Accurate Spectral Characterization of Polarization Dependent Loss

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Abstract – Building on previous work, a rapid, automated, non-mechanical measurement system for spectral characterization of polarization-dependent loss is presented. A deterministic fixed-states method in conjunction with real-time calibrated spectral information is used to infer wavelength-dependent Mueller matrix elements from power ratios at specific polarization states. Voltage-modulated liquid-crystal variable retarders set the input polarization states. A narrow, voltage-tuned filter generates a wavelength sweep from a broadband source. The sweep is calibrated in real-time by hydrogen cyanide reference lines. Actively balanced photodetection is employed to achieve low noise signals. I present polarization-dependent loss measurements from 0.0003 to 0.30 dB at 1550 nm to verify performance and also present results from artifact calibration standards of an all-fiber design.

Introduction

Until the advent of dense wavelength-division multiplexing (DWDM) systems, polarization dependent loss (PDL) was usually characterized only at a specific wavelength [1]. More recently, however, the wavelength dependence of PDL (WPDL) has assumed greater importance. A modification of a previously reported, deterministic fixed-states technique [2] has been implemented that allows the simultaneous characterization of wavelength dependence. The goal is to establish a capability for rapid measurement of WPDL to a resolution finer than 0.005 dB without sacrificing accuracy. This approach uses a non-mechanical technique employing ratio detection and simultaneous spectral calibration that is faster than most tunable-laser systems and more accurate than optical spectrum analyzers [3]. In addition, new results from an all-fiber WPDL artifact reference are presented. This artifact is intended to become a NIST Standard Reference Material (SRM) with a nominal PDL of 0.1 dB for the calibration of commercial instrumentation.

Concept

This method is a further variation of a matrix technique developed by Favin et al. [4], and relies solely on power ratio measurements over a wavelength range using specific polarization states. As in reference [2], four well defined polarization states are necessary to determine the first-row Mueller matrix elements of a component. The global polarization dependence of transmittance can be determined from these (wavelength dependent) matrix elements.

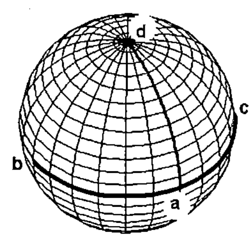

Figure 1A: Initial Poincaré trajectories of the liquid-crystal variable retarder (LCVR) pair.

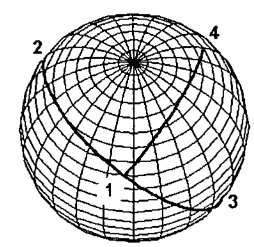

Figure 1B: LCVR trajectories following birefringent displacement

Because the measurement depends only on the relative coordinates of the four states, the only requirements on the set are that they maintain relative angular separations of 90° about the origin of the polarization (Poincaré) sphere, cf. Fig 1.

The four polarization states are produced by

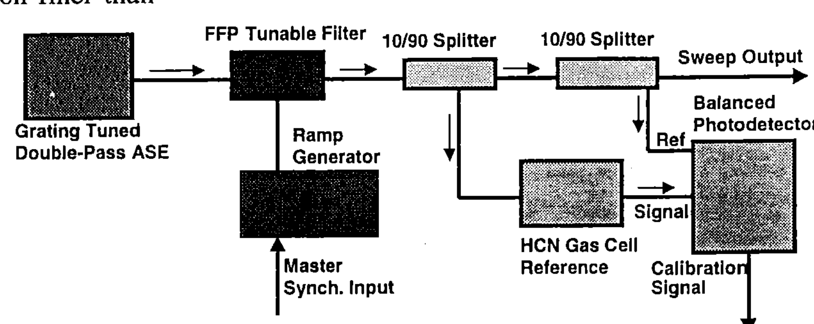

Figure 2: Diagram of swept wavelength source with HCN calibrator (Sweep Source)

two liquid-crystal variable-retarder (LCVR) units in series that hold the state during a wavelength sweep of a low-coherence polarized beam. The beam is generated by a double-pass amplified-spontaneous-emission (ASE) source followed by a fiber-Fabry-Perot tunable-filter (FFP-TF) driven by a ramp generator. The voltage ramp drives the filter across a selectable portion of the ASE spectrum in a repetitive sweep. This swept output passes through splitters and a NIST hydrogen cyanide (HCN) optical wavelength reference cell (SRM 2519), as shown in Fig. 2, which produces intensity modulated output. The HCN absorption

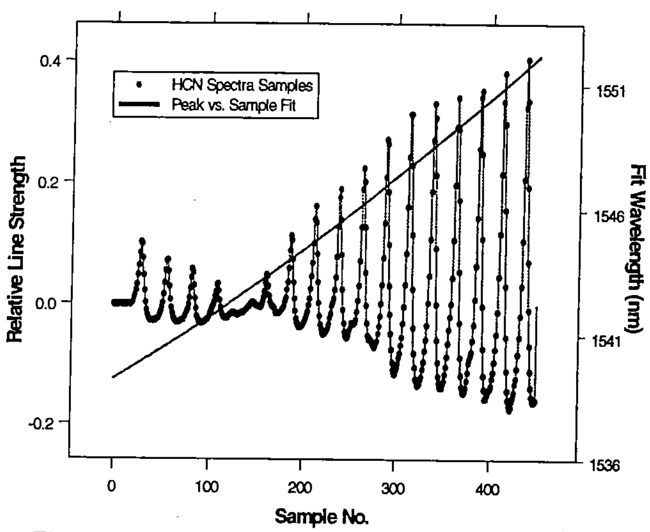

Figure 3: Typical P-branch HCN absorption signature from 1539 to 1551 nm with a quadratic calibration fit.

spectrum is measured by an amplified differential photodetector capable of 50 dB common-mode-rejection through active gain balancing. The absorption peaks are fit by a least squares quadratic to known peak wavelengths following each scan, providing real-time spectral calibration of each sample point. An example of the absorption signature and the subsequent peak fit are shown in Fig. 3.

Following the LCVR units, the light is transmitted by a single mode fiber with arbitrary but relatively stable birefringence through a splitter to both the device-under-test (DUT) and to a second actively balanced photodetector. This detector is operated in a logarithmic ratio mode and senses the four output power ratios ($I_1(\lambda)\ldots I_4(\lambda)$). Input power ratios ($I_a(\lambda)\ldots I_d(\lambda)$) are measured in the same way with the DUT removed to establish a baseline system response. Following wavelength registration to account for drift, the four first-row Mueller matrix elements ($m_{11}(\lambda) \ldots m_{14}(\lambda)$) are calculated from these power ratios as in reference [2]. Information about the global transmittance extrema are contained in the first row matrix elements. The transmittance extrema, $T_{min}(\lambda)$ and $T_{max}(\lambda)$ are

$$T_{\max}(\lambda) = m_{11}(\lambda) + \sqrt{m_{12}(\lambda)^2 + m_{13}(\lambda)^2 + m_{14}(\lambda)^2} \quad ,$$

$$T_{\min}(\lambda) = m_{11}(\lambda) - \sqrt{m_{12}(\lambda)^2 + m_{13}(\lambda)^2 + m_{14}(\lambda)^2}$$

so $\quad WPDL \equiv PDL(\lambda) = 10\log\left[T_{\max}(\lambda)/T_{\min}(\lambda)\right]$

which applies over the entire polarization-state space and wavelength range.

Implementation

Figure 4 shows a schematic of the measurement system. The system consists of five major sections: ASE sweep source, cf. Fig. 2, LCVR polarization state generator, measurement and calibration section, clock, and control computer. The polarization-modulated light is connected to the DUT through a spectrally flattened 80/20 splitter and the power ratio is sampled through single-mode fiber and fiber connectors. Prior to any measurement, the empty

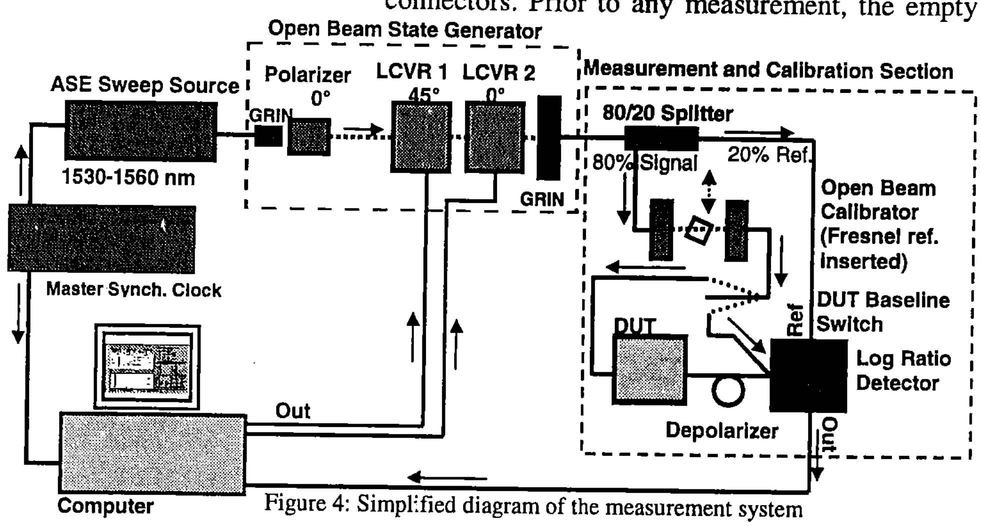

Figure 4: Simplified diagram of the measurement system

calibration cavity is switched directly to the detector for an initial baseline after which the Fresnel reference block is inserted at the appropriate angle to generate a calibration signal. Anti-reflection coated aspherical lenses are used to collimate the open beam and a polished BK7 glass cube acts as the Fresnel reference. The calibration signal is compared to the calculated value to give a calibration multiplier for all subsequent measurements during that session. Following calibration, the Fresnel reference is removed and another baseline is run for the DUT. The DUT is then inserted and switched in. The DUT output is depolarized with 40 m of high NA (0.37) multimode fiber to reduce the impact of PDL in the detector. Finally, the DUT WPDL signal is sampled at 450 points for each 12 nm wavelength scan. A scan period of 285 ms is required for each polarization state, after which the state is changed to the next in the series. An entire WPDL scan over the range of 1539 – 1551 nm takes less than 5 seconds including data processing time, which is currently the limiting factor.

Uncertainties

The design of this measurement system is both simpler and more sophisticated than that described in ref. [2] so that most uncertainties are now reduced by taking ratios. Items 1 and 2 below outline the two major systematic uncertainties in polarization and power that, together, comprise over 90% of the total systematic contributions. Discussion of minor effects will be deferred to a forthcoming publication. Values listed correspond to 1σ deviations in either signal power or polarization at 1545 nm.

1. *Polarization state accuracy.* Polarization state accuracy depends on both the measuring polarimeter and the LCVR bias calibration. I find that linear states exhibit an uncertainty of 0.69 % while the circular states have a 2.0 % uncertainty.
2. *System internal PDL variation.* The system retardance elements contribute their own PDL (0.02 dB) to that of the DUT. Given a maximum observed drift of the internal PDL over 5 minute intervals, this yields an uncertainty of 0.025 %.
3. *Propagated measurement system uncertainty.* Using the uncertainties above inherent to the measurement system, an error propagation model, based on the defining equations, calculates 0.0035 dB at 0.1 dB of PDL.
4. *PDL measurement repeatability.* Ten undisturbed measurements of a 0.12 dB BK7 WPDL were made following the initial baseline measurement. The random 1σ uncertainty averaged over all wavelengths yields 0.0012 dB as the effective single-sweep system noise and incorporates all effects that average down such as optical interference and detector noise. This component does not incorporate residual systematic wavelength dependence.
5. *Combined standard uncertainty.* Items 3 and 4 above are assumed uncorrelated, so the root-square-sum (RSS) at the 0.1 dB level is (0.0012 dB + 0.0035 dB) RSS = 0.0037 dB.
6. *Connector uncertainty.* As in reference [2], a significant source of uncertainty, which is not inherent to the LCVR system, is variations in measured PDL of DUT artifacts with connectorized pigtails following disconnection and reconnection. This could be explained by connector alignment (core offset) errors. For those artifacts, we add an additional 0.0029 dB uncertainty.

Stress and thermal drifts in pigtail birefringence must be minimized over the course of a measurement. The measurement method is sensitive to small errors in the matrix elements,

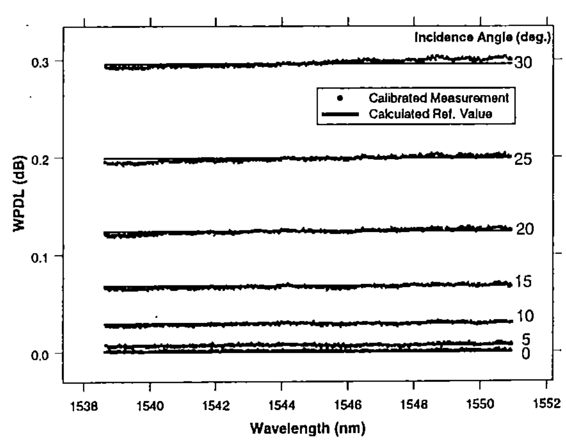

Figure 5: Open-beam BK7 artifact data calibrated at 30° incidence. Centerline is the calculated WPDL value. Residual wavelength slope falls within 2σ uncertainty.

such as those due to rotated, and therefore uncompensated, PDL between the baseline and DUT measurement. For this reason, one should calibrate the system prior to a measurement series.

Results

The primary artifact chosen to test the performance of the system provides a calculable PDL of moderate accuracy. The artifact consists of an open beam launcher/collimator followed by a 2.54 cm, polished BK7 glass cube. BK7 is convenient to use and has a well-known index of refraction. The cube is mounted on a rotation stage with 5' resolution. The beam pickup asphere is translated to compensate for beam displacement following rotation. Calculated (Fresnel) and measured WPDL values as a function of input angle are presented in Fig. 5 and are in good agreement. The residual system PDL was measured at 0° (normal incidence) as a 0.0014 ± 0.0006 dB offset over all wavelengths. A residual slope indicates a systematic uncertainty.

All-Fiber PDL Artifact Results

As mentioned in [5], a series of all-fiber PDL artifacts based on fusion-spliced sections of single-mode, polarizing, and multimode fiber was constructed. These artifacts form the basis of a new calibration transfer standard SRM at 0.1 dB. The artifact section is a few millimeters of polarizing fiber (18 dB/m extinction) that provides relatively stable PDL over the range of 0 - 40 °C. Some recent WPDL measurement results are presented in Fig. 6 using three SRM prototypes. A nearly constant positive slope is typical of

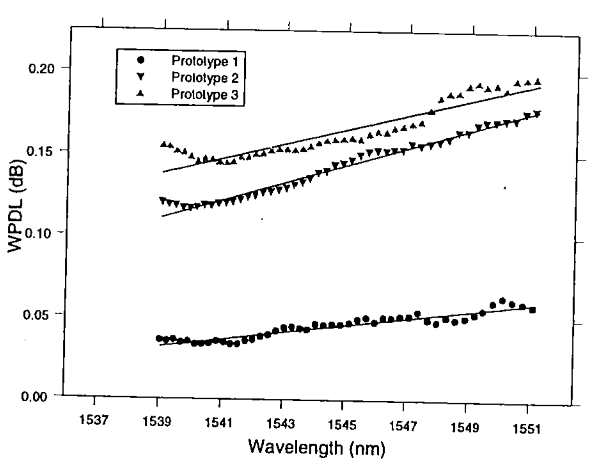

Figure 6: Wavelength dependent PDL for three SRM prototypes. A least-square fit line indicates trend.

polarizing fiber and is evident, with structure, in the data. This measurement system will be used to characterize WPDL in SRM artifacts.

Conclusions

An accurate, rapid, non-mechanical technique of characterizing the wavelength dependence of polarization-dependent loss for both single-mode and bulk-optic devices has been developed that offers advantages over more traditional methods. The technique demonstrates a single measurement uncertainty of 0.0037 dB and 0.0014 ± 0.0006 dB offset from PDL values calculated for an open-beam artifact. Additional measurement sweeps can be quickly averaged to improve random uncertainty by $1/\sqrt{N}$. Overall accuracy is dependent on calibration to a primary artifact.

Three WPDL artifact standard candidates have been tested and show the expected positive slope. Measurement resolution is sufficient to discern the wavelength dependent structure.

References

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