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Gamma irradiation of minimal latency Hollow-Core Photonic Bandgap Fibres

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ABSTRACT: Hollow-Core Photonic-Bandgap Fibres (HC-PBGFs) offer several distinct advantages over conventional fibres, such as low latency and radiation hardness; properties that make HC-PBGFs interesting for the high energy physics community. This contribution presents the results from a gamma irradiation test carried out using a new type of HC-PBGF that combines sufficiently low attenuation over distances that are compatible with high energy physics applications together with a transmission bandwidth that covers the 1550 nm region. The radiation induced attenuation of the HC-PBGF was two orders of magnitude lower than that of a conventional fibre during a 67.5 h exposure to gamma-rays, resulting in a radiation-induced attenuation of only 2.1 dB/km at an accumulated dose of 940 kGy.

KEYWORDS: Radiation damage to detector materials (solid state); Optics; Radiation and optical windows

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Contents

1 Introduction

Ever increasing high-speed data communication has created a continuous demand for larger capacity of data transmission through optical fibres. Although we are able to increase the data capacity of the fibres by creating denser multiplexing schemes, optical nonlinearity limits the power that an optical fibre can transmit and therefore will eventually also limit its capacity. Different approaches have been taken in order to overcome this problem including space-division multiplexing where multiple simultaneous spatial channels are established either by launching several modes into the core or by using multiple cores in one fibre [1]. Hollow-Core Photonic Bandgap Fibres (HC-PBGFs) provide another solution to this problem; because their nonlinearity is about three orders of magnitude lower than that of a conventional fibre and thus more power and more complex modulation schemes can be used. This makes HC-PBGFs very interesting for the telecom industry, provided that they can be manufactured in sufficient lengths.

In HC-PBGFs the light is confined within the hollow core by a microstructured cladding consisting of a two-dimensional array of air holes. Depending on the structure of the cladding more than 99.8% of the light can propagate in air [2]. The periodic 2-D transverse arrangement of high and low dielectric constant materials (glass and air respectively) results in allowed and disallowed bands of wavelengths, referred to as photonic bandgaps, in which transverse propagation of light is forbidden and consequently light with a wavelength that lies within the bandgap can be guided along the fibre with low loss. The structure of the cladding, the size of the air holes, their pitch, shape, and the thickness of the struts in between the holes strongly affect the transmission properties of the HC-PBGF. For example, HC-PBGFs allow operation outside the traditional transparency window of the material which they are made of, e.g. in the case of silica, in the ultraviolet and mid-wavelength infrared. The position of the photonic band gap, in other words the transmission band, is mainly dictated by the amount of glass in the nodes connecting the struts in the cladding in combination with the cladding pitch [3]. It has been predicted that the minimum attenuation in a HC-PBGF will be achieved around 2 μm [4], way above the wavelength band of conventional single-mode silica fibres.

In addition to their high data transmission capacity, HC-PBGFs are low-latency and potentially radiation tolerant which makes them interesting candidates for high energy physics applications.

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Table 1. Properties of the HC-PBGF sample.

Length	Core size	Splice loss	Fibre loss	Central wavelength	Bandwidth
201 ± 2 m	27 μm	7.2 dB	4.4 dB/km	1585 nm	170 nm

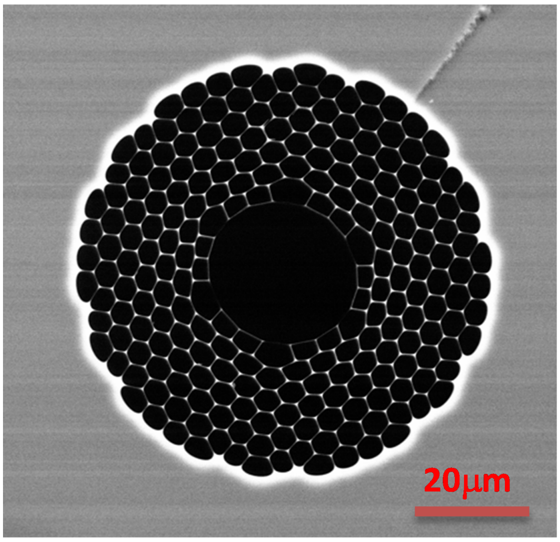

Figure 1. Scanning electron microscope image of the cross section of the HC-PBGF sample.

The air-filled propagation medium suggests excellent radiation hardness because typical radiation damage in fibre is caused by defects in silica glass. However, because the transmission properties of HC-PBGFs are very sensitive to structural changes in the core and cladding we investigated the behaviour of this fibre type under severe irradiation. The details of the gamma irradiation test are discussed in section 2 followed by the results and discussion in sections 3 and 4.

2 Materials and methods

A 201 m long HC-PBGF sample with a 19 cell core geometry and a core diameter of 27 μm was provided by the Optoelectronics Research Centre at the University of Southampton, figure 1. Properties of the sample are listed in table 1. Both ends of the sample were spliced to single-mode fibre (SMF-28) pigtails with FC/APC connectors. The splicing was optimised to ensure that the light was predominantly launched into the fundamental mode of the HC-PBGF (any higher order mode excitation was estimated to be at the -20dB level). An equivalent length of conventional single-mode fibre (Corning SMF28e+) was irradiated at the same time as a reference. Both fibres were spooled on plastic bobbins (POM-H) 50 mm in diameter and placed on a sample holder surrounded by six ^{60}Co rods that produced a fairly uniform gamma flux with a dose rate of 14 kGy/h. The samples were irradiated for 67.5 h which resulted in a total dose of 940 kGy. The gamma irradiation test was carried out in CEA Saclay, France, in December 2012.

A block diagram of the measurement setup is shown in figure 2. The output of a super luminescent diode (Covega SLD 1108) was split between the irradiated fibres (inside the irradiation room) and a short reference fibre (in the control room). The short reference fibre was used to

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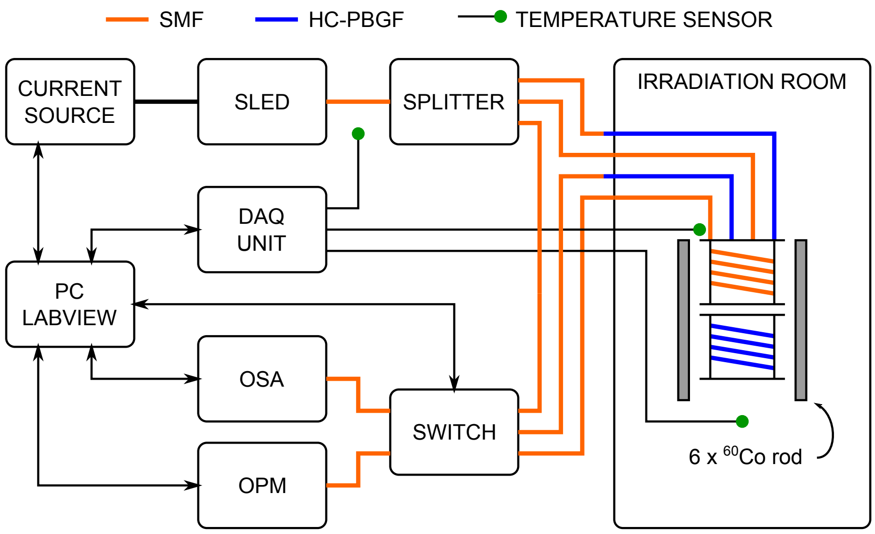

Figure 2. Measurement setup during the irradiation.

monitor fluctuations in the output of the light source. An optical switch guided the light out of the samples into either an optical power meter (Agilent 81636B) or an optical spectrum analyser (Yokogawa AQ6370B). Optical power and spectrum were measured in 1–3 min intervals; shorter (1 min) intervals were used at the beginning of and at the end of irradiation when more rapid changes in attenuation were expected. The temperature in the irradiation room and close to the measurement equipment outside the irradiation room was monitored using four PT100 sensors. Temperature was stable during the irradiation ($\pm 1.5°$C) in all locations and had no significant effect on the results.

A data transmission test was carried out at the end of irradiation using a LeCroy SDA100G sampling scope and time-of-flight measurements using a Luciol v-OTDR optical time-domain reflectometer.

3 Results

The radiation induced attenuation (RIA) as a function of total dose is shown in figure 3 together with optical transmission spectra before and after irradiation. At this dose rate the RIA of the HC-PBGF was two orders of magnitude smaller than that of a conventional fibre across the dose range. After 940 kGy the RIA of the HC-PBGF was 2.1 dB/km while the conventional fibre had become practically opaque with a RIA of 210 dB/km. The RIA in the HC-PBGF is even smaller than in state-of-the-art radiation hard single-mode fibres, which have a RIA of 3–4 dB/km when similar dose rates (11 kGy/h) and total doses are used [8].

Another important parameter which might be affected by radiation is the width of the transmission band. As can be seen in figure 3 the left edge of the transmission band remains stationary. Due to the relatively narrow bandwidth of the light source we cannot observe changes to the right edge of the transmission band in detail, however, despite the poor measurement sensitivity beyond 1630 nm there was still no evidence of a significantly reduced transmission band.

Figure 4 shows the results of transmission tests carried out after the irradiation. Eye diagrams at a data rate of 5 Gbps from both non-irradiated conventional fibre and irradiated HC-PBGF are

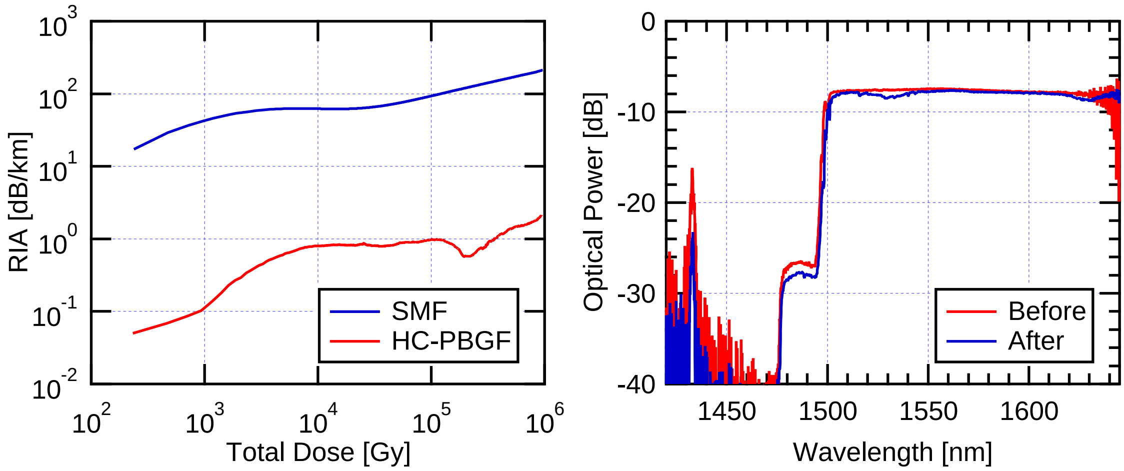

Figure 3. On the left radiation induced attenuation as a function of total dose. On the right optical spectra of the HC-PBGF sample before and after irradiation.

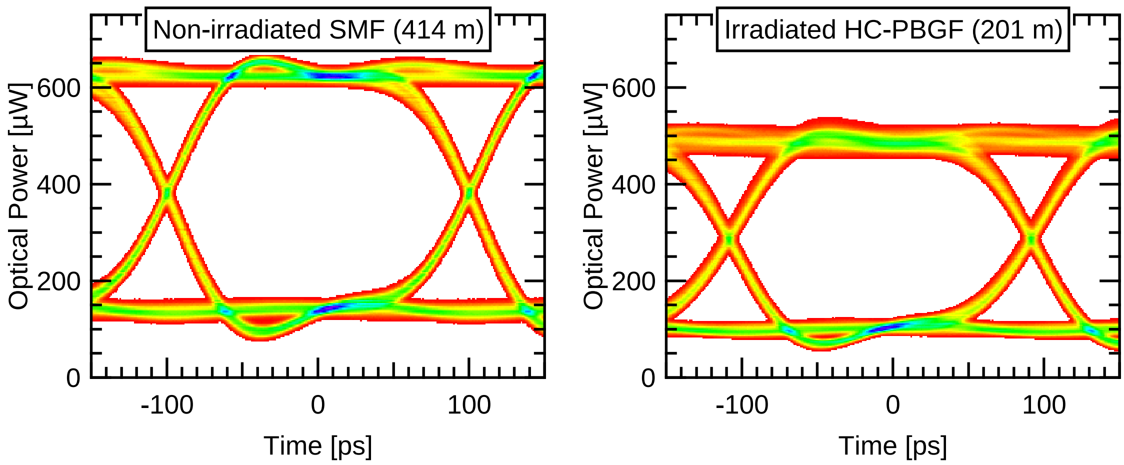

Figure 4. Transmission test at 5 Gbps. On the left reference non-irradiated single-mode fibre measured with the same setup as the irradiated HC-PBGF on the right.

shown. As expected the HC-PBGF sample has higher insertion loss, but the eye itself is wide open with only slightly increased jitter compared to the conventional fibre. A bit-error test was also carried out and the HC-PBGF showed only a small penalty of 0.5 dB compared to a back-to-back measurement at 40 Gbps.

Low latency was confirmed by measuring the time-of-flight in the HC-PBGF shown in figure 5. Light was found to propagate at 2.97×10^8 m/s ($\sim 0.99c$) in the HC-PBGF, which is around 50% faster than in a conventional fibre.

4 Discussion

The results of this test clearly show that HC-PBGFs are tolerant to high doses of gamma radiation. After a total dose of 940 kGy the HC-PBGF sample had a RIA of only 2.1 dB/km; two orders of magnitude lower than in a conventional fibre. Also the transmission band was not reduced or

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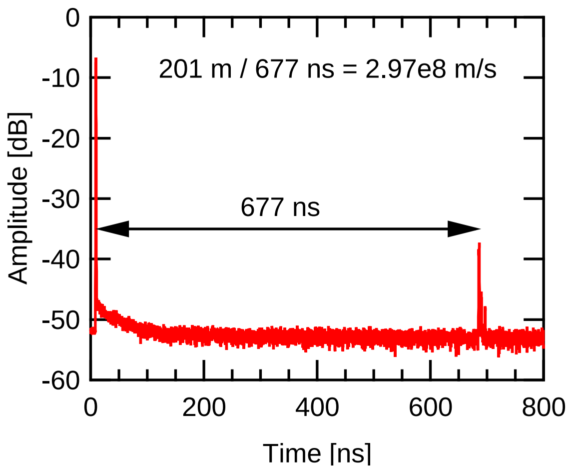

Figure 5. Time-of-flight measurement carried out with an optical time domain reflectometer. The peaks represent reflections from the HC-PBGF ends.

shifted during the irradiation. These observations show that gamma irradiation has no major effect on the structure of the HC-PBGF.

However, some RIA was measured which could be explained by changes to: the silica glass forming the microstructure in the HC-PBGF, the silica-air interface, or the air-filled core. It is well known that radiation causes light absorbing point defects, i.e. colour centres, in glass (see, for example [9]). These defects will increase the attenuation during the irradiation. Even though this has an effect on the RIA it is a minor factor, because the overlap between the propagating light and the silica parts of the fibre is very small.

Any radiation induced changes in surface roughness would also induce additional loss. It is known that the dominant mechanism behind the losses in state-of-the-art HC-PBGFs is scattering from the silica-air interfaces [4]. It is also known that gamma irradiation causes damage on silica surfaces [5]. Any significant increase in surface roughness caused by radiation would increase the scattering loss and therefore the RIA. Also any point defects at the core cladding interface could potentially cause coupling between core guided modes and so called leaky surface modes propagating in the core boundaries. Because the surface modes are strongly attenuated, any increased coupling would manifest itself as an increased attenuation.

A third possible mechanism RIA is the increased attenuation in ionized air. This phenomenon is not well understood, but because almost all of the light propagates in air and the total attenuation levels are very small to begin with it has been speculated that ionized air may indeed have a measurable effect on the RIA [6, 7].

Even though the mechanism behind the observed RIA cannot be explained conclusively from these measurements the small RIA levels prove the usefulness of the HC-PBGFs in harsh radiation environments, such as LHC accelerator control. In addition their minimal latency enables the exploitation of HC-PBGF based optical links in applications where latency requirements otherwise force us to use electrical links. All these features make HC-PBGFs a very promising fibre type for high energy physics applications.

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