International Conference on Space Optics—ICSO 2012

Ajaccio, Corse

9–12 October 2012

Edited by Bruno Cugny, Errico Armandillo, and Nikos Karafolas

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International Conference on Space Optics — ICSO 2012, edited by Bruno Cugny, Errico Armandillo, Nikos Karafolas
Proc. of SPIE Vol. 10564, 105642V · © 2012 ESA and CNES · CCC code: 0277-786X/17/$18 · doi: 10.1117/12.2309167

Radiation Resistant Erbium Doped Fiber for ASE Source and Fiber Gyroscope Application

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Abstract—**A radiation resistant optical fiber used in a broadband source is presented. Both ASE source and Fiber Optical Gyroscope (FOG) commonly used in space missions, suffer from failures and degradation after long term exposure to radiative environment. The aim of this article is to present the results of our investigation on fiber and ASE source architecture in order to design a Radiation Resistant Erbium Doped Fiber that offers long term stability of the gyroscope performances.**

Keywords-component; FOG; Erbium doped fiber; RIA; Broadband source; Gamma radiation; Space application

I. INTRODUCTION

In the past few years, iXFiber, in close cooperation with iXSpace, has devoted significant R&D efforts towards the optimization of specialty optical fiber for both space and radiative environments. The ASTRIX FOG product line developed with ASTRIUM demonstrates this know-how.

The FOG performances are partly based on source characteristics justifying broadband sources or Amplified Spontaneous Emission sources (ASE) [1-2] and many studies are still devoted to improve FOGs reliability. For example, the source stability may vary depending on its architecture: the performances of a single pass ASE backward source are not sufficient for high performances FOGs and double pass is preferred [3].

In space environment, the device will be exposed to radiations, impacting FOG's lifetime and its components performances (e.g.: wavelength drift, bias, etc.) [4]. Moreover, radiation induced attenuation along the erbium-doped fiber, requires loss compensation by increasing the pump signal power within the limits of random self-pulsation regime [2].

Whereas recent works suggest tuning ASE re-amplification in response to the source degradation [5], we propose another approach by hardening the erbium-doped fiber to ensure better efficiency and suitable performances for FOG application.

II. STUDY PARAMETERS

ASE sources use erbium-doped fiber as gain medium to generate broadband spectrum. Several key parameters of the fiber, such as rare earth doping level, aluminum and other co-dopants concentrations have been investigated, while monitoring the fiber efficiency, the Radiation Induced Attenuation (RIA) at different key wavelength and ASE spectrum.

A. *ASE source efficiency*

Erbium concentration has to be optimized to maximize absorption and to extract ASE power sufficiently. High erbium concentration leads to use short fiber length, reducing radiations sensitivity [5]; unfortunately, the source may pulsate related to ion clustering [6]. To avoid this drawback, aluminum is used to limit erbium-ions pair formation. Aluminum also impacts source efficiency because of its effect on cross section and therefor on the source spectrum. High losses under radiations are one of aluminum disadvantages [7].

B. *Stability and ASE source resistance under radiative environment*

During space mission, the efficiency of ASE source under radiations decreases due to darkening of the fiber. Color centers formation is responsible of induced attenuation. Incorporation of cerium in the fiber core composition can minimize this phenomenon [8]. Cerium concentration must be optimized in order to counter the fiber darkening without affecting intrinsic efficiency.

Moreover, to maximize radiation hardening, we can improve the absorption of the fiber by increasing the overlap factor between the guided mode and the erbium-doped area of the core by increasing the cutoff wavelength for example. Our investigation tends to show that such a cutoff modified fiber has indeed an improved resistance.

C. *Self-lasing phenomenon*

Self-lasing operating mode of the source is a severe limitation of ASE sources, in particular on power margin. Double pass architectures are sensitive to component optical return losses (ORL) and Rayleigh related losses along the fiber and can suffer self-lasing operation with high optical gain.

Fiber doping characteristics can also impact this threshold, i.e.: maximum pump power without self-lasing operation. This is especially true for heavily doped erbium fibers, for which erbium ions clusters may act as saturable absorbers.

We have fabricated fibers using the same preform material while modifying the core diameter and thus obtaining different cutoff wavelength ranging from 900nm to 1300nm. The self-lasing threshold can be increased by up to 26% for higher cutoff fibers independently of the radiation exposure. Therefore we can state that for identical core composition, a high cutoff fiber will have an improved radiation resistance due to increased power safety margin towards the end of mission in space environment. We believe that this phenomenon arises from a lower power density in larger core areas. However this self-lasing improvement by way of cutoff wavelength optimization varies depending on core dopants and relative core compositions and for some of the fibers of our experimental plan, the impact of cutoff has but a modest impact on overall performances.

III. Experimentation

A. *Objectives of the experiment*

We carried out a characterization of new radiation resistant erbium-doped optical fiber before, during and after radiation. ASE sources stability is put to the test throughout a thermal cycling (before and after radiation) and under radiation environment via optical power and spectral fluctuations measurement. Several fiber samples have been measured; the fiber called “#B” has been selected and is compared among others with a reference already used in FOG systems.

B. *Experiment setup*

A bench top of 16 fibers is dedicated to the test under radiation or in thermal cycling configuration in a quasi-simultaneous measurement. This setup requires only one pump diode at 980nm and optical switch, to pump the 16 fibers sequentially. To obtain a good efficiency and stable spectrum, a double pass configuration is chosen. Furthermore, without this architecture, we couldn’t use such a short optical fiber, compared with others designs like single pass backward.

A typical spectrum is presented hereafter.

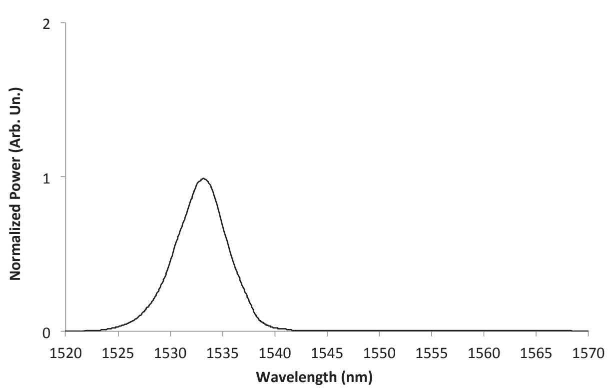

Figure 1. ASE spectrum from optimized source

Spectrum from figure 1 corresponds to a source pumped with 35mW and optimized erbium-doped fiber length (maximized ASE power). Shorter wavelength bandwidth (around 1533nm) is selected through an optical filter.

Optical fibers are irradiated with a Cobalt (^{60}Co) type source according to 310Rad/h constant rate, with up to100kRad total dose.

IV. Experiment results and discussion

The ASE optical power and the optical spectrum are measured as a routine during all the irradiation, allowing us to monitor power losses and spectral shifts thanks to the bench top.

A. *ASE power and centroid behavior under radiations and slope efficiency*

Following results come from an intermittently pumping at 35mW.

Power degradation from fiber #B is linear and reaches a loss level of 2dB after 100kRad. In other words, the slope efficiency is -23mdB/kRad. This value is better than the reference for which the slope is twice as significant as shown in figure 2.

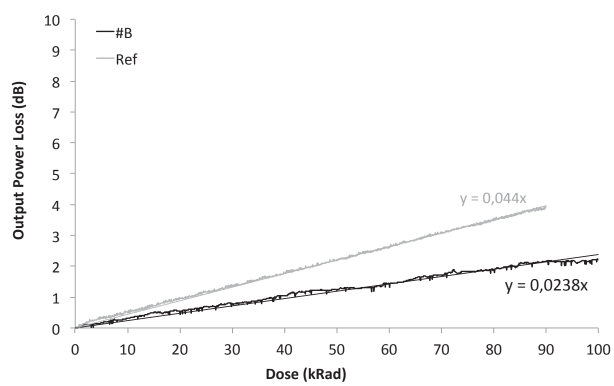

Figure 2. Dependence of the output power loss versus radiation

In terms of efficiency, optical source is pumped beyond to 200mW. Power degradation is highlighted in figure 3; the comparison is given between #B and the reference.

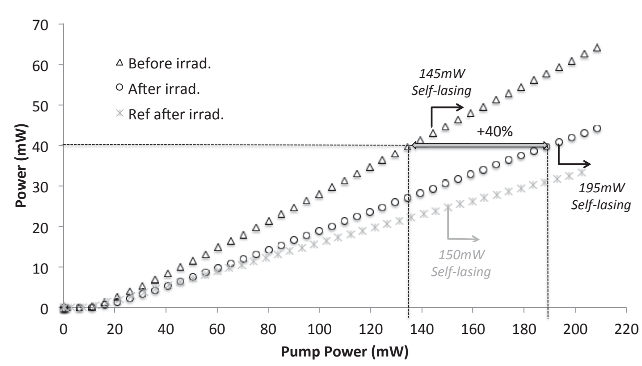

Figure 3. ASE source efficiency comparison (#B before-after irrad. and Ref after irrad. only)

For #B fiber, the source operating limit of output power is about 40mW (16dBm) pumped at 145mW. Beyond, the self-lasing behavior appears, creating a limitation.

A shift of the threshold is visible after darkening because the gain decreases during the irradiation (pump signal absorption increased). Performance of #B fiber, is compared with the reference after irradiation: the maximal extractable ASE power is 25mW (that is 37% lower than #B fiber), given by a pump power at 150mW.

The low #B fiber degradation allows the use of low pump consumption in order to operate with a constant 40mW ASE power. For a dose near 100kRad, the pump power should be increased by 40%.

B. Stability source (ASE power and spectrum) before-after and during irradiation

A thermal cycling between -20°C and 60°C is used to check source's variations with temperature. First of all, ASE power (with 35mW pump power) from no-irradiated and irradiated fiber is monitored during thermal cycling as indicated below.

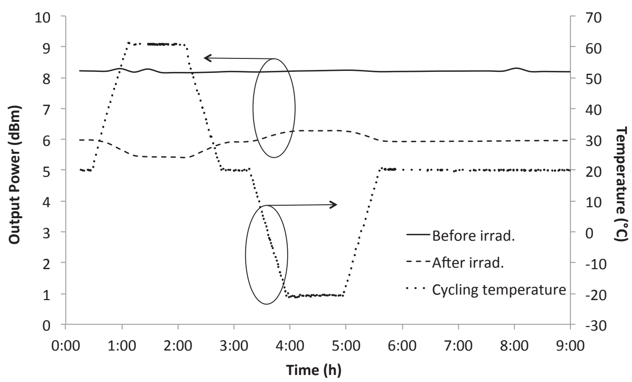

Figure 4. Output power ASE behaviour during thermal cycling (#B)

ASE output power is more temperature dependent after irradiation as we can see in figure 4. The difference between min and max is 0,14dB before radiation whereas after, it reaches 0,86dB. The three last hours represent a constant temperature for which the source is stable. Photo-bleaching is not visible for 2 reasons: low pump power is used in the experimentation and the fiber is only pumped during ASE spectrum and ASE monitoring (meaning 1/16 of total irradiation time).

A synthesis is given below to illustrate fiber behavior.

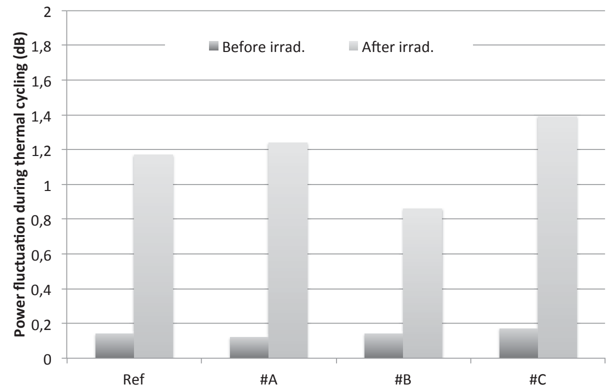

Figure 5. Output power ASE behaviour during thermal cycling (#B)

Results confirm the better power stability of #B fiber during the thermal cycling. Let's note that #A, #C are samples included in the experiment with another fiber composition.

The ASE spectrum stability is analyzed through the density centroid measurement of the spectral density. Indeed, broadband ASE spectrum is affected by wavelength dependent phenomenon (gain variation, pump and signal attenuation, cross section modifications, …)

The following figure gives the spectrum variation measured during the thermal cycling. The power degradation of the fiber is added.

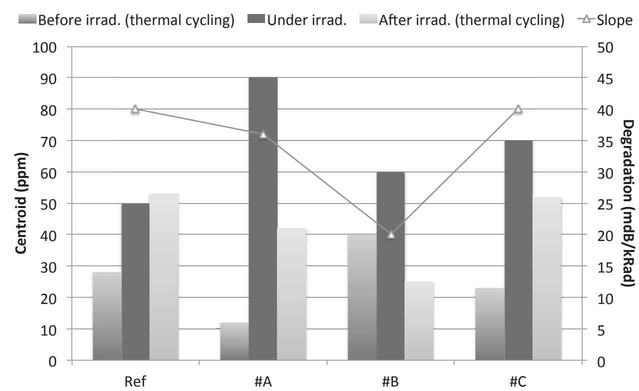

Figure 6. Centroid behavior during thermal cycling and irradiation – slope degradation

This figure 6 illustrates the relationship between the centroid shift and the fiber degradation. From our experiment, we have noticed that a darkened fiber is even more affected by the thermal cycling. We identified a good spectral stability after irradiation on the #B fiber compared to the others. This conclusion is also noticed for power instabilities given by the figure 5.

C. Operating limitation of the ASE source

As discussed previously, self-pulsing can appear in ASE source. This is unacceptable for the use of such a fiber in FOG application. The following graphic is an illustration of pulsation phenomena.

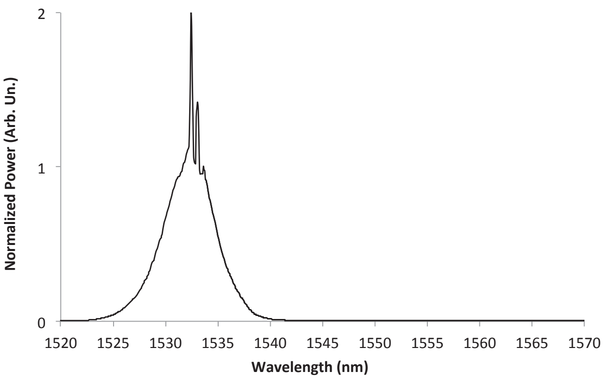

Figure 8. Self-lasing observation from over pumped source

Figure 8 shows that power density for some wavelengths is so important that a pulse appears. This limits maximum usable pump power and thus maximum output ASE power too. During irradiation, the fiber optical gain decreases by means of RIA and results in threshold evolution with higher acceptable pump power (*cf.* Figure 3).

V. Conclusion

iXFiber has developed a new radiation resistant optical fiber for broadband ASE source dedicated to FOGs applications that can be used in space environment. Comparisons between different samples have highlighted the #B fiber performances.

Fiber radiation resistance has been improved by a factor of 2 with power degradation limited to 2dB after 100kRad cumulated dose exposure. The power and spectral stability minimize the scale factor variations and insure a low noise behavior during irradiation but also during thermal cycling.

Finally, with this improved fiber, a constant 40mW output power can be achieved by means of pump power adjustment (automatic ASE power control mode) with a cumulated dose higher than 100kRad, whereas fiber of reference limits the ASE output power to 25mW.

This new fiber has been implemented in actual FOG sources and subjected to preliminary studies in FOG configuration. The experimentation carried out by iXSpace has revealed that inertial performances are identical to reference FOGs.

Acknowledgment

This work has been supported by Centre National d'Etudes Spatiales.

iXFiber and iXSpace are iXBlue companies.

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