300 km-ultralong Raman fiber lasers using a distributed mirror for sensing applications

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Abstract: Several configurations of ultralong Raman fiber lasers (URFL) based on a distributed mirror combined with Bragg gratings or fiber loop mirrors are studied. Two continuous-wave URFL configurations, with single and cascaded cavities using fiber Bragg gratings as mirrors are explored for a 300 km long fiber. For optical sensing, the cavity length was optimized for 250 km using one of the gratings an intensity sensor. Another URFL configuration based in a fiber loop mirror is also reported. For optical sensing using a 300 km long fiber it is shown that the best choice is a hybrid configuration. The sensitivity of the FBG laser sensor range was from $(76 \pm 2) \times 10^{-6}$ $\mu\varepsilon^{-1}$ (for lower strain) to $(9.0 \pm 0.4) \times 10^{-6}$ $\mu\varepsilon^{-1}$ (for higher strain).

OCIS codes: (060.0060) Fiber optics and optical communications; (060.2370) Fiber optics sensors; (060.3510) Lasers, fiber.

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1. Introduction

Raman fiber lasers using a grating structure as a mirror forming a linear cavity have experienced a continuous improvement in the last two decades [1]. During the past few years, an ultralong Raman fiber laser (URFL) topology has been implemented as very attractive solutions for transmission communication links [2, 3]. Basically, the URFL consisted in two pump waves propagating in a standard single mode fiber that produces a distributed Raman gain along the fiber. The linear cavity was formed by fiber Bragg gratings (FBGs) with high reflectivity that reflects radiation, resulting in laser action with the same wavelength of the FBG. In 2009, a resolvable mode structure of an URFL with a 270 km cavity was demonstrated [4]. Recently, a 200 km-long, dual-wavelength URFL using two slightly different-wavelength FBGs, one on each side of the fiber span, was reported [5]. The results proved the generation of two independent Raman lasers with a distributed "random" Rayleigh scattering mirror. Other configurations using this effect based on a distributed "random" Rayleigh scattering mirror were studied. Multiwavelength lasers using high-birefringent fiber loop mirrors were proposed [6, 7]. Comb lasers using Brillouin-Raman combined with a distributed mirror were also reported [8, 9]. In optical sensing, alternative solutions were demonstrated. A specific sensing head based on a Bragg grating structure combined with a distributed mirror was demonstrated for simultaneous measurement for strain and temperature [10]. Recently, a temperature-insensitive strain sensor based on four-wave mixing (FWM) using two wavelength Raman fiber Bragg grating (FBG) laser with cooperative Rayleigh scattering was reported [11]. A new method to extend the range of Brillouin optical time domain analysis (BOTDA) systems was proposed [12]. The work exploits the virtual transparency created by second-order Raman pumping in optical fibers.

For remote optical sensing, several works 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 and 75 km. 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 are steady at about 20 dB for transmission fiber lengths up to 150 km, reducing to ~4 dB when the distance increased to 230. A tunable fiber ring laser configuration with combination of hybrid Raman amplification and erbium-doped fiber amplification (EDFA) was proposed to implement an ultra-long distance (FBG) sensor system [15]. The experimental results show that a 300 km transmission distance was achieved with an optical SNR of 4 dB. The configuration can be improved by converting the signal reflected by the FBG sensor into a signal FBG laser.

In this work, the authors propose several solutions for a 300 km UFRL based on a fiber Bragg grating structure and also based on a fiber loop mirror. The objective is to convert the traditional signal reflected by the FBG sensor into a FBG laser sensor. Two solutions are studied using UFRLs. The first solution is based on a cavity laser FBG mirrors and also in cascaded laser configuration. The last configuration is based in a fiber loop configuration. A Hybrid experimental setup combining a fiber loop mirror (reference mirror) and a FBG mirror (sensor) at 300 km long fiber was reported as highest value reported to date (to our knowledge) in the literature for continuous-wave laser and remote sensing.

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2. Experimental results

2.1 Bragg grating mirrors

Figure 1 presents the experimental setup of two Ultralong Raman Fiber Lasers (URFL). Both experimental configurations use two similar pump lasers at 1455 nm with a maximum power of 2.5 W and two wavelength division multiplexers (WDMs) (1450/1550 nm). Three hundred kilometers of standard single-mode fiber SMF 28 were used to create the linear cavity laser. Figure 1a) also shows two FBGs with a central Bragg wavelength of 1552 nm and a reflection coefficient of 90% that were used as mirrors in the fiber ends. For the cascaded Ultralong Raman Fiber Laser (Fig. 1b), a similar architecture was used, but a total of four FBGs with similar central Bragg wavelengths (1552 nm) and the same reflection coefficient were used between the two ends of the fiber, equally separated by 100 km. An Optical Spectrum Analyzer (OSA) with a maximum resolution of 0.05 nm was used to observe the optical spectrum.

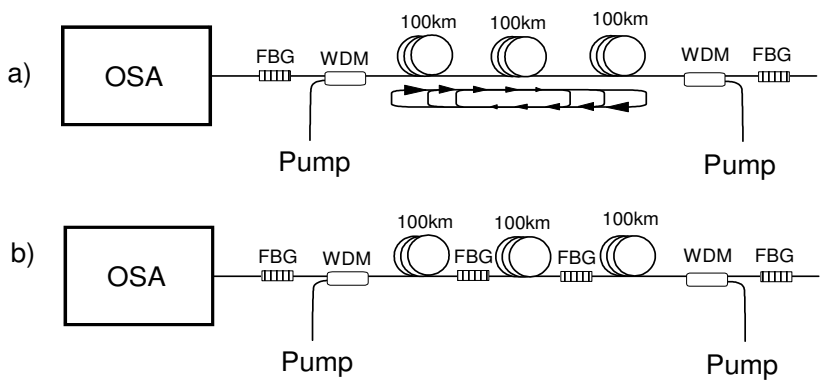

Fig. 1. a) simple URFL and b) cascaded URFL configurations.

In these two configurations, laser cavities are formed between 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 Bragg wavelength, bandwidth and optical signal-to-noise ratio (OSNR) of the lasers. The gain for these lasers is provided by the two 1455 nm pump lasers which create a typical broadband Raman gain on the standard single mode fiber with a maximum around 1554 nm (13.1 THz above the pump lasers frequency). In Fig. 1b), three cascaded fiber laser cavities in series are formed. By creating intermediate smaller laser cavities, higher feedback will be provided, lasing will occur at lower pumping powers and the laser power will be higher if the saturation gain is not reached. This process is similar (but stronger) to the multiple Rayleigh reflections inside the three hundred kilometers linear cavity. Due to losses in the fiber, the gain provided in the cavities close to the pumps is higher than in the middle cavity. Using the experimental setups presented in Fig. 1a) (simple URFL) and Fig. 1b) (cascaded URFL), the laser output power of the spectrum was measured for different (and equal on both) input pump laser powers (Fig. 2). In the inset figures is presented the spectral response of the two lasers with an input pump power of 1.5 W in each end, resulting in a total pump power inside of the cavity of 3 W. The optical signal-to-noise ratio (OSNR) is 33 dB for the single UFRL and 34.5 dB for the cascaded UFRL. As for the full width at half maximum (FWHM), it is the same of the FBG (~0.1 nm). Comparing the lasing threshold pump, the cascaded URFL began at 1.05 W and the single URFL at 1.1 W. The slope efficiency of the lasers output power was 237 ± 8 μW/W (0.0237%) for the cascaded URFL and 112 ± 2 μW/W (0.0112%) for the simple URFL. The experimental setup presented in Fig. 1a) was tested to interrogate an intensity FBG based laser sensor. The

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previous analysis using three hundred kilometers showed a qualitative spectral difference but no laser output power changes when strain was applied. The system was then optimized for 250 km long fiber. The reference FBG, with a central Bragg wavelength of 1554 nm and a reflection coefficient of 80%, was isolated from strain and kept at constant temperature.

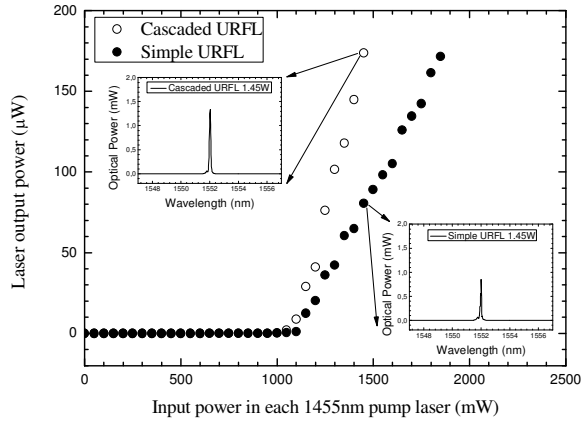

Fig. 2. Relationship between the laser output power and pump power in each pump (inset figures: spectral response of the two lasers with the same pump power).

The FBG laser sensor had a central Bragg wavelength of 1554 nm and a reflection coefficient of 90%. Figure 3 shows the laser output power as a function of the applied strain on the sensing head with a constant input pump power of 1.5 W on both Raman pumps. The central Bragg wavelengths of both FBGs were aligned when the sensing head was unstrained. A linear strain response with a sensitivity of 0.172 ± 0.007 μW/με was observed. This variation is expected since the overlap between 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.

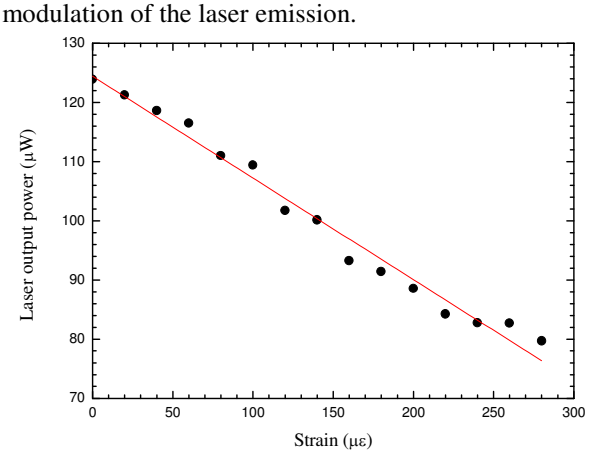

Fig. 3. Strain measurement of the FBG laser sensor.

2.2 Fiber loop mirrors

A new URFL configuration based on fiber loop mirrors (FLM) is presented (Fig. 4a). The FBGs are removed and two FLM are spliced. The FLM consist in an optical coupler of 3 dB where the output ports are spliced. In this case, the two waves travel with identical optical paths in opposite directions and a constructive interference is assured when the waves reenter

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the coupler. All the light is then reflected back into the input port, with the reflectivity limited only by the losses of the splice, fiber and coupler, while no light is transmitted to the output port. The output laser spectrum was observed using a coupler 90:10 that was inserted before the FLW1. Using this experimental setup the laser output power was measured for different (and equal on both) input pump laser powers (Fig. 5). The lasing threshold pump of the URFL-FLM was measured to be 2.32 W (in each pump), resulting in a total pump power inside of the cavity of 4.64 W, and the laser central wavelength was 1567 nm. The slope efficiency of the laser output power was 38.0 ± 0.6 μW/W (0.00380%). The inset figures present the spectral response of the URFL-FLM obtained [by the configuration of Fig. 4a] with an input power of 2.3 W (before the lasing threshold) and 2.6 W (after the lasing threshold) in each laser pump. The optical SNR in this configuration is 28 dB and the FWHM is 1 nm. The URFL-FLM spectrum was observed with the input pump laser 1 switched off and the input pump laser 2 with a power of 2.5 W. The URFL-FLM had an output optical power of 5 nW at 300 km and an optical SNR of 25 dB.

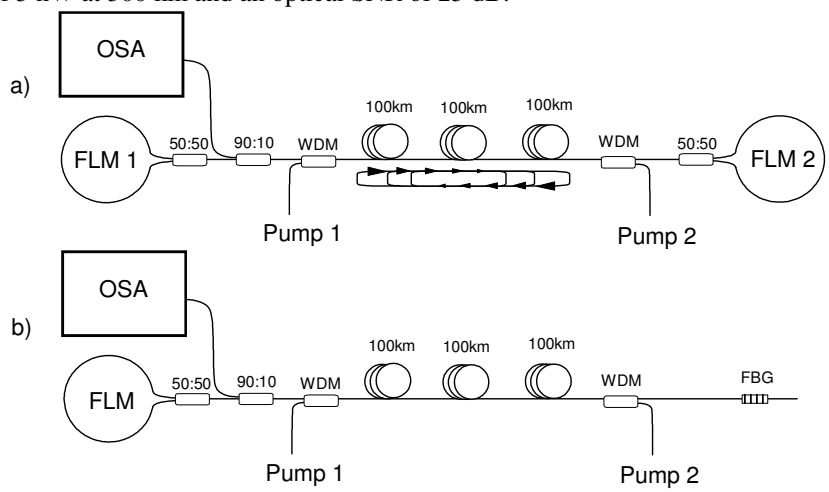

Fig. 4. URFL configuration with a) two FLMs and b) FLM combined with FBG.

In order to use the setup presented in Fig. 4a) to interrogate an intensity FBG based laser sensor, the FLM2 was replaced by an FBG with a central Bragg wavelength of 1568 nm and a reflection coefficient of 90% (Fig. 4b). In this case, we have two lasers: one of them is the reference laser obtained by the FLM combined with the distributed mirror and the other one is the FBG laser sensor combined with a distributed mirror. However, the two lasers are not completely independent, when the two wavelengths are close. The output power depends on wavelength separation due to the increased feedback. The main feedback contribution is the Rayleigh distributed mirror but the small reflectivity in tail of end mirrors (FLM and FBG) can become significant. The reference laser output power had 47 μW when no strain was applied. The FBG laser sensor wavelength was located in the slope region of the reference laser. When strain was applied, the intensity of the FBG laser sensor changed. The ratio (R) between the output power of the FBG laser sensor (P_{sensor}) and the output power of the reference laser (P_{ref}) as a function of the applied strain is showed in Fig. 6. A constant input pump power of 2.5 W on both Raman pumps was used while measuring the strain variation. The response of the sensing head presented an exponential behaviour due to the spectral response of the output power laser of the reference signal, which is close to a gaussian tail behaviour. The sensitivity of the FBG laser sensor was obtained and its range was from (76 ± 2) × 10^{-6} $\mu\varepsilon^{-1}$ (for lower strain) to (9.0 ± 0.4) × 10^{-6} $\mu\varepsilon^{-1}$ (for higher strain). When compared with a previous reported research also associated with a fiber length of 300 km [14], this new configuration presents an OSNR of 17.5 dB, i.e., a fourfold enhancement.

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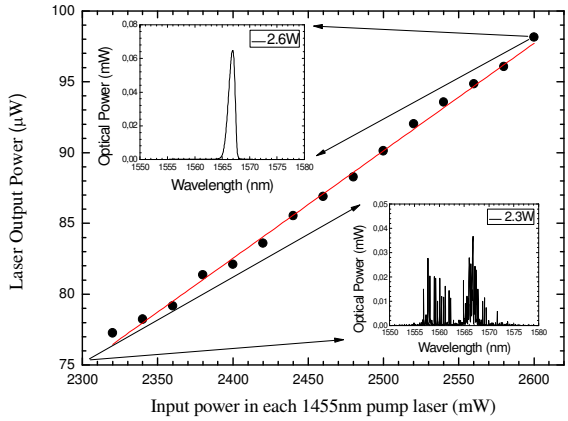

Fig. 5. Laser output power with input pump power in each pump.

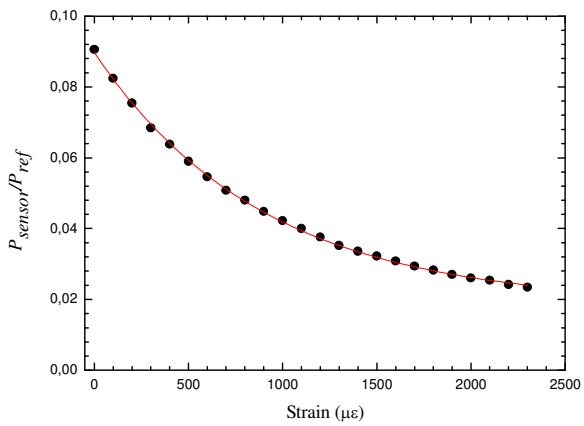

Fig. 6. Strain measurement of the FBG laser sensor.

Conclusions

Different continuous-wave URFL were reported in this work. The first two URFL configurations using FBG as mirrors are interesting for optical communications, namely for cryptography optical systems. The single cavity with a 250 km long fiber can be used for optical sensing. A linear response with a sensitivity of 0.172 ± 0.007 μW/με was obtained. In this case the signal was not referenced, however, using another FBG laser sensor isolated to strain but with the same temperature of the sensing head a temperature-insensitivity strain sensor can be produced. This setup can use the several solutions published in the literature for simultaneous measurement of physical parameter based on FBG structure. The two last configurations using fiber loop mirrors as reflectors are particularly interesting for optical sensing. In this case, the hybrid configuration is the best one for sensing applications. A FBG sensor was used in the fiber end and a fiber loop mirror was used as a reference signal. The sensitivity of the FBG laser sensor range was from $(76 \pm 2) \times 10^{-6}$ $\mu\varepsilon^{-1}$ (for lower strain) to $(9.0 \pm 0.4) \times 10^{-6}$ $\mu\varepsilon^{-1}$ (for higher strain). The last configuration presents the optimal solution at 300 km and comparing with another configuration [14] a fourfold enhancement in OSNR was obtained.

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