The Nature of Fibre Beam-Splitters for Absolute Radiometric Measurements

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We have investigated the performance of several fibre beam-splitters in order to fully understand their contribution to the uncertainty of radiometric measurements. The temperature dependence of the polarisation dependent loss was evaluated for fused biconical and planar beam-splitters at 1310 nm and 1550 nm over the range 10 ºC to 40 ºC and is reported for SMF-28 Ultra and polarisation maintaining fibre beam-splitters, analysed using the Mueller matrix method. The variation in signal ratio between the output ports of multi-port PM splitters was also investigated to determine the baseline uncertainty in such a ratio measurement.

INTRODUCTION

Often with radiant power measurements there is some optical element in the setup between the device under test (DUT) and standard that requires characterisation. This could be a Brewster window or even a plane wedged window, a turning mirror or a beam-splitter. Each adds uncertainty to the measurement. We are interested in evaluating the performance limit of fibre beam-splitters, especially polarisation maintaining (PM) splitters, as the variability of the splitter ratio dominates the DUT responsivity measurement uncertainty of our calibration facility [1]. This work improves and helps assure the performance of our optical fibre-coupled cryogenic radiometer facility.

Fibre beam-splitters are very useful in the field of radiometry. The work discussed here is not only relevant to our fibre-coupled radiometer but is also relevant to the area of few-photon radiometry, where fibre-coupled detectors are calibrated for detection efficiency [2] or compared directly to many other few-photon detectors, including superconducting nanowire single-photon detectors [3].

Passive optical components such as fibre beam-splitters and couplers, exhibit polarisation dependent loss (PDL), whereby the output signal of the device varies as a function of the input polarisation state *S*. Many references can be found in the literature to application notes and standards discussing PDL measurement techniques for fibre components [4]. We use the Mueller matrix method to assess the temperature dependent PDL of the beam-splitters tested.

Further, we assess the impact the optical power level and spectral modal stability of Fabry-Pérot laser diode sources have on the stability of the beam-splitter ratio between any two output ports of multiport PM fibre beam-splitters. The beam-splitter ratio between DUT and radiometer channels is required to relate the power incident on the DUT to the power incident on the standard detector. Splitters are convenient as they enable simultaneous measurement of the DUT and radiometer output signals. For high-accuracy measurements it is important to understand the behaviour of the beam-splitter and the consequence of selecting specific output channels. The variability of the fibre beam-splitter ratio dominates the DUT responsivity measurement uncertainty, hence this investigation.

METHOD

The measurement of the response of a beam-splitter to four separately applied input polarisation states, whose power is known, is enough for the first-row coefficients of the 4 x 4 Mueller matrix to be determined. The minimum and maximum throughput of the DUT can be calculated from these four matrix coefficient values. A 1 x 3 SMF-28 wavelength independent splitter and two planar 1 x 4 PM splitters were in turn placed in an environmental chamber and cycled from 10 ºC to 40 ºC, being soaked for an hour at each temperature. Measurements were recorded for each of four input polarisation states; 0°, 45°, 90°, and RHC generated by a polarisation synthesiser. A schematic of the experimental setup is shown in Fig. 1. The polarisation dependent loss is calculated from Eq. 1;

$$\text{PDL}\,(dB) = 10\log_{10}\frac{T_{max}}{T_{min}} \qquad (1)$$

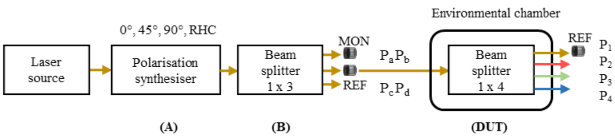

Fig. 1. Setup for the temperature dependent PDL measurement. The input power to the DUT (P_a, P_b, P_c, P_d) and the output power of the DUT (P_1, P_2, P_3, P_4) for each of four input polarisation states; 0°, 45°, 90°, RHC, is measured relative to the power of the monitor photodiode (MON). (A) General Photonics PSY-101 polarisation synthesiser for selecting input polarisation states. (B) 1 x 3 beam-splitter with monitoring channel. The four coloured fibre outputs from the DUT illustrated (1 x 4 PM beam-splitter; 25 % each channel) relate to the colours on charts 2a and 2b below.

A two-detector technique was used to determine the ratio between any two output ports of the beam-splitter, given by Eq. 2;

$$BSR = \sqrt{\frac{M_1(DUT)}{M_2(RAD)} \times \frac{M_2(DUT)}{M_1(RAD)}} \tag{2}$$

where *BSR* is the beam-splitter ratio and M_1, M_2 the detector signals of the fibre-coupled outputs DUT and radiometer (RAD). The Fabry-Pérot laser diode source was fibre coupled to the beam-splitter via a variable optical attenuator (not illustrated) which is used to set the optical power level.

RESULTS

Figures 2a and 2b highlight the decrease in PDL when changing from SMF-28 type splitters to PM type splitters. The PDL of the PM beam-splitters is of the order 1 % at 20 °C, exhibiting a temperature coefficient *ΔPDL / °C* of approximately -0.03. This represents the maximum excursion in fibre output signal given all states of input polarisation. We include a rectangular bounded uncertainty of 0.05 % in our uncertainty budget to account for the PDL of the PM splitters we use.

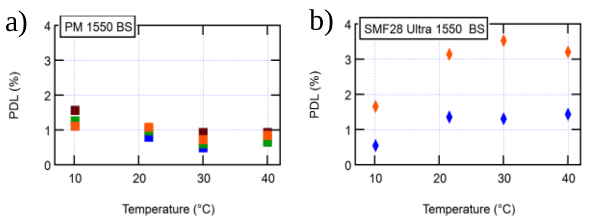

Fig. 2(a). Plot of the temperature dependence of the PDL (%) of 1550 nm 4 channel PM fibre beam-splitter. The four colours; blue, green, red, brown represent the four output channels of the splitter. Fig. 2(b). Plot of the temp. dependence of the PDL (%) of 1550 nm SMF-28 3 port fibre beam-splitter – only 2 channels shown.

The standard deviation of the ratio of the power output from any two fibre ports of the 3 and 4 port beam-splitters tested is 0.03 % maximum over a measurement period of 5 hours. Single element InGaAs photodiodes were used for this purpose at wavelengths 1310 nm and 1550 nm. This represents a quantitative measure of the effect of the temperature dependent PDL of the fibre beam-splitters. It results from temperature fluctuations of ± 0.3 °C / day in the laboratory environment and small changes in the polarisation state of the propagating light, caused by coupling between the slow and fast axes of the optical fibre components, and variability in the modal stability of the laser diode source. The polarisation extinction ratio (PER) is a measure of the strength of this coupling. For the PM splitters tested the PER was 20 dB. An additional uncertainty of 0.02 % was attributed to each fibre as a result of swapping fibres between detectors during a beam-splitter ratio measurement. Summing these contributions in quadrature with the 0.03 % mentioned above, yields an expanded uncertainty of 0.08 %.

CONCLUSION

We have evaluated several fibre beam-splitters in order to understand their characteristics. Results confirm that current beam-splitter technology limits our fibre-coupled cryogenic power responsivity calibration uncertainty to 0.1 % (*k=2*). However, this work has resulted in a 4x improvement in the NIST optical fibre coupled power responsivity calibration uncertainty.

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