Fiber Optic Sensor Systems for Arc Flash Detection

White paper

Introduction

Electrical power grids are amongst the most important infrastructures of the world. They connect over five billion people worldwide to energy, and are indispensable for countless applications, such as industrial manufacturing, communication networks, hospitals. As such, any event that could interrupt the distribution of electrical energy must be avoided. Amongst these events are the short circuits within the electrical power grid.

One type of short circuit is the arc short circuit, which is triggered by a failure in the isolation area between two energized conductors, or between an energized conductor and ground. This failure may be caused by the presence of an unexpected object (animal, tool, …) or by dirt or humidity. Whenever an arc short circuit occurs, it generates an arc flash.

Arc flash events generate very high energy. As such, controlled arc flashes have many applications, for example, illumination, electric welding, steelmaking, and satellite engines. When arc flashes are not controlled, however, this high energy becomes dangerous.

Uncontrolled arc flash events are especially risky when they occur within the power grid, as they may damage not only expensive and critical electric equipment, but also injure people. Within the power grid, the arc flashes may appear in the so-called switchgears.

Switchgears are one of the main components of the electric power grid, as they allow reconfiguring of the grid itself. These elements consist of a combination of electrical disconnect switches, fuses or circuit breakers, and they allow controlling, protecting and isolating electrical equipment.

Figure 1 shows the general schematic of a switchgear and the interconnection between different switchgears. The input/output power line is connected to the switchgear through a so-called cable connection compartment. The breaker compartment allocates the circuit breaker, which is the main part of the switchgear, as it allows connecting or disconnecting of its input or output. Interconnection of the different switchgears is made through the bus bar compartment.

If an arc flash event occurs and it is not detected in time, the high energy produced might cause extensive damage in a matter of a few hundred milliseconds, as shown in Figure 2.

Figure 2 shows that the extent of damage resulting from an arc flash event largely depends on the duration of the event. To maximize the protection against arc flashes, both the arc flash detector and the breaker included in the switchgear must have a very low response time.

This white paper is a guide on how fiber optics sensors are applied to detect these events in medium voltage power grids.

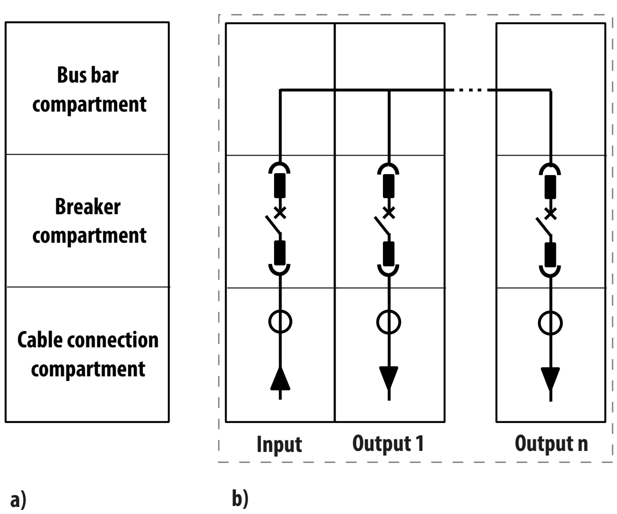

Figure 1. (a) General schematic of a switchgear. (b) Interconnection of switchgears.

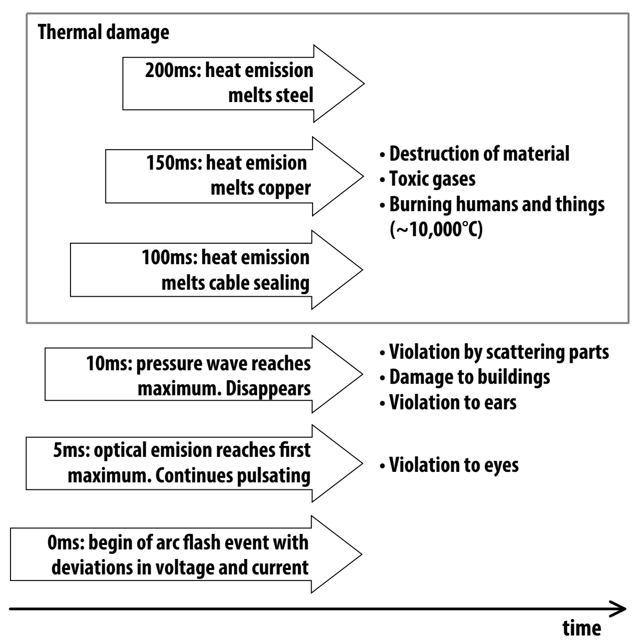

Figure 2. Damage caused by an arc flash vs. time.

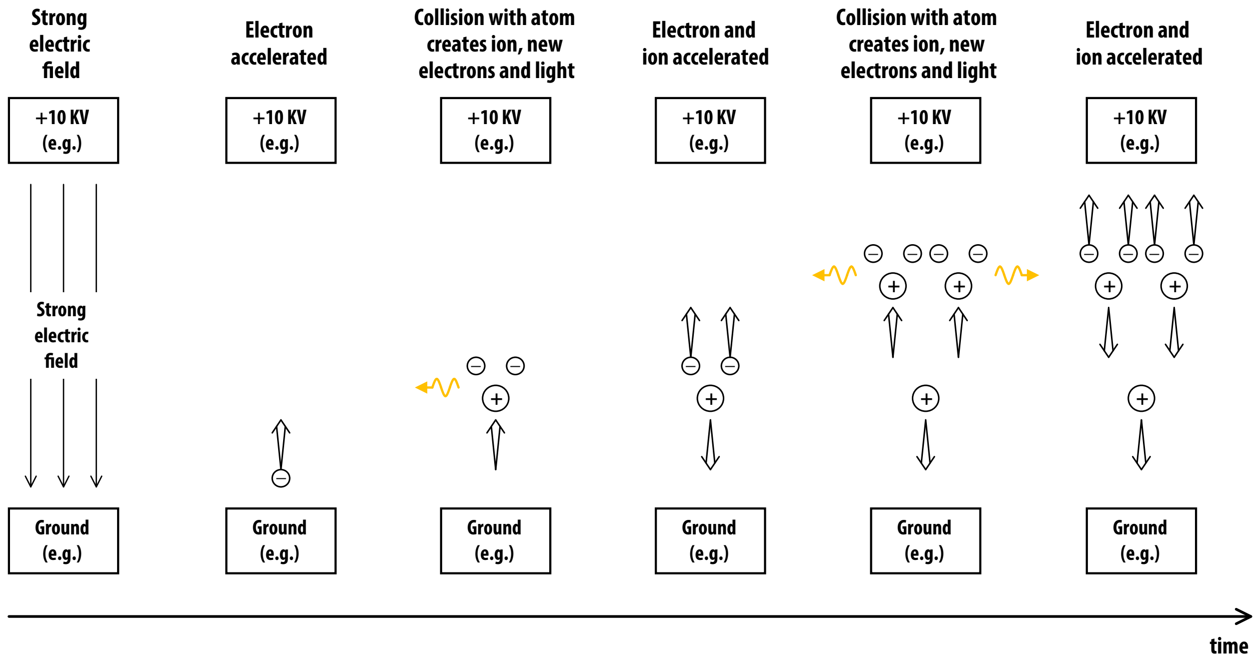

Figure 3. Physical mechanism behind arc flashes.

Physical features of an arc flash

Figure 3 shows the physical mechanism behind arc flashes. An arc flash event is a chain process about how light is generated due to the acceleration of electrons that collide with atoms. The acceleration is caused by a strong electric field.

When designing an arc flash detector based on optics, a few physical features of the arc flash must be taken into consideration. These features include:

Optical spectrum

The spectrum of the light generated by an arc flash may vary from one arc flash event to another one. It strongly depends on the materials involved in the arc flash (gas, humidity, and so on). Figure 4 shows an example of the optical spectrum of an arc flash. It covers a range from 300 nm to 800 nm, with typical copper lines around 500 nm. The optical spectrum of an arc flash is especially important when selecting an appropriate photodiode for the arc flash detection device.

Optical power

The power density of an arc flash is extremely high; as such, it is very important to detect and act on it in time. This power density may be around 10 kW/m^2; compare this against sunlight, whose power density when it reaches the surface of the earth is about 0.74 kW/m^2.

Time

Arc flashes also show a particular time behavior. From the 50 Hz (or 60 Hz) at which the voltage and current waves oscillate in the power grid, it can be easily derived that the frequency at which the optical power of an arc flash pulses is 100 Hz (or 120 Hz). Figure 5 shows an example, obtained through simulations, of the time behavior of an arc flash. The amplitude of the peaks may change from one arc flash event to another one, but the 100 Hz (or 120 Hz) pulsation remains unchanged in all the cases.

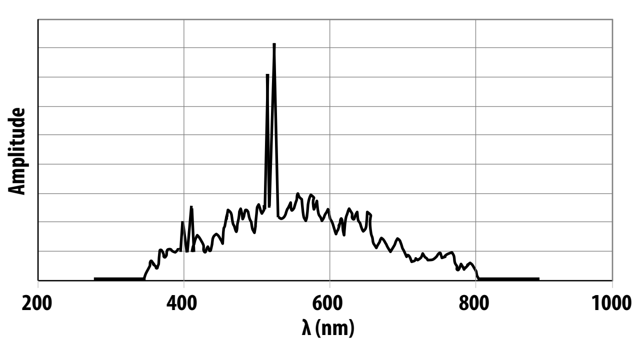

Figure 4. Typical optical spectrum of an arc flash.

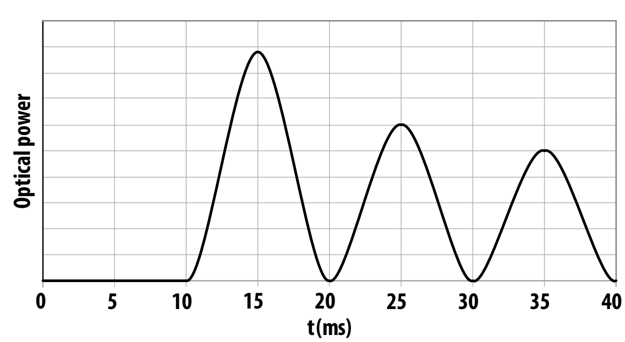

Figure 5. Typical time behavior of an arc flash.

Arc flash detection systems

Currently, arc flash detectors are usually based on sensing current/ voltage. To improve the reliability of the detection system, other objects have also been evaluated. Because it generates a quick response, which minimizes damage, light sensing has become a common characteristic in today's arc flash detection systems.

Light has become the perfect means to detect arc flashes because of its extremely low propagation delay, which reduces the overall response time of the detection system. In addition, it is robust against the high EMI values from the environment where the detector will be used.

An arc flash detection system based on voltage/current and light sensing mainly consists of a voltage/current interrogator, a light interrogator, an arc monitor unit, and a circuit breaker, as shown in Figure 6.

The arc monitor unit continuously receives the values measured by the voltage/current interrogator and the light interrogator. If an arc flash event occurs, both the voltage/current interrogator and the light interrogator supply abnormal values to the arc monitor unit. When this happens, the arc monitor unit sends a command to the circuit breaker to open it and stop the current flow.

Figure 6 shows there are two options for the optical sensor: a) one or more optical sensors are distributed along the different compartments of the switchgear; or b) a single optical sensor covers one or more of those compartments. The first option is known as a point sensor, while the second option is known as a line sensor or fiber sensor.

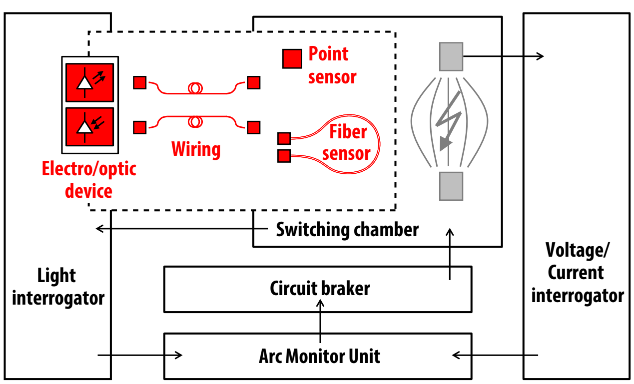

Figure 6. Block diagram of an arc flash detection system.

Point sensor

A point sensor captures light only in a relatively small area around its location.

There are two types of point sensors: opto-electronic point sensor and optical point sensor. An opto-electronic point sensor consists of a photodiode integrated in the head of the sensor, which implements the opto-electrical conversion. For this type of sensor, EMI and ESD should be considered when deciding the location of the sensor. An optical point sensor is based on some translucent material that captures the light, which is then guided to the optical receiver through an optical fiber.

Point sensors may implement a heartbeat capability. The heartbeat capability is especially important in critical systems where an unexpected interruption could cause huge material damage or put human lives at risk. In an arc flash detector, the heartbeat signal consists of an optical pulse that is periodically sent from the transmitter to the receiver. The heartbeat signal checks whether the optical receiver is still working and, consequently, whether the arc flash detection system keeps enabled or not.

Figure 7a shows the block diagram of an optical point sensor with heartbeat capability. Other designs for the point sensors, based on the same principles, are also available.

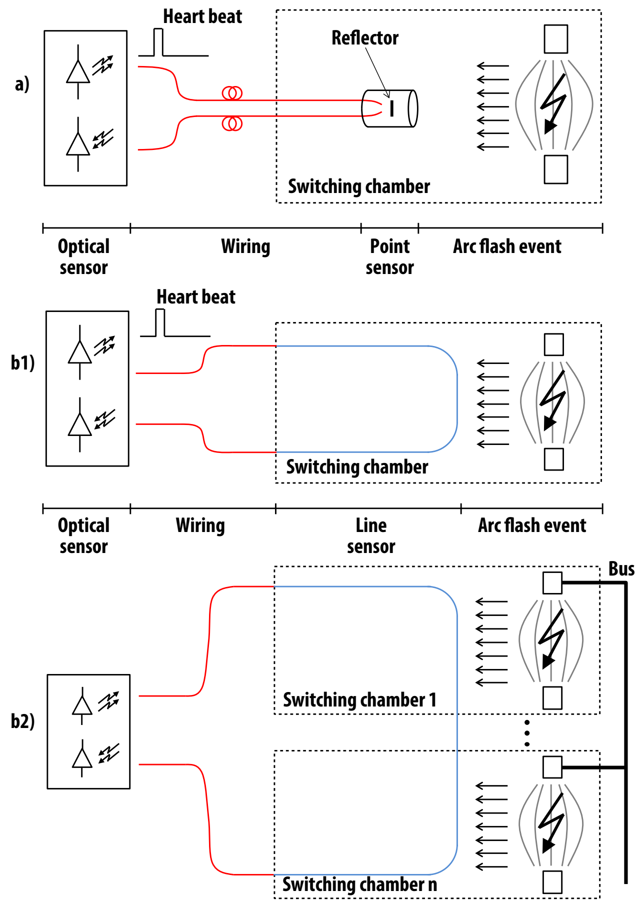

Figure 7. (a) Optical point sensor. (b.1) Line sensor protecting a single switching chamber. (b.2) Line sensor protecting several switching chambers.

Line sensor

A line sensor consists of an optical fiber, in a loop configuration, which captures the light from outside and guides it to the receiver. In contrast to point sensors, line sensors capture light in a large area along the path of the optical fiber. These sensors also include the so-called heartbeat feature.

Figure 7b.1 shows the block diagram of a line sensor.

Ideal line sensors have low transmission losses and high light capturing efficiency. They are usually implemented over plastic optical fiber (POF) or over thick glass fiber, such as plastic clad silica (PCS) fiber with a core diameter of 400µm. For both POF and PCS fiber, the jacket may be transparent or, even, removed.

A line sensor can also be distributed along several compartments within a single switchgear or through a few of them (see Figure 7b.2). Hence, the longer the optical fiber is, the more compartments may be served with a single fiber and, thus, the fewer the number of sensors required to protect a given number of switchgears, which minimizes the price of the protection system. However, the length of the fiber is limited by the sensitivity of the receiver.

Line sensor vs. point sensor

Each type of sensor has advantages and disadvantages compared to the other type; consequently, both types are implemented in arc flash detection systems nowadays.

Table 1 summarizes the main features of both line sensors and point sensors.

Table 1. Line sensor vs. point sensor.

	Line sensor	Point sensor
Shadowing risk	No	Yes
Sensitivity	Lower than point sensors	High
Multiple compartments	Yes	No
Accuracy in locating the arc flash event	Low	High

The Shadowing Risk feature in Table I refers to whether the optical sensor can be placed in a shaded area within the switchgear, which would prevent the sensor from capturing light. Line sensors, due to the length of the capturing fiber, are free of shadowing risk; however, this risk exists for point sensors.

On the other hand, point sensors, since they have been specifically designed for arc flash detection purposes, have a higher sensitivity than line sensors, whose sensitivity is inherited from the physical properties of the optical fiber.

The length of the capturing fiber also allows a single line sensor to be used to cover several compartments within one or several switchgears. This is not possible for a point sensor.

Point sensors are highly accurate in locating where an arc flash event happens. Line sensors, on the other hand, have a much lower accuracy because of the length of the capturing fiber.

Avago Technologies solution for arc flash detection

Avago Technologies has developed an optical sensor transceiver that is ideally suited for arc flash detection applications. Figure 8 shows the optical sensor transceiver, whose form factor is very similar to the RJ-45 connector.

Figure 8. Avago Technologies optical sensor transceiver suitable for the detection of arc flash events.

Transmitter

The transmitter allows the implementation of the heartbeat signal feature in the system. It consists of an LED, which has a central emission wavelength at 650 nm. This LED may reach a launched optical power of around -1 dBm, operating at CW. For pulsed operation, the launched optical power increases. No driving IC is built-in, which allows customizing the implementation of the heartbeat signal in terms of optical power (optimizing the current consumption), pulse width and duty cycle, making it optimal for any scenario.

Receiver

The receiver consists of an ASIC, which integrates the functionalities of a photodiode and a Trans-Impedance Amplifier (TIA). The ASIC provides an analog voltage output to the arc monitor unit (see Figure 6) whose amplitude is proportional to the power of the incoming light.

Based on the duration and the level of the analog output supplied by the receiver of the optical sensor transceiver, the system may distinguish between ambient light, which is not processed, a heartbeat signal and an arc flash event. To trigger the protection, that is, to open the breaker of the switchgear (see Figure 1), both the optical and the voltage/current interrogators must provide abnormal values to the arc monitor unit. This redundancy increases the reliability of the arc flash detection system.

Figure 9 shows the output voltage of a typical ASIC used for arc flash detection applications as a function of the optical input power. The ASIC output is saturated when the optical input power is higher than -10 dBm. Since the detection of the arc flash events is not based on the shape of the received optical signal, but on the thresholds set at the arc monitor unit (see Figure 6), the optical sensor transceiver may still detect arc flash events, with 100% reliability, even if the optical input power is higher than -10 dBm. For optical input power below -10 dBm, the linearity of the ASIC is quite stable. The device is fully functional in the range -40 °C to +85 °C.

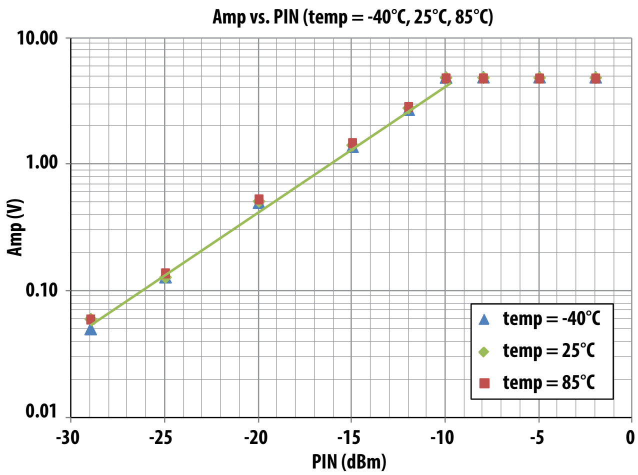

Figure 9. Linearity of a typical ASIC used for arc flash detection applications

The black line in Figure 10 shows the relative spectral sensitivity of the photodiode integrated in the ASIC included in the receiver as a function of the wavelength of the incoming light. As a relative curve, the values are given with regards to the maximum.

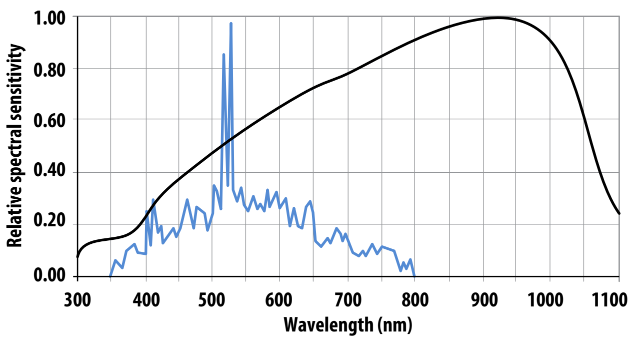

Figure 10. Relative spectral sensitivity of the photodiode.

The blue line in Figure 10 depicts the optical spectrum of a typical arc flash (see Figure 4). The response of the photodiode fully covers the optical spectrum of the arc flash, guaranteeing a perfect detection of the arc flash event.

A typical value for the responsitivity of the receiver included in the optical sensor transceiver is 45 V/mW, at 650 nm.

The rise and fall times of the TIA are below 10 µs, which is just the right order of magnitude for the arc flash detection application.

Wiring and connectors

POF is the type of cable selected by Avago Technologies for its arc flash detection solution, although other types of fibers are also appropriate for this application.

The wiring is divided into two sections: the link between the optical transceiver and the line sensor, which is based on regular POF; and the line sensor itself, which is based on transparent-jacket POF. These two sections are attached to each other through connectors. (see Figure 6)

Typical values of the specific cables employed in the application are 1.0 mm for the diameter of the core plus cladding; 2.2 mm for the diameter of the jacket; 0.5 for the NA; and 0.2 dB/m for the losses at 650 nm.

Avago Technologies has developed an optimized duplex versatile link connector for the connection between the optical transceiver and the first section of the wiring . This connector is shown in Figure 11.

As for the connectors between the two sections of the wiring, different possibilities are available. Due to the size of the POF and the material of which the cable is made, the connectors in the market are cost-effective and highly reliable. Some of them are even field-installable. Versatile Link, SMA and ST connectors are commonly used, although other types of connectors are also be available.

Typical losses for these connectors are in the range of 1.0 dB to 1.5 dB (fiber-to-fiber).

Figure 11. Duplex versatile link connector attaches the first section of the wiring to the optical sensor transceiver

System design

To make the arc flash detection system operate correctly, the system designer must follow three basic steps along the designing process: 1) to create selection rules for the items involved in the system, such as optical fibers, connectors and sensors, amongst others; 2) to develop design rules for the lengths of the different optical fiber cords; and 3) to make adjustment rules for the thresholds implemented at the arc monitor unit (see Figure 6).

Only a certain percentage of the power of the light produced by an arc flash event reaches the photodiode of the arc flash detector. This percentage mainly depends on the sensor type (point sensor or line sensor), the length of the wiring, the location of the arc flash with regards to the sensor, and the intensity of the arc flash. The minimum power that must reach the photodiode is fixed by the sensitivity of the optoelectronic unit of the arc flash detector.

In addition to the light produced by the arc flash event, the heartbeat signal also reaches the photodiode of the arc flash detector. The amplitude of this signal may also vary strongly, although the reasons for this variation are not the same as in the case of the light produced by the arc flash event (see Table 2).

The design of the arc flash detector must allow the detection of both the arc flash event and the heartbeat signal.

Conclusion

Arc flashes can cause great harm. They may occur in the switchgears of the electrical power grid, causing damage in critical and expensive equipment and severe injuries to humans. Arc flash detectors have become a very successful means to reduce, or even avoid, the extensive damage caused by arc flashes. Avago Technologies has recently developed a high-performance cost-effective optical sensor transceiver, based on the latest technology, which has been introduced in this white paper, and may be applied to the detection of arc flash events.

Table 2. Facts affecting the incoming light power at the receiver of an arc flash detector.

	Line sensor		**Point sensor**	
	Heartbeat	**Arc flash**	**Heartbeat**	**Arc flash**
Light source	• LED efficiency • LED current	• Arc flash conditions • Optical power density of the arc flash at the location of the sensor • Spectrum	• LED efficiency • LED current	• Arc flash conditions • Optical power density of the arc flash at the location of the sensor • Spectrum
Sensor capturing		• Length of fiber sensor exposed to the arc flash • Type of fiber sensor and capturing coefficient		• Capturing area • Capturing coefficient, as specified in the datasheet
Sensor losses	• Total length of fiber sensor • Attenuation per meter of fiber sensor	• Total length of fiber sensor • Position of arc flash on sensor fiber (distance to detector side end) • Attenuation per meter of fiber sensor	• Losses as specified in the datasheet	
Wiring losses	• Double length of wiring fiber • Attenuation per meter of wiring fiber	• Total length of wiring fiber • Attenuation per meter of wiring fiber	• Double length of wiring fiber • Attenuation per meter of wiring fiber	• Total length of wiring fiber • Attenuation per meter of wiring fiber
Connector losses	• Attenuation of connection • Number of connections	• Attenuation of connection • Number of connections	• Attenuation of connection • Number of connections	• Attenuation of connection • Number of connections

For product information and a complete list of distributors, please go to our web site: **www.avagotech.com**

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