Optica Applicata, Vol. XLI, No. 4, 2011

Gamma-radiation induced degradation random walk error in interferometer fiber optic gyroscope

Shisen DU*, Xueqin WANG, Song LIN, Chunxi ZHANG

School of Instrument Science and Optoelectronics Engineering, Beihang University, Beijing, 100191, China

*Corresponding author: shisendu@msn.com

Gamma-radiation induced random walk error (RWE) of interferometer fiber optic gyroscope (IFOG) is presented in this paper. Testing was performed at the components and system level with an expanded version of a closed-loop operational fiber optic gyroscope. Primary concerns include attenuation to total dose, angle random walk, and bias stability degradation as a function of dose. Closed-loop transient noise results are evaluated based on radiation test of the 400 m fiber coil. Based on the test result, a random walk coefficient (RWC) prediction model in radiation environment, which is obtained by embedding polarization-maintaining (PM) fiber loss expression into the RWC model, was built following a power law of dose. An IFOG RWC in space radiation environment was predicted from radiation dose rate by the prediction model. The RWC of the IFOG is limited by the detector thermal noise above 1 kGy radiation and the RWC prediction model is verified by radiation experiment.

Keywords: fiber optic gyroscope, gamma radiation, noise, random walk coefficient.

1. Introduction

Fiber optic gyroscopes are currently used in spacecraft systems as essential components [1, 2]. The anticipated environment temperature for interferometer fiber optic gyroscope (IFOG) on the interior of an operating spacecraft is –10 to +45 °C. But during the long term mission life, the radiation levels of many of these spacecraft systems will reach a 1 kGy level. In these cases, it is impractical to establish radiation response by irradiating fiber optic gyroscope at the operational dose rate for years or tens of years. A more practical course is an accelerated life test and the test data is used to extrapolate their response at the low dose rate through an appropriate model. Although the performance of IFOG in space environment is quite attractive, deployment of IFOGs requires addressing issues such as the deleterious effects of the space radiation environment [3].

In 1993, the strong tolerance to radiation of pure silica fibers was reported by Bielas and Taylor [4]. Boucher *et al*. have investigated the effects of space radiation on the performance of a high precision pointing grade IFOG. Closed-loop transient noise results are evaluated based on dose rate testing of the integrate optical chip (IOC), coupler, and fiber coil [5]. It is demonstrated that fiber gyros could survive under the long term radiation environment in space utilizing the E-core fiber [6]. The presence of stressing elements in the fiber structure does not affect its radiation resistance. The loss did not exceed 5–10 dB/km at the radiation dose of 2–10 kGy [7]. Moslehi reported that the open loop fiber optic gyro including the light source, splitter and receiver in one package, a gyro coil that utilizes small diameter, radiation-hard fiber and a small fiber phase modulator is tolerant to over 3 kGy radiation [8]. In this paper, we investigate the radiation induced effects on the component and system level of fiber optic gyroscope up to a total dose of 5 kGy. An random walk coefficient (RWC) prediction model of IFOG is built and verified by radiation experiment.

2. Theory and analysis

The basic sensitivity of the phase shift, Φ_s to the rotation rate is the Sagnac scale factor, given by the quantity G in

$$\Phi_s = G\Omega = \frac{2\pi LD}{\lambda c}\Omega \tag{1}$$

where L and D are the length and average diameter of the fiber coil, λ is the source wavelength, c is the speed of light in vacuum, and Ω is the rotation rate in radians per second. For fiber length $L = 400$ m, diameter $D = 45$ mm, and $\lambda = 1310$ nm, $G = 0.29\ \mathrm{s}^{-1}$.

For a given source power P_0 out of the source pigtail, the detector power is given by

$$P_d = P_0 10^{-\frac{A_c + \alpha L}{10}} \tag{2}$$

where α is the fiber loss in decibels per meter, and A_c includes all other circuit losses due to the fiber couplers, polarizer, IOC and its pigtail, and splices. A_c is about 18 dB and P_0 is 0.6 mW, the detector power will be 2.8 μW. Equations for each of these noise sources are listed next. The Shot noise is [9]

$$\sum_S = \frac{1}{G}\left(\frac{2q}{R_d P_d}\right)^{0.5} \tag{3}$$

where $q = 1.6\times10^{-19}$ coulomb, and R_d is the responsivity of the detector (0.9 A/W). The excess noise is

$$\sum_X = \frac{1}{G}\left(\frac{1}{\Delta\nu}\right)^{0.5} \tag{4}$$

where the effective bandwidth is

$$\Delta\nu = \left(\frac{\pi}{8\ln 2}\right)^{0.5} \frac{c\Delta\lambda_{\mathrm{FWHM}}}{\lambda_0^2} \tag{5}$$

and $\Delta\lambda_{\mathrm{FWHM}}$ is the half-power line width of a Gaussian source spectrum. An estimated value of 30 nm can be assumed for a typical superluminescent diode (SLD). The detected thermal noise is

$$\sum\nolimits_E = \frac{1}{G}\frac{\mathrm{NEP}}{P_d} \tag{6}$$

where the noise-equivalent power (NEP) of a typical InGaAs PIN photodiode is 1.0 pW/Hz$^{0.5}$. The relative intensity noise (RIN) is [9]

$$\sum\nolimits_R = \frac{1}{G}\sqrt{\frac{\lambda^2}{2c\Delta\lambda_{\mathrm{FWHM}}}} \tag{7}$$

The random walk error (RWE) in the output of a fiber optic gyro is limited by the white noise having a flat power spectral density. The sources of white noise in fiber optic gyros include electronics noise, shot noise, excess noise and relative intensity noise. The total RWC is

$$\sum\nolimits_{\mathrm{total}} = \left(\sum\nolimits_S^2 + \sum\nolimits_X^2 + \sum\nolimits_E^2 + \sum\nolimits_R^2\right)^{0.5} \tag{8}$$

3. Experiment and discussion

Figure 1 shows the distributed IFOG layout used for the γ-radiation transient-effects testing. The SLD works at 1310 nm. One PC is required to monitor power in a fiber

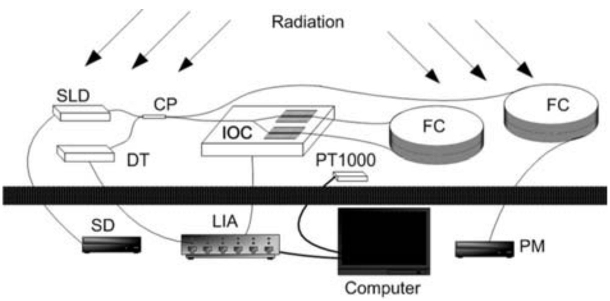

Fig. 1. Experimental arrangement used for the total testing of optic fiber gyro; CP – coupler, DT – detector, FC – fiber coil, IOC – integrate optical chip, PM – power meter, LIA – lock-in amplifier, SD – SLD driver.

coil, the digital output data from the IFOG, and the temperature data during the radiation. Since an IFOG is sensitive to small phase shifts, this distributed IFOG is used to measure any possible noise or transient effect induced by radiation in the optical components. These devices are spread out on an aluminium breadboard to allow γ-radiation of one component at a time. The transient effects are examined at the dose rate of 0.1 Gy/s and the total dose of radiation is about 5 kGy.

The test IFOG is made of a loop of a 400 m fiber produced by YOFC, coiled in a quadrupolar winding. About 0.6 mW of optical power from an SLD is launched into the fiber. Light from the SLD is sent through a fiber coupler, then split by a 3 dB IOC and coupled into the coil in both the clockwise and counterclockwise directions. The output signal from the reciprocal port of the 3 dB fiber coupler is detected with a detector. The detected electrical signals are extracted with a lock-in amplifier and recorded on a computer. Another fiber coil which is the same as the first coil is connected to the fiber coupler. The transmission is recorded during γ-radiation using a power meter.

A PT1000 temperature sensor is placed on the same plate near the fiber coil. So, it is guaranteed that fiber coil and temperature sensors will take the same temperature during the long term radiation. The radiation is performed with a dose rate of 0.1 Gy/s at room temperature. During the radiation we observe a temperature decrease of 0.7 °C that remains nearly constant during the whole irradiation run and decreases to about 25.8 °C after irradiation. Since an IFOG is sensitive to temperature gradient, the bias output of IFOG is compensated by the temperature data using the least squared estimate method.

The attenuation during 50000 s of γ-radiation is presented in Fig. 2. The radiation induced loss increases with time and the saturates apparently at high doses. A total of 47.7 dB of transmission attenuation is observed immediately after 5 kGy of dose giving a radiation. The solid line is the fitted the curve using the exponential function. The measured loss data is shown as open circles. The detected power in Eq. (2) can be obtained using the fiber loss during the radiation.

All the coils tested are coiled with Ge-doped silica core PM fibers, and the fibers are fabricated by the plasma chemical vapor deposition process. In general, the conventional PM fibers consist of a Ge-doped silica core with a pure or doped silica optical

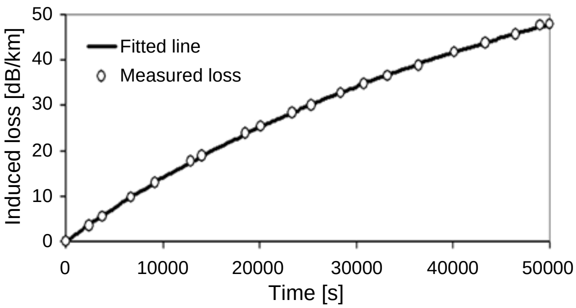

Fig. 2. Induced loss versus time for a 400 m fiber coil during the radiation.

cladding, similar to the structure of conventional telecom single mode fibers [3, 10]. Optical fibers exposed to gamma radiation at room temperature show degraded performance with increase in transmission loss due to generation of radiation induced defect centers in the core and clad glass regions. The magnitude of the radiation damage is due to Ge-related defects [3, 11, 12].

FRIEBELE *et al*. compared the radiation responses between the Ge-doped silica core fibers and all pure silica core fibers. The radiation-induced loss of Ge-doped silica core fibers is about 100 dB/km at 10 kGy radiation, while that of the pure silica core fibers is about 10 dB/km [13]. The differential attenuation measured in the Ge-doped silica core fibers and all pure silica core fibers is most likely due to Ge-related defects. It was observed that the presence of minor quantities of Ge-related defects considerably influences the loss characteristics of the fibers [3].

We also tested the SLD, detector, IOC and coupler before and after radiation. The test results are shown in the Table. The SLD output power decrease from 0.6 mV to 0.59 mV and the detector responsivity does not change after radiation. The detector dark current, coupler attenuation and IOC attenuation also almost do not change after radiation. Based on theses tests, γ-radiation has no obvious effects on IFOG components except fiber coil. The attenuation of the SLD, detector, IOC and coupler induced by radiation could not increase the RWE during the radiation.

The IFOG bias output under radiation conditions is measured by exposing the gyro to the radiation conditions expected in space environment. Figure 3 displays the IFOG output and simulated output power of detector during the radiation. The gyro output

T a b l e. IFOG component radiation test results.

Parameter	Before radiation	After radiation
Detector responsivity [A/W]	0.9	0.9
Detector dark current [nA]	6	10
Coupler attenuation [dB]	0.52	0.57
IOC attenuation [dB]	3.59	4.0
SLD output power [mV]	0.6	0.59

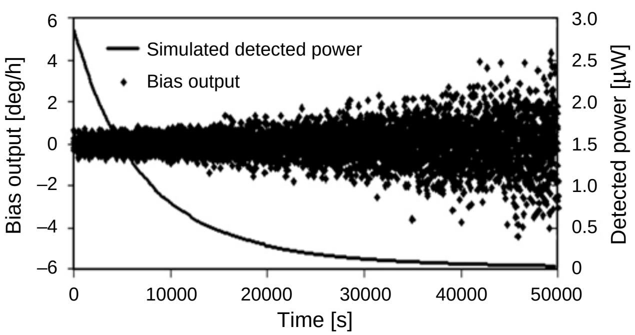

Fig. 3. Bias output and simulated output power of detector during the radiation.

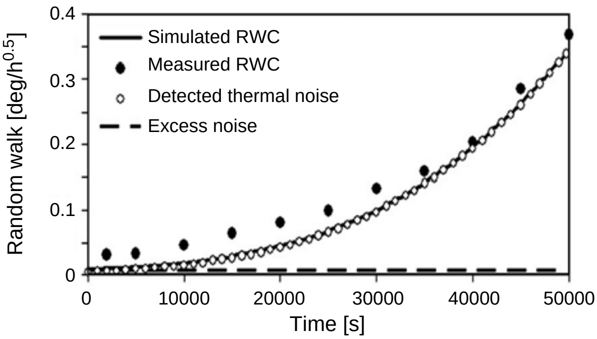

Fig. 4. Measured and simulated random walk during the radiation.

is collected at 1 s intervals during the experiment. As can be seen, the bias stability remains constant during the first 10000 s, and increases from 0.1 deg/h to 0.5 deg/h during the last 40000 s. The detected power quickly decreases from 2.8 μW to 0.25 μW during the first 20000 s, and then slowly decreases during the next 30000 s.

The RWC is predicted by Eq. (8) using the acquired IFOG output data and the induced loss of fiber coil during the radiation. Figure 4 shows the total time history of the annealing process. The filled circles are the measured RWC results and the solid line is the predicted value of RWC. The measured RWC remains at 0.03 deg/h$^{0.5}$ during the first 5000 s, and increase to 0.38 deg/h$^{0.5}$ at the end of radiation. This theoretical detection limit agrees well with the experimental result. The trend of the two curves confirmed the RWC prediction model in Eq. (8).

The detected thermal noise predicted by Eq. (6) is shown as open circles in Fig. 4. Since the detected thermal noise is inversed from the detected power, the detected thermal noise increases rapidly after 10000 s (1 kGy) as the detected power decreases. The excess noise predicted by Eq. (4) is also shown in Fig. 4. The excess noise is independent of the detected power and the excess noise remains at 0.06 deg/h$^{0.5}$ during the whole radiation. For low irradiation (< 1 kGy), the RWC is limited by the excess noise. At higher irradiation (> 1 kGy), the RWC sensitivity is dominant by detected thermal noise. Since the attenuation of the SLD, detector, IOC and coupler remain constant during the radiation; the radiation induced attenuation in fiber coil is the most prior contribution of IFOG's RWE performance degradation.

4. Conclusions

There are several challenges that must be overcome before IFOG can be widely applied onboard spacecraft. In the case of the IFOG, the principal technical challenge is that the sensing coil must be hardened against the space radiation environment. In this paper, we launched a γ-radiation test on the IFOG components and the close-loop IFOG, which show that the SLD source, detector, IOC, and coupler are immune to radiation. However, the PM fiber coil, whose loss is picked up with radiation dose, is the most sensitive to radiation.

Based on the radiation induced attenuation model of fiber, the IFOG RWC prediction model is built. The variety of RWC with radiation can be predicted by Eq. (8). These theoretical noise limits are plotted in Fig. 4 with the parameters of our experimental IFOG. For the time below 10000 s (1 kGy), the RWC remains constant, while the detected thermal noise is dominant for RWC above 5000 s. This theoretical RWC agrees well with the experimental result. This agreement demonstrates unambiguously that the noise of the IFOG is limited by the detected thermal noise after 1 kGy dose radiation and the radiation induced attenuation in fiber coil makes the major contribution to RWE in the radiation environment.

Acknowledgements – This work was supported by the National Natural Science Foundation of China (Grant No. 61007040).

References

[1] LEFEVRE H., *The Fiber-Optic Gyroscope*, Artech House, London, 1993, pp. 1–10.

[2] SANDERS G.A., SZAFRANIEC B., REN-YOUNG LIU, LASKOSKIE C.L., STRANDJORD L.K., WEED G., *Fiber optic gyros for space, marine and aviation applications*, Proceedings of SPIE **2837**, 1996, pp. 61–71.

[3] FRIEBELE E.J., ASKINS C.G., MILLER G.A., PEELE J.R., WASSERMAN L.R., *Optical fiber sensors for spacecraft: Applications and challenges*, Proceedings of SPIE **5554**, 2004, pp. 120–131.

[4] BIELAS M.S., TAYLOR W.T., *Progress in interferoinetric fiber optic gyroscopes for space inertial reference units*, Proceedings of SPIE **2070**, 1994, pp. 132–141.

[5] BOUCHER R.H., WOODWARD W.F., LOMHEIM T.S., SHIMA R.M., ASMAN D.J., KILLIAN K.M., LEGRAND J., GOELLNER G.J., *Proton-induced degradation in interferometric fiber optic gyroscopes*, Optical Engineering **35**(4), 1996, pp. 955–976.

[6] GREENWELL R.A., SCOTT D.M., MCALARNEY J.J., *Nuclear survivable polarization fibers for fiber gyroscopes on spacecraft*, Proceedings of SPIE **1791**, 1993, pp. 322–328.

[7] CHAMOROVSKII YU.K., BUTOV O.V., IVANOV G.I., KOLOSOVSKII A.A., VOLOSHIN V.V., VOROB'EV I.L., GOLANT K.M., *N-doped-silica-core polarization maintaining fibre for gyros and other sensors for application in space industry*, Proceedings of SPIE **7503**, 2009, p. 75036T.

[8] MOSLEHI B.M., YAHALOM R., FARIDIAN F., BLACK R.J., TAYLOR E.W., OOI T., CORDER A., *Compact and robust open-loop fiber-optic gyroscope for applications in harsh environments*, Proceedings of SPIE **7817**, 2010, p. 78170Q.

[9] BLAKE J., SZAFRANIEC B., *Random noise in PM and depolarized fiber gyros*, Proceedings of the 12th International Conference on Fiber Sensors, October, 1997, Williamsburg, Virginia, pp. 121–125.

[10] GIRARD S., KEURINCK J., OUERDANE Y., MEUNIER J.-P., BOUKENTER A., DEREP J.-L., AZAÏS B., CHARRE P., VIÉ M., *Pulsed X-ray and γ rays irradiation effects on polarization-maintaining optical fibers*, IEEE Transactions on Nuclear Science **51**(5), 2004, pp. 2740–2746.

[11] FRIEBELE E.J., GINGERICH M.E., BRAMBANI L.A., HARRINGTON C.C., HICKEY S.J., ONSTOTT J.R., *Radiation effects in polarization maintaining fibers*, Proceedings of SPIE **1314**, 1990, pp. 146–154.

[12] MARRONE M.J., RASHLEIGH S.C., FRIEBELE E.J., LONG K.J., *Radiation-induced effects in a highly birefringent fiber*, Electronics Letters **20**(5), 1984, pp. 193–194.

[13] FRIEBELE E.J., GINGERICH M.E., GRISCOM D.L., *Survivability of optical fibers in space*, Proceedings of SPIE **1791**, 1993, pp. 177–188.

Received April 8, 2011
in revised form June 26, 2011