Robust Remote Calibration of Fiber Polarimeters

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Abstract: We show that a fiber polarimeter can be calibrated in place at a distance of 30km even when the intervening fiber varies in temperature. The calibration accuracy converges after at most 20 random stokes polarizations.
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1. Introduction

Polarimeter measurement of the Stokes parameters and their variation with time is a valuable tool for applications in telecommunications and optical sensors. A drawback of such devices is that they typically require calibration and subsequent recalibration using a generator of known polarizations states and/or a reference polarimeter [1]. Thus, in order to calibrate a polarimeter, another calibrated device is required in close proximity. Moreover, since most polarimeters are not colorless, i.e. require knowledge of the signal wavelength in order to correctly measure polarization, the calibration must be repeated across the entire wavelength range with a few nanometers intervals. Recently a generic, self-calibration procedure (also known as reference-free calibration procedure) using nonlinear least squares fitting was proposed to calibrate a polarimeter without reference polarization measurements using only launched states of polarization (SOP) with degree of polarization (DOP) near 100% [2]. While this work indicated that such a procedure could be used for remote calibration using random inputs, no such demonstration was given. Moreover, in order to ensure a good calibration a very large number of points was used (>100), leaving open the question of the minimum number of points required. The determination of a local metric of the accuracy of the calibration is important in deciding how many points are needed to do the calibration.

In this paper we show that the least squares metric in the fitting routine is correlated with an absolute accuracy measurement obtained from a reference polarimeter, thus showing that it is a good measure of the absolute accuracy of the polarimeter. We demonstrate that in general roughly 20 random launched SOPs with DOP~100% are enough to obtain the correct calibration matrix. We also demonstrate that the calibration source can be placed up to 30 km away from the polarimeter-under-calibration, without any loss of accuracy. We also modify our previous calibration procedure with a universal starting point based on the polarimeter design, thus easing the constraint of using the measured data to determine the first guess in the fitting procedure.

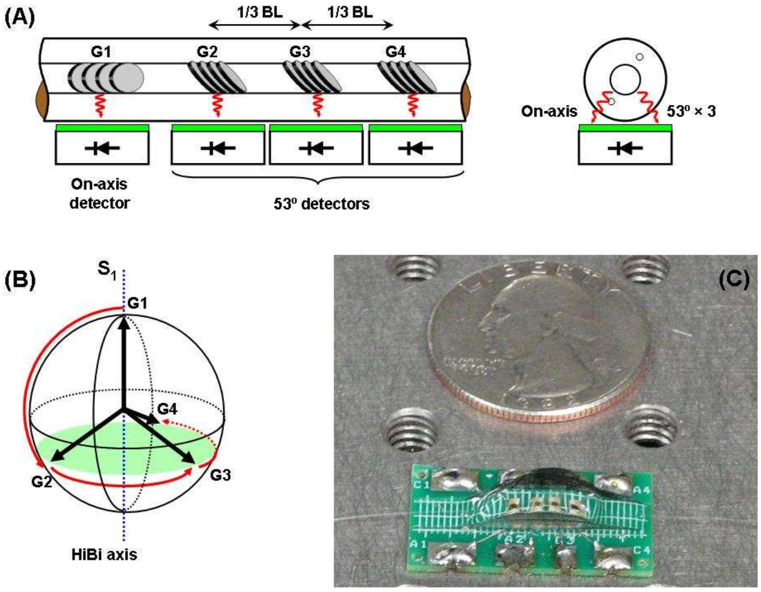

Fig. 1. A: Schematic diagram of the in-line fiber polarimeter. B: Principle of operation of the device. C: Photograph of the device.

2. Fiber polarimeter design

Fig. 1 shows the fiber polarimeter. It consists of four highly tilted gratings with blaze angle near 45 degrees and longitudinal period of roughly 1.07 microns. The period ensures scattering orthogonal to the fiber and the blaze angle maximizes the strength of the scattered light. Through a simple dipole argument, it is clear that such scattering is highly polarization dependent. Thus it acts to measure the projection of the input SOP onto the linear polarization defined by that grating. Birefringence along the fiber (beat length 4.9 mm) ensures that the set of stokes vectors forms a tetrahedron on the Poincare sphere. Because the device is meant for inline measurements, each grating taps out only ~1% of the incoming light when the polarization is aligned. The light path to the detector is roughly 100μm and the detectors are bare InP 300μm diameter photodiodes. The device had 0.5 dB insertion loss, 0.1 dB polarization dependent loss and 450 fs differential group delay. The detectors are integrated with TIAs and an ADC for compact and low noise design. Speed of the detector head was 500 MHz and the TIAs 500 kHz.

3. Reference-free calibration procedure

As discussed previously [1-3], a polarimeter typically requires a calibration matrix that relates measured detector values to the Stokes parameters:

$$S = CD \qquad (1)$$

Where S is the Stokes vector, D are the measured detector values, and C is the calibration matrix (in our case a 4x4 matrix). While this matrix may be determined through measurement of known polarizations [1], it may also be determined by launching many unknown polarizations subject to a constraint such as DOP=1. This constraint may then be used to obtain a best fit calibration matrix. Thus, the calibration matrix can be determined from a least squares fitting routine defined by the minimization of the deviation of the measured DOP from 1:

$$Q = \sum_{n=1}^{N} \left({S_{1n}}^2 + {S_{2n}}^2 + {S_{3n}}^2 - {S_{0n}}^2 \right)^2 \qquad (2)$$

Where the sum is over N data points and the Stokes parameters S_{in} for the n-th measurement are computed from the measured detector values D_n and the calibration matrix C using Eq. 1. The solution to this problem is degenerate under both Stokes rotations and the addition of PDL, since both of these transformations leave DOP =1 unchanged. To remove the PDL degeneracy it is thus necessary to add another constraint. The simplest constraint is the measurement of the power for all input states. Thus the values of S_0 from Eq. 1 must also match the measured powers. In practice it is best to perform a fit of the first row of C (which determines S_0) to the measured power values. The minimization in Eq. 2 is then performed by adjusting the remaining parameters of C. The resulting solution for C is still degenerate under stokes rotations. However, such rotations are not important for measurement of power, DOP and differential changes of the SOP, and can also be removed by appropriate referencing to a given set of polarizations, for instance those determined by the gratings within the polarimeter.

An important aid in performing the nonlinear least squares fitting is a good initial first guess. While we previously considered an estimate for C based on input data, in the present work, we consider a "universal" first guess based on the known design of the polarimeter. In our case the gratings of the polarimeter measure projections of the input power onto stokes vectors that form a tetrahedron on the Poincare sphere. Such a design is known to have low noise and minimal transmission PDL [4]. Therefore, since we known this underlying geometry, we use this as our starting guess for the second part of the calibration (Eq. 2).

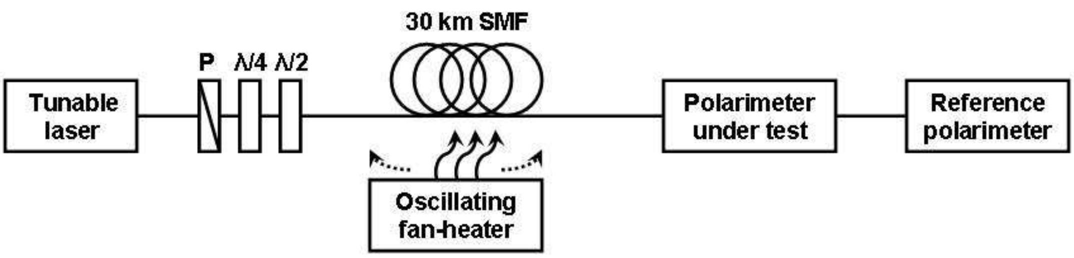

Fig.2 Experimental setup

4. Tests of calibration accuracy and remote calibration

To test our calibration procedure we use the setup shown in Fig. 2. Light is launched into a polarization controller, a length of fiber, which was either a few m or 30km, the polarimeter and then into a reference polarimeter. The reference polarimeter acted as a power meter for the self calibration (in practice it would be replaced by a tap and detector) and also as a reference polarization measurement to check the accuracy of the fiber polarimeter calibration procedure.

While this calibration procedure can be quite accurate, it is inevitable that the device parameters may drift, thus necessitating recalibration. While the initial calibration may be performed in a laboratory setting, subsequent recalibration is preferably performed in place without removing the device from its location. Moreover, it is important that there be a local metric to determine the calibration accuracy, since the polarizations used in self calibration may be chosen “blindly” without any knowledge of their values.

We consider a metric for the goodness of calibration related to the metric used in the nonlinear least squares fitting routine (Eq. 2), namely the standard deviation of the DOP (using 1 as the maximum) over all of the points. To verify that this measure tracks the actual accuracy of the polarimeter we compare it to an absolute metric: standard deviation of the difference between the fiber polarimeter and reference polarimeter. Note that these metrics are both dimensionless, so we can plot them on the same y-axis.

To compare these metrics, we performed a calibration using a very large number of points that covered the entire Poincare sphere. We then performed self calibrations using randomly selected points from this larger data set. For each calibration (for each increasingly larger number of random points), we computed the two metrics. The result is shown in Fig. 3a for a typical data set. As can be seen, the calibration is quite poor with less than 10 points, but all metrics converge to the optimum value after about 20 points. The internal metric related to DOP is correlated well with the absolute metric related to comparison with the reference polarimeter.

To demonstrate remote calibration, we also performed the same calibration through 30 km of standard fiber. In order to emulate the dynamic change of polarization and other fiber parameters the fiber spool was periodically heated using a fan-heater oscillating with approximately 0.1 Hz frequency. The polarimeter acquisition frequency was 220 Hz. In this case the self calibration was performed 200 times on different random sets of polarizations. Fig. 3b shows the two calibration metrics for all 200 calibrations. Once again, they converge to spec after roughly 20 random Stokes points. The fiber polarimeter was also calibrated over 1480-1580 nm wavelength range with 1 nm steps, and gave DOP standard deviation single calibration bandwidth similar to that without the heater and extra fiber.

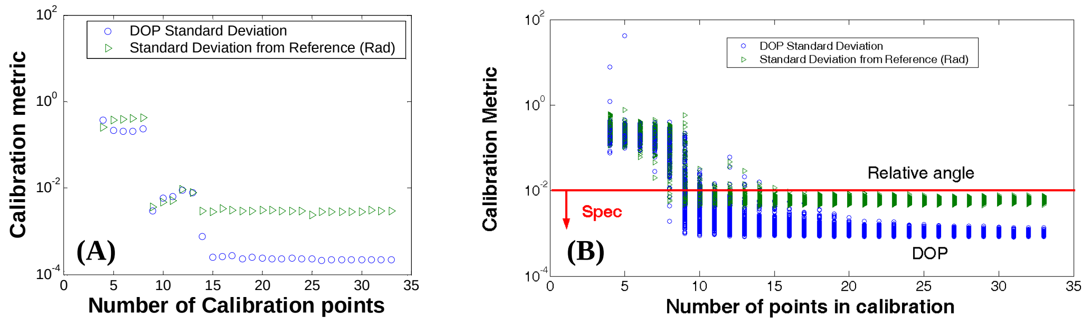

Fig. 3. A: Cal metrics vs number of calibration points without intervening fiber. B: with intervening fiber and heater over 200 sets of calibrations. Polarimeter accuracy spec indicated by red line. Y-axis is both radians and standard deviation of DOP from 1.

5. Conclusions

We have demonstrated that our calibration procedure is valid for remote applications and that it is immune to thermally induced rotations. We also demonstrated a metric that can be used within the polarimeter to verify the accuracy of calibration, and showed convergence after roughly 20 randomly chosen calibration polarization inputs.

6. References

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