Ultra-Long Reach Fiber Distributed Acoustic Sensing for Power Cable Monitoring

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ABSTRACT

This paper reports the longest reach Distributed fiber-optic Acoustic Sensing (DAS) system, without the need for inline amplification This was achieved using a DAS system specifically designed for long distance in combination with different fiber types optimized either for low loss or for high backscatter coefficient. Instrument- and fiber parameters were analysed to model the expected performance with various fiber combinations. A measurement range exceeding 112 km, and 125 km if the far end is optimized, is realized with a suitable SNR for power cable applications.

KEYWORDS

Distributed Acoustic Sensing (DAS), Distributed Fiber-Optic Sensing (DFOS), Coherent Optical Time Domain Reflectometry (C-OTDR), Fiber optics sensors, Fiber properties, Vibration analysis, Power Cable Monitoring

INTRODUCTION

Temperature monitoring of power cables using optical fiber Distributed Temperature Sensors (DTS) is a well-established and widely used technology. The optical fiber cable may either be installed near the power cable or embedded within the power cable itself. In recent years the technology to reliably carry out Distributed Acoustic Sensing has also been widely reported [1]. Distributed Acoustic Sensing (DAS) technology based on coherent Rayleigh backscatter in optical fiber resembles a vast number of "microphones" using a simple passive glass fiber as sensor over long distance and has been a subject of significant interest.

Whilst current commercial DAS systems reach up to 40 or 50 km sensor length, recent research has been presented which increases the reach past this point. Shiloh et al. [2] for example presented in 2017 a reach of 64 km whilst Martins et al. [3] reported 125 km using second-order Raman amplification along the sensor fiber and Wang et al. [4] reported greater than 175 km, utilizing a combination of Raman and Brillouin amplification along the fiber albeit with a 25m spatial resolution. This paper reports a significant advance in the field, pushing the maximum possible reach of a commercial DAS to 112 km covering the whole range or even 125 km with some performance gap along some range in between. Notably, this performance improvement is achieved without the need for amplification along the sensor fiber whilst maintaining a spatial resolution of 10 m. This result is achieved by combining a new DAS system with a sensor fiber that is optimized for DAS applications. With increasing sensor fiber length, the amount of light returning to the DAS interrogator from the far end decreases. At the same time the maximum possible rate for the light pulses launched into the fiber by the DAS interrogator reduces to match the light round-trip time to the fiber end and back to the interrogator. Both degrades the SNR and limits the maximum reach of distributed acoustic sensing (DAS). The reach depends on the DAS stimulus pulse energy E sent into the fiber, the Rayleigh backscatter coefficient B of the fiber describing the fraction of the stimulus energy elastically scattered back to the interrogator and the attenuation of the fiber per kilometer A. These parameters are in general inter-dependent, i.e. tweaking a fiber to higher backscatter may also lead to higher loss per kilometer. The maximum pulse power is limited by the onset of non-linear effects, starting to transfer energy from the stimulus pulse towards shifted frequencies by non-elastic interaction with the fiber material, e.g. by stimulated Brillouin scattering or self-phase modulation as clarified by Izumita et al. [5]. The non-linear limit of optical power at a given wavelength in general depends on the used fiber.

The task is therefore to find fibers with an optimum combination of these parameters to maximize the reach in DAS measurements. We investigated different fibers types and fiber combinations to achieve highest reach in different scenarios, i.e. for cases of single fiber type or combinations of fiber types.

DAS SYSTEM AND SENSOR FIBERS

For this investigation, a commercial DAS system model "N5200A" from AP Sensing was used. It is a phase-based DAS i.e. delivers quantitative strain data (in contrast to non-quantitative intensity-based DAS systems), based on a proprietary "2P Squared DAS" technology, and optimized for long reach measurements. It operates with an interrogation wavelength of 1550 nm, typical range of 70 km and a variable spatial resolution between 5 and 40 m.

Three types of sensing fiber were investigated, and the combination of different fiber types was optimized for extended reach DAS applications. The fiber types are: Ultra Low Loss (ULL) fibers, Enhanced Backscatter (ENHF) Fibers and standard G.652 single mode fibers (SSMF):

Ultra-Low Loss fiber (ULL): Two different very low loss and large effective area fibers, TeraWave SCUBA-125 [5] and SCUBA-150 [6] from OFS with nominal effective areas of 125 µm2 and 153 µm2, respectively were proposed. SCUBA fibers are made with a pure (i.e. Ge-free) Silica core and large effective area which allows for a low loss of 0.155 dB/km and improved nonlinear performance. The large area enables launch of significantly higher input signal power in the fiber without nonlinear penalties. The trench assisted design of the SCUBA fiber index profile makes the fibers resistant towards bending irrespective of the large effective areas. The trench also results in a reduced mode field diameter (MFD) when compared to the effective area, as A_{eff} = 1.06 MFD^2 * π/4, promoting better splice loss performance between SCUBA and SSMF with lower effective areas. Optimized splice losses of 0.1 dB or