# Mitigation of Polarization-Induced Fading in Optical Vector Network Analyzer for the Characterization of km-scale Space-Division Multiplexing Fibers

# Mitigation of Polarization-Induced Fading in Optical Vector Network Analyzer for the Characterization of km-scale Space-Division Multiplexing Fibers

Besma Kalla [1,*], Martina Cappelletti [1,2], Menno van den Hout [1], Vincent van Vliet [1], Simon Rommel [1], Luca Palmieri[2], Thomas Bradley[1] and Chigo Okonkwo[1]

[1] High Capacity Optical Transmission Laboratory, Eindhoven University of Technology, the Netherlands,
[2] Department of Information Engineering, University of Padova, Padova, Italy, *b.kalla@tue.nl

***Abstract*** *We propose an optimized optical vector network analyzer with automatic polarization control to stabilize the reference arm polarization throughout the sweep range. We demonstrate this technique, successfully removing the polarization-induced fading and measurement distortions in insertion loss by characterizing a 10 km multi-core fiber.* 

## Introduction

Space-division multiplexing (SDM) has proven to be a promising technology[1],[2] to increase capacity beyond that of single-mode fiber for long-haul transmission, as it exploits multiple spatial channels for data transmission. Various SDM fiber architectures such as few-mode fiber (FMF), uncoupled and coupled multi-core fiber (MCF), and few-mode multi-core fiber (FM-MCF) have been widely characterized in the laboratory environment. More recently, deployed fibers are increasingly being studied[3]. In these experiments, the performance of optical fibers in spooled, unspooled, or twisted conditions has been shown to present different optical performances depending on the coupling regime[4]. The same type of fiber also showed distinct characteristics[5], highlighting the unique impact of various deployment scenarios.

For the practical implementation of SDM technology, it is important to characterize fibers at every stage, from spooled to cabled and finally deployed. An optical vector network analyzer (OVNA) is a powerful characterization tool in this context. It enables the measurement of the full linear transfer function matrix of SDM systems in a single scan, comprehensively characterizing the optical properties. Based on swept wavelength interferometry,[6] an OVNA utilizes one branch of the interferometer for the device or fiber-under-test, and the other is a reference fiber. The reference path must be length matched to that of the device-under-test (DUT) to maintain coherence between both arms to ensure accurate phase and amplitude measurements across the sweep range of the laser.

However, a challenge arises when measuring kilometer-scale fibers. For the OVNA, the signal in the reference arm undergoes wavelength-dependent polarization rotations, leading to a wavelength-dependent power fading in the beating signal at the receiver end. This results in measurement distortions of the linear fiber-under-test parameters. Previous works demonstrated a digital polarization equalization technique that improved the measurements[7], but equalization becomes impossible in deep-fading scenarios. Another method includes adding a Faraday mirror in the reference arm[4], with the reference fiber being half the length of the DUT[5]. However, the effectiveness of this approach for OVNA measurements has not yet been reported.

In this paper, we present an optimized OVNA setup to mitigate polarization-induced fading using an automatic polarization controller (APC) placed in the reference arm, which allows the characterization of kilometer-scale fiber links, representative of real-deployment scenarios, without additional

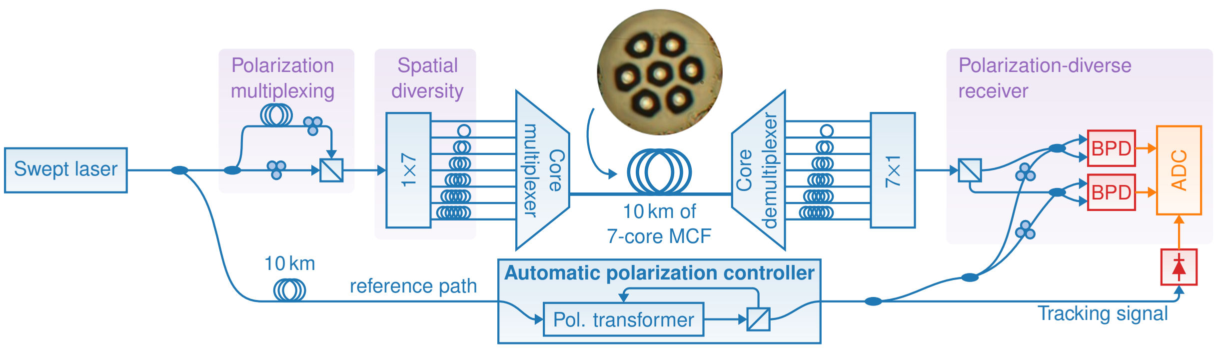


**Fig. 1:** SDM-OVNA setup optimized with an automatic polarization controller and configured to measure 7-core multi-core fiber

requirements on the transmitter or receiver hardware. We demonstrate the effectiveness of this configuration by characterizing a 10 km long MCF with seven uncoupled cores. Our results indicate a more accurate measurement of the insertion loss (IL) derived from the transfer function with automatic polarization control.

**Principle of Operation**

The OVNA, shown in Fig. 1, consists of a swept tunable laser (STL) fed into an interferometric structure with a measurement and reference branch. The non-linear frequency sweep of the laser is corrected for with an auxiliary interferometer[8], not shown in the diagram. A polarization-multiplexing stage at the input allows the launching of the two time-delayed polarizations of the optical field. Polarization controllers (PCs) are used to obtain two orthogonal and equal-power polarizations. Additionally, the setup includes power splitters with different delay lines at the input and output of the DUT for SDM device measurements[9]. In the polarization-diverse receiver, the signal is split into two orthogonal polarizations, each interfered with the polarization-aligned reference to detect both. The two output signals X and Y are then digitized using an analog-to-digital converter (ADC).

To obtain maximum beating between the measurement X and Y polarization path and the reference signal, polarization alignment is needed. This is done by maximizing the beating power using PCs in the reference path. Assuming the state of polarization in the reference arm remains constant over the full sweep range of the laser, this polarization alignment can be achieved by maximizing the power of the fringe pattern. Finally, the complex transfer function is retrieved by following a sequence of digital signal processing (DSP) steps[8], from which the linear device parameters, such as IL, cross-talk (XT), and mode-dependent loss (MDL), can be calculated.

The reference arm of the OVNA contains an optical delay line to ensure coherence between the measurement and reference arms, by approximately matching their path lengths. Moreover, the path length difference should be kept minimal, as the frequency of the fringe pattern is the product of the sweeping rate and this delay. Hence, a large path difference results in higher frequency, requiring higher speed digitizers. This means that to characterize km-scale SDM fibers, a reference of similar length is required.

A challenge arises as the state of polarization of the signal propagating through the long reference fiber delay changes across the sweep due to wavelength-dependent birefringence in the fiber. Consequently, the varying polarization leads to wavelength-dependent fading as the reference polarization is no longer matched to the signal polarization in the polarization diverse receiver. Due to this fading, the measurements of the linear device parameters are distorted.

Hence, we propose adding an APC feature with an optical feedback loop in the reference arm of the OVNA, as shown in Fig. 1, to control the polarization across the entire wavelength sweep range. Using a $LiNbO_3$-based polarization transformer[10], the APC continuously aligns the state of polarization of the reference signal to the expected state for the polarization diverse receiver by minimizing power in the orthogonal polarization. This results in a constant polarization state throughout the measurement sweep, meaning that aligning the reference and the signal at one wavelength ensures co-polarized signals throughout the measurement sweep, thus eliminating polarization-induced fading. A small fraction of the light in the reference at the output of the APC is used for tracking power, referred to as tracking signal. As the light is polarized, any variation in the measured power throughout the measurement sweep is indicative of polarization rotation.

Note that the polarization control has to be fast enough to keep track of the polarization rotation occurring in the reference arm. The variation of the state of polarization can be estimated by the polarization rotation rate R, which is calculated as

$$R = 2\pi\gamma T, \quad (1)$$

where $\gamma$ is the frequency sweep rate of the STL in Hz/s and $T$ the differential group delay of the reference fiber.

**Fading-free Fiber Insertion Loss Measurement**

We employ the proposed polarization tracking and control method to characterize a 10 km MCF as proof of principle with the OVNA configured as shown in Fig. 1 using spatial multiplexers based on laser-inscribed glass waveguides[11]. A key parameter that describes SDM device properties is IL, defined as the average of the squared singular values of the complex transfer matrix[8]. We analyze IL for this MCF to highlight the measurement distortions caused by the polarization rotation when measuring with fibers of km-scale lengths. The laser is swept at 100 nm/s from 1530 nm to 1570 nm. The tracking speed required for this configuration is estimated to be approximately 50 rad/s. The transfer function is extracted digitally from which the IL is calculated. As the focus of this study is the wavelength-dependent variation in the system, we normalize the tracking signal at the output of the APC and the IL to the optimized values obtained at single-wavelength calibration.

We first focus on analyzing the results of a single core to demonstrate the effect of polarization rotation. The sampled waveform at one of

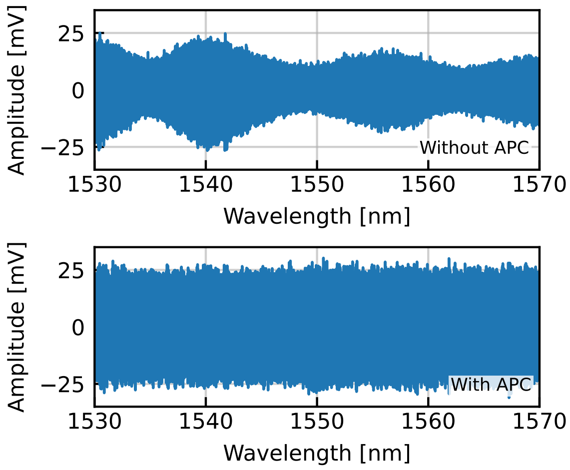


**Fig. 2:** Digitized waveform of one receiver output channel: (top) without (bottom) with automatic polarization control.

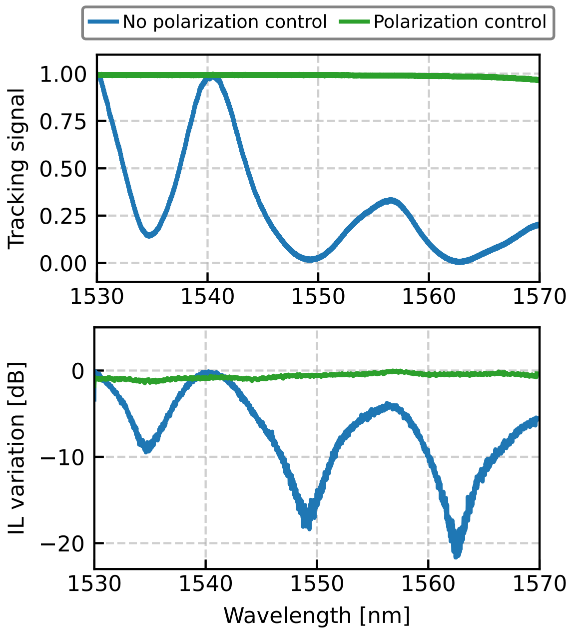


**Fig. 3:** (Top) Normalized tracking signal of the reference arm signal. (Bottom) Normalized insertion loss of the central core of the MCF

the polarization-diverse receiver's balanced photodiodes (BPDs) is shown in Fig. 2. The top figure shows that without automatic polarization control, there is substantial power fluctuation across the measurement wavelength range. The fading is correlated to the trend of the tracking signal, as can be seen at the top of Fig. 3, confirming that the fading in the fringe pattern is induced by the polarization rotation. The IL derived from such measurement is distorted as shown in the bottom of Fig. 3. Significant dips in the IL are observed in the wavelengths where the fading occurs due to lower reference power.

However, with automatic polarization control, the polarization in the reference arm can be stabilized across wavelengths, as seen on the tracking signal at the top of Fig. 3, meaning that the reference and measurement signals are aligned at all wavelengths. This eliminates the fading as can be seen at the bottom of Fig. 2 and provides more accurate IL calculation across wavelength as shown at the bottom of Fig. 3. Note that the slight decrease in power in the tracking signal after 1560 nm is due to the laser variation with wavelength and not from the polarization rotation.

We then proceed to analyze the IL variation with wavelength for all 7 cores of the MCF. Figure 4 shows the variation in IL, relative to the IL where the system optimization was done (1550 nm), across the measurement sweep with and without automatic polarization control. It can be seen that without APC, there is a strong deviation from the optimized IL of up to 4 dB as a result of the fading. However, with APC, the variation is below 0.5 dB with a minor increase in IL from 1550 to 1570 nm, more characteristic of the true wavelength-dependent properties of the fiber. The standard deviation of the wavelength dependent IL of the MCF is reduced from 1.49 to 0.35 dB.

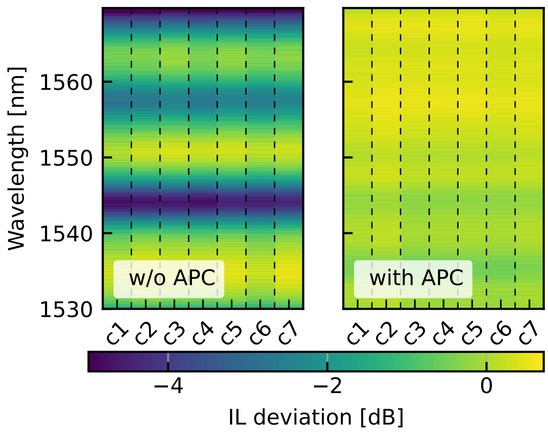


**Fig. 4:** Insertion loss variation with wavelength for the 7 cores of the MCF without and with automatic polarization control, where Cn is the specific core measured

## Conclusions

We have proposed an optimized OVNA setup with automatic polarization control to mitigate the impact of polarization rotation in the reference arm and ensure proper alignment between the reference and the signal in the polarization-diverse receiver, eliminating the polarization-induced power fading. We demonstrate that this improves the wavelength-dependent IL measured with the OVNA for a 10 km 7-core MCF.

## Acknowledgements

We thank Novoptel and Professor Reinhold Noé and his team for support with the automatic polarization controller. This work acknowledges partial funding by the European Union's Horizon Europe Research and Innovation Programme HOMTech Project under the Marie Sklodowska-Curie Grant Agreement No. 101072409 and from the Dutch Ministry of Economic Affairs and Climate Policy, under the PhotonDelta National GrowthFunds.

## References

[1] B. J. Puttnam, G. Rademacher, and R. S. Luís, "Space-division multiplexing for optical fiber communications", *Optica*, vol. 8, no. 9, p. 1186, Sep. 20, 2021, ISSN: 2334-2536. DOI: 10.1364/OPTICA.427631.

[2] B. J. Puttnam, M. van den Hout, G. Di Sciullo, *et al.*, "22.9 pb/s data-rate by extreme space-wavelength multiplexing", in *49th European Conference on Optical Communications (ECOC 2023)*, Institution of Engineering and Technology, pp. 1678–1681, ISBN: 978-1-83953-926-8. DOI: 10.1049/icp.2023.2665.

[3] G. Rademacher, R. S. Luís, B. J. Puttnam, *et al.*, "Characterization of the first field-deployed 15-mode fiber cable for high density space-division multiplexing", in *2022 European Conference on Optical Communication (ECOC)*, Sep. 2022, pp. 1–4. [Online]. Available: https://ieeexplore.ieee.org/document/9979572.

[4] M. Mazur, N. K. Fontaine, R. Ryf, *et al.*, "Transfer matrix characterization of field-deployed MCFs", in *2020 European Conference on Optical Communications (ECOC)*, IEEE, Dec. 2020, pp. 1–4, ISBN: 978-1-72817-361-0. DOI: 10.1109/ECOC48923.2020.9333282.

[5] M. Mazur, N. K. Fontaine, L. Dallachiesa, *et al.*, "Broadband characterization of field-deployed 15-mode graded-index multi-mode fiber cable", in *49th European Conference on Optical Communications (ECOC 2023)*, Institution of Engineering and Technology, pp. 988–991, ISBN: 978-1-83953-926-8. DOI: 10.1049/icp.2023.2409.

[6] G. VanWiggeren and D. Baney, "Swept-wavelength interferometric analysis of multiport components", *IEEE Photonics Technology Letters*, vol. 15, no. 9, pp. 1267–1269, Sep. 2003, ISSN: 1041-1135, 1941-0174. DOI: 10.1109/LPT.2003.816663.

[7] S. Rommel, I. Tafur Monroy, N. Wada, *et al.*, "Polarization equalization in optical vector network analysis for SDM fiber characterization", *IEEE Photonics Technology Letters*, vol. 31, no. 24, pp. 1917–1920, Dec. 15, 2019, ISSN: 1041-1135, 1941-0174. DOI: 10.1109/LPT.2019.2949615.

[8] S. Rommel, J. M. D. Mendinueta, W. Klaus, *et al.*, "Few-mode fiber, splice and SDM component characterization by spatially-diverse optical vector network analysis", *Optics Express*, vol. 25, no. 19, p. 22 347, Sep. 18, 2017, ISSN: 1094-4087. DOI: 10.1364/OE.25.022347.

[9] N. K. Fontaine, R. Ryf, M. A. Mestre, *et al.*, "Characterization of space-division multiplexing systems using a swept-wavelength interferometer", in *Optical Fiber Communication Conference/National Fiber Optic Engineers Conference 2013*, OSA, 2013, OW1K.2, ISBN: 978-1-55752-962-6. DOI: 10.1364/OFC.2013.OW1K.2.

[10] R. Noe, B. Koch, and V. Mirvoda, "LiNbO3-based endless optical polarization control", in *2016 21st European Conference on Networks and Optical Communications (NOC)*, Lisbon, Portugal: IEEE, Jun. 2016, pp. 162–167, ISBN: 978-1-5090-0296-2. DOI: 10.1109/NOC.2016.7507006.

[11] S. Gross and M. J. Withford, "Ultrafast-laser-inscribed 3d integrated photonics: Challenges and emerging applications", *Nanophotonics*, vol. 4, no. 3, pp. 332–352, Nov. 6, 2015, Publisher: De Gruyter, ISSN: 2192-8614. DOI: 10.1515/nanoph-2015-0020.