Single-Ended Coherent Channel Estimation

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Abstract: We demonstrate a novel method for finding the coherent transfer matrix (CTM) of a multi-channel transmission medium utilizing backscattering and coherent optical time-domain reflectometry (COTDR). We measured the CTM for two polarizations of a single-mode fiber with $\pm 0.3dB$ and $\pm 8.5^{\circ}$ amplitude and phase precisions.

1. Introduction

Distortions affect both intensity and phase of optical beams propagating through multi-channel transmission media, such as fibers (single-mode fibers (SMFs) and multimode fibers (MMFs)) and atmosphere. Inherent imperfections, external perturbations and inhomogeneities lead to variations in the refractive index across and along the transmission path and consequently, spatiotemporal distortions [1, 2]. The growing number of applications utilizing free-space optics (FSO) and MMFs would benefit from a quantitative experimental characterization of these distortions. The performance of free-space optical communication systems depends on the beam quality at the receiver [3]. Analogously, MMFs are potentially the best candidates for medical endoscopy [4]; However, imaging performance suffer from wavefront distortions. For applications such as optical communications in which both ends of the transmission medium are accessible, the coherent transfer matrix (CTM) can be estimated using coherent detection and digital signal processing [5]. In imaging through MMF, such an approach is not feasible because the targets are inaccessible.

To estimate the CTM of an optical transmission media without access to the distal endpoint, distributed reflections (e.g., originated from Rayleigh backscattering [6]) can be exploited. Here, for the first time (to the best of our knowledge), we demonstrate the characterization of the CTM of an optical fiber. The theoretical foundation of the proposed method is described and applied experimentally to the measurement of the CTM of two polarization modes in an SMF.

2. Methods

2.1 Theoretical Principles

The CTM H of a transmission medium, such as an optical fiber, can be obtained by relying on the naturally occurring Rayleigh backscattering. The overall scheme of the method is shown in Fig. 1. For simplicity, it illustrates the concept of distributed coherent channel estimation for an SMF with two polarization channels, which can be extended to MMFs supporting many vector modes. An input pulse with a width of a few nanoseconds (Δt) and a known polarization state is used as the input for the fiber under-test. The polarization of an optical beam $E = |E_x| \measuredangle \varphi_x \hat{x} + |E_y| \measuredangle \varphi_y \hat{y}$ can be represented by a point on *Poincare' sphere* by using $\rho = |E_x| / |E_y|$ and $\Psi = \varphi_x - \varphi_y$. We devide the fiber into many segments. The CTM of the optical fiber is the product of the CMTs of the concatenated segments shown in Fig. 1 and can be written as $H = \prod_{n=1}^{N} H_n$, where N is the number of segments along the length of the fiber spaced Δz apart and H_n is the transfer matrix of the n^{th} segment. Matrix H_n is assumed to be near-identity when Δt and Δz are small enough:

$$H_n = \begin{bmatrix} 1+\delta_{11} & \delta_{12} \\ \delta_{21} & 1+\delta_{22} \end{bmatrix}_n, \qquad |\delta_{ij}| \ll 1, \delta_{ij}\delta_{kh} \approx 0 \tag{1}$$

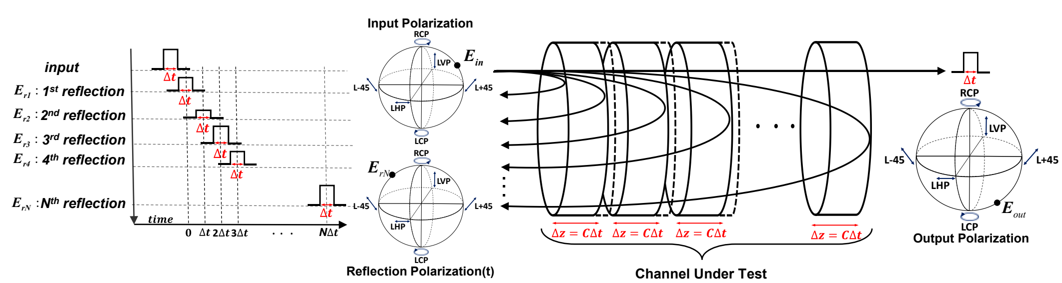

Fig. 1: The proposed experiment. Input beam polarization is known and reflected ones are measured and deployed to estimate the output polarization. Any reflected pulse is from a specific segment of the channel and the length of each segment is determined by the width of the pulse width Δt.

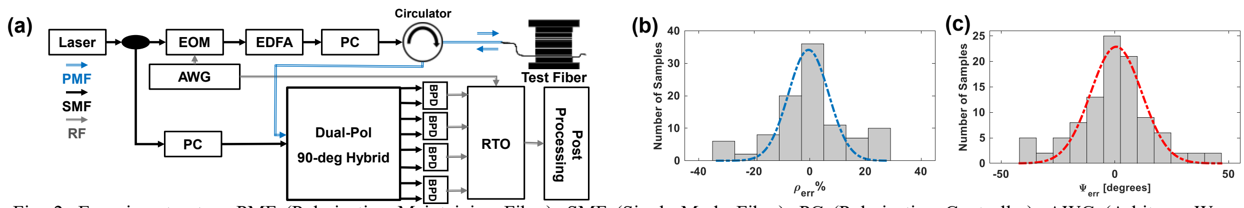

Fig. 2: Experiment setup. PMF (Polarization Maintaining Fiber), SMF (Single-Mode Fiber), PC (Polarization Controller), AWG (Arbitrary Wave Generator), EOM (Electro-Optic Modulator), BPD (Balanced Photodetector), and RTO (Real-Time Oscilloscope). (b) and (c) Distribution for 100 data sets: (b) relative error in the amplitude ratio; (c) relative error in phase difference.

The CTM of each fiber segment is unitary ($H_n^{\dagger} H_n = I$) and symmetric since the loss is the same and negligible for both polarizations in a short piece of the SMF. Accordingly, it can be shown that $\mathrm{Re}\{\delta_{ij}\} = 0, \delta_{11} = -\delta_{22}, \delta_{12} = \delta_{21}$. For the first segment,

$$\left\langle E_{out1} E_{out1}{}^{\dagger} \right\rangle = \left\langle H_1^T R H_1 E_{in1} E_{in1}^{\dagger} H_1^{\dagger} R^{\dagger} H_1{}^{T^{\dagger}} \right\rangle = \left\langle H_1 R H_1 E_{in1} E_{in1}^{\dagger} H_1{}^{\dagger} R^{\dagger} H_1{}^{\dagger} \right\rangle \tag{2}$$

where $R=r\times I$ is the Rayleigh reflection coefficient matrix of one fiber segment and I is the 2×2 identity matrix [7, 8], E_{r1} and E_{in1} are the reflected and the input electric field of the first segment of the fiber, respectively. After straightforward algebraic manipulations, Eq. (3) can be cast into solving for two unknowns δ_{11}, δ_{12} besides Rayleigh reflection coefficient, which depends on both the fabrication process of the fiber and the input pulse width. Once the CTM of the first segment is found, a similar procedure can be used to find the CTM of the next segment and so on.

2.2 Experimental Design

The experimental setup in Fig. 2(a) was designed to characterize the test fiber, which is 96 meters of "AcoustiSens Wideband Vibration Sensor Fiber" with 10-15 *dB* higher Rayleigh backscattering. A narrow linewidth laser (NKT BASIK E15 CW) was split into two parts, one serves as the local oscillator (LO) and the other passes through an electro-optic modulator (EOM), followed by an EDFA, and then enters the test pulse into the test fiber. A polarization controller (PC) on the LO path was used to maintain equal powers in the x and y polarizations. Light passing through the EOM is modulated as 3ns pulses repeating every 1.1μs with an extinction ratio of 27.5 *dB* and passes through a high-power circulator. The reflected signals from the test fiber and the LO interfere in a dual-polarization 90-degree optical hybrid and each pair of outputs are connected to a balanced photodetector (BPD) to capture the electric fields in the two quadratures and two polarizations simultaneously. Since the power received from the Rayleigh reflections is about 60 *dB* lower than the launch power, the received signal is averaged over 3000 periods for accuracy.

3. Results

Let E_{in} , E_{out} , E_{rN} be the input, output, and N^{th} reflection electric fields in Fig. 1, respectively. Since H is symmetric, the expected output electric field ($E_{out\_expected}$) can be found based on the calculated H and the measured E_{in} ($E_{out\_expected} = H \times E_{in}$) and in the meantime, the measured output electric field ($E_{out\_measured}$) can also be found based on the calculated H and the measured E_{rN} ($E_{out\_measured} = H^{-1} \times E_{rN}$). These two conditions must be independently satisfied, which can be used to validate the CTM of the fiber. Ideally, the polarization state is expected to be the same for both $E_{out\_expected}$ and $E_{out\_measured}$ and the difference can be used to determine the accuracy of the proposed channel estimation method. The two sets of values for ρ and Ψ in the expected and measured data are compared. We captured 100 sets of data and Figs. 2(b) and (c) show distributions of ρ_{err} and Ψ_{err} , respectively, over all sets of measurements. The CTM is thus estimated with a precision of $\pm 0.3dB$ in amplitude and $\pm 8.5^{\circ}$ in phase.

In summary, we proposed and experimentally demonstrated a method for measuring the CTM of an SMF. The approach can be extended to other multi-channel transmission media such as MMF and atmosphere, based on measurements performed at only one end. This method is expected to find potential applications in MMF communication links, biomedical imaging and directed-energy weapons.

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