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R.L. Patterson
*Lewis Research Center
Cleveland, Ohio*

and

A.H. Rose, D. Tang, and G.W. Day
*National Institute of Standards and Technology
Boulder, Colorado*

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FIBER-OPTIC SENSORS FOR AEROSPACE ELECTRICAL MEASUREMENTS: AN UPDATE

Richard L. Patterson
NASA Lewis Research Center
Cleveland, Ohio 44135

A. H. Rose, D. Tang and G. W. Day
National Institute of Standards and Technology
Boulder, Colorado 80303

ABSTRACT

Fiber-optic sensors are being developed for electrical current, voltage, and power measurements in aerospace applications. These sensors are presently designed to cover ac frequencies from 60 Hz to 20 kHz. The current sensor, based on the Faraday effect in optical fiber, is in advanced development after some initial testing. Concentration is on packaging methods and ways to maintain consistent sensitivity with changes in temperature. The voltage sensor, utilizing the Pockels effect in a crystal, has excelled in temperature tests. This paper reports on the development of these sensors. It also relates the technology used in the sensors, the results of evaluation, improvements now in progress, and the future direction of the work.

1. INTRODUCTION

Fiber-optic sensors that measure electrical current, voltage, and power have many advantages over conventional sensors. They are relatively immune to EMI, have wide bandwidth, low mass, and excellent isolation. They also will not fail during over-voltages or current-surges that would normally damage a conventional sensor.

Fiber-optic sensors developed for aerospace applications are designed to be broadband and accurate for ac frequencies as low as 60 Hz and as high as 20 kHz. This will allow use in 400 Hz aircraft systems, future 20 kHz spacecraft systems (such as electro-mechanical actuators or Advanced Launch Systems), and 60 Hz terrestrial systems. They are also designed to be stable over broad temperature ranges (-65°C to $+125^{\circ}\text{C}$).

A prototype fiber-optic current sensor has undergone significant testing and has operated successfully at high vibration levels.[1] A second-generation device is

in preparation. The advanced development of this sensor will concentrate on packaging methods to improve the temperature stability.

A prototype optical voltage sensor has been constructed and tested. The sensor has excelled in the temperature tests. Presently the voltage sensor is being modified to reduce sensitivity to vibration.

In this paper we will report the progress made on the development of aerospace current and voltage sensors which use fiber-optic and optical sensing heads. We will describe the technology used in the sensors, the results of evaluation, improvements now in progress, and the future direction of the work.

2. ELECTRICAL CURRENT SENSOR

Technology

Figure 1 is a schematic diagram of the electrical current sensor. The sensor uses the Faraday effect in an annealed coil of single-mode optical fiber through which the current carrying conductor passes.[2] The Faraday effect is a rotation of the plane of polarization of light as it propagates through a material in the direction of a magnetic field. The rotation of the plane of polarization is proportional to the current flowing through the conductor. Multiple turns of fiber increase the sensitivity of the sensor.

A polarization maintaining (PM) fiber transports linearly polarized light from the laser diode source to the sensing coil. Another PM fiber transports the light exiting the sensing coil to a polarizing beam-splitter and sensing photo-diodes. These optical elements convert the rotation of the polarization state into a change in transmittance so that a direct measure of the current in the conductor can be made.

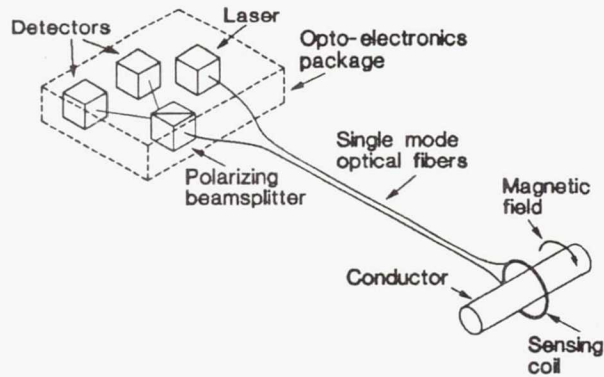


Figure 1 Fiber-Optic Electrical Current Sensor.

One of the prime areas of work during the past year has been on methods of packaging the current sensor, especially determining the best encapsulant for the fiber-optic sensing coil. The best stability achieved to date for an unpackaged coil is $+8.4 \times 10^{-5}/K$. [3] When the fiber is encapsulated, the sensitivity to temperature increases. Changes in the state of encapsulating material, especially at low temperatures, lead to a variation in stress on the optical fibers. The thermally induced stress placed on the fibers changes the sensitivity of the sensor as a function of temperature. Various encapsulants including high viscosity Teflon and silicon lubricants have been investigated; to date only a two-part silicon gel seems suitable for temperatures as low as $-65^\circ C$.

A novel fiber-optic temperature sensor has been placed in the current-sensing head and is used for electronic temperature compensation. The sensor is based on the temperature dependence of the birefringence in bulk SiO_2 or MgF_2 .

Evaluation

Figure 2 shows the uncompensated temperature sensitivity of a current-sensing coil that has been encapsulated with silicone gel. The greatest change in sensitivity is in the low temperature range below $-30^\circ C$. This low temperature zone has been the prime area of difficulty. After as many as 10 temperature cycles, the gel has not changed state and the temperature sensitivity has remained consistent.

An early version of the electric current sensor was subjected to swept vibrations between 5 Hz and 2 kHz at levels up to approximately $196 m/s^2$ (20g, where g is the acceleration due to gravity) (typical of aircraft). It was also tested with random vibrations up to $182 m/s^2$ (18.6g) (typical of spacecraft launch vehicles). The sensor operated without failure under all of the vibration

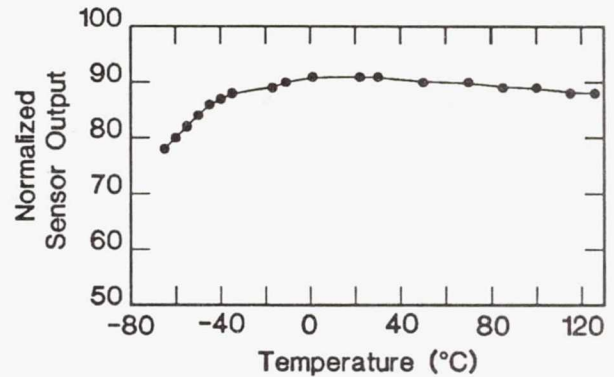


Figure 2 Uncompensated Output of a Current Sensor Using a Fiber-Optic Pickup Coil Encapsulated with Silicone Gel.

testing. Vibrations did, however, induce noise into the output of the sensor, due perhaps to stress being delivered to the sensing fiber coil. The highest noise output occurred when the vibration frequency was between 20 and 700 Hz. At 90 Hz and approximately $49 m/s^2$ (5g) the induced noise was equivalent to a current flow of 4 A rms. An improved sensor package and a coil encapsulated in gel may reduce the induced noise.

3. VOLTAGE SENSOR

Technology

Figure 3 shows a diagram of the fiber-optic voltage sensor which uses a technology very different from the current sensor. The voltage sensor uses the Pockels effect in a small piece of bulk bismuth germanate. Polarized light from a laser diode source is delivered to the bulk material by optical fiber. The voltage to be measured is applied to two conductive plates on opposing sides of the bulk material so that an electric field is set up transverse to the direction of propagation of the polarized light. The electric field induces a linear birefringence that changes the polarization state of the light. The optics translate a change in polarization state into a change in intensity, and the intensity-modulated light returns to the sensing electronics via an optical fiber [4].

A fiber-optic temperature sensor is used to compensate for the temperature dependence of the electro-optic effect in bismuth germanate. The voltage sensor does not require an encapsulant, rather the optical compo-

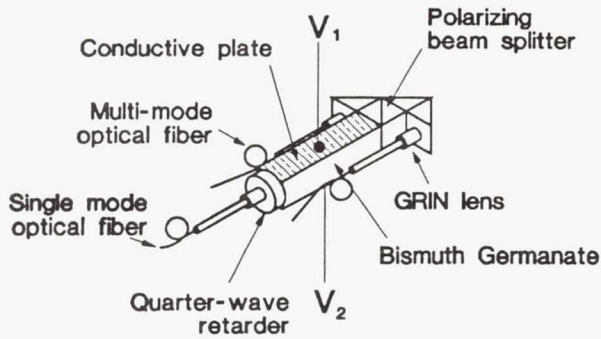


Figure 3 Diagram of the Fiber-Optic Voltage Sensor.

nents are held together with UV-curing glue. An early version of the voltage sensor used two optical fibers to deliver and return light. The noise floor was excessive because of the low light throughput. The latest version employs three fibers (one for input to the sensor head and two for return) and achieves a 10-fold decrease in the noise floor to an acceptable 0.5 to 0.7 V/ $\sqrt{\text{MHz}}$.

Evaluation

The voltage sensor has undergone 30 temperature cycles over the range -65°C to $+125^{\circ}\text{C}$, and its temperature compensated output, as shown in Figure 4, falls within $\pm 1.3\%$ over the temperature range of -70°C to $+130^{\circ}\text{C}$. Output is about 1.2 mV rms per 1 V rms applied to the input.

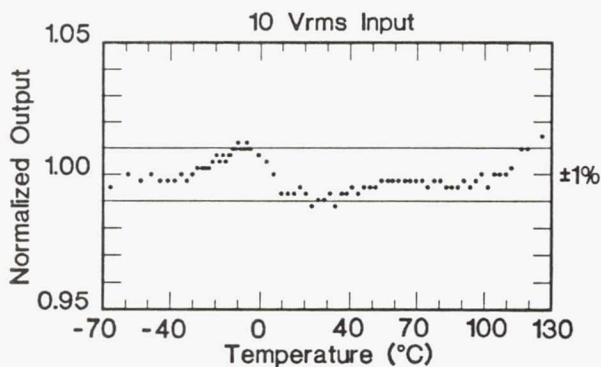


Figure 4 Output of the Voltage Sensor after 30 Temperature Cycles.

With the second version of the voltage sensor it was discovered that movement of the fibers which connect the sensing head to the electronics package caused excessive noise. It is believed that this problem is due to modal noise in the multi-mode fiber used for light input to the sensing head. To remedy the problem

NIST is presently redesigning the voltage sensor to use a single-mode optical fiber for input. After the voltage sensor is rebuilt, it will be submitted to vibration tests very much like those described previously for the current sensor.

4. RELATED WORK IN OTHER ORGANIZATIONS

The US Navy has been supporting similar work at NIST Boulder on fiber-optic current sensors for ship-board applications. The Navy sensor has a different configuration called the vertically annealed design (VAD) seen in Figure 5. In this design, the plane of the sensing coil was turned roughly perpendicular to the direction of the PM input/output fibers. To date, this design has been used successfully over the required 0°C to $+65^{\circ}\text{C}$ range. Operation at lower temperatures has not been as successful, probably because of greater stresses placed on the fiber.

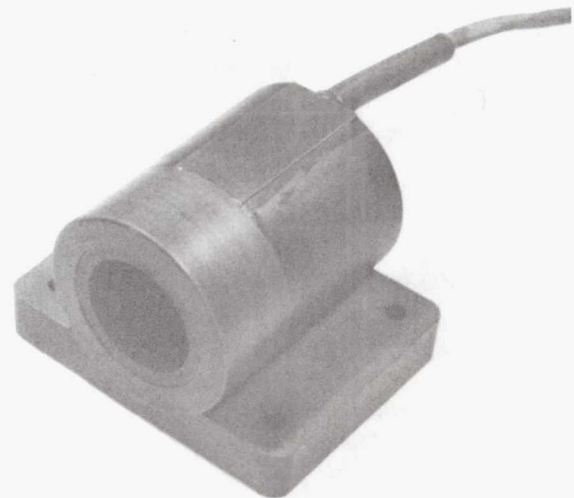


Figure 5 Fiber-Optic Current Sensor Using the Vertically Annealed Design (VAD).

Through a cooperative research and development agreement with NIST, a private U.S. corporation will soon be producing fiber-optic current sensors. Prototypes have been shown to prospective customers, and commercially available units will be offered in early 1992.

5. FUTURE WORK

In the near term, NIST will finish building a second-

generation current sensor with a slightly larger sensor head (for improved vibrational performance) containing the new silicone gel as an encapsulant (for improved temperature stability). The new current sensor will also employ improved electronics for lower noise levels. NASA Lewis will perform vibration tests on the latest current sensor.

In addition, NIST will finish its improvements to reduce vibration sensitivity in the voltage sensor. NASA Lewis will do vibration testing on the voltage sensor also.

In the fall of 1991, NIST will begin design of a fiber-optic electric power sensor which will contain current and voltage sensing devices in the same sensing head. Only optical fibers will connect the sensing head to a package of processing electronics.

6. SUMMARY

The first generation fiber-optic current sensor showed excessive changes in sensitivity with temperature due to stresses impressed on the fibers by encapsulants, especially at low temperatures.[1] The first current sensor was given severe vibration testing and always operated without failure. It did, however, exhibit some undesirable response (noise in the output) to mechanical vibration. Development of the second-generation current sensor is near completion. There are strong indications that the temperature problem has been solved, and that accuracy will be about $\pm 1\%$ full scale over the temperature range of -65°C to $+125^\circ\text{C}$. The new current sensor will be vibration tested.

Very desirably, the output of the voltage sensor changes very little with temperature. The optics have been improved to obtain a noise floor of $0.7\text{V}/\sqrt{\text{MHz}}$. The sensor design is being modified to reduce vibration sensitivity. The voltage sensor will be vibration tested in the summer of 1991.

Design of the fiber-optic power sensor will begin in the fall of 1991.

7. ACKNOWLEDGEMENTS

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8. REFERENCES

- [1] Richard L. Patterson, A. H. Rose, D. Tang, and G. W. Day, "A Fiber-Optic Current Sensor for Aerospace Applications," *Proceedings of the 25th Intersociety Energy Conversion Engineering Conference*, Reno, Aug 12-17, 1990, Vol I, pp. 500-504.
- [2] D. Tang, A. H. Rose, G. W. Day, and S. M. Etzel, "Annealing of Linear Birefringence in Single Mode Fiber Coils: Application to Optical Fiber Current Sensors," accepted for publication in the *Journal of Lightwave Technology*, 1991.
- [3] D. Tang, A. H. Rose, and G. W. Day, "Optical Fiber Current Sensors with Temperature Stabilities near the Material Limit," *Proceedings of the 7th OFS Conference*, Sydney, NSW, December, 2-6, 1990, pp. 77-80.
- [4] A. H. Rose and G. W. Day, "Optical Fiber Voltage Sensors for Broad Temperature Ranges," to be published in the *SPIE Proceedings of OE/FIBERS'91*, September, 3-6, 1991.

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