100 km-Ultralong Raman Fiber Laser using a Distributed Rayleigh Mirror for Sensing Applications

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Abstract —*The spectrum of a continuous-wave ultralong Raman fiber laser (URFL) based on a distributed Rayleigh mirror combined with fiber Bragg gratings (FBGs) is studied. A linear laser cavity using FBGs as mirrors and a 100 km long fiber is explored for optical sensing, using one of the gratings an intensity sensor. The sensitivity of the FBG laser sensor was (16.8 ± 0.8) $\mu W/\mu\varepsilon$.*

Index Terms — Optical remote sensing, Ultralong Raman Fiber Laser

I. Introduction

Over the last two decades, Raman fiber lasers which use fiber Bragg gratings (FBGs) as mirrors to form a linear cavity have experienced a continuous improvement [1]. Ultralong Raman fiber lasers (URFLs) present a very attractive solution for communication links [2, 3] and have been extensively researched during the past few years. In this case, distributed gain along a standard single mode fiber (SMF) is provided by pump waves propagating in the fiber and fiber Bragg gratings (FBGs) with high reflectivity are used as narrowband mirrors, creating a linear cavity with laser action at the same wavelength of the FBG peak.

In 2009, an URFL with a 270 km cavity was demonstrated to have a resolvable mode structure [4]. In 2010, a 200 km-long dual-wavelength URFL was reported [5]. Using two FBGs with different peak wavelengths, one on each end of the fiber span, two independent Raman lasers generated between the FBGs and distributed "random" Rayleigh scattering mirrors were obtained.

Random Rayleigh scattering mirrors combined with other effects have been used in several configurations. Combined with distributed Rayleigh mirrors, multiwavelength lasers using high-birefringent fiber loop mirrors [6, 7] and comb lasers using Brillouin-Raman effects [8, 9] were proposed. In optical sensing, different solutions were proposed and demonstrated. A sensing head using a Bragg grating structure combined with a distributed mirror was demonstrated for simultaneous measurement of strain and temperature [10]. Recently, a temperature-insensitive strain sensor based on four-wave mixing (FWM) using two Raman fiber Bragg grating (FBG) lasers with cooperative Rayleigh scattering was reported [11]. A new method to further increase the range of Brillouin optical time domain analysis (BOTDA) systems was also proposed [12]. In this work second-order Raman pumping in optical fibers is used to create virtual lossless fiber spans.

For remote optical sensing, several researches have been reported in the literature. A 100-km long distance FBG sensor system was demonstrated [13], where the FBG reflected spectrum had a 30 dB signal-to-noise ratio and was amplified by two segments of erbium-doped fiber located at 50 km and 75 km from the sensor head. Another configuration for sensing at 230 km was based on a high-speed swept-wavelength light source [14]. The signal-to-noise ratio of the FBG reflection spectrum was steady at about 20 dB for transmission fiber lengths up to 150 km, reducing to ~4 dB when the distance increased to 230 km. A tunable fiber ring laser configuration employing a hybrid combination of Raman amplification and erbium-doped fiber amplification (EDFA) was proposed to implement an ultralong distance (FBG) sensor system [15]. The experimental results show that a 300 km transmission distance was achieved with an optical SNR of 4 dB.

In this work, the authors propose an optical remote sensor using a 100 km UFRL and FBGs as sensing elements. The idea of the sensor is to convert the traditional signal reflected by the FBG sensor into a FBG laser sensor. The proposed configuration allows optical power interrogation.

II. Experimental Results

Figure 1 presents the experimental setup scheme of a 100 km Raman fiber laser. A pump laser operating at 1455 nm with a maximum power of 5 W, two wavelength division multiplexers (WDMs) (1450/1550 nm) and two fiber Bragg gratings (FBGs), with a central Bragg wavelength of 1550.8 nm and reflection coefficients of 90 %, were used as mirrors at the fiber ends. One hundred kilometres of standard single-mode fiber (Sumitomo) were used to create the linear cavity laser. An Optical Spectrum Analyzer (OSA) with a maximum resolution of 0.05 nm was used to observe the optical spectrum.

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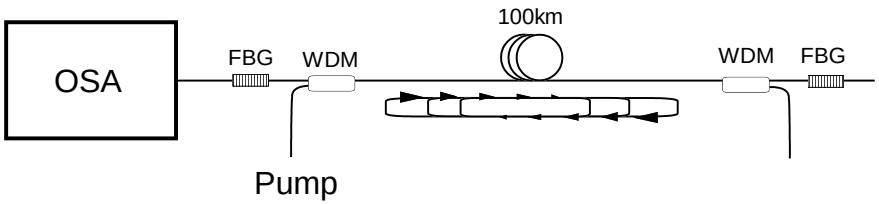

Fig.1 100 km Raman fiber laser configuration

In this configuration, a laser cavity is formed between the FBGs with the same central wavelength. The process is assisted by Rayleigh scattering, which is used as a distributed mirror. The FBGs are used as high reflectivity narrowband mirrors and will determine the central wavelength, bandwidth and optical signal-to-noise ratio (OSNR) of the lasers. The gain for these lasers is provided by the 1455 nm pump laser, which creates a typical broadband Raman gain on the standard single mode fiber, with a maximum around 1554 nm (13.1 THz above the pump laser frequency).

Using the experimental setup scheme presented in Figure 1, the laser output power spectrum was measured for different input pump laser powers (Figure 2). The lasing threshold pump was observed to be 1.05 W. The inset figures present the spectral response of the laser with an input pump power of 1.05 W (immediately above the threshold) and 1.5 W. For an input pump power of 1.05 W, random Rayleigh lasing with an average maximum optical power 40 dB above the optical power of the nearby frequencies is observed. For an input pump power of 1.5 W, lasing occurs at the peak wavelength of the FBG (1550.8 nm); the spectrum full width at half maximum (FWHM) is the same of the FBG (~ 0.1 nm) and the optical signal-to-noise ratio (OSNR) of the laser is 40 dB. The slope efficiency of the laser output power was 12.6±0.3 mW/W (1.26 %).

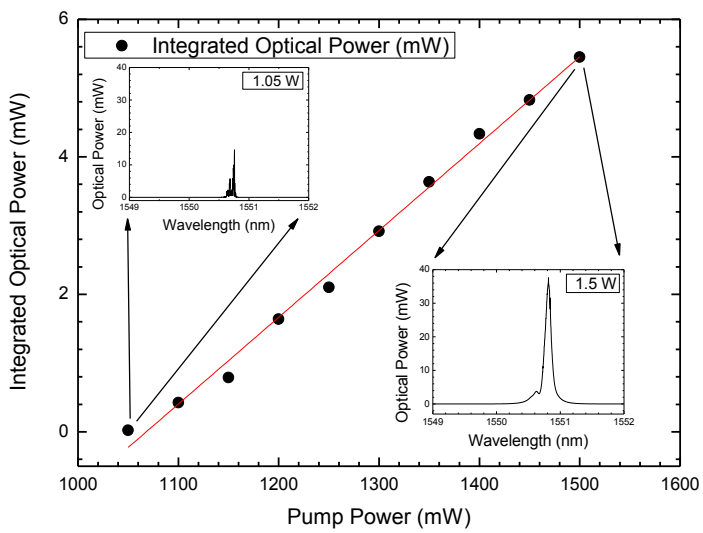

Fig.2 Relationship between the laser output power and the pump power (inset figures: spectral response of the laser with 1.05 W and 1.5 W).

Figure 3 shows the laser output power as a function of the strain applied to the sensing head, for a constant input pump power of 1.5 W. The central Bragg wavelengths of both FBGs were aligned when the sensing head was unstrained. A strain response with a sensitivity of 16.8±0.8 μW/με was observed.

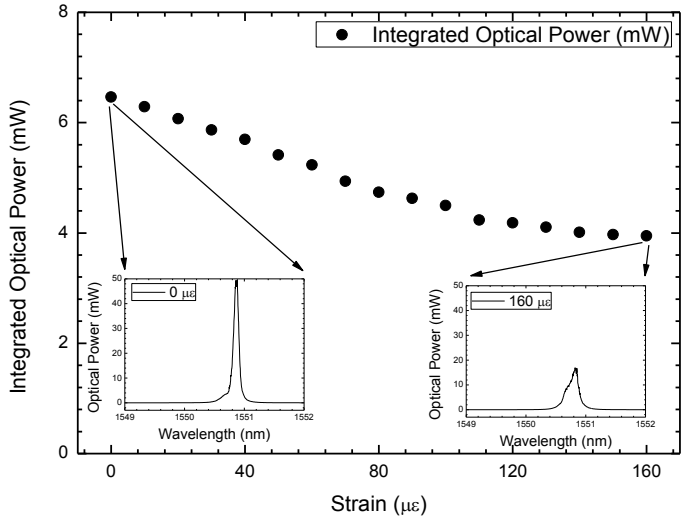

Fig.3 Strain measurement of the FBG laser sensor.

This variation is to be expected since the overlap between the responses of the two FBGs at the end of the laser cavity decreases when the central Bragg wavelength of the sensing FBG is shifted by the applied strain. In this case, the laser cavity will only be formed between one FBG and the Rayleigh scattering; therefore the laser output power will be lower. This allows for strain measurement based on intensity modulation of the laser emission.

With an input pump power of 1.5 W, the laser output spectrum was observed with spans of 50 nm (Figure 4a) and of 300 nm (Figure 4b). In Figure 4b, a typical spectral response was observed, with a sudden reduction of the optical power at 1520 nm due to the action of the WDM placed before the OSA. The input pump laser is observed at 1455 nm, and the laser output at 1551 nm.

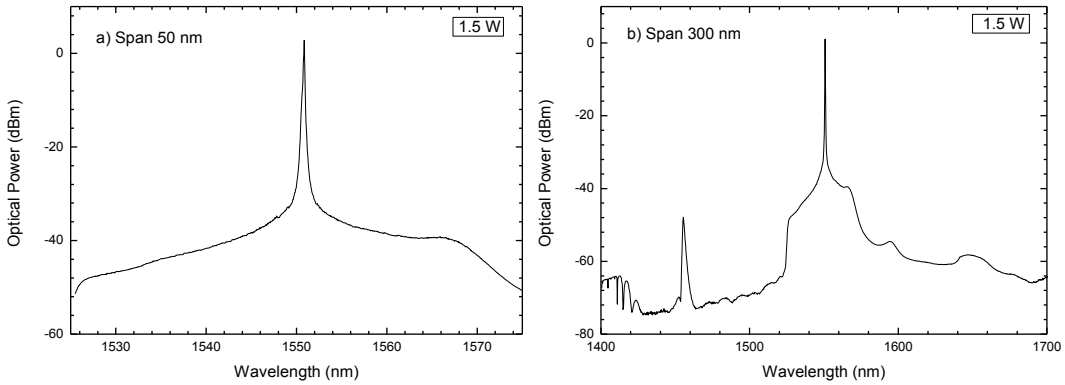

Fig.4 Spectral response of the laser with 1.5 W with a span of a) 50 nm b) 300 nm

III. CONCLUSION

A continuous-wave URFL for optical sensing applications was reported in this work. A 100 km long fiber laser which presented a threshold power of 1.05 W and a slope efficiency of 12.6 ± 0.3 μW/W (1.26 %) was used. A linear response with a sensitivity of (16.8 ± 0.8) μW/με was obtained. In this case the signal was not referenced. However, using another FBG laser sensor, isolated from strain but at the same temperature of the sensing head, a temperature-insensitive strain sensor can be produced. Multiplexing of several FBGs with different peak wavelengths in the Raman gain region is also possible.

Although the sensor was used to measure strain, the presented setup can also be used for measurement of other physical parameters based on the interrogation of FBG structures, such as pressure, curvature, torsion and displacement, using the several solutions published in the literature.

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