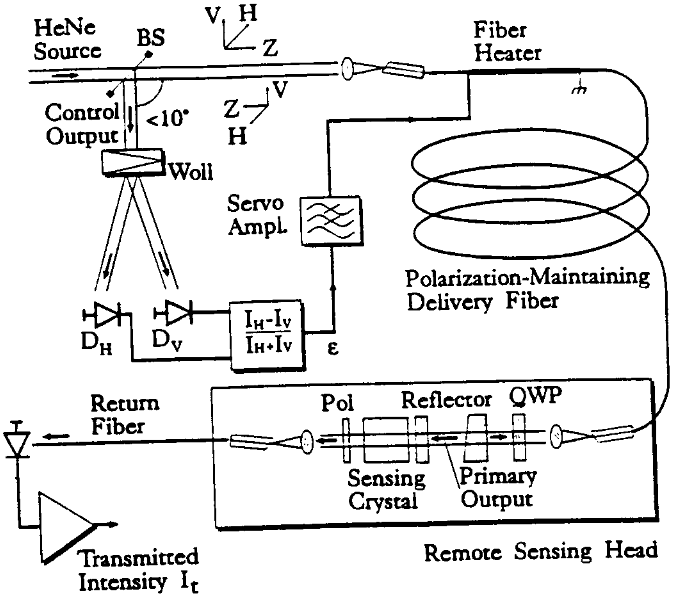

Figure 1: Active SOP control system. Light coupled into the delivery fiber at ±45° to the fiber axes is analyzed after a double pass through fiber and QWP. Active control then locks the Control Output, and with it the Primary Output to a known state. Controlled and normal eigenstate outputs allow unambiguous determination of polarimetric phase of a remote sensing crystal.

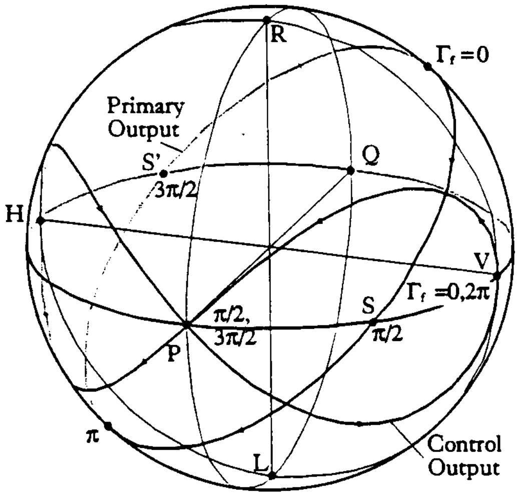

Figure 2: Poincaré sphere representation. As fiber retardation varies, the Primary Output state varies along a great circle, the Control Output in a figure-of-eight. Stabilized Primary Outputs are at S, S'.