Fiber-optic powered remote gas monitor

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ABSTRACT

Many mines rely on toxic gas sensors to help maintain a safe and healthy work environment. This report describes a prototype monitoring system developed by the U.S. Bureau of Mines (USBM) that uses light to power and communicate with several remote electrochemical toxic gas sensors. The design is based on state-of-the-art optical-to-electrical power converters, solid-state diode lasers, and fiber optics. This design overcomes several problems associated with conventional wire-based systems by providing complete electrical isolation between the remote sensors and the central monitor. The prototype accurately monitored three remote gas sensors during a two-week field trial in the USBM Pittsburgh Research Center Safety Research Coal Mine.

Keywords: fiber optics, sensors, power converter, optical power, gas monitor

1. INTRODUCTION

Many underground mines rely on remote gas monitors to help maintain a safe, healthful work environment. For example, carbon monoxide (CO) sensors are often used for fire detection along conveyor belts because of the belts' susceptibility to fires (coal spilled onto seized rollers, defective motors, etc.). These sensors work well for this purpose because combustible materials in mines such as coal, wood, brattice cloth, conveyor belting, and fuels produce CO gas in initial stages of fires. Depending on ventilation rates and other factors, CO sensors may be spaced several hundred meters apart along the belt, often extending many kilometers underground. If the fire detection system should fail, a fire could quickly send toxic fumes to the working area and block off the remaining escape routes. For this reason, every effort must be made to ensure that early-warning fire detection systems are reliable.

Fiber optics (FO) provides reliable long-distance telemetry. Electromagnetic interference (EMI) problems associated with wire-based telemetry systems are virtually eliminated in fiber-optic telemetry systems. FO also eliminates ground loops. Ground potential may vary throughout a mine, which could adversely affect electrical signals. The fragility of optical fiber is a concern of many in the mining industry. However, properly cabled fiber has proven to be surprisingly rugged, as evidenced by the thousands of kilometers of fiber placed on the ocean floor for intercontinental communication systems.

Despite these advantages, FO has not yet made a big impact in industrial applications. One reason is the popular 4 to 20 mA current-loop system that is more cost-effective than fiber-optic systems in most applications. However, the situation for FO should change with the emergence of a fieldbus standard[1] originally chartered to replace the 4 to 20 mA standard with a modern digital equivalent. An all-digital communications standard will also include provisions for fiber-optic implementation. This new protocol that can be implemented with fiber should provide a greater acceptance of FO for industrial applications resulting in a dramatic reduction in costs.

One of the remaining obstacles to widespread use of FO in the mining industry is the need for electrical power at remote sensing locations. Electrical telemetry systems often use the same conductor for power and communication, reducing the number of connections to remote sensors. For this reason, rather than replacing another technology, FO becomes an expensive add-on. However, recent technological developments allow FO to provide communication and power to remote locations in a networked environment as well. The U. S. Bureau of Mines (USBM) has developed a fiber-optic remote environmental warning system (FOREWARNS) to prove this concept and to familiarize designers with this technology.

2. SYSTEM COMPONENTS

A concept drawing of FOREWARNS is shown in figure 1. A central monitoring station (CMS) communicates with and provides power to three remote sensing units (RSU's) via a large core fiber-optic cable. The CMS consists of a control box with a liquid crystal display, a laser housing, and a laser power supply. The optical signal is distributed to each RSU by a fiber-optic splitter. Each RSU contains a gas sensor, an optical-to-electrical power converter, and telemetry circuitry. The RSU responds to the CMS when polled via standard communications grade multimode fiber-optic cable and splitters.

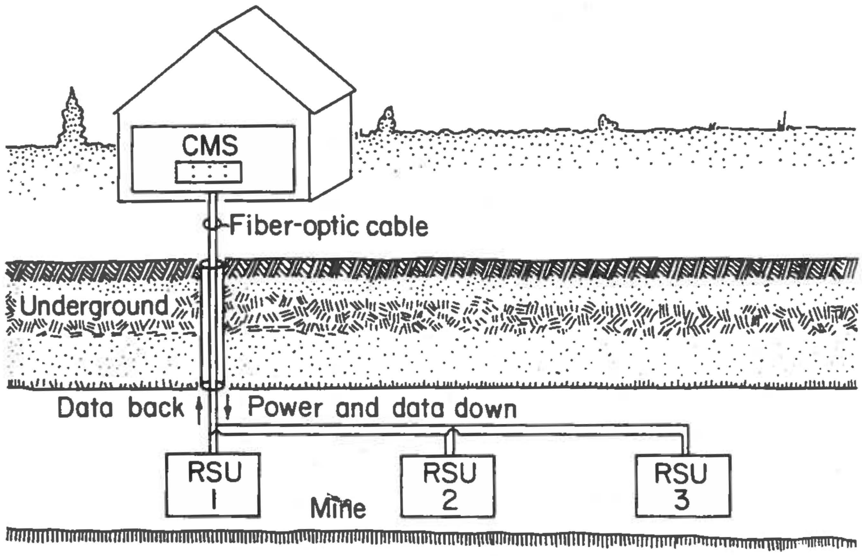

Fig. 1. Communication and power to remote sensors provided by FO.

2.1 Laser

A key component of this system is a fiber-coupled, laser-diode array from SDL Inc.* (formerly Spectra Diode Labs). The SDL laser (model SDL-3450-P5) has a center wavelength of 814 nm and a spectral bandwidth of 3 nm. The array of diode lasers in the device can produce over 5 W of optical power (figure 2). The electrical-to-optical efficiency at this power level is 22%. Up to 5 W are coupled into a dense random fiber-optic bundle pigtail terminating in a SMA-type connector. The bundle diameter at the connector is 400μm and beam divergence is about 50° full width at half-maximum power.

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*Reference to specific products does not imply endorsement by the U.S. Bureau of Mines.

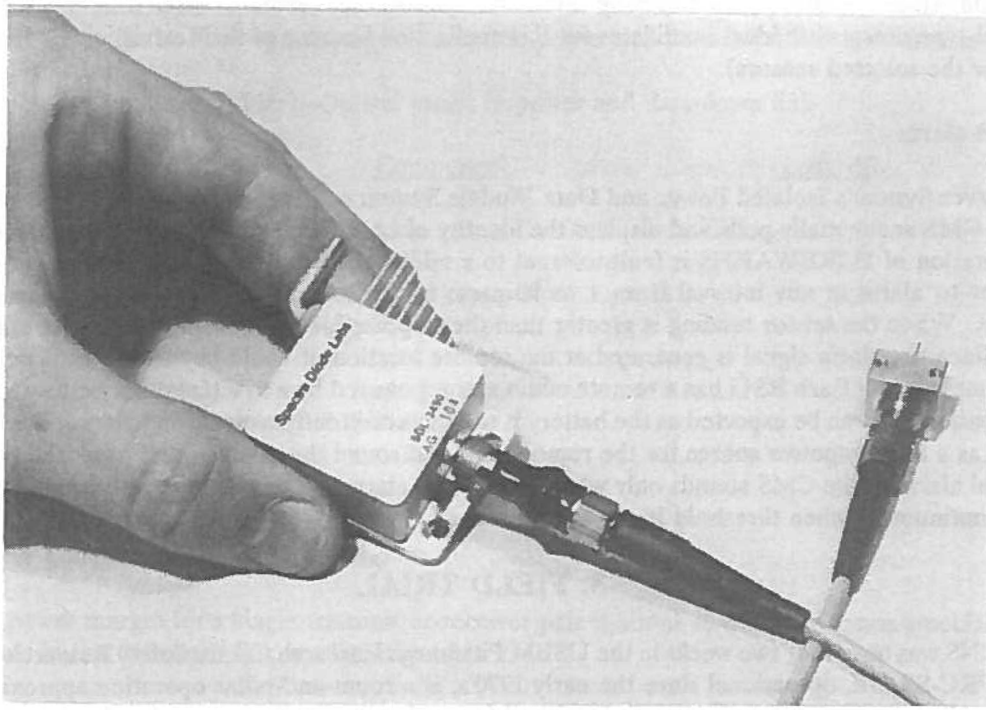

Fig. 2. Optical power supply consisting of a fiber-coupled solid-state laser and power converter.

2.2 Fiber-optic link

A fiber-optic link distributes the modulated laser power to three RSU's, and provides a return path for communication with the central monitor. A light emitting diode in each RSU transmits information back to the CMS. The fiber bundle coupled to the laser diode array connects directly to a single 400-μm-core-diameter, hard-clad silica, step index fiber-optic cable. An SMA-type connector is used at this interface; ST-type connectors are used throughout the rest of the link. The numerical aperture (NA) of the single 400-μm-core-diameter fiber is rather large (0.37) to increase coupling efficiency. The laser power is distributed among the three RSU's via two 400-μm-core fiber-optic splitters, with splitting ratios of 3:1 and 1:1. The return path consists of a 62.5-μm-core fiber-optic cable and two splitters with 1:1 splitting ratios. Fiber-optic connectors are used at all interfaces between fiber-optic components for convenience. A substantial savings in the optical power budget can be realized by replacing connectors at the cable-splitter interfaces with fusion splices. Each of the RSU's and CMS are separated by 100-m lengths of cable.

2.3 Remote sensing units

An optical-to-electrical power converter in each RSU supplies enough electrical power to operate the sensor and telemetry circuitry. These power converters represent another recent technological development. Originally developed by Varian Associates, Inc., and now licensed to Photonic Power Systems, the power converters are made of a monolithic gallium arsenide (GaAs) semiconductor device. They convert light into electrical current at voltages appropriate for powering integrated circuits and sensors. The illuminated area of the power converter is circular with a diameter of about 3 mm, making it ideal for "power-down-a-fiber" applications. The optical-to-electrical conversion efficiency is approximately 50%, exceeding the efficiency of silicon solar cells. The device is most efficient over the 800 to 850 nm wavelength range. The standard GaAs converter's maximum electrical output power is about 2 W. It can also receive data signals at rates up to 250 kHz for data transmission. Each RSU contains one 6-V power converter.

Nitrogen dioxide (NO_2), sulfur dioxide (SO_2), and CO sensors were selected to demonstrate the optical powering concept in field trials. These commercially available sensors all contain electrochemical sensing elements. Electrochemical-type sensors are ideal candidates for this application because of their extremely low power consumption (about 2mW for the selected sensors).

2.4 Control and alarm

Photonic Power System's Isolated Power and Data Module System controls communication between the RSU's and the CMS. The CMS sequentially polls and displays the identity of each RSU, sensor output, and alarm threshold. The parallel configuration of FOREWARNS is fault-tolerant to a malfunction or disconnection of any of the RSU's. Each RSU can be set to alarm at any interval from 1 to 99 ppm, in 1-ppm intervals, by switches located on the remote telemetry board. When the sensor reading is greater than the setpoint for that sensor, the remote station generates an alarm signal. Since the alarm signal is generated at the remote location, it could be used to activate a nearby battery-powered personnel alarm. Each RSU has a remote audio alarm powered by a 9-V transistor battery to demonstrate this feature. Long battery life can be expected as the battery is used intermittently, only during alarm. The battery could also conceivably act as a backup power source for the remote unit and sound the alarm in the event the fiber-optic link was severed. A local alarm at the CMS sounds only when a sensor in alarm status is polled. At the sensor end, the remote alarm sounds continuously when threshold levels are exceeded.

3. FIELD TRIAL

FOREWARNS was tested for two weeks in the USBM Pittsburgh Research Center Safety Research Coal Mine (PRC-SRCM). The PRC-SRCM, operational since the early 1970's, is a room-and-pillar operation approximately the size of a working section in a commercial coal mine. It is utilized for testing new equipment and technology before transferring them to industry. Carbon monoxide, nitrogen dioxide, and sulfur dioxide RSU's were placed inside the mine, each separated by 100 m of cable. All RSU's and cable were placed in intake air. The CMS was located in the mine office just outside the mine portal. A 100-m length of cable was also used to separate the CMS and the NO_2 RSU. The sensors were challenged with a calibration gas twice a day during the first week, once a day the second week. All sensors responded accurately when exposed to the calibration gas. The RSU's were set to alarm when the sensor reading reached the calibration gas concentration; the longest alarm response time observed was just under 3 min.

4. TELEMETRY DESIGN ANALYSIS

The two parameters that tend to be the dominant design criteria for fiber-optic telemetry systems are the transmission rate (how fast) and link length (how far).[2] The transmission rate of this system was chosen to be 5 kHz for two reasons: First, at 5 kHz the sensors can be easily interrogated about once every 10 s, which is sufficient for many applications; second, modulating several amperes of laser-diode current becomes increasingly difficult at higher transmission rates. This transmission rate is sufficiently low that bandwidth limitations on the maximum allowable length of fiber-optic cable are negligible (the bandwidth-length product of the 400 μm fiber-optic cable is 13 MHz·km), leaving only the optical power budget to be considered.

The optical power budget of a fiber-optic communication system is usually defined in terms of optical power levels needed to maintain an acceptable bit error rate (digital systems) or signal-to-noise ratio (analog systems). For this system, however, the optical power budget must also be defined in terms of the amount of optical power needed to maintain acceptable voltage and current at the remote sensor. This is the only consideration on the power and data-down link because the sensor will cease to function properly before light levels approach the signal detection limit of the GaAS power converter. Receiver sensitivity on the data-back link must still be considered.

4.1 Optical power budget: power and data-down link

Researchers determined the minimum laser power needed to operate the remote sensors experimentally. First, each RSU was exposed to a test gas, then the laser power was decreased gradually until the unit failed to respond. The peak power measured at each RSU input just prior to sensor failure was about 70 mW for each. The average optical power at cutoff is about half of this value, as the laser output fell below the lasing threshold at minimum signal modulation. The losses associated with the fiber-optic components in the power and data-down link are listed in table 1.

Table 1.–Optical losses in power and data-down link

Component	Loss, dB
400 μm core fiber, per km	6.0
ST-ST connections (typical)	0.5
Fiber bundle to single fiber connection	2.3
1 by 2 coupler; 3:1 split ratio:	
Port 1-2	5.7
Port 1-3	1.5
1 by 2 coupler, 1:1 split ratio:	
Port 1-2	3.8
Port 1-3	3.4

4.2 Optical power budget: data-back link

The overall power margin for a single transmitter-receiver pair is about 10 dB. The losses associated with the fiber-optic components in the data-back link are listed in table 2.

Table 2.–Optical losses in data-back link

Component	Loss, dB
62.5 μm core fiber, per km	3.0
ST-ST connections (typical)	0.6
1 by 2 coupler; 1:1 split ratio:	
Port 1-2	3.8
Port 1-3	3.55
1 by 2 coupler, 1:1 split ratio:	
Port 1-2	3.7
Port 1-3	3.54

5. LASER SAFETY ISSUES

5.1 Human exposure

All lasers should be operated in compliance with appropriate safety standards. The American National Standards Institute (ANSI) Standard Z136.1 provides guidance for the safe use of lasers and laser systems in terms of human exposure.[3] The standard defines control measures for each of four laser classifications. The laser used in FOREWARNS is an ANSI class 4 laser emitting an invisible infrared beam of high power contained within a fiber-optic cable. Under normal operating conditions, the laser beam is enclosed within the fiber-optic cable and terminated in a RSU so as not to pose a skin or eye hazard. Another control measure not defined in the Z136.1 standard can also help reduce the risk of injury due to exposure: the system can be designed to automatically shut off if communication is interrupted due to cable disconnection or breakage.

One characteristic of the system is the large divergence of the beam exiting the cable at the polished and cleaved connector interface. The angle subtended by the diverging beam (Θ) can be determined from the NA of the step index optical fiber by the equation

$$\Theta=2\sin^{-1}(NA). \tag{1}$$

The NA of the 400-μm cable is 0.37; therefore, Θ is about 43°. With this large divergence, the intensity of the beam weakens dramatically with increasing distance from the emitting surface. The implications in terms of human exposure are best illustrated by a laser hazard evaluation conducted by Rockwell Laser Industries. Rockwell's LAZAN hazard analysis software calculated the Maximum Permissible Exposure (MPE) limits for various exposure conditions based on the laser operational characteristics listed in table 3. The MPE is defined as the radiant exposure that personnel may receive without adverse biological effects. The MPE was then used to determine the Nominal Ocular Hazard Distance/Nominal Hazard Zone (NOHD/NHZ). The NOHD/NHZ is defined as the distance from a laser at which the radiant exposure is equal to the MPE. Figure 3 shows the NOHD/NHZ for various exposure conditions as determined by LAZAN.

Table 3.–Laser operational characteristics

Wavelength	814 nm.
Laser type	GaAlAs diode.
Duty cycle	Continuous wave.
Power	5 W.
Fiber diameter	0.04 cm (multimode).
Numerical aperture	0.37.

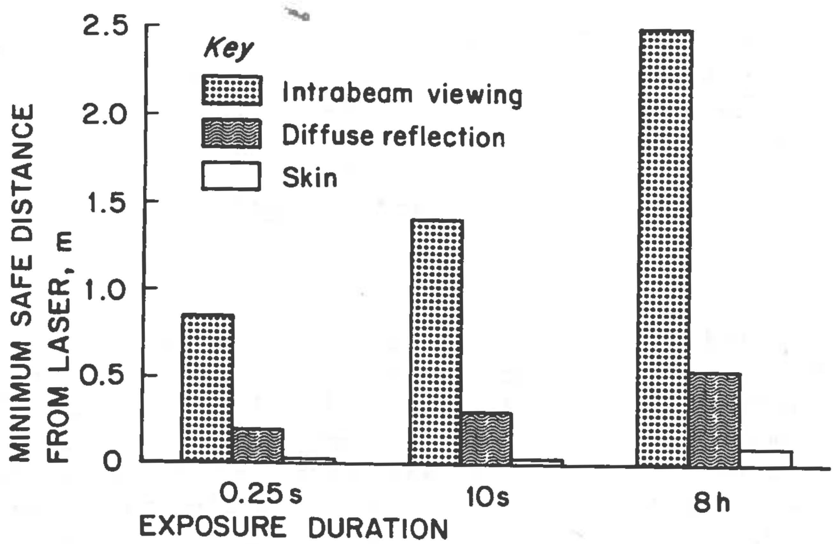

Fig. 3. Nominal ocular and skin hazard distances for laser characteristics listed in table 3.

5.2 Explosion hazard

Another safety concern involves fiber coupled optical ignition of combustible atmospheres.[4,5] According to federal mining regulations, components of atmospheric monitoring systems installed where permissible equipment is required shall be intrinsically safe.[6] Currently, there are no standards or guidelines on the safe use of fiber-optic systems in hazardous (classified) locations in the United States. Without these standards, approval agencies are not likely to approve laser-coupled fiber-optic instrumentation as permissible equipment. The Instrument Society of America has formed the SP12.21 Fiber Optics committee to establish guidelines and be a source of information on this subject. The committee is currently working with international organizations with similar interests to establish an international standard for the safe operation of fiber-optic systems in hazardous locations.

6. SUMMARY

A toxic gas monitoring system that uses a near infrared laser to power and communicate with three remote sensors over fiber-optic cable, has been demonstrated. One advantage of such a system is enhanced reliability afforded by fiber-optic telemetry in locations where electrical power may not be readily available.

Laboratory and field tests led to several observations. Difficulties in modulating several amperes of laser diode current places a practical limit on the maximum transmission rate of this system. The 5-kHz rate chosen is sufficient for many applications. Remote sensor stations required about 35 mW average incident optical power. Control measures defined by existing laser safety standards can reduce the risk of injury resulting from physical exposure; however, no such standards exist in the United States regarding explosion hazards. Approval agencies are not likely to approve laser-coupled fiber-optic instrumentation as permissible equipment in hazardous (classified) locations until such standards are established.

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