In-Line Polarimeter Using Blazed Fiber Gratings

P. S. Westbrook, T. A. Strasser, and T. Erdogan

***Abstract*—We fabricate highly blazed, polarization-sensitive fiber grating taps and show how these may be used in combination with a UV-induced fiber waveplate to form a compact, in-fiber polarimeter. We show how the polarimeter may be employed as a feedback element to control polarization and use the feedback loop to demonstrate the stable, broadband (>70 nm) operation of the fiber polarimeter.**

***Index Terms*—Gratings, optical fiber devices, , polarimetry.**

I. Introduction

CONTINUED demand for increased per-channel and aggregate capacity of lightwave systems promises to make polarization-dependent effects important design factors. Two examples are optical PMD monitoring and compensation [1] at bit rates of $\geq$10 Gb/s, and polarization interleaving [2] of channel spacings $\leq$50 GHz. In order to fully control and utilize fiber polarization properties, an attractive polarization monitor is essential. Such a polarimeter should be compact, broadband, low-cost, and perform an in-line measurement with minimal insertion loss and PDL. Numerous fiber polarimeters have been proposed, including one design using only fiber gratings [3], and even demonstrated using couplers [4], [11], and side-polished fibers [5], [12]. In this letter, we demonstrate the fabrication of a fiber grating-based polarimeter which promises to be more stable, compact, and easily fabricated than these previous designs. We use its output in combination with a polarization controller to stabilize a randomly varying polarization. Use of the polarization feedback loop provides a practical diagnostic of the polarimeter performance, showing that the polarimeter provides stable operation over more than 70 nm.

II. Design and Fabrication

The polarimeter employs blazed fiber gratings as highly polarization sensitive taps [6], [7] to couple light (linearly polarized along the grating tilt axis) out of the core mode directly onto a detector at the fiber surface. Fig. 1 shows a schematic of the polarimeter. In order to determine the four Stokes parameters specifying the polarization of the light in the core, four weak ($\sim$0.15 dB tap) gratings scatter light at azimuthal angles of 0°, 45°, 90°, and $-45°$. These gratings alone are insufficient to determine the state of polarization, since incident circular polarization would yield the same outcoupled light whether it was right- or left-hand circularly polarized. An essential element in the polarimeter is therefore the fiber waveplate which converts circularly (or elliptically) polarized light into differently oriented elliptical states depending on handedness. These states can then be discriminated by a subsequent grating tap. The waveplate was written between the last two gratings and oriented at 0°, making the last grating sensitive to the handedness of elliptically polarized light. The state of polarization can then be determined by noting that the four detector outputs are linearly related to the four Stokes parameters. A simple calibration procedure [8], in which known states of polarization are sent through the polarimeter and the detector values recorded, allows determination of the matrix linking the detector values and the Stokes parameters.

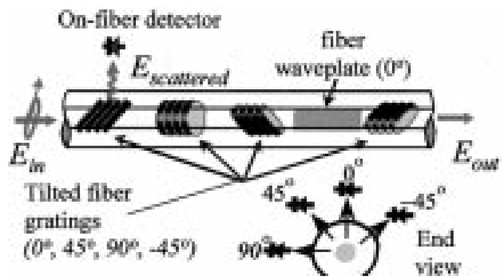

Fig. 1. Diagram of the all-fiber polarimeter.

The polarization-sensitive grating tap was achieved by setting the grating period (1070 nm) to phase-match core guided light at the measurement wavelength (1550 nm) with radiation modes propagating perpendicular to the fiber. Because these rays travel approximately perpendicular to the light guided in the core, they must be highly polarized in the direction perpendicular to the plane of incidence (s-polarized), and this scattered light is therefore proportional to the s-polarized light in the grating. In order to maximize the efficiency of this scattering (and, therefore, the detector signal), the gratings were blazed at 45°, resulting in strong scattering into a narrow azimuthal angular range. The resulting grating transmission spectrum had a broad (>100 nm) radiation mode spectrum as shown in Fig. 2(a). Polarization extinction ratios (P_p/P_s) for a given grating were measured to be in excess of 20 dB. Fig. 2(b) shows a volume current theory [9] calculation of the extinction ratio using estimates of the index modulation amplitude ($\sim$0.001) and a detector acceptance angle ($\sim$11°) adjusted to fit the extinction ratio, along with data from the actual polarimeter gratings.

The intracore gratings were written in deuterium-loaded Corning Flexcore 1060 using an excimer pumped frequency doubled dye laser at 242 nm in an interferometer as shown in Fig. 3. The blaze angle was achieved by rotating the fiber with respect to the interferometer plane. Because the fiber focuses the UV fringe pattern cylindrically, the required fiber tilt angle

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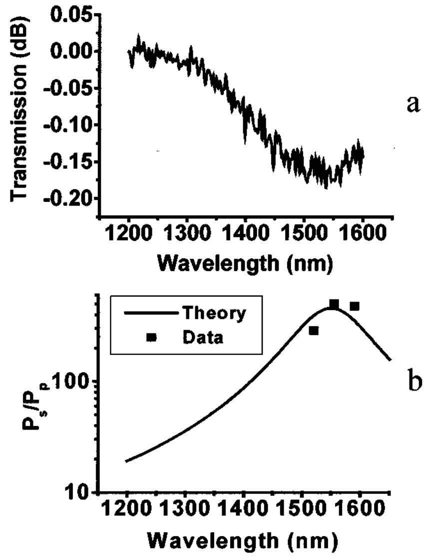

Fig. 2. (a) Transmission spectrum of unpolarized light through a single 45° blazed grating tap. Noise is due to white light source.(b) Theoretical estimate of ratio of s- to p-polarized scattered light versus wavelength plus data from polarimeter gratings.

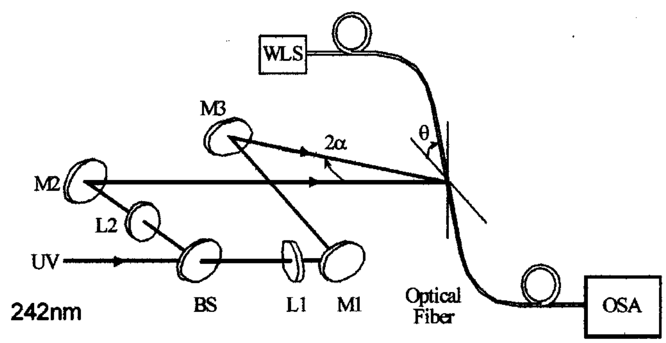

Fig. 3. UV Interferometer used to fabricate highly tilted gratings. M: mirror; L: lens, BS: beam splitter; θ: fiber tilt with respect to interferometer plane.

θ is 33.7° with respect to the plane of the interferometer for a 45° grating tilt within the fiber core. The UV fluence in each beam was 120-mJ/cm^2 pulse, and exposure time was about 200 s for each grating. The fiber waveplate was also fabricated using exposure to 242-nm radiation by exploiting the effect of UV-induced birefringence [10]. Two sequential 600-s exposures (fluence $= 120$ mJ/cm^2 pulse) yielded a $\sim$1 cm UV-induced waveplate with a retardation angle of order 20°.

III. Polarimeter Characterization

To characterize the fiber polarimeter we compared its measured values with those measured on the Hewlett Packard 8509B polarization analyzer. Random polarizations spanning the entire Poincare sphere were simultaneously measured by each polarimeter and compared. The Stokes parameters agreed to within the HP8509B accuracy of 1.5%. Moreover, since the grating taps were 0.15 dB, the total PDL of the device was less than 0.15 dB measured from 1520 to 70 nm.

A more practical test of the fiber polarimeter involved using the polarimeter output as a feedback signal to drive a commercial polarization controller (via a computer feedback algorithm) to provide active stabilization of a randomly varying input polarization. The feedback loop experiment is shown in Fig. 4. The polarimeter output is used to drive a polarization controller comprised of three (LC) waveplates (E-Tek) whose birefringence is determined by a control voltage. The effect of each waveplate is to rotate the Stokes vector about an axis determined by the waveplate orientation and subsequent waveplate birefringence. A geometrical calculation then provides the required voltages to cause the Stokes vector to reorient toward the set point Stokes vector. A randomly varying polarization was obtained by passing light at 1550 nm through 10 km of Corning

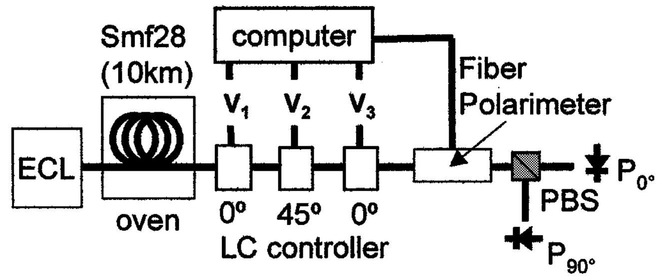

Fig. 4. Polarization feedback loop used to test fiber polarimeter. LC: liquid crystal; PBS: polarizing beam splitter; ECL: tunable external cavity laser.

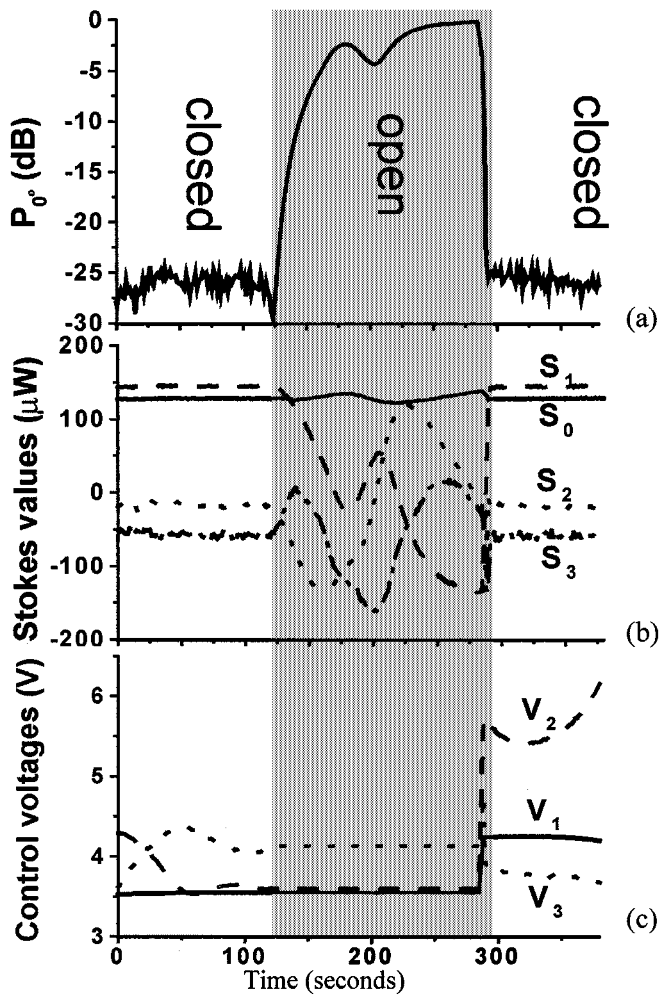

Fig. 5. (a) Power at nulled PBS port (P_{0°) with and without active feedback from polarimeter. (b) and (c) show the measured Stokes parameters and the polarization control signals, respectively.

SMF28 cooling in an oven. The feedback loop set point Stokes values were adjusted to minimize one port of a fiber polarizing beam splitter (PBS). Fig. 5 shows the open- and closed-loop behavior as the fiber cooled. Fig. 5(a) shows that the signal in the minimized port of the PBS was nulled by -25 dB from its maximum value and that it quickly rose to much higher levels without the feedback loop. Turning the feedback loop on restored the -25-dB extinction. Fig. 5(b) and (c) shows variations in the measured Stokes parameters and in the liquid-crystal (LC) control voltages in the open- and closed-loop states.

As a measure of the polarimeter optical bandwidth, the feedback loop was activated and the wavelength was changed in steps of 10 nm from 1520 to 1590 nm. The stabilized power level remained at less than -25 dB for all these wavelengths without any change in the feedback loop set point, showing that the polarimeter provides stable, accurate polarization measurements over a bandwidth in excess of 70 nm.

IV. Conclusion

We have demonstrated the fabrication of an all-fiber polarimeter with a unique set of desirable features including small size and wavelength insensitivity. The polarimeter output was tested by using the measured Stokes parameters in a feedback loop to convert a randomly varying polarization input to a specified fixed polarization output. The active polarization control provided continuous extinction of >25 dB through a fiber polarizing beam splitter over a bandwidth of 70 nm.

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