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OPTICAL SENSORS FOR AERONAUTICS AND SPACE

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SUMMARY

A review of some NASA and DOD programs to develop optical sensors with fiberoptics for instrumentation and control is presented. Fiberoptic systems offer some distinct advantages. Noise immunity is one important asset. Fiberoptic systems do not conduct electricity and therefore can be used in and near areas that contain explosive or flammable materials. One objective of these programs is to produce more reliable sensors and to improve the safety and operating economy of future aircraft and space vehicles.

INTRODUCTION

This article reviews some NASA and DOD programs to develop sensors for use in fiberoptic instrumentation and control systems. Fiberoptic systems offer some attractive advantages for aerospace instrumentation and control. Fiberoptic cables do not conduct electricity and therefore can be used in and near areas that contain explosive or flammable materials, such as fuel tanks. Fiberoptic systems are insensitive to EMI and RFI, which improves the safety and operational capability of aerospace vehicles using fiberoptic control systems.

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Largely stimulated by communications industry research, optical signal transmission has matured to the point where operational fiberoptic data transmission systems are relatively commonplace. To exploit this technology for aerospace applications, optical sensors must be developed to measure pressures, temperatures, and positions (rotary and linear). Ideally these sensors should interface directly with optical fibers.

The basic concept of an optical sensor system is shown in figure 1. The sensor is located at the point of measurement. Optical cables transmit an optical signal to the sensor. The sensor modulates the optical signal and sends it back to an optical detector over an optical cable. The optical detector converts the optical signal into an electrical signal and this signal is accepted as input data by the electronic computer. For many aerospace applications, the optical sensor and fiberoptic cables must survive extremes of temperature and vibration. The light source and light detectors are located in a controlled environment suitable for electronic hardware, such as a computer.

In the remainder of this article, several optical sensors based on this concept will be discussed.

NASA PROGRAMS

NASA Johnson Space Center

NASA Johnson Space Center became interested in optical sensors for instrumentation on manned space flight vehicles because a potential explosive hazard was identified in liquid hydrogen and oxygen tanks. The instrumentation system which measures the liquid hydrogen and oxygen levels, temperature, and pressure, requires an electrical penetration of the tanks. This

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electrical penetration of the tanks carries a risk of a spark causing a catastrophic explosion.

The passive, optical sensor eliminates the electrical penetration into the explosive environment. In late 1977 a contract was awarded to TRW, Inc., Defense and Space Systems Group, Redondo Beach, CA to develop fiber-optics and optical instrumentation technology suitable for use with the space shuttle external tanks. Under this contract optical sensors were developed to measure liquid levels, pressure, and temperature of the liquid hydrogen and liquid oxygen. The sensors were designed for use in a cryogenic environment. The temperature range was from -276° to 100° C. The pressure range was between 14.7 to 300 psia. The fiber optic path-length was 61 meters.

The concept chosen for the liquid level sensor is the unclad fiber method. Figure 2 shows a sketch of a section of the fiberoptic cable with some cladding removed. The performance of this sensor is based upon total internal reflection. With no liquid surrounding the unclad fiber, the light is reflected internally, and the incident light flux is equal to the return flux. As liquid covers the unclad fiber, the index of refraction outside the fiber increases and most of the incident light enters the liquid. The flux removed from the incident beam indicates the presence of liquid. The problem of a thin liquid film remaining on the unclad fiber as the level lowers is not severe. Although the thin film removes light from the fiber at the liquid/fiber interface, the liquid/air interface totally reflects the light which then is reflected back into the fiber.

The concept selected for the temperature sensor depends on the absorption band edge in a semi-conductor. If the photon energy of light incident on a semiconductor is greater than the band-gap energy the photon is absorbed. The corresponding optical wave length of the band-gap energy is known as the fundamental absorption edge. The absorption edge is temperature dependent. As the temperature increases the wave length of the absorption edge increases. Figure 3 shows how the band-edge wave length shifts as a function of temperature for indium phosphorous (InP) and for gallium arsenide (GaAs). The temperature sensor design is shown schematically in figure 4. The sensor is an InP crystal and the laser diode is GaAs. The laser diode is a spectral source whose center wave length shifts to longer wave lengths as it is heated. The temperature of the laser diode versus the center wavelength of the output is a repeatable curve. Figure 5 shows a plot of transmission versus wave length for GaAs for a number of different temperatures. A similar plot can be made for InP. The temperature of the laser diode is cycled over a suitable, controlled temperature range. Its output is transmitted to the sensor crystal. When the center wave length of the laser diode is below the band-edge fundamental wave length, the crystal absorbs the incident light and the detector sees a small signal. When the laser diode center wave length is equal to the band-edge wave length the crystal transmits the incident light, resulting in a large signal at the detector. When transmission occurs through the sensor crystal, the wave length of calibration light transmitted by the crystal is known and from a calibration curve of band-edge wave length versus temperature for the crystal, the temperature of the crystal is determined and hence the temperature of the crystal's environment.

The concept selected for use as a pressure sensor depends on reflection from a diaphragm. Figure 6 shows the sensor head. This concept uses a deformable diaphragm and a bifurcated fiber cable. Light is transmitted through one leg of the cable and is incident on the Invar diaphragm. The diaphragm reflects the incident light into the field of view of the adjacent cable which returns a portion of the reflected light to a photodiode for detection.

At atmospheric pressure the distance between the cable and diaphragm is adjusted so the incident light beam gives a maximum illumination of the return fibers, and a maximum output of the detector. As pressure increases the diaphragm deforms towards the optical cable and reduces the amount of light reflected into the return fibers. Thus the amount of reflected light is a measure of the deflection of the diaphragm which is proportional to the applied pressure.

NASA Lewis Research Center

One of the responsibilities of NASA Lewis Research Center is the development of advanced control concepts for aeronautical propulsion systems. Digital electronics is emerging as a promising technology for engine control applications because of the enormous computational power of digital computers. This computational power can be used to implement sophisticated control algorithms for improving engine performance parameters such as fuel efficiency. However, electronic control systems generally suffer from low reliability.

In order to improve overall engine control system reliability new sensors must be developed. NASA Lewis Research Center embarked on a program to develop new, more reliable, sensors that are passive, requiring no electrical power. The use of optics and fiberoptic waveguides with passive sensors is attractive because of the noise immunity of optical systems and the potential improvement in reliability. Four contractors were chosen to develop optical, passive sensors.

One of the first contracts was awarded to Spectronics Inc. of Richardson, Texas, to build an optical rotary postion encoder and an optical tachometer. Optical encoders and tachometers are available from many sources but with electronics located in the sensor.

Figure 7 is a picture of the rotary position encoder and the tachometer. The optical tachometer has nine transparent sections and nine opaque sections resulting in nine pulses/revolution. The rotary encoder consists of 9 bits that form a digital word in Gray code. 360 bit combinations are available such that the resolution of angular position is 1 degree. A fiber optic cable 3.65 m long is used to connect the light source/-detectors with the sensors. These two sensors were installed on an F100 engine during recent altitude tests run at Lewis. The rotary encoder measured compressor variable vane positions. The tachometer measured speed at a point on the power take-off pad. The engine ran for more than 100 hours. The sensors operated satisfactorily for the entire test program.

Studies have shown large performance penalties can arise when substantial clearances exist between the rotor blade tip and casing in compressors and turbines. Excess clearance in the turbine area allows a portion of the gas to flow over the blade tip and thus perform no useful work. Future engines will require some form of clearance control if peak engine efficiencies are to be maintained. Optical tip clearance sensors have been developed for use in test facilities. These devices use an optical triangulation scheme to measure clearances (fig. 8). A laser beam is directed through the lens and prism to the blade tip. Depending on the tip position at A or B, the reflected light is focused by the lens on the output fiber-optic tip at positions A' or B'. The fiber bundle is coherent and transmits the light spot to a photodiode array. The spot's linear position on the array corresponds to the blade tip clearance. The sensor, however, depends on a laser source and because of this, may require further development to operate as an engine mounted, flightworthy device.

Figure 9 shows one concept being developed under contract with General Electric, Evendale, Ohio, to build a sensor that doesn't require a laser source. The operation of the sensor is as follows. A light beam is directed across the gap tangent to the turbine case. As the blade intercepts part of the beam between A and B, the image between A' and B' is also partly blocked from light. The output fiber optic bundle is coherent and transmits light to the detector array. The blade clearance is determined by position of the boundary between light and dark on the detector array.

Two other contracts sponsored by NASA Lewis are for the development of optical temperature sensors. The temperature ranges that these sensors must measure, are from -73° to 648° C and from 282° to 1115° C. The optical cables connecting the sensor with the light source and detector will experience temperatures between -48° to 243° C.

United Technologies Research Center (East Hartford, Conn.) is under contract to NASA Lewis to study a concept using rare earth materials to measure temperature optically. Figure 10 is a sketch of what the temperature sensor might look like. In this scheme, glass, doped with a rare earth, europium, is drawn into a fiber. The fiber is coiled and placed inside a protective housing that is in the hot gas stream. Changes in transmission through the doped fiber are measured. This measurement has a direct correlation to the temperature of the doped fiber. Rare earth materials, like europium, have energy levels that are located relatively close to the ground state. These states are optically connected to higher excited states with energy differences corresponding to wave lengths in the visible region. The energy states of europium are shown in figure 11(a). The change in optical density through a europium doped fiber as a function of temperature is shown in figure 11(b). The absorption peaks correspond to energy transitions between the ground states and the higher excited states. As seen from the sketch shown in figure 11(b) transitions between $^7F_0$ -

$^5D_1$, states decrease absorption strength as temperature increases from 27° to 402° C while the $^7F_1$ - $^5D_1$, transition increases slightly and broadens. A transition peak, not present at the lower temperature, for the $^7F_2$ - $^5D_1$, transition appears at the elevated temperature.

A second concept to measure temperature optically is being developed under contract with Rockwell International (Anaheim, Calif.). The principle of operation is based on the optical filtering provided by a Fabry-Perot gap. The way in which the transmitted spectrum changes with the Fabry-Perot gap is shown in figure 12. As the gap increases, first, a single spectral band moves across the 4000 - 12 000 Å spectrum. With further gap increases the light bands move across the spectrum cyclically. Each time a band or group of bands move across the visible spectrum there are more bands in the moving pattern. Figure 13 shows how a temperature sensitive gap might be constructed. In the figure "g" represents the Fabry-Perot gap and "s" represents the temperature-sensitive spacer. Light is brought to the gap and directed away by fiber optic cables. As the temperature of the spacer increases, the gap increases thereby increasing the number of transmitted optical bands as shown in figure 12. Figure 14 shows the variation of spectra from the Fabry-Perot sensor as temperature changes. The temperature range is very narrow. This demonstration was for proof of concept. Further work will be required to accommodate the temperature ranges to be measured in airbreathing engines. Figure 15 shows the assembled probe with optical cables.

OTHER PROGRAMS

The following discussion will provide some insight into the long term goals of other government agencies in the area of optics and its role in engine and flight controls.

Additional research is required to produce a passive, optical pressure sensor, both absolute and delta P sensors. These pressure sensors will be subjected to the same external environmental conditions (-54° to 250° C) specified for the temperature sensor. The pressure sensors will have to include provisions to compensate for temperature effects.

Naval Avionics Center

The optical sensor development program conducted at the Naval Avionics Center (NAC), Indianapolis, Indiana, is directed towards the needs of digital status monitoring devices for Navy aircraft. The program is funded and directed by the Naval Air Systems Command (NASC), Washington, D.C. The program was initiated in 1977 with the award of concept design contracts to Boeing Aerospace, Seattle, Washington, and to the United Technologies Research Center (UTRC), Hartford, Connecticut. These were parallel concept development efforts directed toard the development of a family of optical sensor types which provide sensor information in digitally encoded form.

The program at Boeing and UTRC emphasized sensor requirements of flight critical systems for engine control. Such sensor parameters as pressure, temperature and linear displacement were investigated as being important to these control systems. Other parameters investigated included fuel flow rate and fuel level.

Currently a contract for an optical linear displacement transducer is in negotiation. This sensor will be utilized in a Navy experimental program for the development and test of a digital flight control system. The optical linear displacement transducer will be used in two places in the experimental flight control system. In one application a transducer with 8.75 cm stroke will be utilized to sense the position of the aircraft rudder, and provide this information as feedback to the digital flight control computer. A similar transducer will utilize a 2.54 cm stroke and be mounted directly to the rudder foot pedal control. Development of this transducer system will require construction practice and pre-flight testing suitable for subsequent use in the flight test program. Flight test will be performed on a North American Rockwell T2C airplane.

In parallel with this development activity NAC has begun a program to investigate the application of fiber optics technology and electro-optical techniques to a total digital flight control system. This includes optical control of actuator as well as the use of fiber optics coupled optical sensors (temperature, pressure, displacement, etc.). It is expected that this program will result in well defined requirements for such sensors to be utilized in future development activity.

Army Applied Technology Laboratory

The Applied Technology Laboratory (Army) has as its objective the development of advanced flight control systems to provide improved mission performance capability, reliability, and maintainability along with battlefield compatibility. A pure digital flight control system will provide the handling qualities and mission performance improvements with hardware that is lighter, simpler, and consumes less power than current systems. The optical sensors and fiberoptic signal paths will provide complete immunity of that part of the system from all electrical interferences, which is extremely important for digital flight control systems.

During FY79, the Army cofunded the Navy program to develop an electrically passive optical position transducer which will be applied to measure rudder pedal input and rudder position on a T2C trainer aircraft. This will provide side-by-side in-flight performance comparisons with LVDT's which will be in parallel with the optical transducers.

The Army FY80-81 fiberoptic efforts will be oriented toward developing electrically passive flight control system transducers for linear and rotary motion and differential pressure. Other efforts are analysis of control media mechanization, optical control system architecture and development of optically controlled actuators. A total optical control system feasibility flight demonstration will be initiated in late FY81 using the earlier technology programs as a basis.

Long term research is also being done in the area of optical computers and optical computing components to determine their place in the future of all digital control systems that use optical sensors and optically activated actuators.

CONCLUDING REMARKS

This paper has summarized the current work sponsored by the Government to develop and test new concepts for sensors and fiberoptic systems. One objective is to produce more reliable sensors and to improve the safety and operating economy of future aircraft and space vehicles. It is hoped that this information will stimulate further interest and research in the field of optical sensing and control concepts, and make potential users aware of the benefits and opportunities available in this new field.

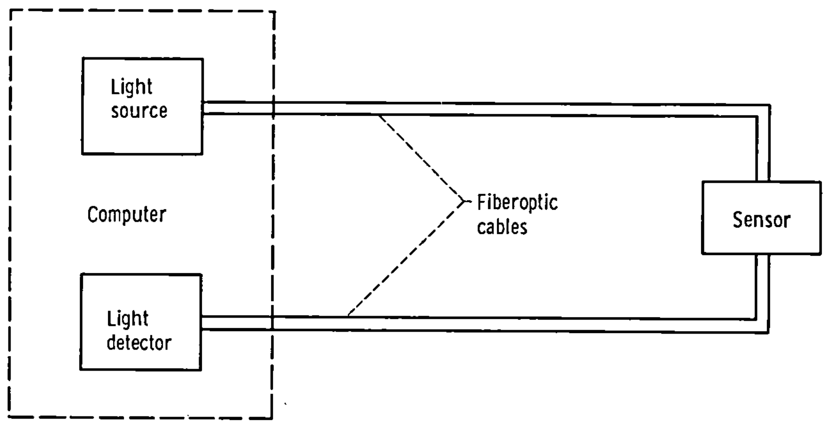


Figure 1. - Passive optical sensor system.

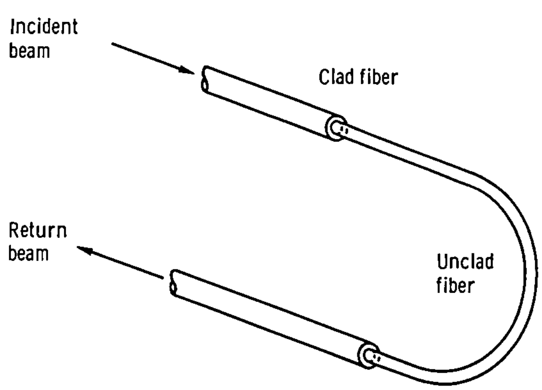


Figure 2. - Unclad fiber level detector.

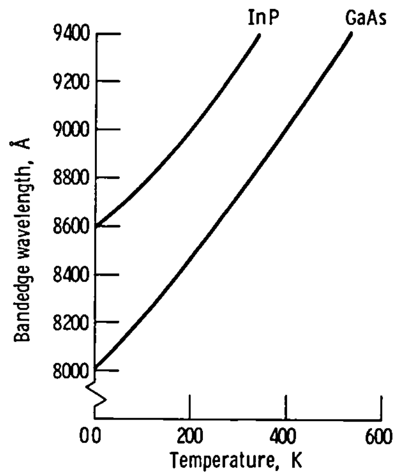


Figure 3. - Temperature dependence of bandedge location for indium phosphorus (InP) and gallium arsenide (GaAs).

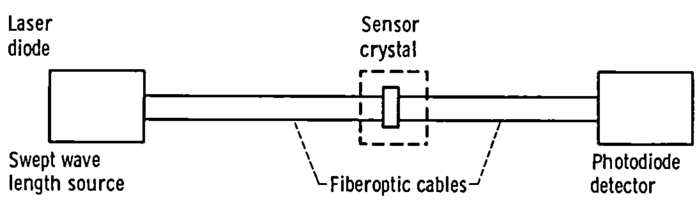


Figure 4. - Semiconductor bandedge shift temperature sensor.

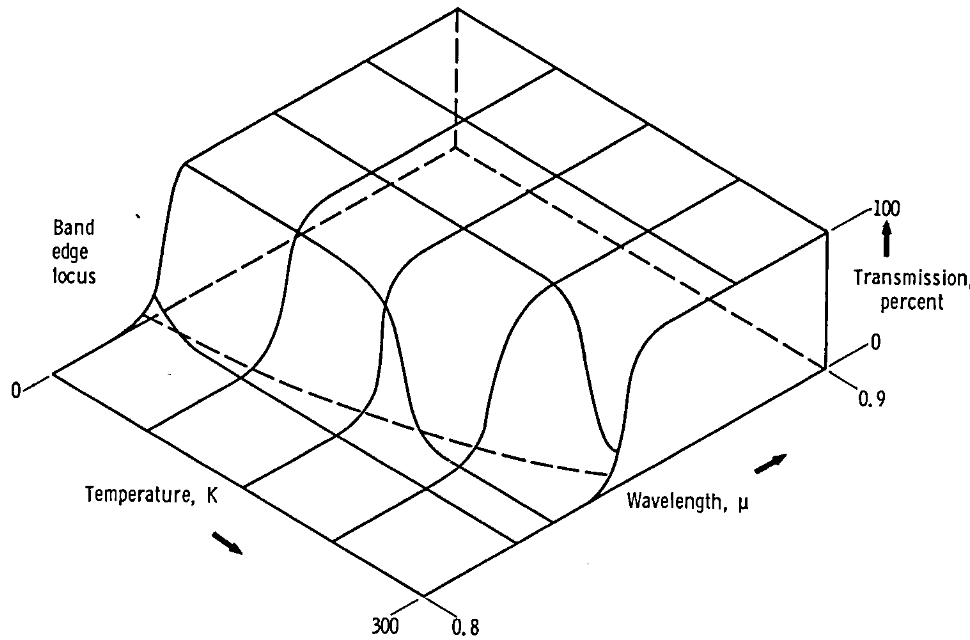


Figure 5. - Qualitative sketch of temperature, wavelength transmission of GaAs.

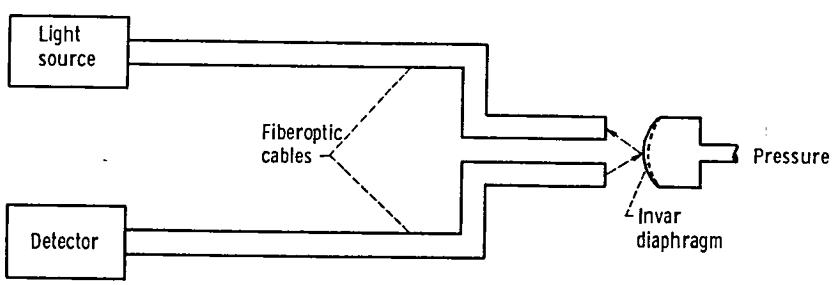


Figure 6. - Reflection type pressure sensor.

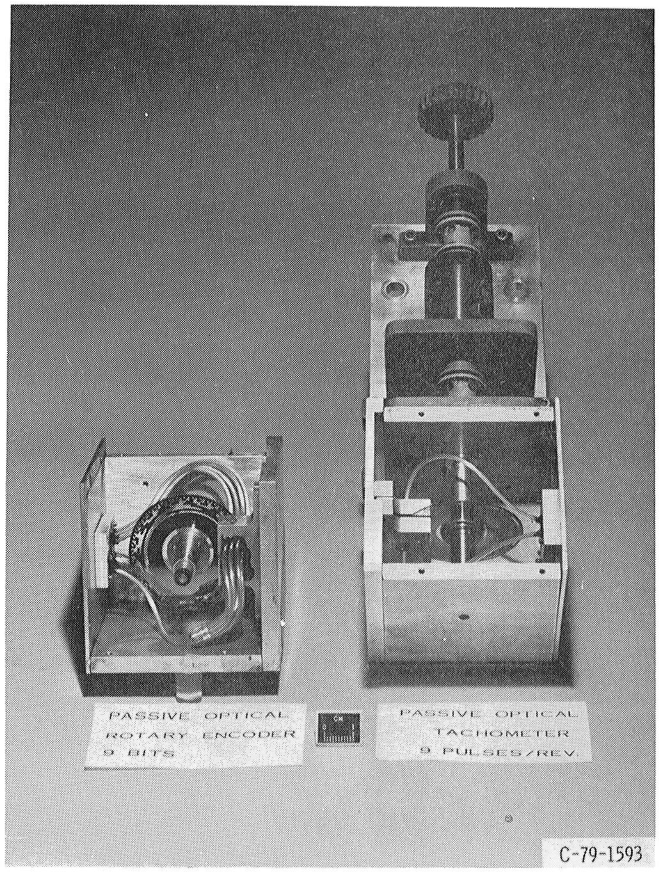


Figure 7. - Optical rotary encoder and optical tachometer.

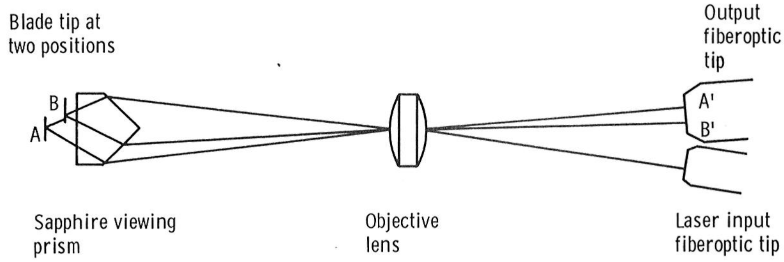


Figure 8. - Trangulation scheme for measuring tip clearance.

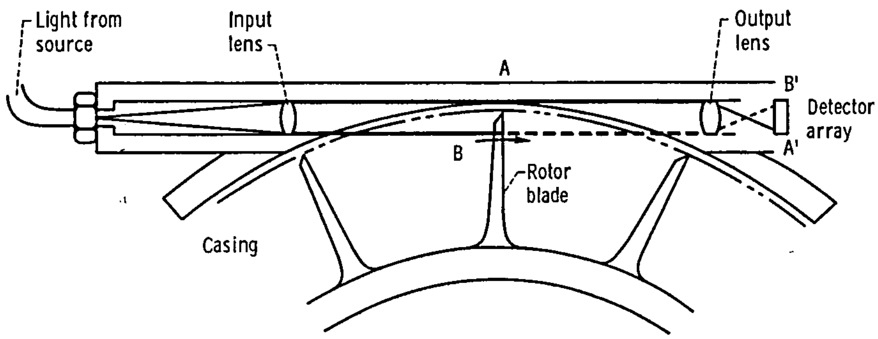


Figure 9. - Light interruption scheme for measuring tip clearance.

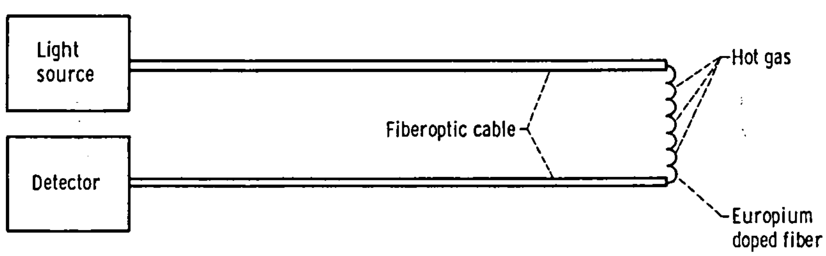
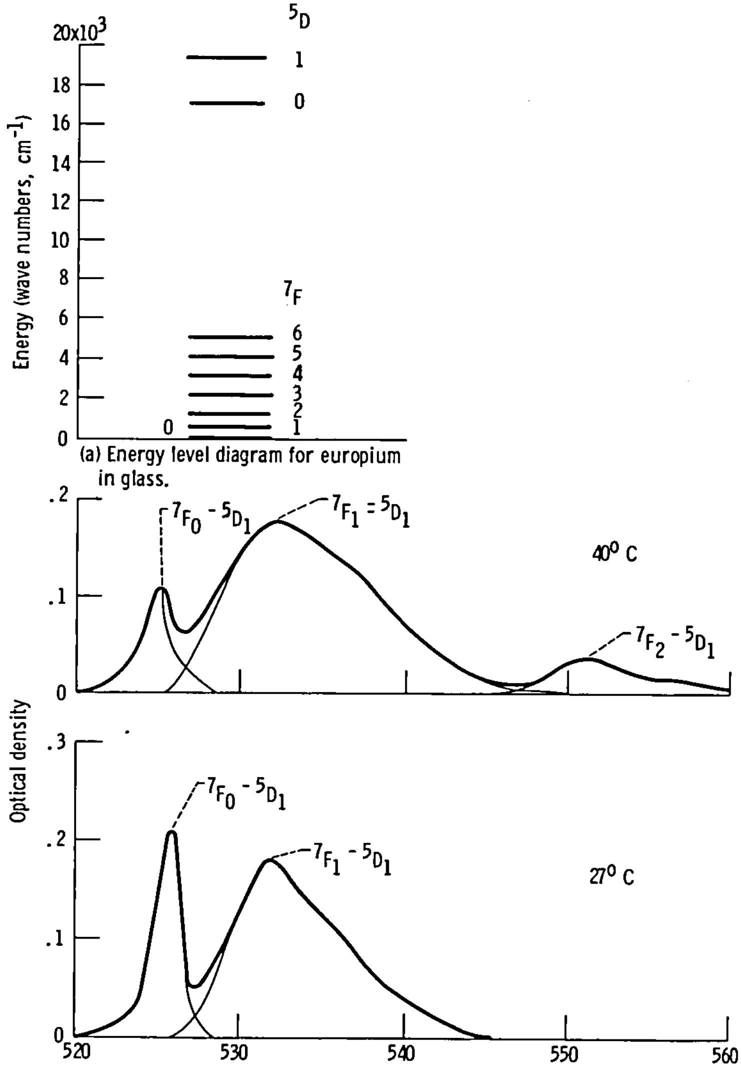


Figure 10. - Rare-earth temperature sensor.



(b) Variation in transmission for europium doped fiber as function of temperature.

Figure 11. - Characteristics of europium doped glass change temperature of middle plot from 40° to 402° C.

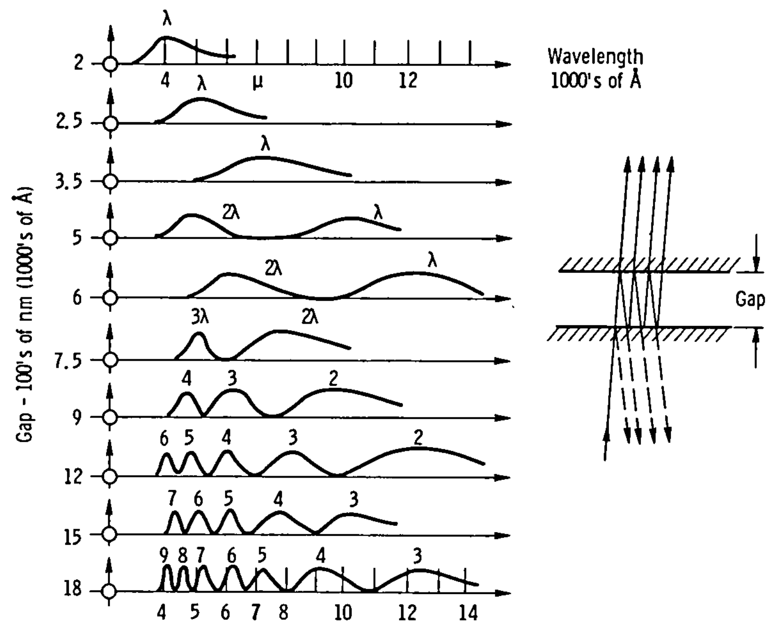


Figure 12. - Fabry-Perot spectral distribution with variation in gap width.

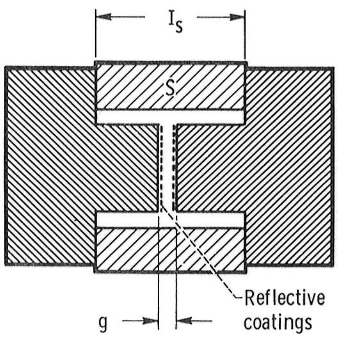


Figure 13. - Temperature sensitive gap for use in Fabry-Perot temperature sensor.

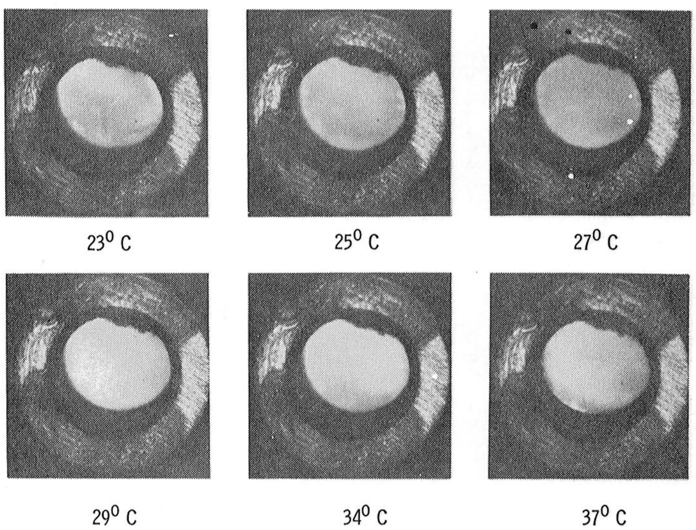


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Figure 14. - Fabry-perot spectra variation as a function of temperature.

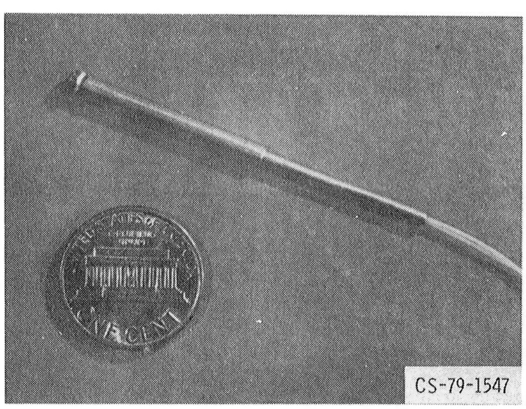

Figure 15. - Fabry-perot temperature sensor construction.

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16. Abstract

A review of some NASA and DOD programs to develop optical sensors with fiberoptics for instrumentation and control is presented. Fiberoptic systems offer some distinct advantages. Noise immunity is one important asset. Fiberoptic systems do not conduct electricity and therefore can be used in and near areas that contain explosive or flammable materials. One objective of these programs is to produce more reliable sensors and to improve the safety and operating economy of future aircraft and space vehicles.

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