FIZOPTIKA

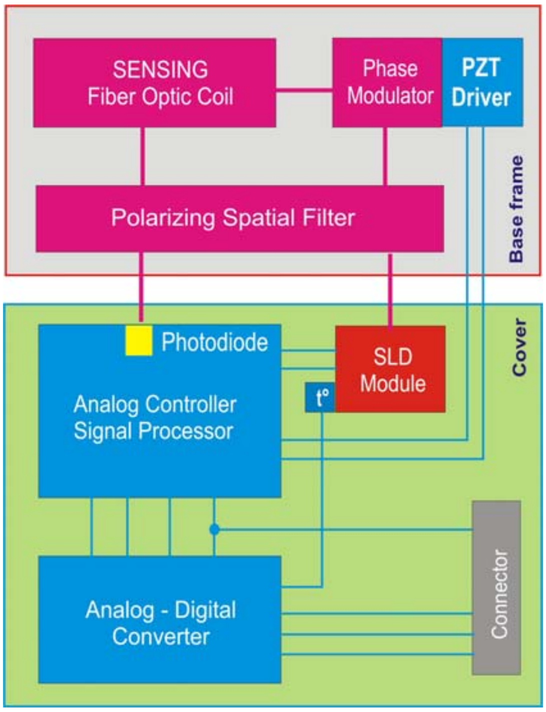
FIBER OPTIC ROTATION SENSORS VGxxx

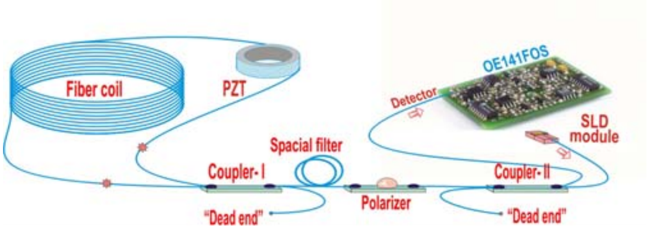
General description

The interferometric sensor is the one where the optical path or phase difference in an interferometer is dependent on an external physical effect. The fiber optic gyro is the example where the rotation of the fiber loop results in a phase difference due to the relativistic Sagnac effect. High noise immunity in the presence of strong electric fields is an advantage of photons in a waveguide vs. electrons in a conductor. Polarization preserving fiber is used extensively in interferometric arrangements to eliminate the effects of field rotation and polarization state changes that occur in the fiber. Optical sensing assembly complemented by advanced processing electronics provides superior stability and accuracy

VGXXX is a precise fiber optic rotation sensor (fiber optic gyro - FOG). Based on a relativistic optical effect it converts the absolute angular velocity into the output voltage. The sensor comprises fiber optic open-loop “minimum configuration” sensing assembly and advanced analog processing electronics. VGxxx is a robust, reliable, maintenance-free electro-optical device offering all the advantages of the optical sensing technology. The main frame of the sensor is made of aluminum alloy or quartz (VG035Q) or plastic (VG949P, VG910P etc), it tolerates wide temperature range and high levels of vibration and shocks. By special tuning the optical assembly may acquire immunity to electromagnetic interference eliminating the need for heavy shielding. Possibility to use plastic housing gives to the sensor lowest weight in its size. All sensors are produced using Fizoptika spliceless technique when optical components are fabricated along the single fiber length. Analog processing of the optical signal is performed by miniaturized electronic board fabricated in the conventional SMT technique. Some sensors has digital D-version where analog output converted into digital form and sent via RS232 interface.

PRINCIPLE OF OPERATION





Open-loop “minimum configuration” fiber optic gyro assembly.

The basic open-loop FOG is illustrated by Fig. The broadband light-emitting diode (SLD module) is used to couple the light beam into an input/output fiber coupler (II). The input light beam passes through a polarizer and a spatial filter that are used to insure the reciprocity of the counterpropagating light beams through the fiber coil. Another coupler (I) splits the two light beams into the fiber optic coil where they pass through a modulator (PZT) that is used to generate a time-varying output signal indicative of rotation. The modulator is offset from the center of the coil to impress a relative phase difference between the counterpropagating light beams. After passing through the fiber coil, the two light beams recombine and pass back through the polarizer and are directed onto the photodetector. When the fiber gyro is rotated in a clockwise direction, the entire coil is slightly displaced, increasing the time it takes the light beam to traverse the fiber optic coil (the phenomenon called “Sagnac effect”, discovered in 1913). The speed of light is invariant with respect to the frame of reference; so the coil rotation increases the pathlength when viewed from outside the fiber. Thus, the clockwise propagating light beam has to go through a slightly longer optical path-length than the counterclockwise beam which is moving in a direction opposite to the motion of the fiber coil. The net phase difference between the two beams is proportional to the rotation rate. By including a phase modulator loop offset from the fiber coil center, a time difference in the arrival of the two light beams is introduced, and an optimized demodulation of the signal can be realized. An open-loop fiber optic gyro has predominantly even order harmonics in the absence of rotation. Upon rotation, the open loop fiber optic gyro has an odd harmonic output whose amplitude indicates the magnitude of the rotation rate and the phase indicates direction. The result is that the first or a higher order odd harmonic can be used as a rotation rate output and an improved dynamic range and linearity are realized. Synchronous demodulation behind the detector converts the rotationally-induced first harmonic signal into a corresponding output voltage.

ANALOG OUTPUT

Some general properties of the sensor’s output may be deduced from fundamental physical arguments making a few very general statements (assumptions) without reference to the particular design of the open-loop fiber optic gyro.

No dead zone or hysteresis. The open-loop gyro is just a passive detector of the Sagnac phase. The Sagnac phase responds to rotation nearly instantly and without distortions. That’s why the relation between the output voltage and the input angular rate is perfectly proportional. In a certain sense, the open-loop gyro is an ideal sensor of rotation.

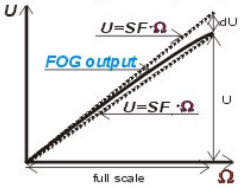
Instant response. The delay between rotation change and Sagnac phase change is determined by the light transit time through the fiber loop of the interferometer (0.8 µs) which is far below any reasonable mechanical transient period. Therefore, for the practical purpose VGxxx may be considered as an instant rotation converter. Actually, the operating frequency range is formed by output LP 450Hz (or 1kHz) filter which gives 0.3 ms response time.

Bias insensitivity to a constant acceleration. The constant acceleration (or gravity) does not create the phase difference between counter-propagating waves of the ring interferometer. Even mechanical distortion which happens under very high acceleration may theoretically affect only the scale factor of the sensor.

Highly-symmetrical output characteristics. The same arguments as in clause 1 prove the stated feature. If the detection circuit does not introduce an error the resultant output must be perfectly symmetrical. This means, among other things, that the polynomial presentation of the output characteristics does not contain even degree components.

The output of the sensor is defined as the voltage between the contacts OUT (output) and AGND (analog ground). Though AGND and GND (power ground) are not electrically insulated, a certain voltage difference between them may exist. The output impedance is 1 kOhm. It is formed by the resistor between the contact OUT and the output of the end amplifier. Its main purpose is to protect the amplifier against erroneous connection.

The sensor starts operating within 0.1 s after power-on. Warm-up lasts about 1 min. Warm-up bias transient does not exceed 20 µV, SF transient – 0.2%. When the sensor is rotated far beyond its input measurement range, it may fall in a non-operating state. In such a state, the sensor’s output voltage is no determined function of the input rate. Its data may be interpreted as random. Normal operating of the sensor is restored within 0.1 s after the rotation rate is again within the input range.



Output characteristics

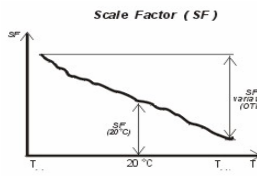
At a normal operating state the sensor's output voltage is a function of the angular rate and the *steady* temperature of the sensor's frame (SLD and electronics temperatures well correlate with a frame temperature). The simple model of the output can be presented as follows:

$$U = SF \cdot \Omega + U_0 \qquad SF(t°, \Omega) = SF_0 \cdot k_t \cdot k_\Omega$$

$$U_0 = U_0(t°, \ldots.)$$

$$k_\Omega = 1 - K_2(\Omega/\Omega_{max})^2 - K_4(\Omega/\Omega_{max})^4 \ldots$$

$$k_t = 1 + T_1 \cdot t° + T_2 \cdot (t°)^2 \ldots$$



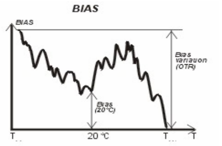
SF vs. Temperature (typical)

a) k_Ω - the term describing the deflection of the output characteristics from the linear curve. Such intrinsic (for the open-loop interferometric sensors) nonlinearity is larger at faster rotation and reaches ~ 15% at the maximum input rate (K_2, K_4 ≈ 0.05–0.1). Nonlinearity error may be well modeled by a simple polynomial of odd degree (see the above expression for k_Ω).

b) k_t – the term describing temperature dependence of the scale factor. k_t - is the repeatable quasi-linear function ($T_1 \approx -0.05\% / °C$, $T_1 \gg T_2, T_3$). The major cause of this dependence is SLD wavelength temperature change. The secondary cause is a slight temperature sensitivity of the electronics components parameters.

c) The bias (U_0) has several components:

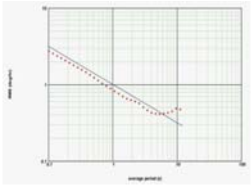
- "electronic" – the bias of operational amplifiers, dynamic detection error, interference of detection and oscillator circuits. This bias may be characterized by repeatable quasi-linear dependence on temperature. It is also slightly sensitive to the supply voltage (≈ 0.5 μV/V).
- "quadrature" – if the detection circuit does not suppress completely the quadrature signal, the minor fraction of it is also detected together with the rotation signal and appears as a bias. This bias may be characterized as a quasi-sine faintly repeatable function of ambient temperature with a period from fractions of to several °C.



Bias vs. Temperature (example)

- "optical" - when spatial or polarization filters do not operate perfectly, non-suppressed secondary optical waves form an additional erroneous signal indistinguishable from the rotation signal. It may also be characterized as a quasi-sine random function of temperature. The amplitude of that function is determined by the quality of filtering and how polarization degrades along the fiber loop.
- "magnetic" – the bias based on a truly nonreciprocal effect – magneto-optical Faraday effect. It depends on the fiber twisting rate. In VGxxx magnetic component of the bias may be eliminated by special tuning of polarizer.
- "temperature transient" occurs when the temperature of the sensor varies. In VGxxx temperature transient of the bias is eliminated by using for fiber coil the bobbin made of fused quartz. This material has nearly zero temperature expansion.

d) Output noise results from quantum fluctuations of the light beam intensity and thermal fluctuations in the electronic circuit. It appears as the scatter of data which is dependent on the time of measurement (average period). The noise power spectrum density (PSD) is nearly uniform within the working frequency range, it may be characterized as "white noise". VGxxx PSD is 5-10 μV/ √Hz. "White noise" gives the reverse square root dependence of data variations (RMS) on the averaging period (illustrated by Alan plot). For example, at 1 s average period RMS of the output voltage is about 5 μV. Variable acceleration (such as vibration or shock) results in dynamic frame deformations which may modulate the phase difference between counterpropagating beams on the same way as PZT works. The corresponding signal arises at the frequency of vibration and may be estimated as 1 μV per 1 m/s³.



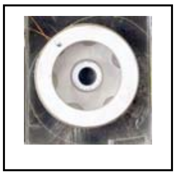
Alan plot – output RMS vs. Averaging period

Frequency (kHz)	0.05	0.1	0.2	0.3	0.4	0.5	0.6
Attenuation	0.99	0.99	0.94	0.87	0.78	0.66	0.54
Phase lag (deg)	10	20	40	70	90	110	130

e) The sensor has uniform frequency response in a working frequency range. The range is formed by Bessel low-pass filter of the third order with the cut-off frequency about 450Hz (or 1 kHz). The table shows filter's main parameters for 450Hz cutoff.

MAJOR PARTS AND COMPONENTS

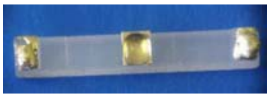
Fiber optic sensing coil – about 100 m of the birefringent polarization maintaining fiber wound on a aluminum or quartz bobbin to form a quadrupole pattern resulting in suppression of the vibration and temperature transient (Shupe effect) response of the sensing coil. Constant low tension is applied to the fiber during winding to achieve uniform and symmetrical mechanical structure of the coil. The fiber is specific and developed exclusively for the gyro application. It possesses a number of features: small diameter of cladding, high numerical aperture, high birefringence, etc. Every parameter is essential for the particular gyro performance or for the production yield.



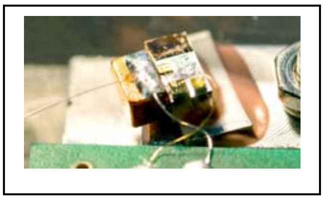
Phase modulator – about 0.5 m fiber length wound on the side of a piezoelectric cylinder (PZT). The PZT is mounted on the holder with soft silicon interlayer. This interlayer works as a mechanical isolator to avoid the leakage of oscillator energy to the sensor main frame.

Fiber optic fused coupler – an evanescent wave optical device which is to share equally optical energy between the two fibers. Both fibers shaped as biconical tapers are placed and fused in close proximity to one another. In a taper waist region, there is a leakage of optical wave beyond the core into cladding. Since another waist is placed nearby, this evanescent tail tends to couple to the adjacent fiber waist. The amount of cross-coupling depends on a number of parameters including wavelength, refractive index of the medium where coupler is placed, interaction length etc. To achieve predetermined coupling (3 dB), the corresponding signal is being measured continuously during coupler fabrication. After the process is finished, the coupler is mounted on a quartz substrate to ensue mechanical and thermal stability. It is covered with silicon gel to reduce vibration sensitivity.

Fiber-crystal polarizer – an evanescent wave optical device developed to suppress one of the two polarization states propagating inside the fiber. There are highest technical demands to the polarizer performance to ensure low bias of the entire sensor. The polarizer is a fiber biconical taper buried in a birefringent crystal. If the fiber outer diameter is essentially reduced by adiabatic tapering, there is a leakage of the propagating light beyond the core into cladding and into adjacent medium around cladding. As a result, in the taper waist region the optical wave interacts with the surrounding crystal. Material of the crystal is chosen so that propagating conditions for one polarization mode are broken while kept for the other. The taper in the vicinity to the crystal is twisted to adjust the birefringent axis at 45 deg with respect to the polarizer axis. This weakens magnetic sensitivity and normalizes interferometer transmission loss. Since the device is based on tapered fiber, it may be fabricated in spliceless technique. The polarizer is mounted on a quartz substrate and covered with silicon gel to ensure mechanical and thermal stability.



Light emitting SLD module – "zero-order" interference in the Sagnac interferometer makes it possible to use a low coherence light source, such as SLD – superluminescent diode. The diode is based on the amplification of the spontaneous radiation emission in the semiconductor laser structure to achieve an extremely bright but low-coherence output light beam. The low-coherence source brings to the sensor the reduction of noise and drift.



"Dead end" – a specially processed fiber end with eliminated back reflection. It is covered with silicon gel which refractive index matched to the refractive index of fused quartz.

ANALOG ELECTRONICS DESIGN

The open-loop sensor requires electronics to drive SLD current and PZT voltage for signal conditioning and for precise demodulation of the interferometric signal after its conversion from the optical power to the receiver voltage. The top level scheme for implementing the electronics is illustrated by block-diagram .

PHOTOAMPLIFIER is a broadband low-noise converter of the optical signal to the voltage.

SLD CONTROLLER is to provide DC drive current to the SLD. Operates in DC signal servo by using the photoamplifier output.

LOCK-IN DETECTOR (f) demodulates the first harmonic with the amplitude proportional to the rotation rate.

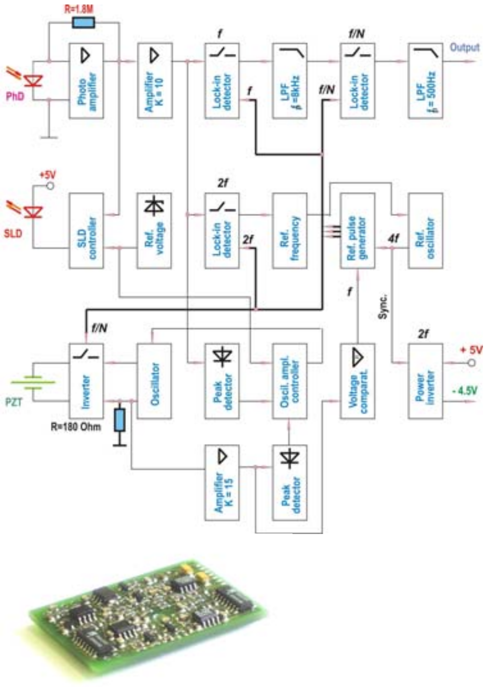
LPF (500Hz) is an active third order Bessel filter damps satellite harmonics of switching frequency in the output signal of the lock-in detector. It forms the output bandwidth of the sensor.

REFERENCE VOLTAGE BLOCK develops voltage reference levels which are used by SLD and PZT controllers.

LOCK-IN DETECTOR (2f) is used to detect and stabilize the relative phase shift between reference pulses and the photoamplifier output. Its output is used to drive reference oscillator frequency.

SELF-EXCITED OSCILLATOR uses PZT as a part of the feedback circuit to set oscillation frequency close to PZT resonance frequency.

VOLTAGE COMPARATOR (VC) transforms a sine signal of the oscillator to the rectangular pulses which are used for reference signals control.



Block-diagram and appearance of the OE141FOS

FREQUENCY GENERATION BLOCK develops the drive frequencies (2f, f, f/N) for lock-in detectors and synchronization signal for the power inverter. Contains VCO – the reference oscillator with voltage-controlled (~4f) frequency and logic circuit to form reference pulses.

POWER INVERTER is used to generate negative supply voltage for electronics operating. Conversion frequency is synchronized with PZT frequency to avoid unstable cross-coupling with demodulating circuits.

The electronics design concept is a single 4-layers PCB sized 45 mm x 30 mm. It is fabricated in conventional SMT technique and uses active and passive industrial-grade components.

DIGITIZED OUTPUT

In the digital (D) version of the VGxxx rotation sensor a special PCB is installed to digitize the sensor's analog signal. Its powering (+5 V, 35 mA) and input range are adapted to the analog sensor. The rotation rate data and some extra (X) data are sent via RS232 serial interface. The digital sensor starts operating in 1 s after power-on. Due to low consumption, a conventional USB port may be used as a power source and data line (with RS232 to USB converter). Software for primary data acquisition is available (DOS, W98, Wxp).

Appearance of digital PCB

Electrical interface

Definition	Contacts	Comments
Power supply	Power supply (+5 V) Power ground (GND)	+5 VDC (0.5 A max) regulated from 4.90 to 5.25. Ripple (0…1MHz) < 10 mV
Digital output	Tx of RS232 Digital ground (DGND)	Asynchronous, 8 data bits, 1 stop bit, no parity control. Digital ground may be combined with power ground (GND).

Operating mode

The sensor sends digital data continuously at 300.0 Hz ± 100 ppm repetition rate, 38 kbps transmission rate (default mode).

The rotation rate data has instantaneous bandwidth about 100 Hz.

The sensor may be factory set to “FAST MODE” or “SLOW MODE”.
In the “fast-mode” transmission rate is 115 kbps, repetition rate – 1200 Hz ± 100 ppm, instantaneous bandwidth - 300 Hz.
In the “slow-mode” transmission rate is 9.6 kbps, repetition rate – 75.00 Hz ± 100 ppm, instantaneous bandwidth – 30 Hz.

Digital data content

Rate data - Output of the analog sensor (Volt) = $2.5 \cdot RATE / 2^{23}$; RATE is a binary complementary 24-bit word

Xdata - temperature (taken from AD TMP36 sensor), supply voltage, analog sensor’s consumption current, diagnostics signal (option). These data (16 bits each) are transmitted completely in series of 16 sendings.

PRODUCTION TECHNIQUE

All the sensors are fabricated in specialized in-line technique. The fundamental of that technique is the fiber with a number of peculiar optical and mechanical characteristics. The fiber maintains its optical guiding ability under high elastic or even plastic deformations. This makes possible the fabrication of various fiber optic components directly on a fiber length by shaping it at high temperatures when quartz glass becomes soft. The sequent fabrication of the ring interferometer components (couplers, polarizer, SLD module) on a single fiber length makes them naturally connected without optical loss. For fiber shaping, an fusion-tapering technique and equipment were developed. During the couplers fabrication process the two fiber leads are installed together and held by two moveable holders. A stabilized high-frequency arc discharge is applied to the fibers so that they melt together. Simultaneously, the two fiber holders are moved apart so that a fused tapered region is formed. To ensure a low-loss coupler (polarizer), it is essential that the holders move apart in a straight line with no sideways motion or vibration. The speed of separation and heating length control the shape of the resulting taper and this also has a significant influence on the resulting loss. The arc-flame is of particular careful consideration. It is necessary to use an optimal arc length and arc current not to disturb the taper. The quality of the single-mode fiber is extremely important. The core and cladding must be highly circular and concentric with one another. Inferior quality fibers can result in high losses in the resulting coupler. It is also possible to monitor the coupler’s power-splitting ratio during fabrication and to make a coupler with any required splitting ratio at a given wavelength. The fabrication of the polarizer begins with a similar tapering process, with bigger elongation to achieve the waist diameter about 5 microns. After that, the fiber waist is placed into melt material from which the birefringent crystal is grown in such a way that the fiber is buried in the middle of the crystal body. The taper length and size of the crystal determine the polarizer extinction ratio. To build SLD-module the soldering process is used. SLD crystal and fiber lead are soldered each to the separate copper blocks. The blocks are soldered one to another at lower temperature after precise mutual alignment. Both major techniques (fusion and soldering) produce temperature and mechanically stable components that bring to the sensor reliable and stable performances in a wide range of various environments. Just after fabricating all optical components are mounted inside the sensor’s case and covered with protecting silicon gel. Electronics is mounted on the top cover of the sensor for a better thermal conductivity to the ambient media.

ACCEPTANCE TEST

The accuracy of the sensor and its resistance to the environments are determined by the sensor’s design and components specifications. All purchased components and materials pass incoming quality check. While a fiber optic component is fabricated, its performance is automatically controlled and registered. Just as the performance criteria are fulfilled, the next manufacturing step begins, so that the sensor with nonconforming component does not come out from the production. Assembling procedures are the subject of visual control. The correspondence of the manufactured sensor with its specification is proved during a functional check performed at normal conditions. The scale factor and consumption current are measured and registered as passport data. A 24-hours burn-in test is performed to ensure product stability. An optional performance test may be done to check the sensor operating in a specified temperature range.

TO READ MORE ABOUT FIZOPTIKA FIBER OPTIC GYROS

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