Wavelength Dependence of Polarization State in Single-Mode Fiber: Implications for BOTDA

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***Abstract*—We measured the evolution of the state-of-polarization (SOP) versus wavelength in 25km fibers and the impact of bend by analyzing the S_1 parameter. Results suggest the SOP mismatch caused by Brillouin frequency shift is negligible.**

Keywords— state-of-polarization, BOTDA.

I. INTRODUCTION

Brillouin Optical Time-domain Analyzers (BOTDA) utilized for distributed temperature or strain sensing along optical fibers offer significant societal benefits, with wide-ranging applications in structural health monitoring (SHM) [1-4], often over long distances, and are increasingly used for dynamic sensing [5] including micro-strain and vibration detection, and monitoring passive optical networks [6].

Polarization control is a critical aspect of BOTDA systems because the efficiency of Stimulated Brillouin Scattering (SBS) depends strongly on the relative SOPs of the pump and probe waves [7]. Besides the polarization alignment between probe and pump light, understanding the extent to which the SOP changes with wavelength is also crucial given the inherent frequency (Brillouin frequency shift, f_B) difference between the pump and probe signals in BOTDA. Although the wavelength-dependent polarization of erbium-doped single-mode fiber has been measured in the past, studies specifically targeting BOTDA applications have not yet been reported [8]. If the SOP rotates significantly over the frequency interval f_B, it could lead to misalignment between pump and probe SOPs along the fiber even they are match at the beginning, degrading the SBS interaction efficiency and the sensor's performance. This necessitates investigating the wavelength dependence of SOP to inform the design of appropriate polarization control or mitigation strategies.

II. EXPERIMENT DESIGN

A fiber-based Polarizing Beam Splitter (PBS)-based polarimeter was employed to monitor the SOP evolution. This setup measures the power projected onto two orthogonal linear polarization states, allowing the calculation of the normalized Stokes parameter $S_1 = (P_1 - P_2)/(P_1 + P_2)$, where P_1 and P_2 are optical powers at the two orthogonal output ports of the PBS. It can be proven that $S_1 = \cos 2\nu$, where 2ν is the great-circle angle between the point corresponding to the output SOP and that to the horizontal linear polarization (HLP) in the Poincare sphere. Here HLP corresponds to the state of $P_1 = 1$.

Assume that the evolution of the SOP of a BOTDA system on the Poincare sphere has equal probability in all directions. If we set the reference state (for base wavelength λ_{base}) at the point of HLP, the deviation of the SOP of other wavelengths can be roughly estimated by the value ν. Specifically, the interference visibility between the system SOP and the HLP equals to $\cos\nu$. Therefore, though S_1 doesn't provide the complete SOP information, this approach is still practical [9].

The experimental setups are depicted in Fig. 1. A CoBrite DX1 tunable laser source served as the light source. A fiber-based PBS (Thorlabs PFC1550A) was used to separate the light into components aligned with its slow and fast axes. The power aligned with the slow axis was measured by power meter PM1 (P_1), and the power aligned with the fast axis was measured by power meter PM2 (P_2). The polarization extinction ratio directly after the laser (aligned to the PBS basis) is exceeding 17 dB.

Two Fiber Under Test (FUT) configurations (Fig. 1) were studied: **Setup 1:** A 25 km SMF spool placed inside an acrylic container to minimize ambient temperature fluctuations. **Setup 2:** A 2 m SMF patchcord, tested sequentially in an unwrapped (straight) configuration and a wrapped configuration (coiled around a post with a diameter of 3.7 cm). This setup simulates conditions involving tighter bends. A 20 dB optical attenuator was inserted before the FUT due to the high laser power relative to the short fiber length. A Thorlabs 3-Paddle fiber polarization controller (PC, ≈ 27 mm loop diameter) was positioned before the FUT in both setups. Prior to each wavelength scan, the PC was adjusted to maximize the power P_1 (slow axis) and minimize P_2 (fast axis) for $\lambda_{\text{base}} = 1550$ nm, so that the reference point is set to a position close to the case $\nu = 0$.

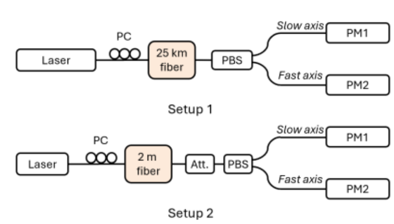


Fig. 1. Setups of measurement; Setup 1: 25 km SMF with PBS-based polarimeter; Setup 2: 2 m SMF (wrapped or unwrapped) with PBS-based polarimeter; PM: power meter, PBS: polarization beam splitter, Att.: optical attunator.

The birefringence of SMF is known to be sensitive to environmental factors, particularly temperature. To verify the stability of the fiber's polarization properties during the measurement period and ensure the collected data was free from significant disturbances, an interlaced wavelength scanning pattern was employed. This method involved periodically returning to a baseline wavelength ($\lambda_{\text{base}} = 1550$ nm) during the scan. The scanning sequence was: $\{\lambda_0, \lambda_{\text{base}}, \lambda_1, \lambda_{\text{base}}, \lambda_2, \ldots, \lambda_{\text{base}}, \lambda_N\}$. Consistent power readings (P_1, P_2) at λ_{base} throughout the scan confirmed the stability of the fiber's state.

The parameters used are: **Setup 1:** Wavelength range: 1550 - 1568 nm. Scanning interval: 0.5 nm. **Setup 2:** Wavelength range: 1550 - 1553 nm. Scanning interval: 0.1 nm.

III. Experiment Result

Setup 1 (25 km SMF): Both the temperature readings and the measured baseline wavelength powers (P_1, P_2) remained highly stable during the measurement, suggesting a stable state of fiber. Fig. 2 plots the measured normalized Stokes parameter S_1 across the full wavelength scan (1550 nm - 1568 nm). The value ν as a function of the wavelength is plotted in the same figure. It is found that the maximum change of ν as a function of wavelength is 0.0165 rad/0.1 nm (0.1 nm≈12.5 GHz around 1550 nm). The maximum inference visibility deviation $cos(\Delta\nu)$ therefore is 0.9998.

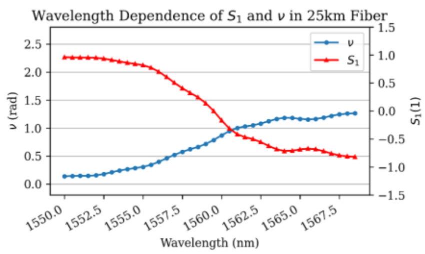
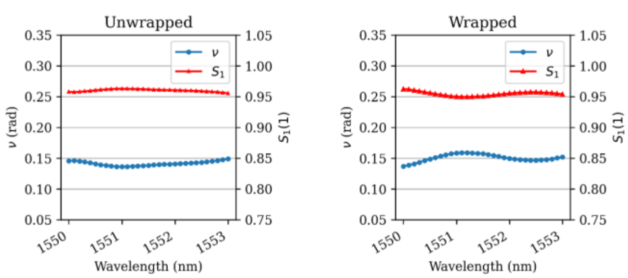


Fig. 2. Wavelength Dependence of S_1 and ν in 25km Fiber

Setup 2 (2 m SMF): Experiment showed stable power readings and temperature at the baseline wavelength, indicating reliable measurement conditions. Fig. 3a and 3b present the measured S_1 and ν versus wavelength (1550 - 1553 nm) for the unwrapped and wrapped short fiber, respectively.



(a) (b)

Fig. 3. Wavelength Dependence of S_1 and ν in (a) Unwrapped, and (b) Wrapped short Fibers.

Fig. 3a and 3b compare the wavelength dependency of S_1 and ν between the unwrapped and wrapped states, where the maximum change of value ν is 0.013 rad for the unwrapped and 0.022 rad for the wrapped. This result suggests that wrapping will increase the wavelength dependency of the SOP of the fiber.

Accurate characterization and management of polarization effects are crucial for optimizing BOTDA sensor performance. This study investigated the wavelength dependence of the SOP in SMF using a simplified PBS-based polarimeter. Two main conclusions were drawn:

In a long (25 km) SMF, the SOP evolution with wavelength was relatively slow. The change of the angle ν from the interference visibility was found to be less than 0.0165 rad/0.1 nm (0.1 nm ≈12.5 GHz around 1550 nm). This suggests that over the frequency range corresponding to the Brillouin frequency shift, the SOP change is expected to be negligible. In a short (2 m) SMF, wrapping the fiber into coils (3.7 cm diameter) did increase the wavelength dependence of the SOP compared to the unwrapped state over the tested 3 nm range.

These findings imply that the inherent frequency difference between pump and probe in BOTDA systems does not cause severe SOP mismatch, while bending of the fiber will exacerbate the wavelength dependency of the SOP. This insight could support the development of simplified BOTDA systems, potentially employing alternative polarization control or tracking mechanisms that rely on slower SOP dynamics.

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