Fresnel Reflection for Fibre-Coupled Cryogenic Radiometric Measurements

M G WHITE[1, 2], E BAUMANN[1, 2], I VAYSHENKER[3], M S STEPHENS[3], M SMID[4], J H LEHMAN[3]

[1]*Associate of National Institute of Standards and Technology, Boulder, Colorado 80305 USA*
[2]*Department of Physics, University of Colorado, Boulder, Colorado 80309, USA*
[3]*National Institute of Standards and Technology, Boulder, Colorado, 80305 USA*
[4]*Czech Metrology Institute, Prague, Czech Republic*
Corresponding e-mail address: m.white@boulder.nist.gov

We have measured the temperature dependent Fresnel reflection loss and Rayleigh backscatter of single-mode SMF-28 fibre, polarisation maintaining (PM) single-mode fibre and PM photonic crystal fibre (PCF). We show that the relative effective refractive index of these fibres reduces by 0.11 %, 0.15 % and 0.30 % respectively from room temperature to 5 K. At the same time the Rayleigh backscatter increases 15x for SMF-28 and PM fibres, and 4x for the PM PCF fibres. As a fibre is cooled, the refractive index reduces, which increases the fibre's output power. It is this change we quantify in order to apply a correction to our fibre radiometer measurements. We use an in-situ beam-splitter measurement technique to measure the Fresnel reflection at 1310 nm and 1550 nm and we confirm the results at 1550 nm with optical frequency domain reflectometer measurements.

INTRODUCTION

Optical return loss (ORL) of a fibre encompasses Fresnel reflection from the media boundary interface and Rayleigh back-scatter within the fibre [1]. The temperature dependent effective refractive index n_{eff} of the fibre can be determined from a measurement of each of these parameters as the fibre is cooled.

Recently we reported a fibre-coupled cryogenic primary standard for the calibration of optical fibre power meters [2]. The system used commercial all-fibre beam-splitters and single-mode fibre to direct light from attenuated fibre-coupled laser diode sources to the device under test (DUT) and either of two absolute standard detectors.

The fibre within the cryostat is thermally anchored to a temperature stabilised stage, irradiating a cryogenic detector operating at 7 K. As the fibre from the beam-splitter to the cryogenic detector is cooled, the refractive index reduces. This causes a reduction in the Fresnel reflection R at the media boundary of refractive index n_1 = 1.47, propagating to a material of index n_2 = 1.00 (vacuum), leading to an increase in fibre output power, Eqn 1. The beam-splitter ratio

$$R = \left|\frac{n_1 - n_2}{n_1 + n_2}\right|^2 = 0.036 \qquad (1)$$

between radiometer and DUT is measured at room temperature, and therefore this change in fibre output is required to be measured in order to apply a correction to the room temperature beam-splitter ratio measurement. A measurement of the Fresnel reflection not only enables a correction to the beam-splitter measurement, but also allows us to calculate the temperature dependent effective refractive index n_{eff}. We are interested in quantifying this effect to the best uncertainty possible in order to improve and assure our DUT calibration uncertainty. The work presented here is also applicable to the single-photon detection community where detectors are calibrated for detection efficiency [3].

METHOD

Five fibres were investigated using an in-situ beam-splitter measurement technique, Fig. 1. The results were confirmed at 1550 nm with optical frequency domain reflectometer (OFDR) measurements. The fibres tested included SMF-28 Ultra, PM15-U25D and PM13-U25D (PM single mode fibre), and LMA-PM-10 and PM-1550-01 (PM PCF fibre). The PCF fibre was included in the assessment as it provides the possibility of using one fibre within the cryostat and thus one cryogenic detector, to cover the visible and near infrared wavelength region. This would considerably reduce the complexity around the cryogenic detector. The difficulty of using PCF fibre relates to the evacuation of air within the micro-capillary structure in preparation for cooling.

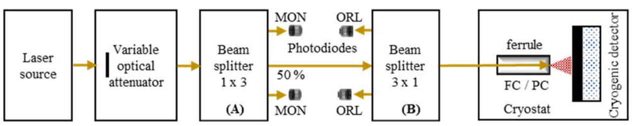

Fig. 1. In-situ beam-splitter setup for the measurement of Fresnel reflection and Rayleigh backscatter. (A) 1 x 3 beam-splitter with monitoring (MON) channels. (B) 3 x 1 beam-splitter connected in reverse to facilitate ORL measurements.

The crosstalk of the beam-splitter is first assessed and then the change in Rayleigh scatter of the fibre measured as it is cooled. This is facilitated by attaching 4 m of fibre to the 4 K cold plate with both ends exiting the cryostat. Light is launched into one end while the other is monitored as the fibre is cooled. This enables the scatter to be calculated. The monitored end is then withdrawn into the cryostat, anchored to the cold plate, and the system cooled. The change in Fresnel reflection is calculated from the measured value of the ORL and Rayleigh backscatter. These measurements were repeated for all five test fibres at 1310 nm and 1550 nm.

A Luna OFDR 4600 swept-wavelength reflectometer, set to a centre wavelength of 1550 nm, was used to record the time of flight along the length of fibre. The change in Rayleigh back-scatter was determined by integrating the signal 10 mm after the source connector to within 10 mm of the plane cut end facet at room temperature, 77 K and 5.2 K. The signal was also integrated 10 mm about the two reflection peaks (Fig.2). By comparing the room and low temperature measurement results, the Fresnel reflection loss change could be determined.

RESULTS

We observed a 15x increase in the Rayleigh backscatter with both techniques for SMF-28 and PM fibres, and a 4x increase for the PM PCF fibres. The results for the five fibres tested are listed in Table 1 below. The effective refractive index n_{eff} is calculated from the measurement of the Fresnel reflection signal. Fig. 2 illustrates a typical *OFDR* measurement result – in this case a 4 m length of PM PCF fibre with inset showing the distinctive dual reflection peaks of a PM fibre.

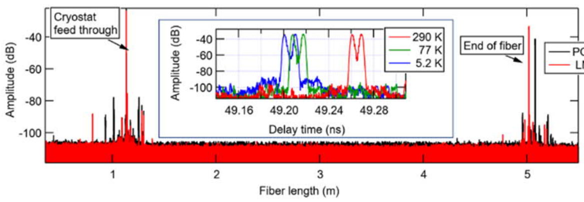

Fig. 2. Fresnel reflection at 1550 nm for plane cut end facet PM PCF fibres; PM-1550-01 and LMA-PM-10 with each fibre connectorised FC / APC at one end only, with modal adaptation of 10 mm fused SMF-28 fibre. Inset: time of flight (ns) for approx. 4 m of PM-1550-01 PM, high index, solid core, PCF fibre at room temperature, 77 K and 5.2 K showing the reflection nodes of the slow and fast axes as the fibre is cooled.

The effective group index of refraction is calculated to change 0.11 ± 0.01 % for SMF-28 fibre, 0.15 ± 0.01 % for standard PM fibre and 0.30 ± 0.02 % for the PM-1550-01 PCF fibre (holey PM rod structure), Table 1. The signal exiting the fibre end facet increases relatively from 96.40 % to 96.42 %, 96.43 % and 96.46 % for SMF-28 fibre, standard PM fibre and PM PCF fibre respectively, (Eqn 1).

Table 1. Temperature dependent effective refractive index for various fibres at 1310 nm and 1550 nm wavelength.

Fibre Type and Wavelength	Effective Refractive Index n_{eff}		
	293 K	77 K	5 K
1310 nm			
SMF-28 Ultra	1.4676[3]	1.4664[1]	1.4661 (0.10%)[1]
PM13-U25A	1.4679[1]	1.4665[1]	1.4660 (0.13%)[1]
1550 nm			
SMF-28 Ultra	1.4682[3]	1.4670[1, 2]	1.4666 (0.11%)[1, 2]
PM15-U25D	1.4684[2]	1.4667[1, 2]	1.4662 (0.15%)[1, 2]
LMA-PM-10	1.4664[2]	1.4679[2]	1.4662 (0.014%)[2]
PM-1550-01	1.4733[2]	1.4705[2]	1.4688 (0.30%)[1, 2]

[1]Beam-splitter measurement, [2]OFDR measurement, [3]from Corning product info SMF-28 ultra-optical fibre. The numbers in parentheses represent the relative change in output power of the fibre.

CONCLUSION

We have developed an in-situ beam-splitter measurement technique to measure the change in output of the optical fibres within our measurement facility as they are cooled. This change is applied as a correction to the room temperature beam-splitter ratio measurement between radiometer and DUT. This work helps assure our calibration uncertainties. The PM PCF results are promising which encourages further work to understand the dynamics of the fibre within a low temperature vacuum environment.

REFERENCES

1. Subcommittee 86B, Fiber optic interconnecting devices and passive components: Basic test and measurement procedures part 3-6: Examination and measurements, return loss, IEC/CEI-61300-3-6:2008, IEC, Geneva, Switzerland 2008.
2. M.G. White, Z.E. Ruiz, C.S. Yung, I. Vayshenker, N.A. Tomlin, M.S. Stephens, and J.H. Lehman, "Cryogenic primary standard for optical fibre power measurement", Metrologia **55**(5), 706-715 2018.
3. I. Mueller, R.D. Horansky, J.H. Lehman, S.W. Nam, I. Vayshenker, L. Werner, G. Wuebbeler, and M.G. White, "Verification of calibration methods for determining photon-counting detection efficiency using superconducting nano-wire single photon detectors", Opt. Express **25**(18) 21483-21495 2017.