THREE-AXIS FIBER OPTICAL GYROSCOPE FOR ROCKET&SPACE APLICATIONS

Yu.N. Korkishko[1], V.A. Fedorov[2], V.E. Prilutsky[3], V.G. Ponomarev[4], V.G.Marchuk[5], I.V.Morev[6], E.M. Paderin[7], S.M.Kostritsky[8]
RPC "OPTOLINK" Ltd.", Moscow 124498, Zelenograd, proezd 4806, h.5, Russia
Tel. (+7-495) 536-9933, Fax (+7-495) 536-9934, E-mail:korkishko@optolink.ru

V.N.Branets[9], V.S.Ryzhkov[10]
S.P.Korolev Rocket and Space Corporation Energia, 141070, Korolev, Moscow region, Russia
Tel. (+7-495) 516-0481, fax (+7-495) 513-6766.

Abstract

Key words: optical fiber, closed-loop fiber optical gyroscope

The Optolink's three-axis closed-loop fiber optic gyroscopes are described. The optical and electronic blocks of closed-loop gyroscopes with integrated optic components are considered. The results illustrate the versatility of the technology, showing its potential to meet both the low-cost, compact sized needs of tactical guidance, as well as the very high performance needs of inertial navigation and precision applications in spacecrafts.

Introduction

Other the last 30 years the interferometric fiber-optic gyroscope (FOG) research and development has evolved from promising experiment to an industrial device used for many applications. FOG is based on the Sagnac effect [1] which states that an optical path length difference is experienced by light beams propagating along opposite directions in a rotating frame. In fiber optical gyroscopes these two counterpropagating waves propagates at closed fiber coil. The obtained phase difference $\Delta\Phi$ is proportional to rotation rate Ω.

Fiber optical gyroscopes are being developed as attractive devices for many navigation and guidance applications. These all solid state devices have many advantages such as light weight, long life time, absents of moving parts and low voltage power.

1. Three-axis FOG with time multiplexing

Our 3-axis FOG TRS-500 has minimum configuration (Fig.1) that provides reciprocal optical paths for two beams counter-propagating in a fiber loop. The FOG TRS-500 consists of the one Light Source – Superluminescent Light Emission Diode with central wavelength 830 nm, one Photodetector, two Fiber Splitters (1:1 and 1:2) to divide the light into three parts, three ring interferometer to sense three orthogonal angular rates, and printed circuit boards installed signal processing circuits. The ring interferometer consists of a multifunction integrated optic chip (MIOC) and polarization maintaining (PM) fiber coil [2,3]. The MIOC is a three-port optical gyrochip fabricated at lithium niobate wafer by high temperature proton exchange technique [4,5] which provides three functions. First, it polarizes the propagating light to reduce bias instability due to polarization non-reciprocity. Second, it splits the light into clockwise and counterclockwise waves, each with equal optical power and recombines them with a Y-junction waveguide. Third, with electro-optical phase modulator, it applies a biasing phase shift between the counter-propagating beams. PM fiber is used in order to reduce both the drift caused by the polarization cross coupling and the drift caused by earth's and outside magnetic field via the Faraday effect.

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[1] Doctor of Phys.-Math. Sciences, Professor, General director.
[2] Doctor of Phys.-Math. Sciences, Professor, Technical director.
[3] Chief of Saratov's branch.
[4] Ph.D., chief designer.
[5] Principal engineer.
[6] Principal engineer.
[7] Chief technologist.
[8] Ph.D., chief of department.
[9] Doctor of Phys.-Math.Sciences, Professor, Vice-president.
[10] Ph.D., chief of department.

Block of electronics produced three voltages U_1, U_2 and U_3 for saw-tooth phase modulation for compensation of the Sagnac phase as well as for making constant phase difference $\pi/2$ between two waves.

At TRS-500 gyro the modulation switching with frequency 1 KHz is realized. This uses the fact that the each of three channels provides rate output only when an electrical modulation signal is applied to the phase modulator in the light path of interferometer. Therefore, simple switching of an electrical signal is used to activate only one axis at a time ≈ 333 μs. In a consistent design the same electrical functions are used for all axes in a time sequence, which on the other hand avoids any crosstalk between the axes as only the functions for one axis are active at the same time. With the exception of the electrical switches, which are readily available, and a small overhead of digital logic to control the switching, the same optical configuration and the same signal processing scheme are used as in the single-axis FOGs [2,3].

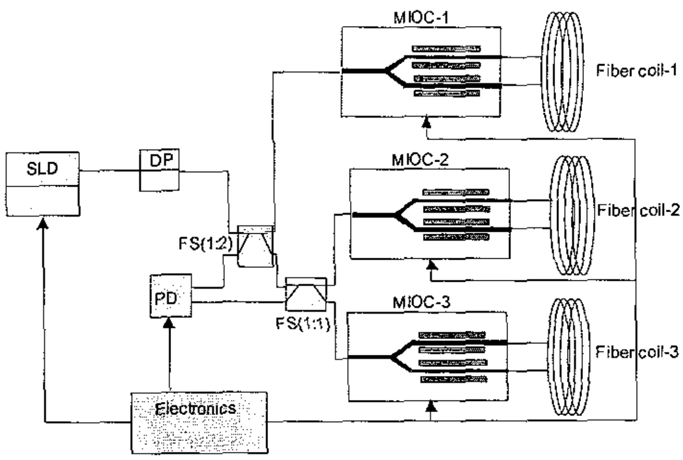

Fig.1. Minimum configuration of three-axis FOG TRS-500:
SLD- superluminescent diode, DP- depolarizer, FS- fiber splitter,
PD– photodetector, MIOC- multifunction integrated optic chip

In this case the measured rotation rate is determined as following:

$$\Omega = \frac{\lambda n}{\pi D} \varphi_{rs} f \tag{1}$$

where φ_{rs} and f are amplitude and frequency of saw-tooth, respectively.

In our three-axis FOG a frequency is stabilized by quartz resonator so, f= const. Therefore, rotation rate can be determined by measuring amplitude of saw-tooth $\varphi_{rs} = \frac{\pi D}{\lambda n f}\Omega$. This value is determined by measuring voltage U, which create this amplitude of saw-tooth. In this case

$$\varphi_{rs} = K_{PM}\, U \tag{2}$$

where $K_{PM} = \frac{\pi}{V_\pi}$ - efficiency of phase modulation, V_π - half-wave voltage. Therefore

$$U = \frac{V_\pi D}{\lambda n f}\Omega \tag{3}$$

So as V_π is proportional to wavelength λ, the scale factor of FOG does not depend on λ. This is worth because temperature stability of FOG is increasing.

Analog to digital processor (ADP) transfers analog outputs A1, A2 and A3 to digital output D1, D2 and D3 with RS485 interface.

Table 1 shows parameters of FOG TRS-500.

Table 1

Parameters of Optolink's three-axis fiber optical gyroscope TRS-500

Parameter	Three axes TRS-500
Range of measured angular rate, deg/s	±500
Bias drift at fixed temperature, deg/h	<10.0
Scale factor repeatability, %	≤0.5
Bandwidth, Hz	From 100 to 500
Random walk, deg /√h	≤0,05
Weight, kg	1.1
Dimensions, mm	110x110x90
Power consumption, W	<6
Output	Analog and Digital RS485

The TRS-500 gyro was established into control system of landing module of Russian manned transport spacecraft Soyuz TMA-5, developed and manufactured by S.P.Korolev Rocket and Space Corporation "Energia" in frame of International Space Station program. Flight test has been successfully performed at period from October 2004 to April 2005. The device has been established in the container at the landing module on an arm so, that its sensitivity axes X, Y, Z have been focused parallel to corresponding axes of regular 3-axis electromechanical gyroscope (EMG) with accuracy not worse than ± 2°. Signals «TRS 1», «TRS 2», «TRS 3» were given out from device TRS-500 to the system of the information record proportional to projections of the angular rotation rate to the X, Y and Z axes of the device with a steepness (0,150 ± 007) V·sec/deg and with ± 20 deg/sec range of the linear zone of measurement. TRS-500 was switched on from the cosmonauts control panel before division of compartments of the landing module and a device-modular compartment.

The performance of fiber optical gyro TRS-500 was estimated from device outputs which are proportional to projections of angular rates to orthogonal axis X, Y, Z of regular device EMG. Fig.2 and fig.3 show the output of X-axis channel for negative and positive rotation rates. The measured by TRS-500 angular rotation rates were in good agreement with ones measured by regular EMG. Six months flight test showed that FOG TRS-500 was efficiently workable at spacecraft "Souz TMA-5".

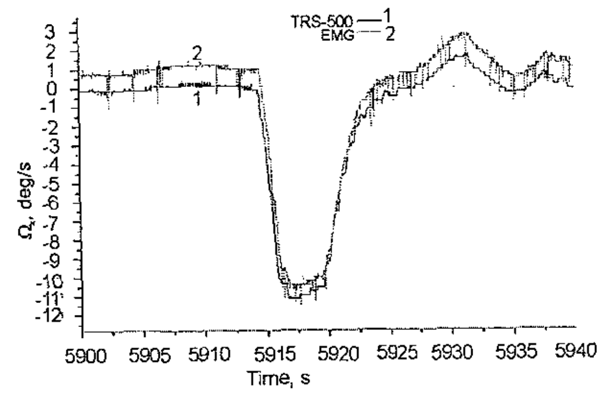

Fig.. 2. Output of X-channels of gyros TRS-500 and electromechanical gyro EMG at large negative rotation rates

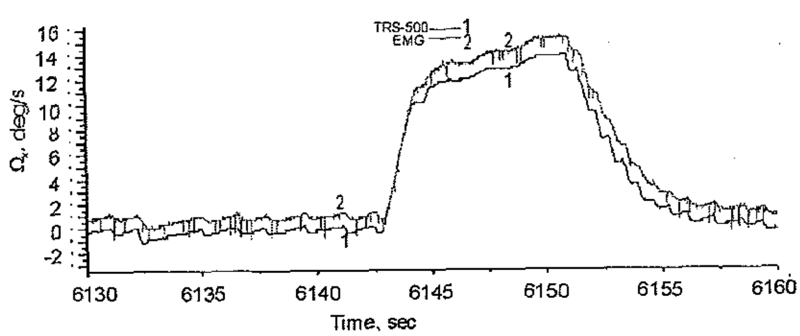

Fig. 3. Output of X-channels of gyros TRS-500 and electromechanical gyro EMG at large positive rotation rates

After successful flight tests, RSC "Energia" decided to use gyros TRS-500 as regular in a landing control system of the spacecrafts "Souz TMA". At "Soyuz TMA-7" spacecraft, launched at October 1st, 2005 to International Space Station, the traditional electromechanical gyros were replaced by TRS-500 FOGs.

2. Three-axis FOG with parallel work of channels

Based on TRS-500 gyro the modified 3-axis FOG TRS-500M has been developed. The main differences between TRS-500 and TRS-500M FOGS are following:

- working wavelength was changed from 830 nm (TRS-500) to 1550 nm (TRS-500M);
- analog processor replaced to digital signal processor (DSP);
- optical block of TRS-500M contains three photodetectors, all three channels works independently (no time multiplexing).

The FOG consists of the one Superluminescent Light Emission Diode (λ=1550 nm), three Photodetectors, four Fiber Splitters (1:1) and one Fiber Splitter (1:2) to divide the light into three parts, three ring interferometers to sense three orthogonal angular rates, and printed circuit boards with installed digital signal processor.

Configuration of TRS-500M with DSP is presented at Fig.4.

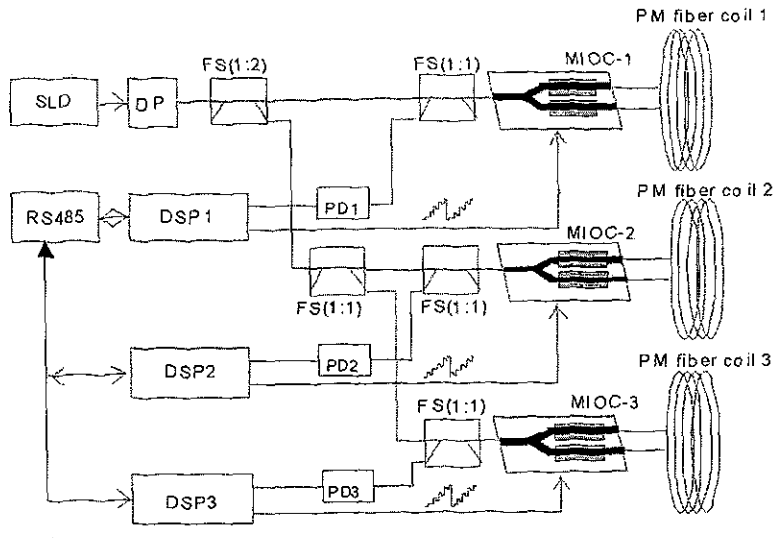

Рис.4. Configuration of TRS-500M:
SLD – superluminescent diode, DP-depolarizer, FS-fiber splitter, DP- depolarizer, FS- fiber splitter, PD–photodetector, MIOC- multifunction integrated optic chip, DSP - digital signal processor

As at TRS-500, the TRS-500M FOG uses only one light source – Superluminescent Light Emission Diode with central wavelength λ=1550 nm, but there are three photodetectors and three signal processors (DSP). It enables to work all there channels simultaneously. Each DSP generates voltage for "sawtooth" light modulation for compensation of Sagnac phase shift and to make fixed phase shift $\pi/2$. As a result, each channel is working in closed-loop regime.

Fig.5 shows the scheme of DSP.

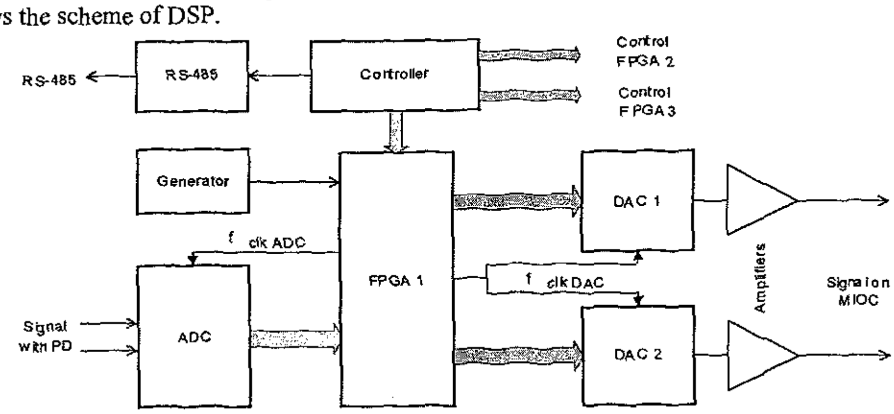

Fig.5. Block diagram of DSP.
ADC - analog to digital converter, DAC- digital to analog converter, FPGA- Field Programmable Gate Array

Analog signal from analog phase sensitive detector (PSD) that processes the output of the FOG photodetector is amplified and passed to high frequency analog to digital converter (ADC). The digital signal is demodulated by Altera Field Programmable Gate Array (FPGA). Obtained code passed to digital integrator. The code of signal from integrator is using to obtain the slop of phase "saw-tooth" which corresponds to rotation rate. The Digital to Analog converter creates the analog signal as saw-tooth voltage and pass it to MIOC. The wideband integrated optic phase modulators placed at both arms of MIOC are employed to introduce phase ramp modulation, thus enabling close-loop operation. The loop closure scheme uses a digitally synthesized saw-tooth (serrodyne modulation) of 2π amplitude in optical phase shift. In this case the Sagnac phase shift is compensated by saw-tooth modulation of light with calibrated amplitude 2π and frequency f, determined from well-known equation:

$$f = \frac{D}{n\lambda}\Omega, \tag{4}$$

where Ω is a rotation rate, D – diameter of fiber coil, n- effective refractive index of waveguiding mode, λ - wavelength.

The frequency of resulting ramp is then a digital measure of the rotation rate, with each ramp reset proportional to the angular turned, i.e. one ramp is equal to $\frac{n\lambda}{D}$. To increase resolution of gyro the rotation rate is determined by measuring slop of phase saw-tooth.

Each of three DSP represents the circuit based on Altera's FPGA. Each DSP is connected with high-speed ADC and with two fast Analog Devices's DAC. Clock pulse for DAC and ADC are drawing up by FPGA. Work of FPGA are clocked by external thermo-stabilized generator.

On one of DSP the Atmel's microcontroller is established which is working as the loader for FPGA. Controller provides an exchange on interface RS-485 with external devices. The monitor for device settings is realized based on this controller. Except for loading FPGA, the controller reads out the data of measurements from FPGA.

Fig.6 shows the functional scheme of the digital automation realized on FPGA.

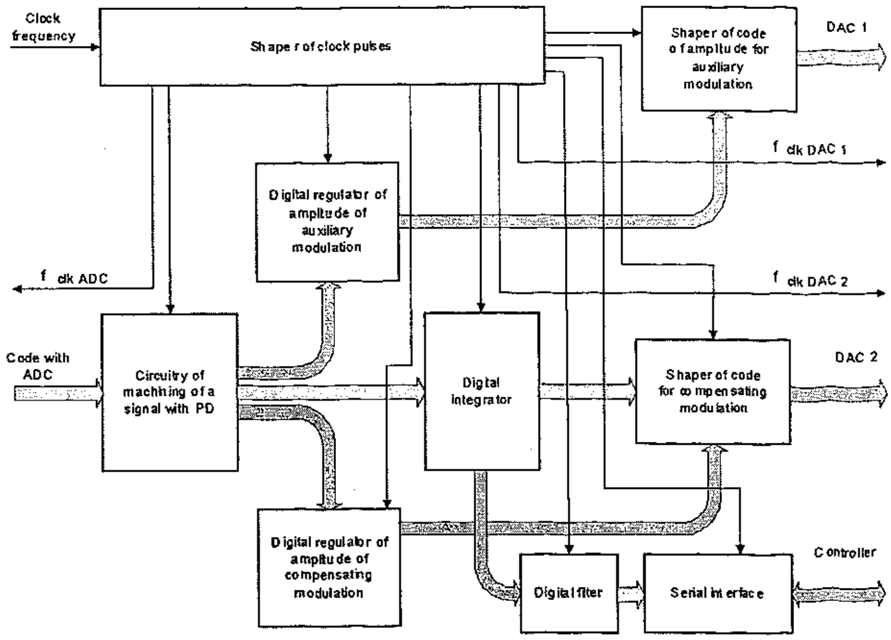

Fig.6. Functional diagram of the digital automation

The shaper of clock pulses transforms clock frequency to a set of impulses for synchronous work management of all devices and units. Fig.7 shows the operation diagram of the shaper of clock pulses. Clock frequency f_{clk} gets out to multiple frequency AMf_{am} Clock pulses for DAC are formed on fronts AM. Clock pulses for ADC are formed so that to exclude measurements on fronts of a signal from PD.

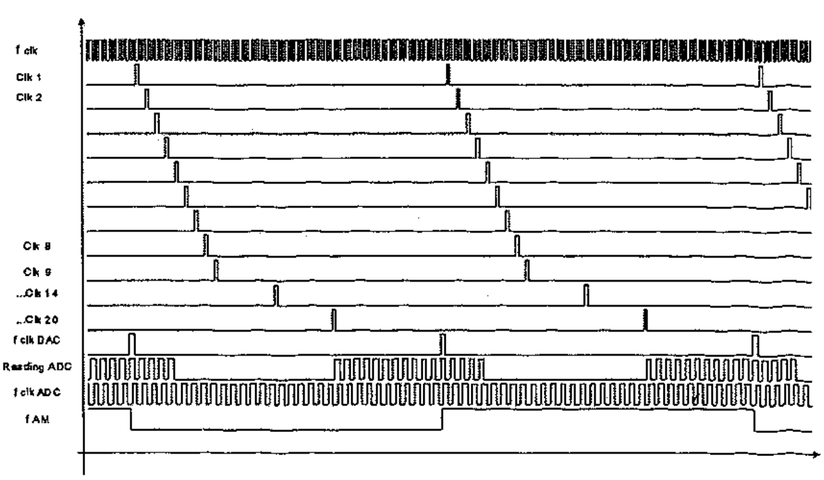

Fig.7. Diagram of operation shaper of clock pulses

The circuit of processing the signal coming from PD consists of the integration block, the buffer for storage of the measured value and the differencing circuit. The sum of the values of mismatch signal measured on the current phase AM is collected at integration block. On the buffer the sum of the values measured on previous phase AM is stored. After the measurements the values from the integration block and from the buffer pass to the differencing circuit. Depending on current phase of AM, one number passes as deducted and another as the subtractor. Thus the amplitude of a variable signal is allocated taking into account its sign.

The code with sign, corresponding to a sign of a mismatch signal, passes to the digital integrator which consists of the multiplier and the summing unit with the circuit of restriction. The time constant of the digital integrator is setting by the multiplier. The summing unit is used as the integrator. The code from the integrator passes to the shaper of the code for compensating modulation and through the digital filter to the serial interface of connection with the controller.

The shaper of a code for compensating modulation includes the summing unit which forms the "saw-tooth" code and the second summing unit which is used in a contour of a digital regulator of amplitude of compensating modulation. The signal from the circuit of processing of a signal from PD taken off at the moment of recessions of "saw-tooth" serves as signal of a mismatch for a digital regulator of amplitude of compensating modulation. The same signal is used for fine tuning of amplitude of auxiliary modulation.

Fig.8. illustrates the performance of our SRS-1000 FOG. Here the uncompensated output is plotted as a function of time. The Bias drift is less than 1 deg/h.

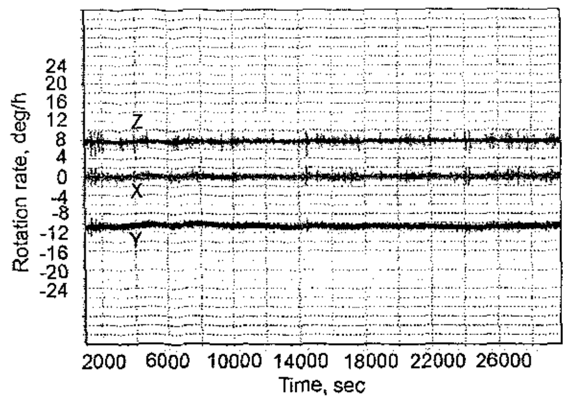

Fig.8. Uncompensated room temperature data for TRS-500M device

The parameters of modified 3-axis FOG TRS-500M are presented at Table 2.

Table 2

Parameters of TRS-500M

Range of measured angular rate, ° /sec	±300
Bias drift at fixed temperature, ° /h	<1.0
Scale factor repeatability, %	≤0.03
Bandwidth, Hz	300
Random walk, $^\circ/\sqrt{h}$	≤0,005
Weight, kg	1.1
Size, mm	110x110x90
Output	RS485

RSC "Energia" have made decision to perform flight tests of TRS-500M FOGs at landing module of "Soyuz TMA-9" spacecraft.

Conclusion

We presented results in development and fabrication of three-axis closed-loop fiber optical gyros at RPC OPTOLINK. Such gyros are using as regular devices in a landing control system of the spacecrafts Souz TMA. According to technical parameters of FOGs, such devices can be used also at other rocket and space systems. Future R@D aimed reduce size, increase accuracy and increase cost efficiency of fiber optical gyros

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