

# In-Line, High Speed Fibre Polarimeter with Large Calibration Bandwidth and Accurate Reference-Free Calibration Procedure

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**Abstract** We demonstrate an integrated HiBi fibre polarimeter with 32nm single calibration bandwidth (1% standard deviation of DOP) and RF bandwidth in excess of 500MHz. We also describe an accurate self-calibration procedure that does not require any special polarization reference optics.

## Introduction

Measurement of light polarization and its variation in time is important for many photonics applications, including telecommunications and fibre sensors. Widespread use of polarimeters has been limited because they are typically made of bulk optic components, have an electrical bandwidth less than 1MHz, and require recalibration to cover large wavelength ranges, making them not “colorless”<sup>1,2</sup>. Moreover, in order to calibrate a polarimeter, a reference polarimeter or a high quality generator of known polarization states is required.

In this paper we report for the first time, a polarimeter which is not limited by these constraints. We demonstrate a compact low-loss, in-line fibre polarimeter with a colorless 32 nm single calibration bandwidth and 500 MHz electrical bandwidth, allowing measurement of very fast acoustic polarization and PMD

variations. We also present a unique self-calibration procedure, using only a polarized laser, polarization controller or scrambler and power meter. We use the term “self-calibration” to indicate that no reference polarimeter or polarization optics are required for our calibration procedure, allowing for hot in-place calibration of the polarimeter.

## Device design and characterization

Figure 1 shows a schematic of the all-fibre polarimeter. Fibre gratings tilted near 45° were inscribed in the core of OFS TruePhase® polarization maintaining (HiBi) fibre using an excimer laser and a tilted phase mask. The gratings were each 300 μm diameter. One grating was on-axis and the other gratings were off-axis by roughly 53°, and separated by 1/3 of the fibre beat length (4.9 mm). The HiBi fibre acts to add birefringence thus enabling the measurement of helicity. Each grating acts as a

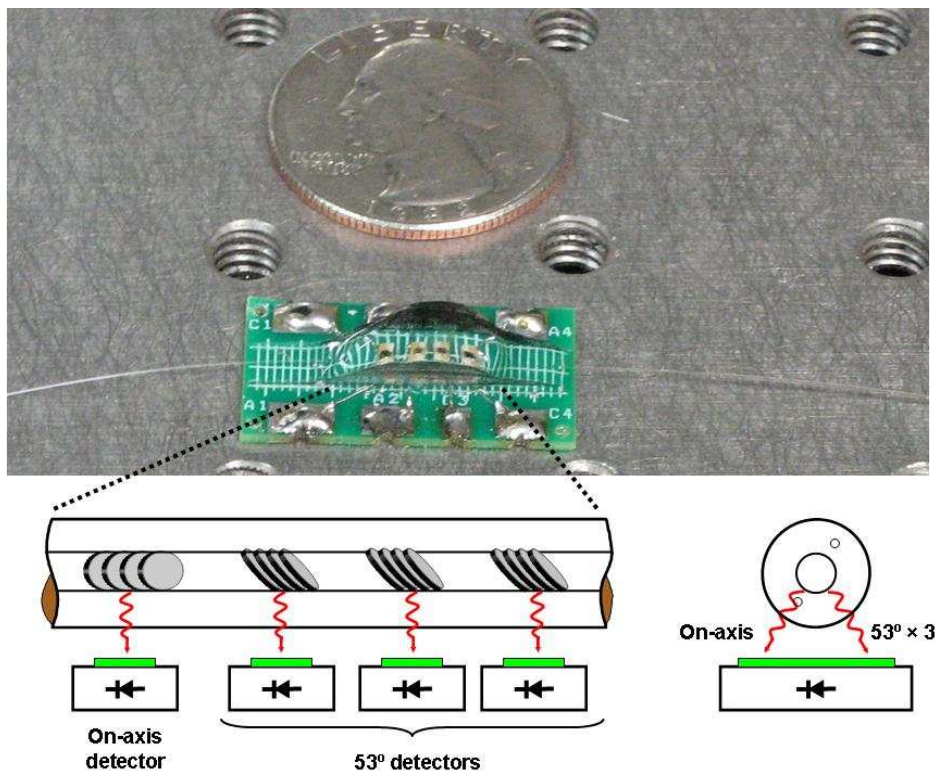


Fig. 1: Schematic and actual picture of HiBi polarimeter.

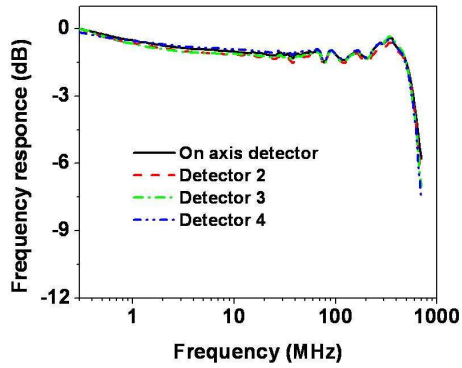


Fig. 2: RF bandwidth of each polarimeter detector

polarization sensitive tap, scattering approximately 1% of the incoming light when the polarization is aligned parallel to the grating planes, and close to zero when the polarization is orthogonally aligned. The annealed gratings were glued to 4 InP 300  $\mu\text{m}$  wide photodetectors using IR-transparent index matching epoxy. Figure 1 shows a photograph of the polarimeter optical head. The overall device dimensions are 25x14x5 mm. The device had 0.5 dB insertion loss (including connectors) and  $<0.1$  dB PDL. The polarization extinction ratio was the same as an equivalent length of PM fibre with 2 connectors and was  $\sim 40$  dB (limited by measurement accuracy). The electrical bandwidth of the device was characterized using a lightwave network analyzer by launching modulated light and measuring the frequency response of each detector (Fig. 2). The resultant 3 dB bandwidth was 550 MHz for all 4 detectors. Moreover, the variation of frequency response from detector to detector was better than  $\pm 0.1$  dB limited by the measurement accuracy, which simplifies frequency normalization of polarization measurements. The DGD of the device was  $<450$  fs and was determined by the entire length of HiBi fibre, including connectors (40 cm), used in the device. Note that  $<10$  fs of DGD are required for the polarimeter and any residual DGD can be cancelled by an orthogonally spliced HiBi fibre of equal length.

#### Calibration procedure and bandwidth

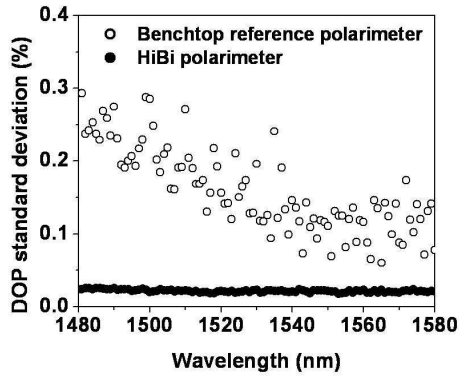
The four detectors of a polarimeter require a 4x4 calibration matrix to relate their voltages to the 4 Stokes parameters defining the SOP of the light. The simplest calibration procedure is the four point calibration<sup>3</sup>. Four known, non-degenerate states of polarization are launched into the polarimeter and the detector values are recorded. A matrix inversion gives the calibration matrix. While this procedure is very efficient, it requires the generation or accurate reference measurement of SOPs (i.e.

referenced calibration), which is often not practical, especially in telecom applications.

A more desirable procedure is a “self-calibration” which does not require external polarization reference, relying primarily on the measured data from the polarimeter. Here we describe one such procedure that employs a least squares fit of the 16 calibration matrix elements to a set of measured detector values corresponding to a given input set of unknown SOPs. Our self-calibration procedure relies only on the constraint that the source is a polarized laser with DOP $\sim 100\%$ . Single frequency lasers can maintain this condition over long lengths of fibre, making the DOP $\sim 100\%$  condition robust and “transportable” to even a distant polarimeter. We also require a polarization controller (PC). Power measurement must be included if there is significant PDL between the PC and the polarimeter. If the power is constant during calibration, then power measurement is not necessary.

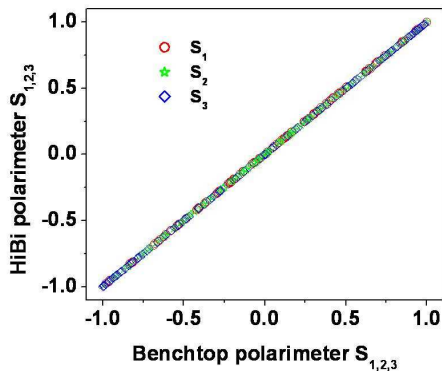
The self-calibration data is taken by moving the PC between several random unknown SOPs and recording the detector values for each state. Our calibration procedure then has three steps. In the first step an approximate calibration matrix is obtained using the raw detector values through a procedure similar to that in ref<sup>4</sup>. In the second step, the first row of the calibration matrix is adjusted to fit the power measurements using a least squares fit. If the power was constant during the calibration procedure, then the first row is fit to a constant power. In the third step, the remaining elements of the calibration matrix are adjusted so that the DOP=100% for all measured SOPs. A good first guess is obtained by scaling these remaining elements using the first row. Accuracy can be increased simply by launching more polarizations. Note that the procedure does not require any knowledge of the input SOPs, only that DOP $\sim 100\%$  for all of them, however, after the calibration any DOP value can be measured by the calibrated device. Note also that the output calibration matrix has an arbitrary orientation in Stokes space. In many fibre applications, especially those measuring DOP, such an absolute polarization reference is not necessary since polarization is always changing in fibre links. An absolute reference can be obtained, though, by exploiting the HiBi axis of the fibre into which the polarimeter is written, for example, by launch of light on the HiBi axis.

It should be noted that this calibration has no reference to the particular polarimeter design, nor any limits imposed by imperfections such as crosstalk or imperfect extinction ratios, and



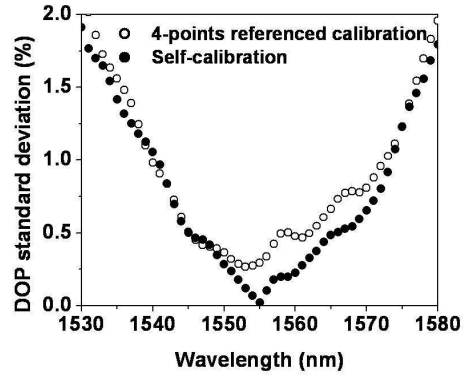
**Fig. 3:** SD-DOP of HiBi and benchtop polarimeters

therefore can be used for any polarimeter. In order to evaluate our calibration procedure we analyzed the standard deviation of the DOP (SD-DOP) measured for 121 random SOPs. The CW signal from a tunable laser was launched into the polarimeter-under-test via motorised polarization controller. The measured SOP was compared to the SOP measured by the reference calibrated benchtop polarimeter, connected to the output of HiBi polarimeter. The benchtop device was also used as a power meter during the self-calibration procedure. Figure 3 shows the SD-DOP measurement results for the HiBi polarimeter and the reference polarimeter over 1480-1580 nm wavelength span. Both polarimeters were calibrated at each wavelength using the



**Fig. 4:** Normalized Stokes vector components measured by HiBi polarimeter vs reference

self-calibration procedure for HiBi, and built-in calibration for the benchtop polarimeter. The maximum SD-DOP across the wavelength span was 0.025 % and 0.29 % for HiBi and bench-top polarimeters respectively. Another important measure of the HiBi polarimeter and calibration procedure is the deviation of the measured Stokes vector from the Stokes vector measured by the reference polarimeter. As shown in Figure 4, there is no deviation from the straight line for  $S_{1-3}$  measured by HiBi polarimeter and plotted as a function of the  $S_{1-3}$  respectively, measured by the reference



**Fig. 5:** Calibration bandwidth of HiBi polarimeter

polarimeter. The maximum angular deviation between the Stokes vector measured by HiBi and reference polarimeter was  $0.3^\circ$ . We also investigated the ability of the polarimeter to preserve the calibration over a certain wavelength range. The single calibration bandwidth was defined as the bandwidth where the measured SD-DOP was less than 1%. The single calibration bandwidth represents the “colorlessness” of the device. Figure 5 shows the measured SD-DOP as a function of signal wavelength for the HiBi polarimeter calibrated using self-calibration and 4-point referenced calibration. Note, that the device was only calibrated at 1555 nm and the DOP was measured using this calibration across the wavelength range (in Fig. 3, the device was recalibrated at every wavelength). The 1% SD-DOP bandwidth for the polarimeter was 32 nm for both calibration techniques, although as can be seen on Fig. 5 self-calibration always outperformed the 4-point referenced calibration.

### Conclusions

We have demonstrated an integrated, high speed all fibre polarimeter suitable for demanding power and polarization measurement applications in telecom and fibre sensing. To the best of our knowledge, our polarimeter has highest reported electrical bandwidth of >500 MHz, and widest reported calibration range of 32 nm, making this the first demonstration of colorless polarization measurement. A generic self-calibration procedure yields highly accurate calibration without the need for specialized polarization components. Rapid, in-place recalibration is thus possible even at some distance from the calibrating source.

### References

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