Ultra-Long Distance BOTDA Sensor System Employing Hybrid Amplification and Advanced Noise Reduction Techniques

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Distributed Optical Fiber Sensing (DOFS)

Introduction

a) Rayleigh scattering: Vibrations, strain, temperature
b) Brillouin scattering: Strain, temperature
c) Raman scattering: Temperature

Advantages with optical fibers as sensors:
- Small size and light weight and easy deployment
- Immune to electromagnetic interference (EMI)
- Harsh environment measurement capability
- Safety
- Chemically inert
- Long-range distributed/multiplexed measurement

Conventional electrical/mechanical sensors are discrete in nature, and more problematic.
DOFS Application Examples

- **Structural Health Monitoring (SHM):** Cracks/deformations in buildings, bridges, and airborne structures, tunnels, natural gas pipelines, railways, etc.; strain/temperature measurements with **BOTDA**
Physical Parameter Estimation in BOTDA

➢ Brillouin Frequency Shift (BFS), \( \Delta \nu_{BFS} = C_T \Delta T + C_\varepsilon \Delta \varepsilon \)

➢ Location using “Time of Flight” method

Brillouin Frequency Shift (BFS) (~11 GHz) 

\[ V_{BFS} = V_{pump} - V_{probe} \text{ (at peak gain of BGS)} \]

Brillouin gain spectrum (BGS) line width 30 MHz @1,550 nm

@ pump pulse width > 40 ns

BFS changed to new frequency location after applying temperature/strain

SENSITIVITY

20 \( \mu \varepsilon \) \( \Leftrightarrow \) 1 MHz

1 \( ^\circ \)C \( \Leftrightarrow \) 1 MHz

Standard BOTDA: 50/60 km @ 5 m resolution

Beyond this range: Challenges!!
Challenges in Long Range-BOTDA

➢ Fiber loss @ 1,550 nm: 0.2 dB/km, for 100 km fiber, minimum loss would be 20 dB
➢ Pump depletion for strong probe powers
➢ Increase signal-to-noise ratio (SNR) by increasing the pump power: Nonlinear threshold (< 20 dBm)
➢ SNR decreases at longer ranges due to noise dominant poor gain, erroneous measurements

➢ Existing solutions to go beyond 100 km: Raman distributed amplifications for pump/probe, inline Erbium doped fiber amplifiers (EDFA), pump pulse coding, etc.

Our solution:

A combination of hybrid amplification (Raman + inline EDFA) + efficient signal denoising for reaching to 150 km fiber length
EDFA and Distributed Raman Amplifiers

- **EDFA**: Uses optical fiber doped with \( \text{Er}^{+3} \) ions and pump source with 980 nm or 1,480 nm laser light, amplifies seed signal @ 1,550 nm; **Discrete, strategic location important**
- **Raman distributed amplifiers**: Single mode fibers pumped at 1,455 nm, emits stimulated emission at @ 1,550 nm along the fiber length for the weak seed signal; **Distributed**
Experimental Setup

BOTDA with Hybrid Amplification

Interrogation parameters used:
Raman pump: ~340 mW
Pump power: ~16 dBm
Probe power: ~12 dBm
EDFA 3 power: ~13 dBm
Pump pulse width: 80 ns
Averaging: 1,024 trace averages
Scan width: 85 MHz

ISO: Isolator; WDM: Wavelength division multiplexer; PSM: Polarization scrambler; PC: Polarization controller; RF: Radio Frequency generator; EOM: Electro-optical modulator; ASE: Amplified spontaneous emission; DAQ: Data acquisition; SOA: Semiconductor optical amplifier; EDFA: Erbium doped fiber amplifier; CIR: circulator

50 m fiber @ 150 km placed inside heating chamber.
Results and Discussion

BGS Profile of 150 km Fiber: Each Fiber is 25 km, a Total of 6 Spools

- Gain increases at the end of the fiber: Raman contribution to pump and probe.
- Gain increases @ 75 km due to inline EDFA.
Results and Discussion

BFS Profile of 150 km Fiber

- BFS profiles within 20 MHz; Interaction of pump-probe all over the fiber.
- More noise after the inline EDFA might be related to the deterioration of pump pulse extinction ratio after amplifications.
Non–Local Means (NLM) Filtering Effect on BFS Uncertainty

Results and Discussion

Non–Local Means (NLM) Filtering Effect on BFS Uncertainty

➢ BFS uncertainty of **4.5 MHz** reduced to **~1 MHz** with NLM filtering.

**NLM Parameters:**
- Search window size: 21 x 21
- Patch size for similarity: 3 x 3
- Smoothing parameter: standard deviation of the base probe (unamplified position)
Results and Discussion

Temperature Measurements: @40 °C/Baseline @25 °C

➢ At the end of fiber: BGS shifts its peak due to heating.
Results and Discussion

Temperature Measurements: @40 °C/Baseline @25 °C

➢ At the end of fiber, the high accuracy of measurements were obtained with an error of ~1 °C.

➢ BGS width is <35 MHz.
Summary

➢ Long-range BOTDA is crucial for monitoring long distance infrastructures such as “natural gas pipelines”
➢ Range enhancement can be achieved with hybrid amplifications using inline EDFA and Raman distributed amplifications
➢ 150 km fiber interrogation was performed with hybrid amplification supported by NLM filtering: temperature accuracy of 1 °C, and SNR of ~ 8 dB was achieved at the peak gain trace
➢ Future work:
  ➢ Commercial EDFA replacement with custom built passive EDFA (no need of power supplies at the middle of the fiber)
  ➢ Spatial resolution enhancement to reach below 5 m using pump pulse coding
  ➢ Range enhancement with bidirectional Raman pumping with low RIN Raman laser sources to reach 200 kms
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