

Advances in Open-loop FOG Sensors

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Abstract: An all-fiber, open-loop FOG design with digital signal processing electronics for the control, demodulation, and calibration is presented along with typical performance data.

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1. Introduction

KVH Industries has been involved in the design, fabrication, and sale of fiber optic rate sensors for the past 15 years. Until 2002, these sensors were produced with analog electronics. That changed in 2002 when KVH introduced the DSP5000 and in 2003 the DSP3000 single-axis rate sensors, which contain digital signal processing (DSP) electronics that greatly improved the product performance and enhanced the features. This new class of DSP-based rate sensors is now widely used in a variety of commercial and military applications, including factory automation, vehicle navigation, camera and turret stabilization, and torpedo guidance.

2. All-Fiber, Open-Loop FOG Design

In 1981 the first all-fiber optic gyroscope was demonstrated at Stanford University [1]. This device, commonly referred to as the IFOG (interferometric fiber optic gyroscope), was further refined by many different universities and companies around the world to produce a sensor that today is capable of measuring a small fraction of the earth's rotation rate.

The introduction of the fiber medium into the optical path of the Sagnac interferometer does not alter the Sagnac effect directly, but does produce spurious signals. These unwanted signals limit the sensitivity and reduce the stability of the rotation measurement. The modern IFOG employs various techniques intended to minimize the effect of these error sources on gyro performance [2]. Highly birefringent, low loss optical fiber and components are used in the interferometer to hold a single state of polarization and minimize optical back-scattering. Also, proper consideration of optical reciprocity, optical source characteristics, and biasing requirements yield a highly accurate and stable rotation sensor.

The FOGs are based on KVH's E-Core[®] Polarization Maintaining (PM) Fiber [3], and fiber component technology. The KVH PM Fiber uses an elliptical shaped core designed to propagate a single longitudinal mode. The fiber's cladding is keyed in a D-shape with the flat of the D aligned to the long axis of the elliptical core. A photo of the E-core fiber cross-section is shown in Figure 1.

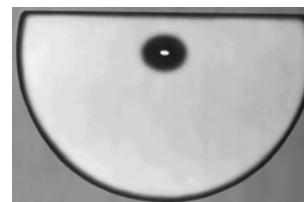


Figure 1. KVH E-Core Fiber Cross-Section.

The D-shaped cladding facilitates alignment of the PM fiber core during splicing and component fabrication. The KVH PM Fiber and fiber component technology allow the construction of low-cost, robust FOG sensors.

The KVH all-fiber, open-loop FOG presented in this paper is based upon the DSP3000 product line. The DSP3000 is a single-axis sensor with a 100-meter, level wound, PM fiber coil and an average coil diameter of 2.6 inches. The sensor is constructed using a minimum configuration [4], optical circuit in order to maintain optical reciprocity [5]. A laser diode operating below lasing threshold is used as the light source. The spectrum for the light source is significantly broad to reduce spurious errors in the interferometer and improve the stability of the sensor. A silicon photodiode with high gain transimpedance operational amplifier is the mechanism used for light detection and conversion to electrical signal. The 1st and 2nd couplers are PM type with approximately 50/50 splits. The 2nd coupler has a high degree of polarization extinction. A fiber polarizer is located between the 1st and 2nd couplers. The optical phase modulation is provided via a disc shaped Piezo-Electric Transducer (PZT) with high Q [6], and operating near the resonant frequency of 135 kHz. The proper or Eigen frequency for the 100 meter coil is approximately 1 MHz. Thus, the sensor is operated significantly off-proper frequency, as is typical of a short coil, open-loop FOG design.

Advances in coating stripping and coupler fusion have been made by incorporating a CO₂ laser into the manufacturing process. These advances reduce the amount of fiber handling, which has led to increased reliability of the optical circuit.

The fiber optic components are joined together using only three fusion splices in the locations shown in Figure 2. Since the FOGs are assembled with a reduced number of splices, it reduces the amount of extra losses and spurious signals, as well as material and assembly costs.

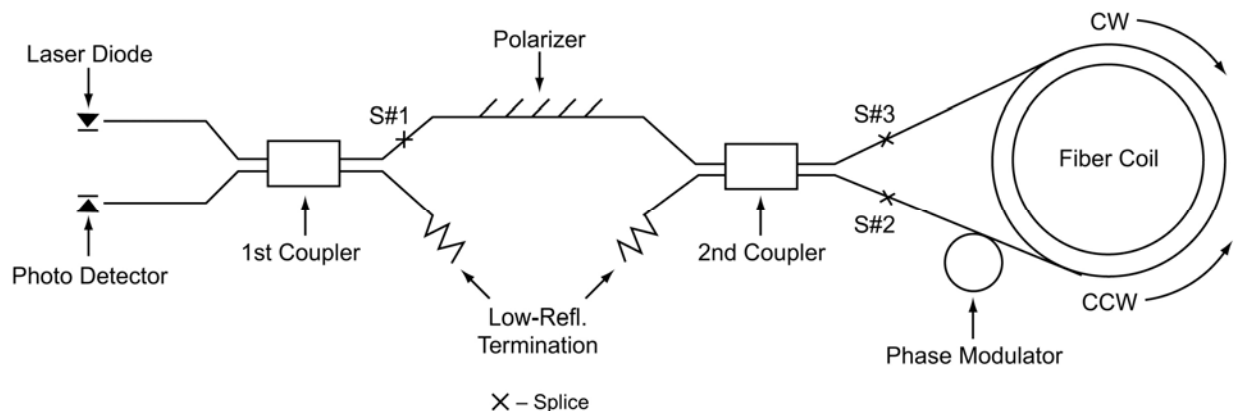


Figure 2. KVH FOG Optical Circuit Minimum Configuration

3. Digital Signal Processor Based FOG Electronics

The KVH traditional analog signal processing electronics architecture [7], is an approximation to the analytic approach based on a short length coil and limited input rate. The sensor signal processing occurs in an approximately linear region of the sensor's output response. Operating the PZT modulator in a self-resonant mode and monitoring the electrical response of the PZT modulator achieve modulation depth control. As the electrical to optical transfer function of the PZT modulator changes with temperature and time, the operating point changes and overall performance is limited. Monitoring the second harmonic amplitude of the detector output signal, which varies little with the limited rate input, controls laser power. If the input rate exceeds the assumed maximum rate, the performance degrades as the operating region becomes less linear and the second harmonic amplitude decreases.

The new KVH DSP electronics architecture for open-loop fiber optic sensors [8], shown in Figure 3, is based on the harmonic division algorithm [9]. This approach provides rate computations that are insensitive to changes in optical power and electronic gain. The DSP architecture also provides a modulation depth control based on the optical signal at the detector rather than the electrical response of the PZT. This approach allows for superior operating point control enabling improved scale factor control over a larger input range and improved bias performance.

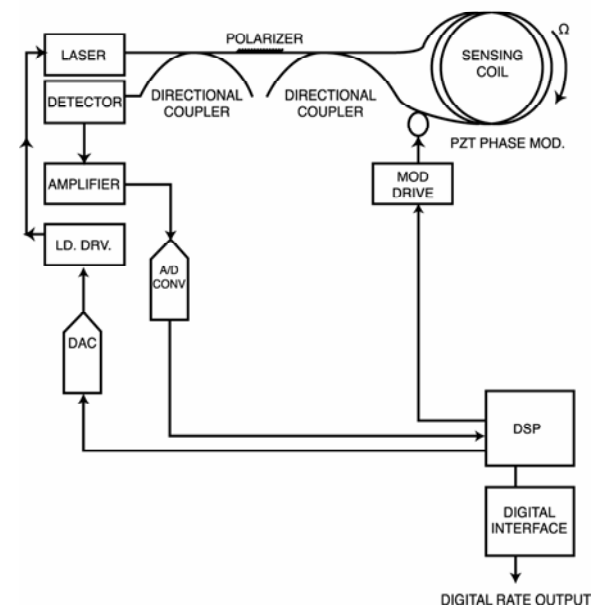


Figure 3. KVH DSP Electronics Architecture

Table 1 on the following page illustrates the performance improvement that may be attributed to the improved digital signal processing. The KVH RD2000 product is an analog electronics based sensor, while the KVH DSP3000 is a DSP electronics based sensor. The optical circuit design of both sensors is very similar in that both are all-fiber, open-loop sensors as described in Section 2 above. The data clearly shows the improved performance due to digital processing. The maximum rate range, bias and scale factor performance are each improved by at least factor of 3. Alternative control algorithms are possible and double the maximum input rate with a small increase in scale factor linearity error. Also, digital processing allows the sensor output rate and bandwidth to be easily modified for specific applications. KVH currently provides 10, 100, 1000, and 6000 Hz output rates with sensor bandwidths ranging from 4 Hz to 2500 Hz. Some sensors offer single pole filtering while others offer fourth-order filtering.

Performance Attribute	RD2000	DSP3000
Maximum Input Rate	± 100 deg/sec	± 375 deg/sec
Angle Random Walk	≤ 5 deg/hr/rt-hz	≤ 4 deg/hr/rt-hz
Bias Stability (room temp)	≤ 3 deg/hr	≤ 1 deg/hr
Bias Stability (full temp)	≤ 18 deg/hr, 1σ	≤ 6 deg/hr, 1σ
Scale Factor Error (full temp)	≤ 1500 ppm, 1σ	≤ 500 ppm, 1σ
Scale Factor Linearity	≤ 5000 ppm, 1σ	≤ 1000 ppm, 1σ

Table 1. KVH FOG Performance Comparison – Analog vs. DSP Electronics.

4. Sensor Calibration

Another significant feature of the DSP electronics architecture is that calibration tables for bias and scale factor temperature sensitivity and scale factor linearity can be stored in FLASH memory and then recalled to correct for output errors from the FOG. Bias correction tables have been developed that compensate for both the absolute bias change with temperature and bias errors associated with the time rate of temperature. The time rate of change compensation is essential for correcting bias errors due to optical non-reciprocity resulting from thermal gradients across the sensing coil. This level of calibration provides further improvement in sensor performance over large environmental changes.

5. Sensor Performance

The KVH DPS3000 sensors are calibrated for temperature then run through verification tests for noise, bias stability, bias temperature sensitivity, scale factor linearity, and scale facture temperature sensitivity. Typical single-axis performance data is shown in Figure 4. Notice bias, scale factor and linearity performance are significantly below the specifications listed in Table 1. This is typical of the performance margin provided by the DSP sensor electronics.

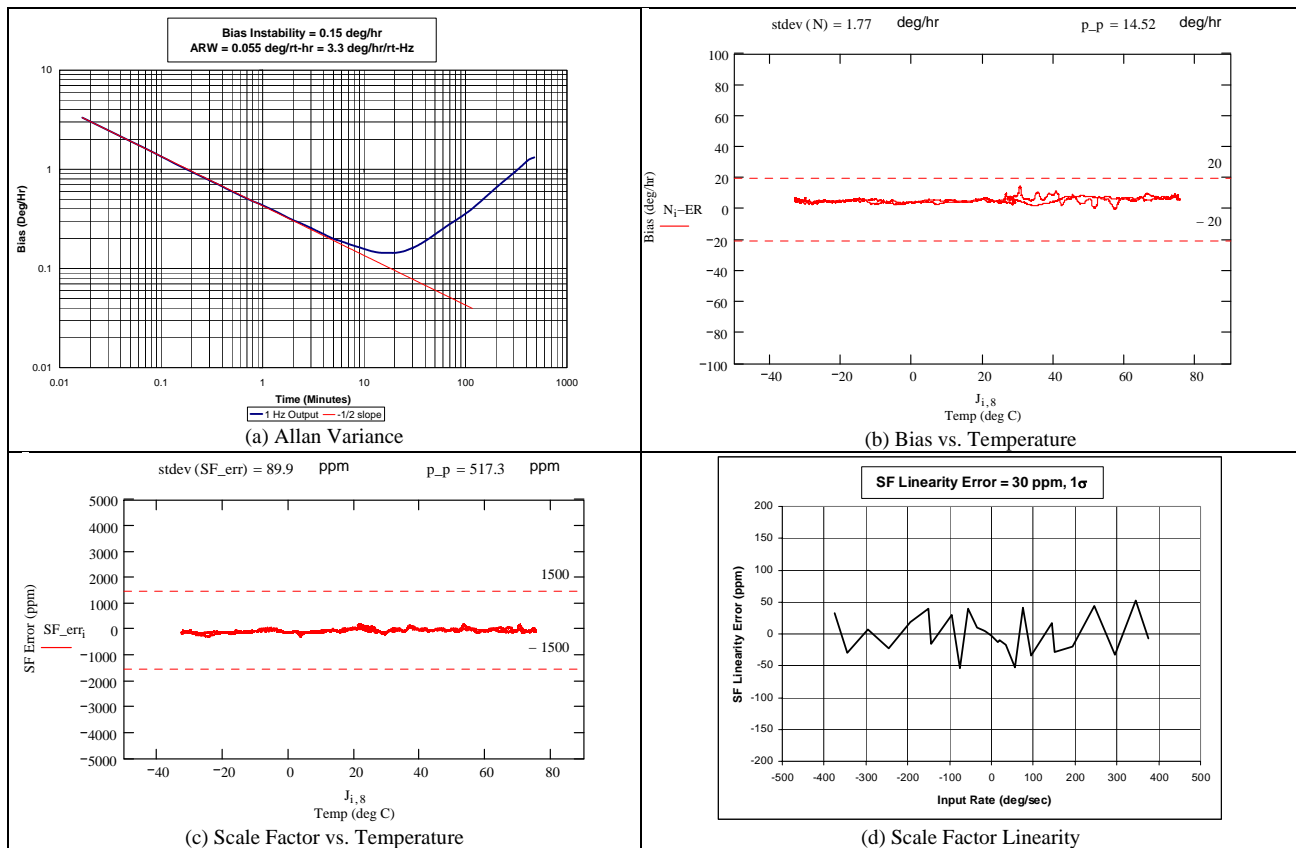


Figure 4. KVH DSP3000 Typical Performance.

6. Summary

In summary, when implemented properly, digital signal processing methods improve open-loop FOG performance and provide product flexibility for a wide range of applications.

7. References

- [1] R. A. Bergh, H. C. Lefevre, and H. J. Shaw, "All-single-mode-fiber-optic gyroscope with long term stability," *Opt. Lett.*, vol. 6, pp. 502-504, (1981).
- [2] R. A. Bergh, H. C. Lefevre, and H. J. Shaw, "An Overview of Fiber-Optic Gyroscopes," *IEEE Jour. Light. Tech.*, vol. LT-2(2), pp. 91-107, (1984).
- [3] Dyott, R. B. and P. F. Shrank, " Self-locating elliptical cored fiber with an accessible guiding region," *Electronics Letters*, Vol. 18, pp. 980-981, (1982).
- [4] R. Ulrich, "Fiber-optic rotation sensing with low drift," *Opt. Lett.*, vol. 5, pp. 173-175, (1980).
- [5] R. E. Collin, *Field Theory of Guided Waves*. New York: McGraw-Hill, (1960).
- [6] R. B. Dyott, and S. R. Emge, "Support System For Resonating Element of Phase Modulator", United States Patent # 5,739,944 (1998).
- [7] S. Emge and S. M. Bennett, "Reduced Minimum Configuration Interferometric Fiber Optic Gyroscope with Simplified Signal Processing Electronics", United States Patent # 6,351,310 B1 (2002).

- [8] S. M. Bennett, and R. B. Dyott, "DSP Signal Processing for Open-Loop Fiber Optic Sensors: United States Patent # 6,429,939 (2002).
- [9] Y. Gronau and M. Tur, "Digital signal processing for an open-loop fiber-optic gyroscope," *Applied Optics*, Vol. 34, No. 25, pp 5849-5853 (Sept. 1995).