Ultra-long (275 km) Random Distributed Feedback Fiber Laser for Remote Sensor Monitoring

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Abstract: An interferometric sensor located 275 km away from the monitoring station has been interrogated by a double-pumped random distributed feedback fiber laser, reaching the longest distance in fiber optic remote sensing reported up to date.

OCIS codes: Lasers, fiber (140.3510); Lasers, distributed-feedback (140.3490); Scattering, stimulated Raman (290.5910); Optical sensing and sensors (280.4788);

1. Introduction

Fiber optic low-coherence Interferometry (FOLCI) [1][2] is an interesting approach that allows the absolute measurement with high accuracy of many parameters, such as temperature [3], pressure [4], strain [5] and refractive index [6]. The measuring technique is intensity-based; however, the measurement accuracy is ideally insensitive to optical power fluctuations between the monitoring station and the sensor location. Moreover, it offers higher resolutions than other conventional intensity-based sensors. FOLCI systems can also provide absolute displacement measurements, not requiring the previous characterization of the sensors involved. Despite their insensitivity to optical power fluctuations in the transmission channel, the low output power (compared to laser sources) of the broad-band sources commonly used in FOLCI systems prevent the remote interrogation of this type of sensors.

On the other hand, random distributed feedback fiber lasers (RDFB-FL) have been intensively studied lately due to their interesting characteristics when compared to traditional laser cavities [7]. Their mode-less behavior, stability and high power make them particularly suitable for ultra-long range applications. RDFB-FL can also be internally modulated without frequency restrictions, which was exploited in [8]. In that work, a hybrid technique which combines wavelength division multiplexing with time domain multiplexing was used to interrogate ten fiber Bragg gratings (FBG) located as far as 200 km, significantly improving the multiplexing capability with respect to other remote structures previously proposed. Another interesting property of random fiber lasers is that their natural emission bandwidth (up to some nanometers) is wide enough to make them suitable for FOLCI.

In general terms, optical fiber systems for remote sensing present the ability to remotely monitor an extensive range of parameters at long distances. Remote systems deal with a main challenge: to reach the maximum distance at which the remote sensor can be interrogated without the need of electrical power supply at the sensor location. During the last years, several remote structures have been proposed [9], using different types of amplification. In [10], a high-speed sweep-wavelength light source amplified by an Erbium doped amplifier was used to interrogate a sensor located 230 km away from the monitoring station. Raman amplification was used in [11], where a remote FBG multiplexing system was demonstrated, reaching a maximum distance of 250 km and multiplexing four sensors. The maximum distance reached up to date was presented in 2011 in [12], where a long-period grating displacement sensor was interrogated 253 km away with an optical time domain reflectometer.

In this work, a double pumped RDFB-FL is used to interrogate a FOLCI scheme, which sensing interferometer is located 275 km away from the header. This is, as far as the authors are aware, the longest distance achieved for a remote fiber optic sensing system. The distinctive properties of RDFB-RL, such as their high power in combination with their spectral width, have allowed the remote interrogation of an interferometric sensor in a FOLCI scheme.

2. Experimental set-up and principle of operation

2.1. Experimental set-up

The presented setup consists of two 275 km optical paths. The first one is part of a single-arm forward-pumped random DFB fiber laser intended to illuminate the interferometric sensor. The second path is employed to guide the sensor´s signal back to the detection sub-system. The two optical fibers are required to avoid the counter-propagating noise generated in the arm of the laser, which exceeds the sensor response. On top of that, this type of scheme with two optical paths simplifies sensor systems which address some dominating limitation factor such as noise in the upper path. The economic justification of using two paths, which doubles the needed fiber in the system, is based on the reduction of the effective cost of fiber optic components, especially SMF cables. Furthermore, in practical applications, the final cost of the installed cable does not have a significant increment if a cable of two fibers is used instead of a cable of one.

The fiber laser structure consists of two wavelength division multiplexers (WDM) used to inject two pump lasers (RLD-5K-1360 and RLD-5K-1445) into the distributed cavity formed by 50 km+275 km of single mode fiber (SMF). The fiber acts as the active medium for amplification due to the stimulated Raman scattering effect. In addition, it acts as the distributed mirror required for the laser generation, providing a weak feedback along it given by the Rayleigh scattering effect. The WDMs are connected in series with a 50 km SMF fiber spool between them. This fiber enhances the generation of a secondary pump signal at 1445 nm which is then assisted by the 1445 nm-pump laser in order to achieve second-order Raman amplification. The backscattered light is redirected into the cavity by using a loop mirror formed by a 3-port circulator. Finally, an optical isolator is placed at the output of the laser, right before the sensing interferometer, to avoid any feedback that could potentially destabilize the operation of the random laser.

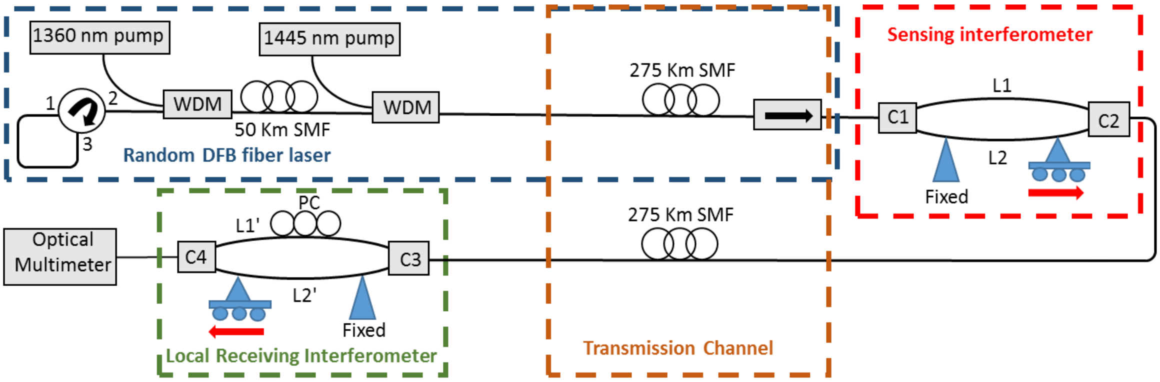

Fig.1. Schematic setup

The FOLCI sensing scheme is composed by two Mach Zehnder interferometers: a sensing interferometer (SI) located 275 km away from the monitoring station and a local receiving interferometer (LRI). Each interferometer is formed by two 50:50 optical couplers (C1, C2 and C3, C4) connected by two SMF arms, *L1*, *L2* and *L1'*, *L2'*, respectively, with an approximate length of *L1*≈*L1'*=2 m and *L2*≈*L2'*=4 m. Both ends of *L2* and *L2'* have been fixed onto two separate displacement stages, equally formed by a fixed platform and a mobile micro-positioner (Newport M423) that controls the displacement applied to the fiber. A polarization controller is used in the LRI arm *L1'* in order to maximize the fringe visibility of the interference signal. Finally, an optical multimeter (ANDO AQ-2140) is connected at the output of the LRI to measure the optical power arriving at the monitoring station.

2.2. Principle of operation

A FOLCI scheme is formed by a light source that illuminates two interferometers connected in series. The optical path differences (OPDs) of the SI (*OPD1*=|*L1*-*L2*|) and the LRI (*OPD2*=|*L1'*-*L2'*|) must be arranged to be several times larger than the coherence length of the light source L_c so there is no coherent interference generated by each Mach Zehnder individually. However, whenever the difference between *OPD2* and *OPD1* is adjusted to be smaller than L_c, |*OPD2*-*OPD1*|< L_c, interference will occur at the output of the LRI and the optical intensity detected (I) will be given by:

$$I = I_0\left(1+\sqrt{K_1K_2K_3K_4}exp\left(-\left(\frac{2\Delta L}{L_c}\right)^2\right)\cos(k\Delta L)\right) \tag{1}$$

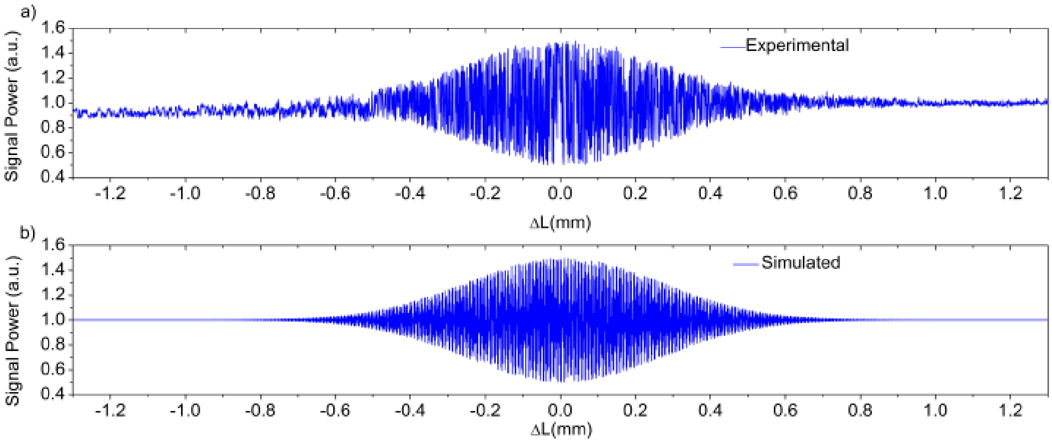

Fig.2. a) Normalized experimental and b) simulated traces detected at the output of the FOLCI scheme

where $\Delta L=OPD2\text{-}OPD1$, k is the wavenumber, I_0 the total optical power arriving at the detector and K_1,K_2,K_3 and K_4 are the power split ratios of the couplers used in the SI and the LRI respectively [2]. Commonly, this technique employs low-coherence broad-band sources, such as light emitting diodes (LED), which present spectral widths from 30 to 60 nm. Then, the coherence length is short (compared to laser sources) and the detected interferogram is narrower. The RDFB-FL used in the experiment acts as the broad-band source required in the FOLCI system. Its linewidth is several times narrower than LED sources but significantly wider than conventional laser sources. An example of the interferogram measured using the proposed setup with the SI located at 275 km can be seen in Fig. 2(a). Additionally, simulations have been performed to validate the experimental results [Fig. 2(b)].

Both the experimental and simulated traces present a Gaussian profile with a total width $\approx 2L_c$. From (1), it can be inferred that any change in the OPD of the SI (*OPD1*) will lead to a change in the fringe visibility and the phase of the signal detected, modifying the central fringe position. In order to interrogate de sensing interferometer (i.e. measure absolute *OPD1* changes), a displacement sweep is done in the receiving interferometer (*OPD2*) to identify the central fringe position of the interferogram [2].

3. Experimental results

The laser source used in this experiment allowed to perform 275 km remote measurements, which is as far as the authors know, the longest distance achieved in remote fiber optic sensing. Only one 3W 1445 nm pump laser is needed to interrogate a sensor located 250 km away from the monitoring station using the random DFB fiber laser configuration showed in this work. However, the optical power generated using this single 3 W pump laser does not allow to surpass a 250 km distance. As a consequence, a Raman assisted second order amplification scheme [13] has been employed to overcome that distance barrier and reach a 275 km distance. The power injected by the 1360 nm-pump laser into the first 50 km fiber spool generates by itself a first Stokes amplifying signal at 1445 nm. This secondary pump is intensified by the 1445 nm-pump laser injected afterwards, amplifying the signal centered at 1550 nm through a longer distance. The pump powers used in both pump lasers, emitting simultaneously at 1360 and 1445 nm, have been chosen to maximize the optical power reaching the sensing interferometer (3 W in both pump lasers). The optical spectrum measured after 275 km (between the optical isolator and C1) is depicted in Fig. 3(a), showing a central wavelength located at 1555 nm and a peak power of -32 dBm.

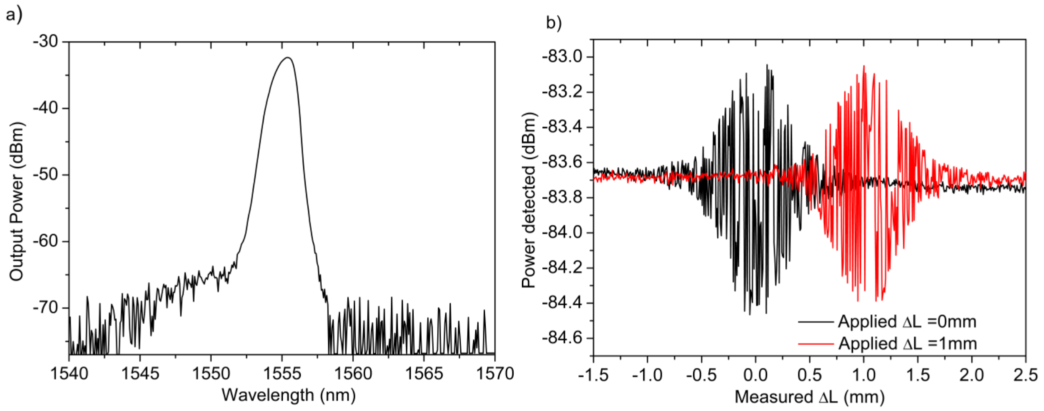

Fig.3. a) Optical spectrum of the random DFB fiber laser measured after 275 km and b) Experimental traces detected at the output of the FOLCI scheme for two different sensor states.

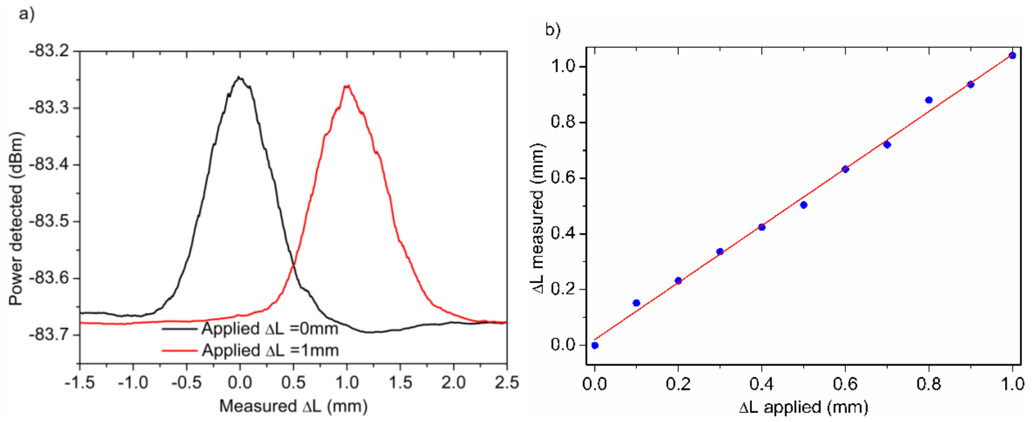

Fig.4. a) Experimental traces detected at the output of the FOLCI scheme after post-processing and b) Experimental displacement measurements.

In the experiment, the sensing interferometer has been validated as displacement sensor by tracking length variations induced in *OPD1*. A micro-positioner, with a resolution of 10 µm, has been used to apply a displacement from 0 to 1 mm with 0.1 mm steps in the SI arm *L2*, located 275 km away from the monitoring station. To perform the interrogation, *L2'* in the LRI has been attached to an independent micro-positioner, with a resolution of 20 nm. Then, a displacement sweep has been performed every 14 µm to determine the central fringe position, that represents the displacement of the sensing interferometer. The detected signals at the LRI output for 0 mm and 1 mm displacements are displayed in Fig. 3(b). Fig. 4.(a) shows the same detected signals after a simple post-processing employed to simplify the measuring process, which includes using the absolute value and a smoothing (moving average). As can be seen in the figures, the displacement of the central fringe position is clearly distinguished and measurable. The maximum of each trace is represented in Fig. 4(b), showing the displacement ΔL measured for each displacement ΔL applied. The results exhibit a linear trend with a slope of 1.02. The deviations of the measured data with respect to the ideal line may be due to possible the intrinsic error of the micro-positioners and vibrations during the measuring process. Contrary to the expected, the small signal to noise ratio of the obtained signals does not affect the accuracy of the measurements, since in FOLCI systems the accuracy is virtually insensitive to optical power variations.

4. Conclusions

As far as the authors are aware, the longest distance achieved for a remote fiber optic sensing system sensing has been accomplished in this work. An interferometric sensor located 275 km away from the monitoring station has been interrogated by means of a double-pumped random DFB fiber laser. The high output power, long cavity and wide spectral width make this type of lasers a suitable source to interrogate FOLCI systems at long distances. The absolute displacement applied to the sensing interferometer of a FOLCI scheme has been measured by detecting the optical power at the output of the LRI using an optical multimeter. The results show a linear trend with a slope of 1.02. In further work, the accuracy of the measurements could be improved by just reducing the sweeping step from 14 µm to the minimum step of the micro-positioner (0.02 µm). In addition, several sensing interferometers could be coherence multiplexed by adjusting the OPDs of each interferometer. Moreover, this system could be used in combination with other types of multiplexing techniques, increasing the total number of sensors interrogated and therefore, reducing the total cost per sensor of the remote sensing system.

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