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Characterization of the Spectral Properties of Fibre Optics Components and Devices by Use of a Filtered Supercontinuum Laser Source

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Abstract *We present a measurement system for the calibration of the spectral properties of fibre-coupled devices. The system is continuously tunable from 700 nm to 1800 nm. Application fields range from telecommunication to sensors and to rapidly growing domains like quantum communication and cryptography. ©2022 The Author(s)*

Introduction

The spectral responsivity of photodetectors, and, more generally, the spectral properties of optical components are quantities which are often measured using filtered white-light sources [1,2]. Nevertheless, these techniques offer a low dynamic range, which strongly limits their domain of application.

In this paper we present an all-fibre versatile setup, based on a supercontinuum laser, combined with a two-stage passive spectral filtering system. It allows reaching:

- high power, up to the milliwatt level,
- wide spectral ranges, namely from 700 nm to 1800 nm, and
- narrow spectral linewidth, typically 1.5 nm.

Thanks to these characteristics, it is possible to measure the spectral properties of fibre optics components and devices in a very broad spectral range, and thus allowing investigating their properties in "out of band" regions, where their behaviour may become critical, for example in quantum cryptography, where out-of-band features may be used to eavesdrop secure quantum communication systems.

Calibration of the spectral responsivity of photodetectors

The spectral responsivity (SR) of fibre-coupled detectors can be easily calibrated using the system as shown in Fig. 1, by simultaneously measuring the generated optical power with the Device Under Test (DUT) and with a Transfer Standard (pyroelectric detector, ref PD). The light source consists of a supercontinuum fibre laser with a repetition frequency of 78 MHz. The collimated laser output is coupled into a Pellin-Broca prism, which acts as a first stage bandpass filter. The filtered beam is then coupled into a single grating monochromator for final filtering. This system is continuously tunable from 700 nm to 1800 nm and generates a narrowband signal with a FWHM spectral width of about 1.3 nm. The filtered signal is finally coupled into a G.652 single mode fibre. A small part of the filtered signal is used to drive a feedback-loop for power stabilisation, by directly controlling the pump power level of the supercontinuum laser through a PID controller. This allows achieving an averaged relative power instability at the 0.05 % level. The MEMS switch outputs 1 and 2 are then connected to both, the DUT and the ref PD.

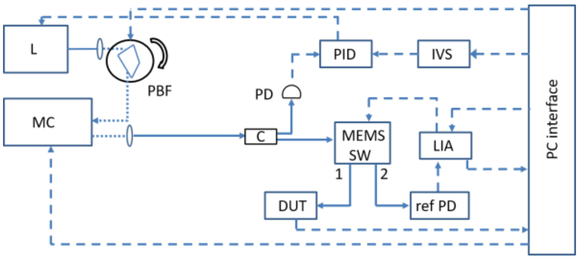

Fig. 1: Setup for spectral responsivity measurements. L: Supercontinuum Laser; PBF: Pellin-Broca Prism Filter; MC: Grating monochromator; C: optical fibre coupler; PD: Photodetector; PID: Proportional-Integral-Derivative module; IVS: Isolated Voltage Source; LIA: Lock-In Amplifier; MEMS SW: micro-electro-mechanical optical switch; DUT: Device Under Test; ref PD: Transfer Standard. Solid line: optical fibre; dotted line: free propagating collimated beam; dashed line: electrical signal.

The reference signal is chopped at a frequency of 37 Hz by directly modulating the control voltage of the MEMS switch and using a Lock-In Amplifier (LIA) for the synchronous detection. Due to the wide spectral domain covered by this measurement system, two different MEMS switches have been implemented: a single mode switch covers the 1310 nm to 1800 nm range, and a multi mode switch, combined with two mode conditioners, addresses the 700 nm to 1300 nm spectral domain. The SR is then determined according to Eq. (1),

$$SR = k \cdot \frac{R_{DUT}}{P_{REF}}, \quad (1)$$

where R_{DUT} is the reading value from the DUT and P_{REF} is the reference optical power level measured with the ref PD. k is the power coupling ratio between path 1 and 2. The coupling ratio is determined by performing two successive series of measurements between which the DUT and the reference paths are swapped. This yields:

$$k = \sqrt{\frac{R_{DUT2}}{P_{REF2}} \cdot \frac{P_{REF1}}{R_{DUT1}}}, \quad (2)$$

where the indexes 1 and 2 indicate the two successive series of measurements.

Fig. 2 shows the results of the measurements, performed on a fibre-coupled germanium power meter, of the deviation of R_{DUT} from the reference optical power. The deviation is expressed in percentage. The instrument was measured in steps of 10 nm. Typical power levels ranging from 20 μW up to 200 μW were used for the calibration.

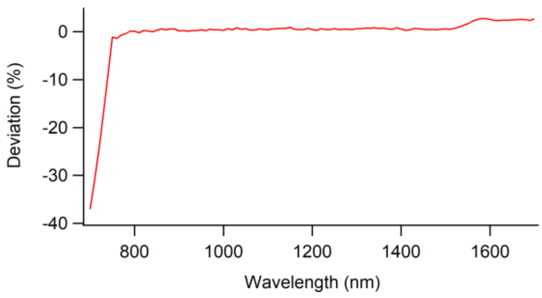

Fig. 2: Deviation from the reference optical power of the reading values of a fibred-coupled germanium power meter.

Calibration of the spectral transmission of fibre optics components

The setup for measuring the spectral properties of fibre optics devices is shown in Fig. 3. In this case the linearity of the reference detectors is the key parameter, since the detected optical power may span over several orders of magnitude with the wavelength. The DUT is connected at the output of the MEMS switch. A mode conditioner is additionally placed in front of the DUT for multi mode calibrations. The spectral transmission is measured by performing two successive series of measurements of the transmitted power levels with two linearity standards, ref PD1 and ref PD2; the first measurement is performed with the DUT connected to the switch output 1 and the second one with the DUT connected to the switch output 2.

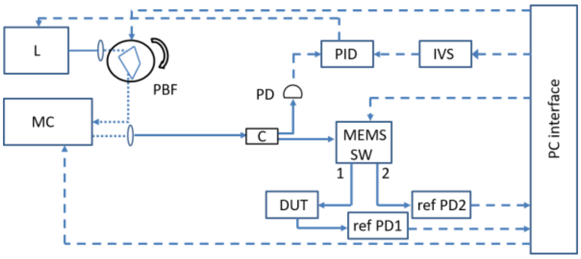

Fig. 3: Setup for the the measurement of the spectral transmission of fibre optics components. L: Supercontinuum Laser; PBF: Pellin-Broca Prism Filter; MC: Grating monochromator; C: optical fibre coupler; PD: Photodetector; PID: Proportional-Integral-Derivative module; IVS: Isolated Voltage Source; MEMS SW: micro-electro-mechanical optical switch; DUT: Device Under Test; ref PD: Transfer Standards.

These two measurement series allow compensating for the power splitting ratio of the switch. The spectral transmission is then given by Eq. (3),

$$Tr = \sqrt{\frac{P_{PD11}}{P_{PD21}} \cdot \frac{P_{PD22}}{P_{PD12}}}, \quad (3)$$

where P_{PDi1} and P_{PDi2} are the optical power levels measured by the detectors ref PD1 and ref PD2 during each measurement sequence i (i = 1, 2).

Fig. 4 shows the results of the spectral transmission measurements of a fibre-coupled narrow band Wavelength Division Multiplexing (WDM) filter. According to the specifications, the filter should be centered around a wavelength of 1310 nm, with a FWHM spectral width of 4 nm. The spectrum shows a transmission peak at the specified wavelength of 1310 nm, with vanishing transmission in its vicinity. At wavelengths above ~1520 nm, however, we observe a large set of out-of-band transmission features. These out-of-band transmission features may be detrimental in strategic fields like quantum communication systems; the use of exotic wavelengths for attacking a quantum security chain could indeed result in data loss and/or stolen information, if these wavelengths are not filtered out by the optical chain.

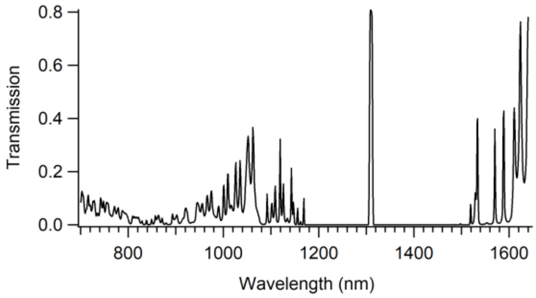

Fig. 4: Spectral transmission of WDM filter centred at 1310 nm.

Uncertainty budget

In Tab.1, we summarize the uncertainty budget for both the spectral responsivity and the spectral transmission measurements. Multi mode and single mode geometry were evaluated independently. Details on the calculation of the uncertainty budget are given in Ref. [3].

Tab. 1: Rounded expanded uncertainty (k=2) for the spectral responsivity and the spectral characterization calibrations. MM stands for multi mode geometry, SM for single mode geometry.

	MM geometry (%)	SM geometry (%)
Spectral Responsivity	1.1	0.7
Spectral Transmission	1.0	0.6

Conclusions

We presented a SI-traceable, fibre-coupled system for the spectral characterisation of fibre-optics components, either active like photodetectors and power meters, or passive like filters, attenuators, isolators, circulators and couplers.

With this measurement system is possible to calibrate the spectral characteristics of fibre-optics components in a very broad spectral range, allowing to demonstrate possible vulnerabilities when used in critical aplications. This has gained a lot of interest with the development of quantum based communication and cryptography systems, where a very tight control of the spectral properties of the used photonics components has become a critical issue [4].

An extension of the application fields of this versatile setup is under consideration. The authors plan to introduce, in a traceable way, an attenuators chain in order to be able to characterize a new family of devices, like the few photon detectors. This could be achievable in a short time and first results could already be presented at the conference.

Acknowledgements

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