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FINAL TECHNICAL REPORT
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Optical Sensors for Use in Propulsion Control Systems

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presented to

Glenn Beheim, Ph.D.
NASA Technical Officer
Engine Sensor Technology
Lewis Research Center
National Aeronautics and Space Administration
Cleveland, Ohio

prepared by

Klaus Fritsch, Ph.D.
Department of Physics
John Carroll University
Cleveland, Ohio 44118

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I. Introduction

This final technical report describes the results of a cooperative effort which was originally established between John Carroll University and the Instrumentation and Control Technology Division at NASA Lewis Research Center on November, 1982, and then continued with the Engine Sensor Technology Branch at NASA Lewis until March, 1995. All work at John Carroll University was directed by the principal investigator of this grant, Klaus Fritsch, Ph.D. For the first two years of this grant this effort was supervised at NASA by Mr. Robert J. Baumbick and for the remainder of the grant by Dr. Glenn M. Beheim. All research was carried out in close cooperation with Dr. Beheim.

Electrically passive optical sensors for measurands such as pressure, temperature, position, and rotational speed are required for aircraft engine control in fly-by-light digital aircraft control systems. Fiberoptic data links and optical multiplexing techniques should be used for combining and processing the outputs from several sensors, sharing as many optical end electronic parts as possible.

The overall objective of this grant was to explore techniques for designing and constructing such electrically passive optical sensors for measuring physical parameters in jet aircraft engines and for use in aircraft control systems. We have concentrated our efforts on pressure, temperature, and position sensors employing techniques which are relatively immune to transmissivity variations of the fiber links and to variations in intensity of the light source. Infrared light-emitting diodes are employed because of their longevity and immunity to vibration. We have also studied a number of multiplexing techniques.

On the following pages I will give thumbnail sketches of the projects carried out under this grant and provide references to publications and John Carroll M.S. theses which resulted directly from this work and which describe these projects in greater detail.

II. Digital Rotary Position Encoder

The primary focus of this development effort was the proof of concept, prototyping, and design work for a 10-bit digital rotary position encoder. A possible application of such an encoder would be to measure the power lever angle (PLA) of a jet engine. This sensor uses wavelength division multiplexing employing a microoptic spectrometer and two light-emitting diodes (LED) with overlapping spectra as "broadband" lightsource. After initial tests of various concepts an encoder using a 50mm diameter code plate was built. After extensive testing three completed encoders were delivered to NASA. The mechanical and optical design of the sensing head and early development of the electronics was carried out at John Carroll University. The final development of the flight electronics was carried out by Mr. Bathhurst and Mr. Joseph Flatico at the NASA Lewis Research Center. The encoders were fully characterized and one encoder was tested on an F100 aircraft engine located in the Propulsion Systems Lab at the NASA Lewis Research Center. A new housing was designed appropriate for mounting the unit in the baggage compartment of a McDonnel-Douglas test aircraft under the OPMIS program.

Around 1991 we designed and built a smaller and simpler encoder head employing a 36 mm diameter code plate. Three of these units were delivered to NASA Lewis. Three additional heads were prepared for tests on an aircraft at Langley Research Center. One of the encoders was prepared for flight testing on a commercial aircraft under the OPMIS System Integration Program. A dummy encoder used for test-fitting to the NASA aircraft was also constructed and delivered. One of the encoders and associated electronics was successfully flight tested on fifteen flights on the engine of a NASA F15 aircraft at NASA Dryden under the FOCSI program.

Detailed information may be found in references 13, 18, 21, 23, 26, and 27.

III. Other Spectrum-Modulating Fiber-Optic Sensors

Standard intensity-modulating sensors can be very simple but are quite unstable. Since the transmissivity is a monotonic function of the measurand, the intensity delivered to the final sensing element is influenced by any changes in the transmissivity of the fiber links due to replacement of components, effects due to unreliable connectors, temperature effects, etc. For link independence spectrum-modulating sensors in conjunction with a broadband source are used. In such a system the sensor modulates light of different wavelengths at substantially different functions of the measurand. We constructed several temperature sensors using Fabry-Perot cavities. For example, we carried out extensive testing on sapphire-fiber and TiO_2 coated interferometric Fabry-Perot temperature sensors. A graduate student (Yiting Mi) carried out "A Comparative Study of Fabry-Perot Fiber-Optic Temperature Sensors."

We designed and tested other kinds of pressure and temperature sensors which use properties of the spectra of various materials. We built a pressure sensor which uses two Fabry-Perot cavities, one located at the location where the pressure is to be measured, the other one located in the avionics bay. The sensing cavity changes its length in proportion to the pressure. By using a feedback loop and "white light" fringes produced by a broadband source, the local cavity length is made to track the remote cavity. The length of the local cavity is measured using a capacitive technique reported in reference 15. We completed a breadboard setup of such an interferometric pressure sensor using a fiberoptic link and an infrared LED as light source. We have made static pressure tests up to 500 p.s.i. The results were reproducible to within 0.1% over several hours.

Additional information may be found in references 3, 7, 16, 17, 18, 19, 20, 21, 22, 23, 24, and 25.

In another type of temperature sensor spectral shifts with temperature were monitored and the intensity transmitted at two different wavelengths was used to obtain a ratio independent of the transmitted intensity. We built and tested a fiberoptic GaAs temperature sensor based on this principle. The temperature of a wafer of GaAs is deduced by analyzing the spectrum of the transmitted light in the near infrared. This spectrum is modulated as a function of temperature as the optical absorption edge shifts toward longer wavelengths with increasing temperature. This spectrum was analyzed using the same microoptic multiplexer that is used in the digital rotary position encoder. The temperature sensor is accurate to +/- 2 deg C in the range 20 deg C to 160 deg C.

Additional information may be found in reference 2.

IV. Multiplexed Systems

Since many sensors are needed on an aircraft we pursued a number of ways of using common signal processing optics and electronics to analyze the output from several sensors. We have tried techniques of using time-division multiplexing to process the output from several spectrum-modulating sensors using a single microoptic spectrometer. We used two fiberoptic silicon temperature sensing elements and used a single microoptic multiplexer, photodiode array, and common electronics to analyze the light modulated by the two sensors. Initially fiberoptic couplers and an electromechanical switch were used to route the signals. Operation between 20 deg C and 160 deg C was found satisfactory.

Additional information may be found in references 5, 20, and 27.

V. Loss-Compensated Intensity Sensors and Pulsed Systems

The disadvantages of an intensity-type sensor may be removed by using a four-beam technique to measure transmissivity variations in the sensor. This referencing method provides a measurement that is largely independent of the transmission properties of the optical fiber link including its connectors. We have tried this in a system where two LEDs are turned on and off in an alternating fashion, at essentially dc. We tested an intensity-modulating fiberoptic pressure sensor using a Ronchi ruling to provide the intensity modulation as the pressure is changed. This sensor was tested under static conditions to 750 p.s.i. Stability was excellent at constant temperature. A rather large temperature dependence was observed, easily explained in terms of the physical construction of the sensor. Redesign of the sensor would alleviate this problem.

We also constructed several systems in which 10ns pulses generated by a laser diode were used and multiplexed over fewer fibers. We started work on such systems with the intent of ultimately using such sensors in time-division multiplexed systems. Initially a "gray wedge" was used as a dummy sensor. It was found that intensity changes in the connecting links were compensated for to within +/- 1.5%. Some instabilities were caused by mode propagation problems in the discrete fiberoptic couplers. Integrated-optics couplers should be used for future work.

Additional information may be found in references 1, 6, 8, and 24.

VI. Optically Powered Sensors

Advantages of all-optical sensors have been described in the literature. These include immunity to electromagnetic and radio frequency interference (EMI/RFI), avoidance of ground loop problems, and reduction of the destructive effects of lightning. Several disadvantages also accrue. These sensor are very complex. Also, typically every type of sensor is based on a different physical principle; the development is a slow process; each sensor has to be individually proved.

During 1994 to the end of this grant we experimented with electrical sensors using optical transmission links for power delivery and for sensor data retrieval. The advantage of such fiber-optically-powered electrical sensors is that standard, off-the-shelf, proven sensors may be used and that relatively simple sensors may be constructed. Such optically powered sensors lead to increased safety and increased precision. Because standard electrical sensors may be used in some situations, this reduces overall cost and leads to increased reliability and efficiency while, at the same time, achieving most of the advantages of fully optical sensors.

This has become more feasible as higher-powered, relatively cheap light sources have become available which may be efficiently coupled into standard optical fibers. Furthermore, solar cells with up to 50% conversion efficiency in the infrared are now available. During the last year of this grant we experimented with various combinations of available optical power sources, electrical power converters, power conditioning circuits, and sensors. The results look promising. Since this information has not been published elsewhere, the details are reported here.

Additional details may also be found in references 9, 10, and 11.

A. Optically-powered electrical sensors

Experiments were carried out to test the feasibility of optically powered sensors for aircraft propulsion applications. Figure 1 illustrates the test setup. An optical power source in the avionics bay of the aircraft provides the sensor power. It is selected for maximum output power and long life. This light is transmitted to the sensor system, which is electrically shielded, by means of an optical fiber. A photovoltaic power

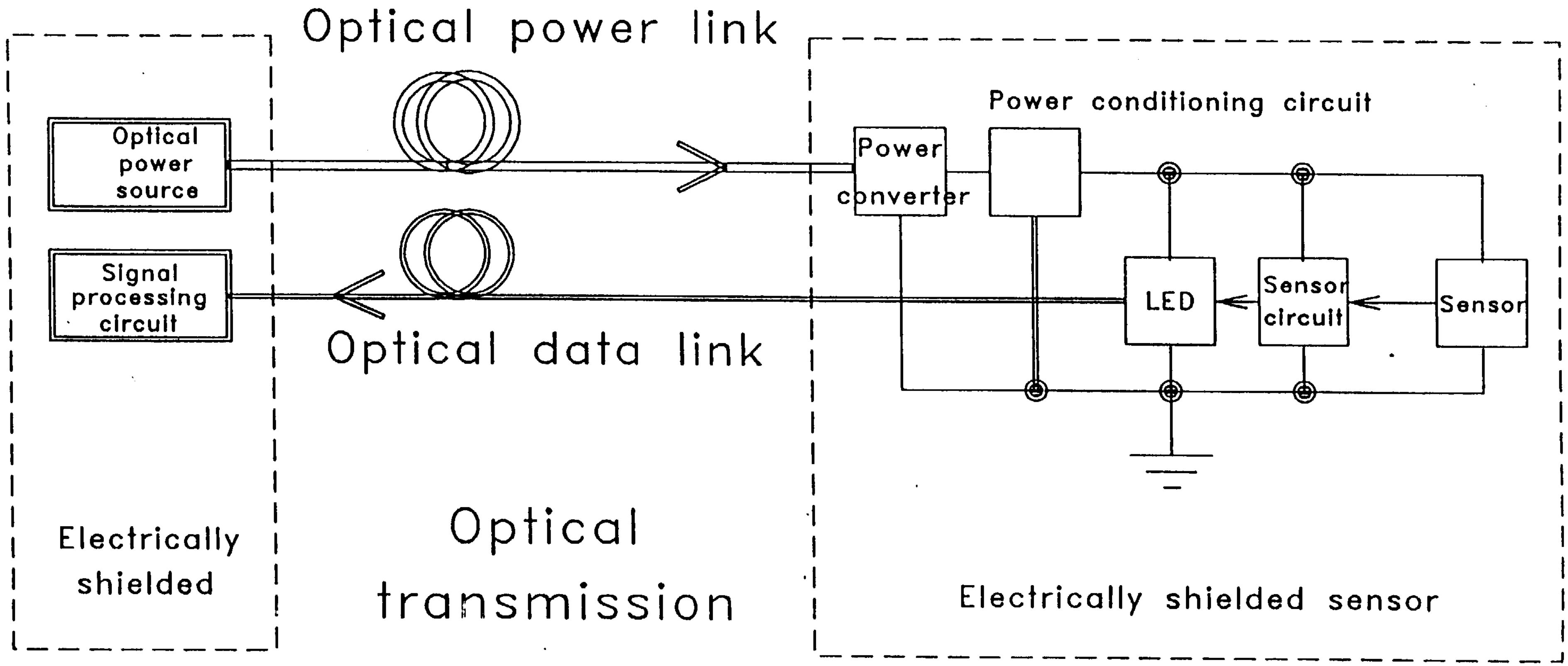

Fig. 1. Optically powered sensor.

converter (solar cell) converts the light into electrical power. Since this conversion occurs at low voltage, a step-up power conditioning circuit may have to be used. To transmit the sensor output (proportional to the measurand) back to the avionics bay, a pulsed infrared LED is employed. The typical transmission format might be a pulse train with frequency proportional to the measurand. Commercial chips are available to transform voltage to frequency (at the sensor) and frequency to voltage (at the receiver) with high precision. Since we are observing the direct output of the LED, extremely little power is required, i.e., most of the electrical power will be available to power the sensor support circuitry. It was found that as little as 0.1 mW average electrical power is sufficient to drive the signal transmitting LED in pulsed mode. A number of experiments were carried out to determine the amount of optical power necessary to power various electronic circuits and to determine the conversion efficiency of the solar cells and power conditioning circuits.

B. Solar cells

Since solar cells are used as photovoltaic power converters, it may be worthwhile to review the behavior of a solar cell. Usually we will want to connect several cells in series to generate a sufficiently high voltage, although there are a few circuits available which will operate reliably from power supply voltages as low as 1.1 Volts. How do solar cells behave under various load conditions? What happens when they are placed in series? We answered these questions by using the PSPICE® simulation program and by making measurements on selected photocells. The simulations agreed very well with measurements performed on actual photocells. Simulation made it easier to evaluate the effect of placing cells in series and the effect of asymmetric illumination of these cells. The current versus voltage behavior under load for a single Si cell is shown in Fig. 2. For a given incident optical power, a Si (or GaAs) solar cell will produce maximum output voltage of about 0.6 Volts (2 Volts) when it is open-circuited and a maximum output current, when it is short-circuited. It reaches the open-circuit output voltage if sufficient light falls on the cell. The short-circuit current will increase with increasing light input. Thus, for a given amount of incident light, maximum power is generated at a voltage below the open circuit voltage and with a current lower than the short-circuit current. Figure 3 shows power versus load resistance. It may be seen that at a particular load resistance the power delivered by the photocell is maximized. Theoretically, as two cells are placed in series to increase the terminal voltage, this should not change the conversion efficiency. However the peak power occurs at higher voltage, lower current,

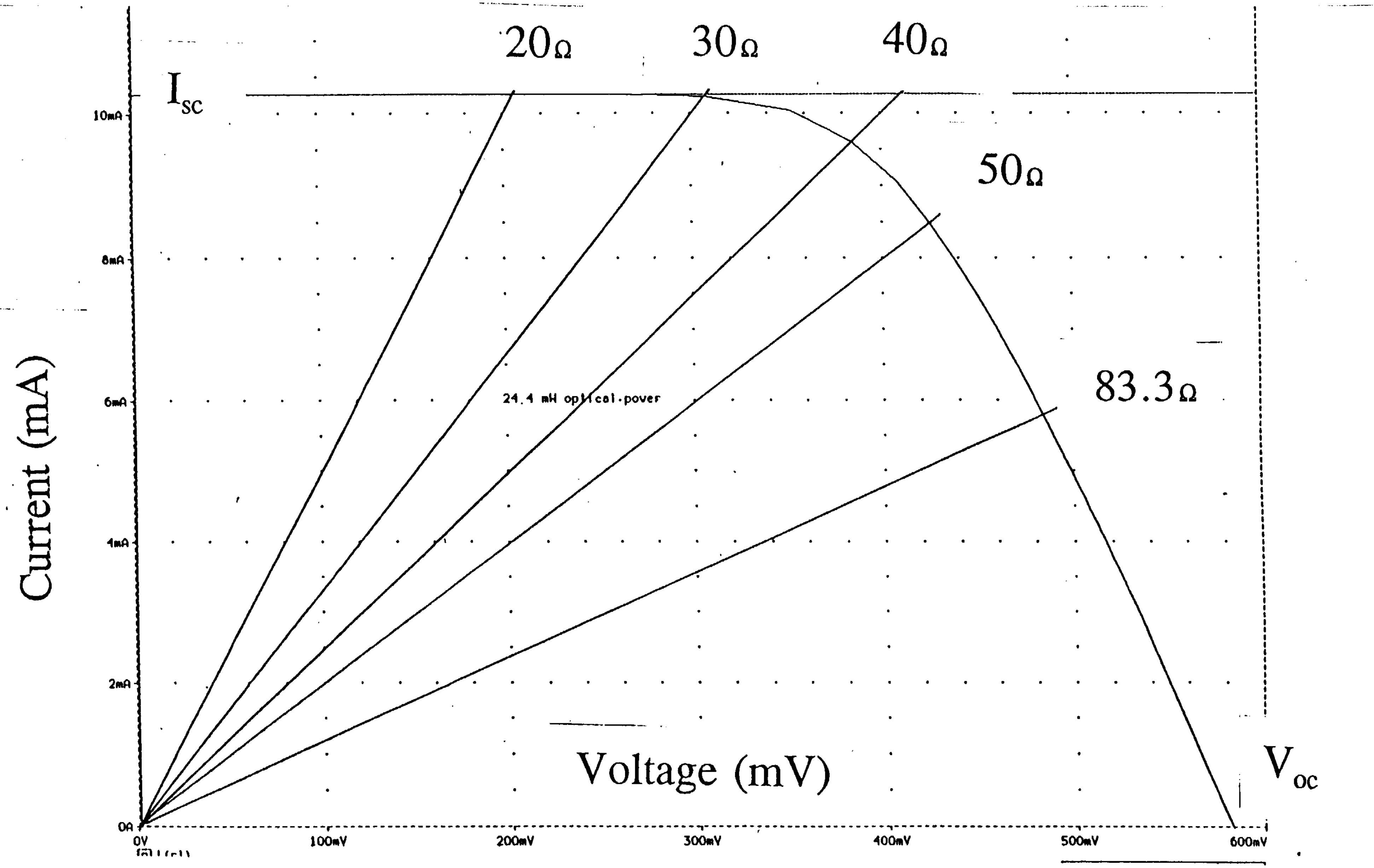

Fig. 2. Current-voltage characteristic of a Si solar cell.

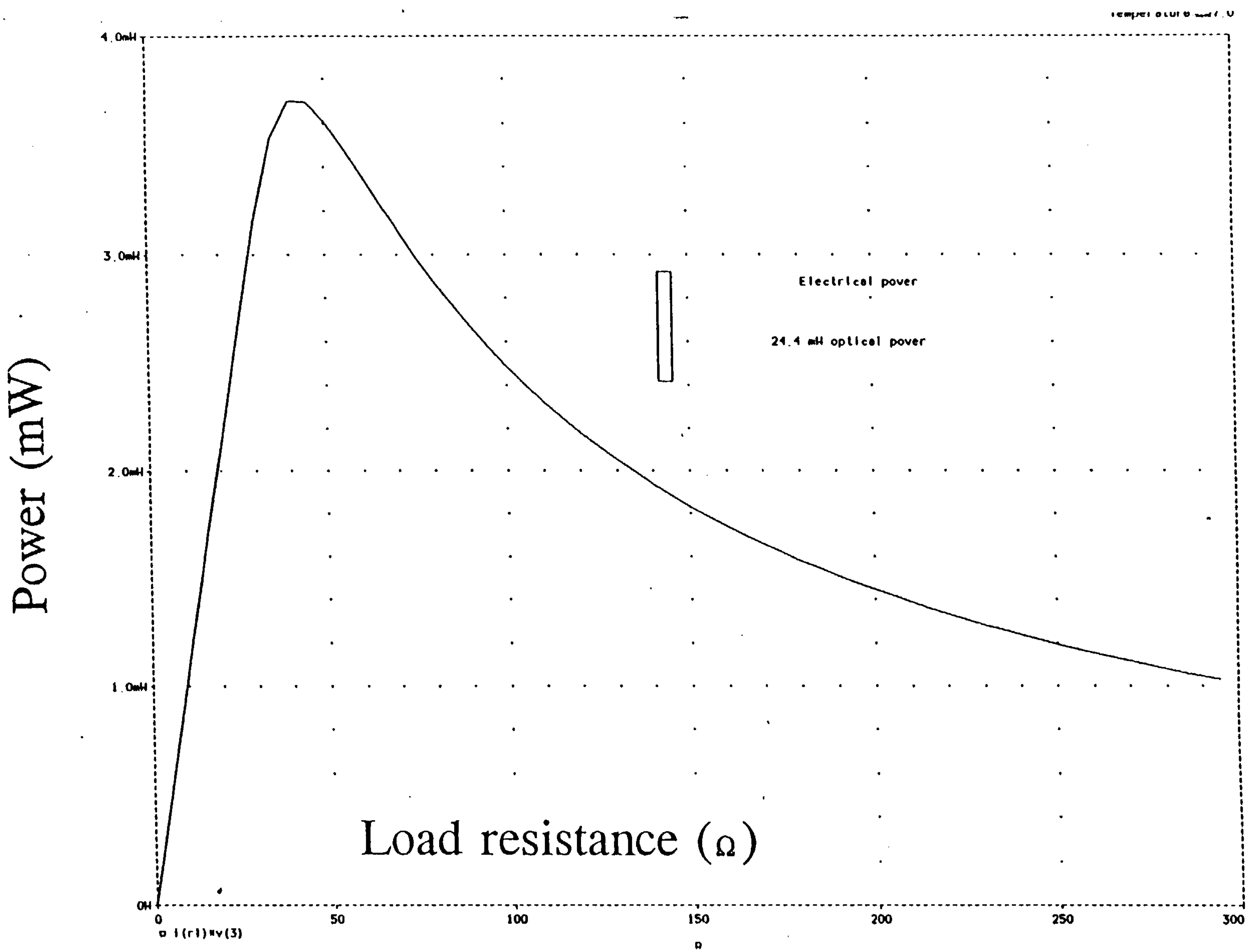

Fig. 3. Electrical power vs. load resistance for a Si solar cell.

and higher load resistance. We are assuming the incident amount of light has not been changed. Note however that it is extremely important, that each cell receive the same amount of light. In practice we observed lowered efficiency as cells were connected in series. For a particular cell, the maximum conversion efficiency occurred at 40 ohm for a single cell, at 170 ohms for two, and at 720 ohms for four cells in series, if each cell sees exactly 100%, 50%, and 25%, respectively, of the total incident light. If there is a mismatch between the four cells, the effect is as follows:

Observed electrical output	%-mismatch
4.26 mW	0% (matched)
4.10 mW	10%
3.77 mW	20%
3.00 mW	30%

It should also be noted that as the illumination decreases, the peak of the power versus load resistance curve moves in the direction of increased resistance with the maximum conversion efficiency being unchanged (see Fig. 4).

C. Test of various combinations of light sources, transmission fibers, and solar cells

1) Initially, a 24 mW HeNe laser was used as light source. The light was injected into a 100/140 μm fiber using a X20 microscope objective lens. We obtained an output power of 15 mW from the end of the fiber. Various commercial solar cells were tested with this laser, both as single cells and in stacks to increase the output voltage. Best results were obtained with a Radio-Shack Si solar cell #276-124A. With a single cell we obtained a conversion efficiency of 18%. When four such cells were connected in series, maximum efficiency decreased to 11%.

2) A 230 mW laser diode (820nm) manufactured by Photonic Power Systems, Inc., connected to a 100/140 micron optical fiber with a numerical aperture of 0.3 produced 90 mW of electrical power. This company also sells GaAs photocells with 2 V output (2 cells in series) and 6 V output (six cells in series) in a small package and with connector. Some of these cells reach 50% conversion efficiency.

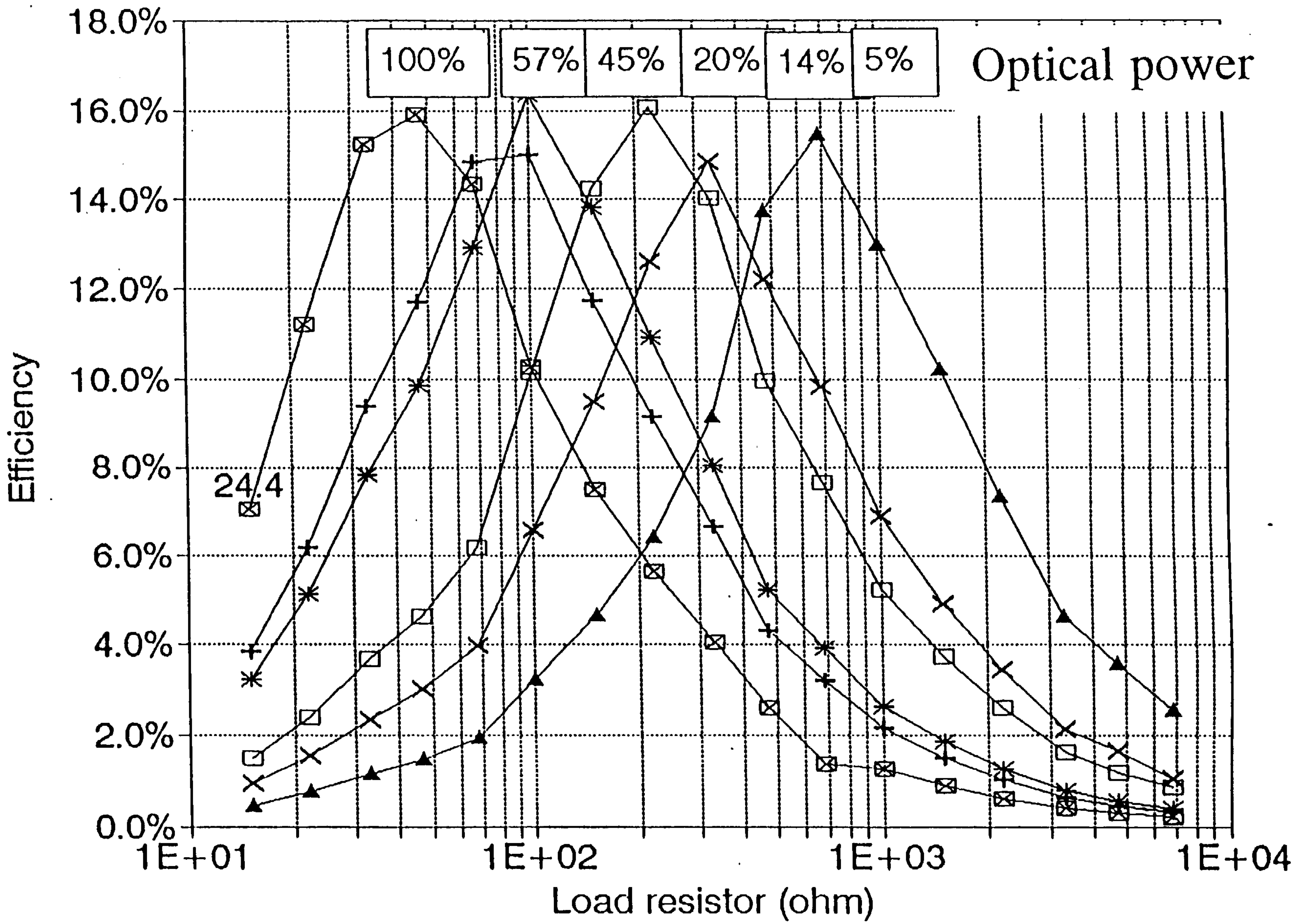

Fig. 4. Conversion efficiency vs. load resistance and incident optical power.

3) ABB HAFO Inc. LEDs were also tried as power sources. The ABB HAFO 1A313 LED connected to a 400/430 micron fiber, sold by RIFOCS Corp., produced 6.8 mW at the output at a wavelength of 860 nm. We paired this with a PHOTONICS GaAs photocell to obtain 29% conversion efficiency. Evidently the PHOTONIC Power Systems cell was not well matched geometrically to the large diameter RIFOCS fiber cable. This LED has an expected lifetime of about 50 years when operating at 125 °C. The following table summarizes conversion efficiency data.

Solar Cell	No. of cells in series	Max. efficiency at 633 nm	Max. efficiency at 820 nm
RCA C-30808	1	16%	15%
PANASONIC SunceramII	1	10%	
Radio Shack #276-124A	1	16%	12%
	4	9%	5%
Photonic PS 2ST	2	55%	
Photonic PS 6ST	6	43%	

It is clear that the power converters sold by Photonic Power Systems, Inc., clearly should be used in aircraft applications for reliability, efficiency, and reduced need for heat removal. This company also sells complete optically powered temperature sensors.

Of particular interest for our applications is the combination of the ABB HAFO 1A313 (7 mW) LED combined with the 2ST power converter, yielding about 3.5 mW of usable electrical power. This may be sufficient for some applications!

D. Power conditioning circuits

Preliminary experiments were carried out to determine overall efficiency of power conversion between light source, solar cell, and power conditioning circuit. It was of particular interest to learn about the interaction between the solar cell with its particular voltage-current characteristic and the power conditioning circuit which basically is a switching converter. We examined the MAXIM Integrated Products 3.3V/5V step-up dc-dc converter, MAX858. Initial experiments were carried out by using a 210 mW laser diode as light source with the Photonic PS 2ST power converter and the MAXIM MAX858 dc-dc converter set for 5V output. We obtained an electrical conversion efficiency of 80% with a 500 ohm load and 60% efficiency at 300 ohms, corresponding to peak of the output power curve of the solar cell. This leads to overall efficiencies of 44% and 33%, respectively. Obviously, a bit of work has to be done to match the maximum power points of solar cell, dc-dc converter, and load.

When the dc-dc converter was set for 3.3 V output, we obtained an electrical efficiency of 70% into a 110 ohm load at the peak of the power output curve of the solar cell.

E. Ultra-low power experiments

We carried out preliminary experiments to determine the lower limit power requirements to build an optically powered sensor, to see whether it might be possible to use the 7 mW LED mentioned above as power source. One circuit of interest is the LM3909 which has been around for many years. It is an LED flasher circuit. We used this circuit to drive an I.R. LED for transmission of the data pulses. No additional circuitry is involved. This IC will work from a 1.1 V power supply. In other words, at the sensor end the only items required are the solar cell, the IC, a capacitor, and the LED. This circuit could be used for a capacitive pressure sensor, for example. Or it could be used in connection with a resistive sensor. Of course, this cheap IC is not linear and the output frequency is power supply voltage dependent and temperature dependent. We observed that it required a power of 0.2 to 3 mW including drive for the LED while flashing at 1 kHz. In other words, this device can be powered by the ABB HAFO 1A313. We have also carried out preliminary experiments with the TLC555 low power timer chip. This and many similar chips could be used for these experiments.

F. Future plans

Should NASA be interested in pursuing this further, I would propose to set up a complete optically powered sensor using a standard, off-the-shelf, electrical sensor, and voltage-to-frequency as well as frequency-to-voltage converters. It would also be of great interest to investigate problems with multiplexing sensors. In the power delivery, only excess losses in the optical couplers would have to be considered. In the data return link a substantial light would be lost in the demultiplexing coupler. However, once again this is tolerable, since the receiving photocell is exposed directly to the light emanating from the data transmitting LEDs by way of the transmission links and coupler, i.e., this light is not attenuated by an intervening sensor.

Additional information may be found in references 9, 10, 11.

VII. John Carroll University M.S. Theses that report research under this grant:

1. Richard N. Poorman, "Loss-Compensated Intensity Modulating Fiber-Optic Pressure Sensor," May, 1987.

2. Promit Das, "Fiberoptic Gallium-Arsenide Temperature Sensor," May, 1988.

3. Vilnis E. Kubulins, "A Fabry-Perot Type Fiber Optic Temperature Sensor," May, 1989.

4. Dipak Patel, "A Laser Diode Velocimeter and Rangefinder," May, 1989.

5. Margaret L. Eastman, "Multiplexing Fabry-Perot Type Fiber Optic Temperature Sensors," April, 1990.

6. Thomas L. Laurence, Jr., "Intensity Sensor Loss-Compensation Achieved by Temporally Separated Reference And Sensor Pulses," May, 1990.

7. Yiting Mi, "A Comparative Study of Fabry-Perot Fiber-Optic Temperature Sensors," May, 1993.

8. Frank R. Piunno, Jr., "Fiber-Optic Pressure Sensor Using Pulsed Light With Loss-Compensation," July, 1995.

9. Aaron J. Becker, "An Optically Powered Electrical Temperature Smart Sensor With Optical Data Communication," July, 1995.

10. Angela R. Harrivel, "An Optically Powered and Interrogated Multi-sensor Employing an Electrically Programmable Analog Circuit," April, 1996.

11. Joseph Flatico, "A Very Low Power Optically Powered Sensor System," October, 1996.

VIII. Publications and Symposium Proceedings that resulted from the collaboration between John Carroll University and the NASA Lewis Research Center on this research. Items marked with an asterisk report research supported by this grant:

12. Beheim, G. and Fritsch, K., "Remote Displacement Measurements Using A Laser Diode," Electron. Lett. 21, 93-94 (Jan. 1985).

* 13. Fritsch, K. and Beheim, G., "Wavelength-Division Multiplexed Digital Optical Position Transducer," Opt. Lett. 11 (Jan. 1986), 1-3.

* 14. Beheim, G. and Fritsch, K., "Range Finding Using Frequency-Modulated Laser Diode," Appl. Opt. 25 (May 1986), 1439-1442.

* 15. Fritsch, K., "Linear Capacitive Displacement Sensor with Frequency Readout," Rev. Sci. Instrum. 58, 861-863 (May, 1987).

* 16. Beheim, G., Fritsch, K. and Poorman, R.N., "Fiber-linked Interferometric Pressure Sensor," Rev. Sci. Instrum. 58, 1655-1659 (Sept. 1987).

* 17. Fritsch, K., "Capacitive Displacement Sensor with Frequency Readout," NASA Tech Briefs 13, (Jan. 1989), 21.

* 18. Beheim, G., Fritsch, K., "Spectrum-Modulating Fiber-Optic Sensors," NASA Tech Briefs 13, 4 (April 1989), 24.

19. Beheim, G., Fritsch, K. and Azar, T.M., "A Sputtered Thin Film Fiber-Optic Temperature Sensor," Sensors 7, 37-43 (1990).

20. Beheim, G., Fritsch, K., Flatico, J.M., Azar, M.T., "Silicon-Etalon Fiber-Optic Temperature Sensor," NASA Tech Briefs, 54 (1993).

* 21. Beheim, G. and Fritsch, K., "Spectrum-Modulating Fiber-Optic Sensors for Aircraft Control Systems." 1st International Military and Government Fiber-Optic and Communications Exposition, Washington, D.C., March 18-19, 1987. Also available as NASA Technical Memorandum 88968.

22. Beheim, G., Fritsch, K. and Anthan, D.J., "Fiber-Optic Temperature Sensor Using a Spectrum-Modulating Semi-conductor Etalon." O-E/Fibers '87. Symposium on Fiber Optics and Integrated Optoelectronics, San Diego, Calif., 16-21 August, 1987. Published in SPIE Proceedings.

* 23. Fritsch, K. and Beheim, G., "Fiber-linked Optical Sensors for Aircraft Control Systems." 30th Midwest Symposium on Circuits and Systems, Syracuse Univ., Aug. 16-18, 1987.
Proceedings, eds. Glasford and Jabbour, North-Holland, 1988, pp. 808-811.

24. Beheim, G.M., Anthan, D.J., Rys, J.R., Fritsch, K. and Ruppe, W.A., "Modulated-Splitting-Ratio Fiber-Optic Temperature Sensor," SPIE's International Symposium on Fiber Optics, Optoelectronics, and Laser Applications, Boston, Sept. 6-9, 1988. SPIE Proceedings, Vol. 985, p.82- (1988). Also available as NASA Technical Memorandum 101332.

25. Beheim, G., Fritsch, K., Flatico, J.M. and Azar, M.T., "Silicon-Etalon Fiber-Optic Temperature Sensor." SPIE <u>1169</u> (1990), 504-511.

* 26. Fritsch, K., Beheim, G. and Sotomayor, J., "Digital Angular Position Sensor Using Wavelength Division Multiplexing," SPIE Proceedings, Vol. 1169 (Fiber Optic and Laser Sensors VII), p. 453-460 (1990).

* 27. Beheim, G., Krasowski, M.J., Sotomayor, J.L., Fritsch, K., Flatico, J.M., Bathurst, R.L., Eustace, J.G. and Anthan, D.J., "Wavelength-Multiplexed Fiber-Optic Position Encoder for Aircraft Control Systems," SPIE Symposium, San Jose, Sept. 18, 1990. Published in Proceedings of SPIE <u>1369</u> (1990), p. 50-56.