Fast wavelength-parallel polarimeter for broadband optical networks

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We describe a novel wavelength-parallel polarimeter operating in the light-wave band that measures the complete state of polarization of 256 wavelengths in parallel within 20 ms (software-limited), with the potential for submillisecond operation. By use of fast switching ferroelectric liquid crystals in conjunction with an InGaAs arrayed detector, selection and wavelength-parallel detection of individual polarization components can be achieved within approximately 150 μs. This instrument offers unprecedented sensing capability that is relevant to the compensation of polarization-related impairments in high-speed light-wave communications.

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Effects related to the polarization state of light have recently emerged as key issues in extending the performance of optical communication systems.[1] The state of polarization (SOP) of light emerging after propagation through a length of single-mode optical fiber is usually scrambled, even for input light with a well-defined SOP. This condition places stringent requirements on the polarization-dependent loss specifications of components used in fiber systems. For sufficiently high-speed and broadband systems (e.g., 40 Gbits/s), polarization-mode dispersion (PMD) can cause significant pulse spreading and distortion, which leads to errors in digital communications as well as to the degradation of analog light-wave system performance.[2] When the PMD-induced spreading is greater than the input pulse's duration, the output signal is characterized by a complex wavelength-dependent SOP, along with wavelength-dependent and polarization-dependent delays, all of which can vary strongly within the bandwidth of a single data channel. In recent years there has been a great deal of research activity dedicated to compensation for PMD effects. Such compensators need to respond fast enough to track the dynamic changes in the polarization spectrum of broadband light induced by PMD, preferably of the order of milliseconds.[3,4] Naturally, measurements of the SOP can be important for the control of such compensators. Optical polarimeters that are currently available can provide measurement speeds of as much as a few kilosamples per second but work on only one wavelength channel at a time. This is a significant shortcoming for wavelength-dependent multiplexing systems that employ ten to hundreds of wavelengths as well as for short-pulse systems. For these reasons we have developed a novel wavelength-parallel polarimeter for the light-wave band that measures the complete SOP of 256 wavelengths in parallel in 20 ms in a single apparatus, with the potential for submillisecond measurement times.

In a typical polarimeter, intensities (I) of four polarization components of the light under test, such as linearly polarized components oriented at 0° (I_0), 90° (I_{90}), and 45° (I_{45}) as well as the right-hand circular polarization (RHC) component (I_{RHC}) are first measured. The Stokes parameters (S_0, S_1, S_2, and S_3) that describe the complete SOP of the incident light can then be determined.[5] In one approach to measuring the desired four polarization components, the incident light is split into four equivalent beams. Each beam then passes through a different set of polarization-altering elements including a polarizer to extract a different polarization component.[5] In an alternative, single-beam arrangement, the optical components are manipulated to provide a series of different polarization transformations in a time-sequential manner, thereby facilitating detection of a set of desired polarization components with a single element. Because current commercial light-wave polarimeters are all single-wavelength channeled, they are often adapted for use in multiwavelength and broadband systems by a swept-frequency approach, e.g., by use of tunable filters. However, this approach is wasteful of power, and measurement speed is severely limited by the tunable filters, which also cause measurement delays from one wavelength to the next. Thus such setups are not suitable for fast, multiwavelength polarization measurements.

To overcome these limits we devised the wavelength-parallel polarimeter setup shown in Fig. 1. This may be considered an extension of the single-channel, time-sequential polarimeter approach to permit fast wavelength-parallel operation. Our polarimeter is based on two significant innovations: the use of fast-switching ferroelectric liquid-crystal (FLC) retarders for time-sequential polarization transformations and

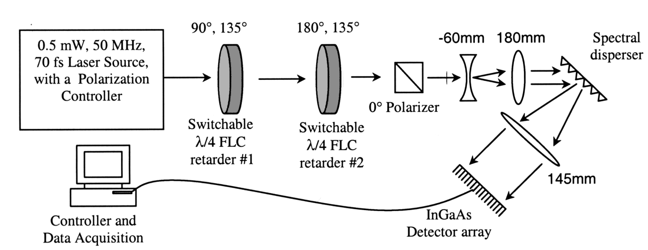

Fig. 1. Experimental setup of the wavelength-parallel polarimeter.

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the use of a spectral disperser with an arrayed detector to measure hundreds of wavelengths in parallel at an unprecedented speed. Also, because no mechanical movements are required during operation, the system is capable of accurate and repeatable measurements for each of the wavelength channels.

In the experimental setup shown in Fig. 1, two FLC cells (antireflection-coated; Displaytech LV1300-OEM) are used to manipulate the polarization of the incident light, causing different polarization components to pass through the linear polarizer (whose orientation is taken to be 0°). The FLC cells were designed for quarter-wave retardance and can be switched within less than 100 μs between two stable optic axis orientations that are separated nominally by 45°.[6] Thus four distinct polarization components can be extracted for measurement (see Table 1 for the FLC switching sequence). After passing through the polarizer, the light is spectrally dispersed by a 600-line/mm grating and a 145-mm focal-length lens onto a 256-pixel linear InGaAs detector array (Sensors Unlimited, SU256LX-17T1-0500–A/H). The grating was aligned at an incident angle of 13°, with 5° of dispersion angle at 1530–1630-nm light, and the arrayed detector had a 50-μm pixel pitch and a 500-μm pixel height. The spot size before the grating was ~12 mm in diameter. Our setup resulted in a 100-nm wavelength span from 1530 to 1630 nm falling onto the detector array with 0.4 nm of resolution (limited by the detector's pixel size). One can select different wavelength ranges and frequency resolutions by altering the spectral disperser setup. We used our detector array with a 52-μs readout time and with a typical total input power of 0.5 mW (~2 μW/pixel). The potential total acquisition time for one complete polarization measurement set is $4 \times (100\ \mu s + 52\ \mu s) = 612\ \mu s$. With a millisecond measurement goal, more than 350 μs are left for software processing. Currently, our measurement time has been limited to 20 ms because of constraints of our data acquisition electronics and because of inefficient software coding.

We have performed experiments that confirm that 256 SOP measurements can be acquired over a wavelength span of 100 nm (1530–1630 nm) from a broadband laser source in parallel at less than 0.5 mW of total power. Some sample measurement data plotted on Poincaré spheres are shown in the figures below. In a first test, light was launched into a 10-cm length of polarization-maintaining fiber (PMF) with a beat length of ~2 mm, with the input SOP intentionally misaligned with respect to the axes of the PMF. This PMF provides approximately two full waves of retardance difference at 1530–1630-nm wavelength light. As a result, the measured wavelength-dependent SOP should make two full rotations about the sphere centered at the principal SOP of the PMF. From Fig. 2(a) we can see that the result is as expected. Finally, Fig. 2(b) shows the wavelength-dependent SOP data that result from a cascade of two concatenated PMFs with slightly different lengths and misaligned optic axes. The SOP exhibits a more-complicated trajectory on the sphere as a function of wavelength, which again is in accord with the expectation.

Ideally, each step in our measurement sequence is designed to yield independently a value for I_0, I_{90}, I_{45}, and I_{RHC}. However, because of the real behavior of the FLC cells, some errors will be introduced during measurements. First, the FLC cells do not switch by exactly 45° because of the physics of the liquid crystal.[6] Second, for a fixed birefringence of the FLC cell the retardance must be wavelength dependent, which departs from our assumption of perfect $\lambda/4$ cells. Fortunately, these errors can be minimized by application of a software correction algorithm, as described below.

To assess the measurement error we input various known polarizations into the polarimeter. Figure 3(a) shows measured data for 45° linearly polarized input light over the 100-nm wavelength span mentioned above. All 256 points, which represent 256 wavelength-dependent SOP samples, are clustered about a single spot at the 45° point on the sphere, as expected. Figure 3(b) shows data obtained for 90° input light, which exhibits the worst case for the wavelength of the system (comparable results occur for 0° polarized light). The measurement error at each wavelength is shown in Fig. 3(c) for the 90° input case. The measurement error is taken to be the angle between measured normalized Stokes vector **S** and actual normalized Stokes vector **S**′ (Ref. 7):

$$\text{degrees of error} = \cos^{-1}[(S_1{}^*S_1{}' + S_2{}^*S_2{}' + S_3{}^*S_3{}')/(S_0{}^*S_0{}')]/\pi * 180°. \quad (1)$$

To reduce measurement error that results from wavelength dependence and other nonideal properties

Table 1. Truth Table for the FLC Switching Sequence

Polarization Component of Interest	First $\lambda/4$ FLC Fast Axis (°)	Second $\lambda/4$ FLC Fast Axis (°)
0°	90	180
90°	135	135
45°	90	135
RHC	135	180

[a]In all these cases the polarization state before the 0° polarizer is 0.

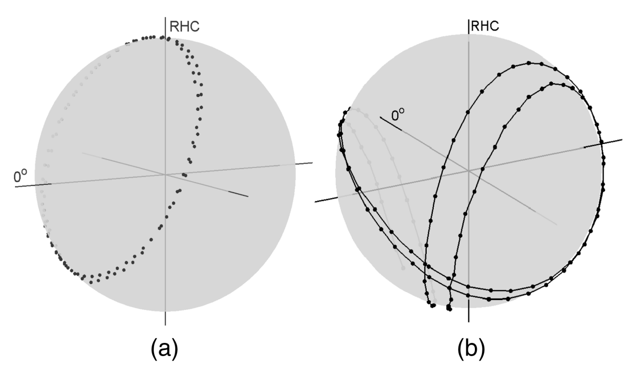

Fig. 2. (a) Experimental data for measuring wavelength-dependent SOP produced by a 10-cm-long PMF. Each point represents a SOP at a different wavelength, with 0.4-nm wavelength spacing. (b) Measured data after the 10-cm-long PMF is replaced with two concatenated PMFs.

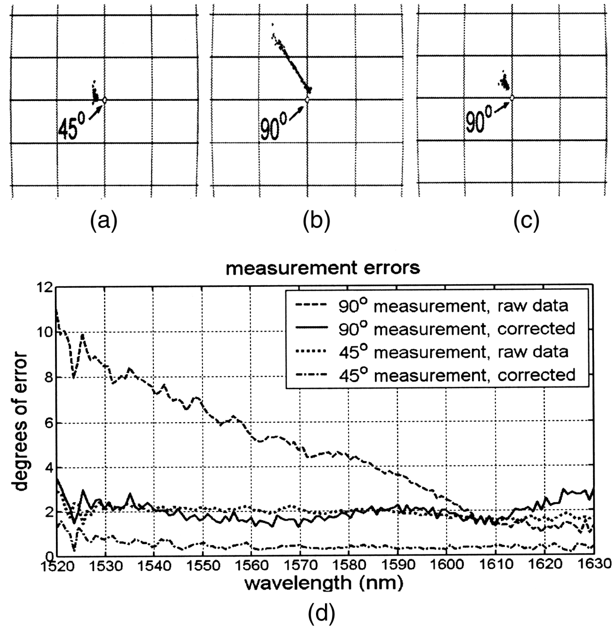

Fig. 3. (a) Measured data for each of 256 wavelength components for 45° linearly polarized light. Each grid division represents 5° in both longitude and latitude of the Poincaré sphere. (b) Measured data for 90° polarized light, showing the measurement error that is due to wavelength dependence and other nonideal factors. (c) 90° measurement after correction. (d) Measurement error versus wavelength for 45° and 90° measurements, both before and after the correction algorithm has been applied.

of the system, we apply a correction algorithm to the measured data. We begin by performing a calibration procedure in which we take measurements for several different known polarizations, e.g., 0°, 45°, 90°, and RHC. These known polarizations are produced by a polarizer and an achromatic quarter-wave plate.[5] Then, for each known input polarization with Stokes vector $[S]$, we formulate an equation $[D] = [M] * [S]$, where $[D]$ is the length-four vector whose elements correspond to the four data values recorded during our four-step measurement sequence. $[D]$ is related to $[S]$ by a 4×4 calibration matrix $[M]$. By recording $[D]$ for four or more known polarization inputs, we can calculate $[M]$.[5] Now, after the calibration is completed, we can measure $[D]$ for light with unknown Stokes vector $[S]$. $[S]$ can then be calculated by $[S] = [M]^{-1}[D]$ by use of the stored values of $[M]$ from the calibration procedure. Note that both the calibration procedure and its subsequent use for error reduction are performed for all wavelengths in parallel, consistent with our arrayed detection measurement approach. From Fig. 3(c) we can see that the measurement errors are dramatically reduced when this correction algorithm is applied to $\sim 2°$ or less over most of the wavelength range for our worst-case situation at 90°.

In summary, we have demonstrated a novel parallel polarimeter that captures the complete state of polarization of more than 256 wavelength components in the light-wave band in less than 20 ms, with potential for submillisecond response if improvements are made in the software. We anticipate that the unprecedented capabilities of this new wavelength-parallel polarization sensor will contribute to the field of PMD compensation.

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