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ELECTRICAL POWER OVER FIBER OPTICS

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Abstract- Providing electrical power over optical fiber has unique advantages including total immunity from electrical noise and complete isolation of the power source. Recent advances have resulted in more compact high power lasers and an improved type of photovoltaic cell, produced by Photonic Power Systems. Optical fiber is necessary to effectively transfer optical power, but has its own power handling limitations that are now readily exceeded by compact laser sources. In this study, we focused on the practical power handing limits of standard commercial optical fiber and the ability to convert this power to useful electrical power. We will also discuss some of the high power damage mechanisms present in fibers and some methods to overcome them.

Keywords: Fiber Optic, Optical Power, Efficiency of a Power Converter.

I. INTRODUCTION

Optical fiber has long been used to provide illumination, communication links, and a sensing platform, but has been little utilized as a means for providing electrical power through conversion of light into a useable voltage and current. Fiber-provided electrical power has the advantage of providing total immunity from electrical noise and complete isolation of the source and system. Applications exist in a number of areas including powering sensors in areas of high electromagnetic fields, providing an isolated power and data link to sensors in high voltage areas such as substations, allowing for all-optical networks containing active components without the need for a separate electrical connection, and providing power to areas of high sensitivity to RF emissions. Devices operating on fiber- provided power have the additional advantage of using the same fiber for high bandwidth data transmissions.

Although many applications do not require high levels of electrical power, other applications, such as powering motors or actuators, require watts or more of power. One limitation lies in the optical power handling capabilities of a fiber. This area has been studied, especially with regard to the need for higher power in long communications links [1] and in the area of laser to fiber coupling [2], but the application to power transmission has not. Other limiting factors in optical power transmission include the coupling efficiency of the laser and the efficiency of the opto-electronic converter.

Optical fibers have several limitations in their power transmitting capabilities. The first of these is absorption that results in heating above the melting point of the material. Silica, commonly used in optical fiber, can theoretically handle up to 100 kW of optical power in a 100-micron diameter fiber or 10 kW in a 10-micron diameter fiber [3]. However, other factors produce more stringent limitations. These are fiber fusing, end point damage, and bending failures. Fiber fusing is an effect whereby the local power density in a fiber is greatly increased due to contaminants, end point reflections, self focusing, or some other means. At this location, the fiber actually melts and forms a trigger for a second fusing event and so forth, producing a chain reaction that can propagate along the length of a fiber. Fiber fuses of as much as 1.5km have been observed [1]. End point damage is the most common form of fiber failure. This is most likely to occur at connectors where an epoxy is commonly used. The epoxy heats rapidly when illuminated by high powers (due to its higher optical absorption) and can result in melting of the end point. End point damage is less likely with non-connectorized fibers, but can still occur due to scratches or contaminants on the end point that form a point of localized heating. Bending failures can occur when a fiber is bent to a small radius of curvature. As the radius decreases, more light is coupled into the cladding of the fiber and reaches the outer plastic coating. The coating is much more absorptive and thereby heats more readily under high power.

II. TECHNICAL BACKGROUND

A. Definition

An optical fiber is a light guide governed by Snell's Law, which defines the passage from a medium of refractive index n_1 to a medium of refractive index n_2 by a light ray having an angle of incidence θ_1 as shown in Figure 1 and expressed by Equation (1) [4].

$$n_1 \sin\theta_1 = n_2 \sin\theta_2 \quad (1)$$

where:

n_1 is the refractive index of medium 1;
n_2 is the refractive index of medium 2;
θ_1 is the angle of incidence in the medium 1;
θ_2 is the angle of refraction in the medium 2.

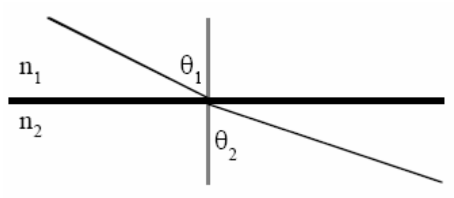

Figure 1. Snell's Law

Assuming that $n_1>n_2$, the angle of refraction is always greater than the angle of incidence ($\theta_2>\theta_1$) and tend to become 90º when de angle of incidence is less than 90º. Therefore, for angles of incidence greater than this critical value the light is reflected with high efficiency. The value of this limiting angle (φ) is expressed by Equation (2) [4].

$$\sin\varphi = \frac{n_2}{n_1} \quad (2)$$

In this way, it can be noticed that total internal reflection occurs at the interface between two mediums of differing refractive indices when: (a) the light is incident on the medium of higher index, and (b) the angle of incidence of the light exceeds a certain critical value.

B. The Numerical Aperture

The numerical aperture defines the maximum angle that the incident beam must make to ensure that it propagates in the fiber; and this section aims to obtain an equation to determine the numerical aperture [4]. When the light rays enter the fiber (Figure 2) from a medium of refractive index no ($n_1>n_2>n_0$), there will be, from Snell's Law, a relationship between the refractive indices and the incident ray of light as expressed by Equation (3).

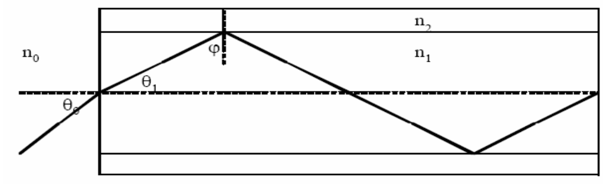

Figure 2. Angle of incidence

$$n_1 \sin\theta_1 = n_0 \sin\theta_0 \quad (3)$$

From Figure 2 it can be seen that $\sin\theta_1 = \cos\varphi$ because sine of any angle (φ) is equal to the cosine of the complementary angle (90-φ). Thus Equation (3) can be rewritten as Equation (4).

$$n_1 \cos\varphi = n_0 \sin\theta_0 \quad (4)$$

But, knowing that for any angle β, $\cos\beta = \sqrt{1-\sin^2\beta}$, and Equation (4) can be rewritten as Equation (5).

$$n_1\sqrt{1-\sin^2\varphi} = n_0 \sin\theta_0 \quad (5)$$

As the condition for reflection to occur in a fiber optic is the one expressed by Equation (2), the replacement of $\sin\varphi$ in Equation (5), results in Equation (6). With some mathematical adjustments it is possible to obtain Equation (7) [4].

$$n_0 \sin\theta_0 \le n_1\sqrt{1-\left(\frac{n_2}{n_1}\right)^2} \quad (6)$$

$$\sin\theta_0 \le \frac{\sqrt{n_1^2-n_2^2}}{n_0} \quad (7)$$

Assuming that the right-hand side of Equation (7) be lower than 1, the largest angle at which light can be transmitted through the fiber is obtained when the two sides of the equation are equal. If the right-hand side is equal 1, rays up to 90º to the axis are accepted, and at 90º the ray reaches the core-cladding interface at the limiting angle of reflection. If the right-hand side is lower than 1, rays up to 90º to the axis are accepted, but at 90º the ray reaches the interface at an angle greater than the limiting value. Therefore, the right-hand side of Equation (7) is an important expression in fiber optics and is defined as the numerical aperture (*NA*) of the fiber as shown by Equation (8) [4] .

$$NA = \frac{\sqrt{n_1^2-n_2^2}}{n_0} \quad (8)$$

The *NA* of an optical fiber is usually of the order of 0.2 to 0.3 [5]. States that practical working zone of numerical aperture for illumination are between the values of 0.4 and 0.6. The greater the *NA*, the greater the luminous power injected into the fiber because the greater the *NA*, the greater the angle of incidence, as can be seen in Figure 3 [5]. This Figure was developed for a situation where the medium 0 is the air, that is, when $n_0 = 1$.

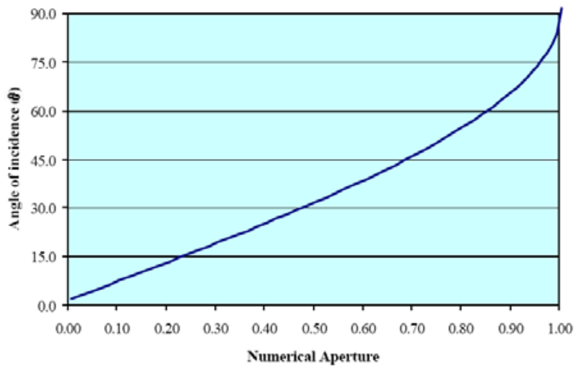

Figure 3. Equation for the angle of incidence as a function of the *NA*

Finally, having *NA*, the angle of incidence can be determined using Equation (9), derived in this work.

$$\theta = \frac{180}{\pi} a\sin(NA) \quad (9)$$

C. Attenuation Losses in dB/km

Attenuation losses are defined as a number calculated as 10 times the logarithm (base 10) of the amount of light that comes in the fiber at a particular point divided by the amount of light that goes out at a point 1km further [5]. This is shown by Equation (10).

$$\rho_{\text{dB/km}} = 10\log_{10}\left(\frac{\alpha_{in}}{\alpha_{out}}\right) \qquad (10)$$

where:

$\rho_{\text{dB/km}}$ is the attenuation loss in dB/km;

α_{in} is the amount of light that comes in the fiber;

α_{out} is the amount of light that goes out the fiber.

Through mathematical rules it is known that if $\log_{10} A = B$, then $A = 10^B$. Thus, from Equation 10), it is possible to obtain Equation (11), which becomes the first step to convert losses from dB/km to percentage.

$$\frac{\alpha_{in}}{\alpha_{out}} = 10^{\left(\frac{\rho_{\text{dB/km}}}{10}\right)} \qquad (11)$$

C.1. Losses in %/km

As it is intended to convert these losses to percentage losses, it is important to know that, in general, percentage losses are given by Equation (12).

$$\rho_{\%} = 100\left(\frac{\alpha_{in} - \alpha_{out}}{\alpha_{in}}\right) = 100\left(1 - \frac{1}{\alpha_{in}/\alpha_{out}}\right) \qquad (12)$$

Therefore, it is then possible to replace Equation (11) into Equation (12) and obtain Equation (13) derived in this work, which permits to calculate percentage losses as a function of dB/km.

$$\rho_{\%/\text{km}} = 100\left(1 - \frac{1}{10^{\left(\frac{\rho_{\text{dB/km}}}{10}\right)}}\right) = 100\left(1 - 10^{-\left(\frac{\rho_{\text{dB/km}}}{10}\right)}\right) \qquad (13)$$

Figure 4 and Table 1 present the percentage attenuation losses (%/km) as a function of dB/km obtained from Equation (13) [5].

D. Losses in %/m as a Function of dB/km

In terms of building applications it is preferable to have attenuation losses expressed per meter rather than kilometer. Therefore, it is important to deal with Lambert's Law, which states that equal lengths of material cause equal amounts of attenuation. Thus, if 1km of fiber attenuates 50.00% of the light then 2km of fiber will attenuate 76.00%, 3km 87.50% and so on in other words, attenuation is exponential. Table 2 shows the exponential variation of absorption and the equal amounts of attenuation to equal lengths. Thus, using the Lambert's Law approach, attenuation losses in the first kilometre are given by Equation (13) and ensuing losses are given by Equation (14) [6].

$$\rho_n = \rho_{n-1} + \rho_1(\rho_{n-1} - \rho_{n-2}) \qquad (14)$$

where ρ is the attenuation loss (%/km) and n is the length unit (km).

Following Lambert's Law and using Equation (14) it is now possible to determine an equation appropriate to each length unit as shown in Table 3.

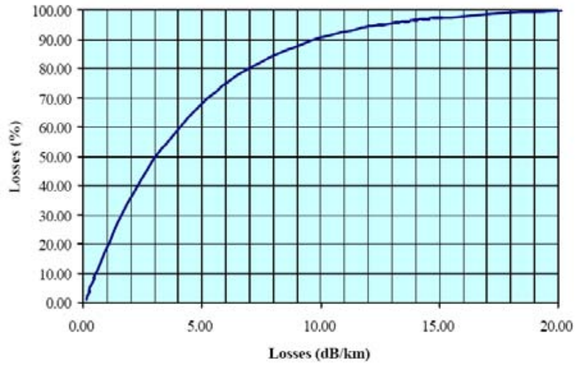

Figure 4. Variation of losses in %/km as a function of dB/km

Table 1. Losses in %/km as a function of dB/km

Attenuation losses					
(dB/km)	(%/km)	(dB/km)	(%/km)	(dB/km)	(%/km)
0.00	0.00	2.00	36.90	13.00	94.99
0.10	2.28	3.00	49.88	14.00	96.02
0.20	4.50	4.00	60.19	16.00	96.84
0.30	6.67	6.00	68.38	16.00	97.49
0.40	8.80	6.00	74.88	17.00	98.00
0.50	10.87	7.00	80.05	18.00	98.42
0.60	12.90	8.00	84.15	19.00	98.74
0.70	14.89	9.00	87.41	20.00	99.00
0.80	16.82	10.00	90.00	30.00	99.90
0.90	18.72	11.00	92.06	40.00	99.99
1.00	20.57	12.00	93.69	50.00	100.00

Table 2. Lambert's law

Length (km)	Loss (%)	Loss (%/km)
1	50.0000	50.0000
2	76.0000	50.0000
3	87.5000	50.0000
4	93.7500	50.0000
5	96.8750	50.0000
6	98.4375	50.0000
7	99.2188	50.0000
8	99.6094	50.0000
9	99.8047	50.0000
10	99.9023	50.0000

Table 3. Equations derived from equation 14

$\rho_2 =$	$\rho_1 + \rho_1^2$	$= \rho_1 + \rho_1^2$
$\rho_3 =$	$\rho_1 + \rho_1^2 + \rho_1^3$	$= \rho_2 + \rho_1^3$
$\rho_4 =$	$\rho_1 + \rho_1^2 + \rho_1^3 + \rho_1^4$	$= \rho_3 + \rho_1^4$
$\rho_5 =$	$\rho_1 + \rho_1^2 + \rho_1^3 + \rho_1^4 + \rho_1^5$	$= \rho_4 + \rho_1^5$
$\rho_6 =$	$\rho_1 + \rho_1^2 + \rho_1^3 + \rho_1^4 + \rho_1^5 + \rho_1^6$	$= \rho_5 + \rho_1^6$
$\rho_7 =$	$\rho_1 + \rho_1^2 + \rho_1^3 + \rho_1^4 + \rho_1^5 + \rho_1^6 + \rho_1^7$	$= \rho_6 + \rho_1^7$
$\rho_8 =$	$\rho_1 + \rho_1^2 + \rho_1^3 + \rho_1^4 + \rho_1^5 + \rho_1^6 + \rho_1^7 + \rho_1^8$	$= \rho_7 + \rho_1^8$
$\rho_9 =$	$\rho_1 + \rho_1^2 + \rho_1^3 + \rho_1^4 + \rho_1^5 + \rho_1^6 + \rho_1^7 + \rho_1^8 + \rho_1^9$	$= \rho_8 + \rho_1^9$
$\rho_{10} =$	$\rho_1 + \rho_1^2 + \rho_1^3 + \rho_1^4 + \rho_1^5 + \rho_1^6 + \rho_1^7 + \rho_1^8 + \rho_1^9 + \rho_1^{10}$	$= \rho_9 + \rho_1^{10}$

Therefore, attenuation losses per length unit will be given by Equation (15), derived in this work.

$$\rho_{(n-1)\to n} = (\rho_n - \rho_{n-1})^{\frac{1}{n}} = \frac{\rho_n - \rho_{n-1}}{\rho_{n-1} - \rho_{n-2}} = \rho_1 = \text{constant} \quad (15)$$

Where ρ is the attenuation loss in %/km or %/m and n is the length unit in km or m.

It must be remembered that if attenuation is given in dB per km, then percentage losses will also be per km. Losses per meter can again be calculated following Lambert's Law. Therefore, using equations in Table 3 it is noticed that when ρ_{10} is a known %/km loss, ρ_1 will be the equivalent %/100m. When this ρ_1 becomes ρ_{10}, the new ρ_1 will be equivalent to %/10m and so on. In this way, developing an equation of a factor $(\rho_{\%/km})/(\rho_{\%/m})$ as a function of $(\rho_{\%/km})$ it is possible to obtain an equation of $\rho_{\%/m}$ as a function of $\rho_{dB/km}$. This is expressed by Equation (16), derived in this work.

$$\frac{\rho_{\%/km}}{\rho_{\%/m}} = 0.03\rho_{\%/km} + 1 \quad (16)$$

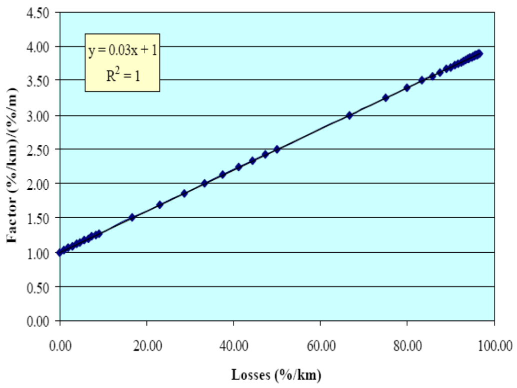

Figure 5. Determination of the factor $(\rho_{\%/km})/(\rho_{\%/m})$ as a function of $(\rho_{\%/km})$

The variation of the factor $(\rho_{\%/km})/(\rho_{\%/m})$ as a function of $(\rho_{\%/km})$ is shown in Figure 5 where $y = 0.03x + 1$. Similarly, it is possible to determine factors of (%/km)/(%/10m) and (%/km)/(%/100m) as shown in Equations (17) and (18), respectively, which were also developed in this work.

$$\frac{\rho_{\%/km}}{\rho_{\%/10m}} = 0.02\rho_{\%/km} + 1 \quad (17)$$

$$\frac{\rho_{\%/km}}{\rho_{\%/100m}} = 0.01\rho_{\%/km} + 1 \quad (18)$$

Finally, using Equations (13) and (16), Equation (19) shows the formula to determine losses in %/m as a function of dB/km. This equation and also the following ones were derived in this work.

$$\rho_{\%/m} = \frac{100\left(1-10^{-\left(\frac{\rho_{dB/km}}{10}\right)}\right)}{4\left(1-\frac{3}{4}10^{-\left(\frac{\rho_{dB/km}}{10}\right)}\right)} \quad (19)$$

Similarly, it is possible to determine losses in %/10m and %/100m as shown by Equations (20) and (21), respectively.

$$\rho_{\%/10m} = \frac{100\left(1-10^{-\left(\frac{\rho_{dB/km}}{10}\right)}\right)}{3\left(1-\frac{2}{3}10^{-\left(\frac{\rho_{dB/km}}{10}\right)}\right)} \quad (20)$$

$$\rho_{\%/100m} = \frac{100\left(1-10^{-\left(\frac{\rho_{dB/km}}{10}\right)}\right)}{2\left(1-\frac{1}{2}10^{-\left(\frac{\rho_{dB/km}}{10}\right)}\right)} \quad (21)$$

Through some mathematical rules, Equations (19) to (21) can be rewritten in a better way as shown by Equations (22) to (24).

$$\rho_{\%/m} = \frac{100}{3}\left(1-1\Big/1+3\left(1-10^{-\left(\frac{\rho_{dB/km}}{10}\right)}\right)\right) \quad (22)$$

$$\rho_{\%/10m} = \frac{100}{2}\left(1-1\Big/1+2\left(1-10^{-\left(\frac{\rho_{dB/km}}{10}\right)}\right)\right) \quad (23)$$

$$\rho_{\%/100m} = 100\left(1-1\Big/1+\left(1-10^{-\left(\frac{\rho_{dB/km}}{10}\right)}\right)\right) \quad (24)$$

If attenuation losses are given in dB/m, losses in %/m should be determined directly through Equation (13). Using the equations previously presented, attenuation losses in %/m, %/10m, %/100m and %/km as a function of losses in dB/km were calculated and are shown in Figure 6 and Table 4 [5-6].

E. Losses in %/m as a Function of the Length

Through the development of the equations presented previously, it was noticed that there are factors of 3, 2 and 1, respectively for attenuation losses per 1m, 10m and 100m. This logarithmic variation shows that it is possible to have factors for specific lengths of fiber and these factors can be determined by using Equation (25), derived in this work. This equation is obtained through the chart presented in Figure 7.

$$\delta = -0.4343\ln(x) + 3 \quad (25)$$

Therefore, attenuation losses in a specific length of fiber (x) will be given by equation 26, which is valid for fiber lengths shorter than 1000m. [7].

$$\rho_{\%/xm} = \frac{100}{\delta}\left(1-1\Big/1+\delta\left(1-10^{-\left(\frac{\rho_{dB/km}}{10}\right)}\right)\right) \quad (26)$$

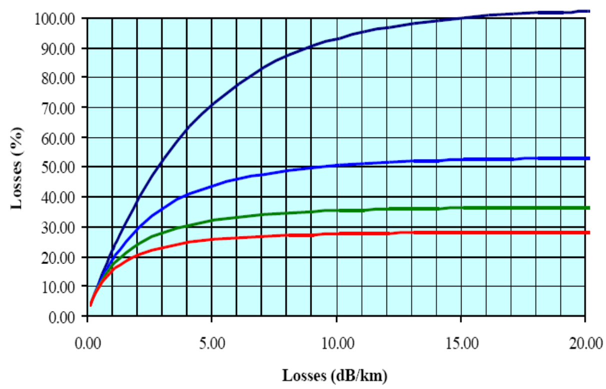

Figure 6. Variation of losses in percentage as a function of dB/km

Table 4. Attenuation losses in percentage as a function of dB/km

	Attenuation losses			
(dB/km)	(%/km)	(%/100m)	(%/10m)	(%/m)
0.0	0.00	0.00	0.00	0.00
0.1	2.28	2.23	2.18	2.13
0.2	4.50	4.31	4.13	3.97
0.3	6.67	6.26	6.89	6.56
0.4	8.80	8.09	7.48	6.96
0.5	10.87	9.81	8.93	8.20
0.6	12.90	11.43	10.26	9.30
0.7	14.89	12.96	11.47	10.29
0.8	16.82	14.40	12.59	11.18
0.9	18.72	16.77	13.62	11.99
1.0	20.57	17.06	14.57	12.72
2.0	36.90	26.96	21.23	17.51
3.0	49.88	33.28	24.97	19.98
4.0	60.19	37.57	27.31	21.45
6.0	68.38	40.61	28.88	22.41
6.0	74.88	42.82	29.98	23.07
7.0	80.05	44.46	30.78	23.53
8.0	84.15	46.70	31.36	23.88
9.0	87.41	46.64	31.81	24.13
10.0	90.00	47.37	32.14	24.32
11.0	92.06	47.93	32.40	24.47
12.0	93.69	48.37	32.60	24.59
13.0	94.99	48.71	32.76	24.67
14.0	96.02	48.98	32.88	24.74
15.0	96.84	49.20	32.97	24.80

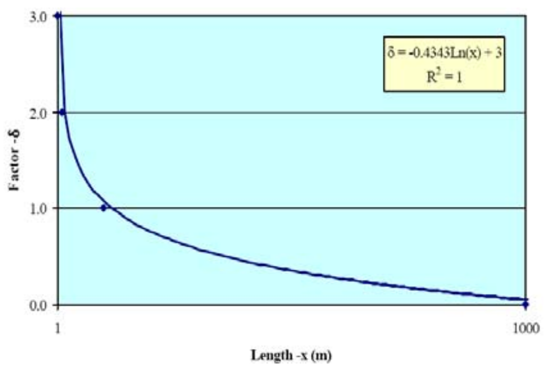

Figure 7. Determination of a logarithmic factor as a function of the fiber length

F. Flexibility

Fiber optics is produced in long lengths and so it is impossible to handle them without bending. Manufacturer's guidelines on bending radii should be followed, otherwise bending stresses can be produced, which reduces the life span of the fiber and affects the system reliability [4]. In this respect, fiber flexibility must be known because fiber-optic cables have to be bent when used in building applications.

Reference [6] suggests a minimum bend radius of 8 times the core diameter when fibers are end-emitting and 4 times the core diameter when fibers are side-emitting. Reference [6] recommends a minimum bend radius of 30mm. States that glass fibers should not be bent more than 10 times (radius) the diameter of the light guide. For plastic fibers the bend radius should be between 4 and 10 times the diameter of an individual fiber. Reference [8] also emphasizes that no type of fiber should be bent beyond 90°. However, that author does not mention that if bend radius is large fiber can be bent past 360°.

G. Life Span

When fiber optics are installed and cabled in accordance with recommended procedures it is expected that the fibers have a long service life [7]. Reference [7] mention that the expected life span of their fiber optics is higher than 30 years. Reference [8] reports that optical fibers are specifically designed to operate for more than 40 years. Reference [10] states that there are operating examples of glass fibers over 30 years old.

H. Typical diameters of Fiber Optics

In Reference [11] typical fiber diameter are presented as follows: Glass fibers have a diameter typically between 0.05 and 0.15mm; Small plastic fibers have a diameter typically between 0.13 and 2.03mm; and Large plastic fibers have a diameter typically between 2.03 and 11.94mm. Nowadays, the international standard is to have cladding diameter of 125μm. Table A.5 shows typical fiber optics sizes [11]. It is possible to obtain multimode fibers in several core sizes, however, the most commonly used sizes are 50μm and 62.5μm.

Table 5. Fibre optic sizes

Fibre optic type	Diameter (μm)	
	Core	Cladding + Core
Single-mode	8-10	125
Multimode	50	125
	62.5	125

The difference between single-mode or mono mode and multimode fibers is that the latter have a much larger core than the former, which permits hundreds of rays, or modes, of light to be propagated through the fiber simultaneously.

Single-mode fibers have a much smaller diameter, which allows only one mode of light to be propagated through the core. Reference [6] reports that single-mode fibers have higher information-carrying capacity because they can retain the integrity of each light pulse over longer distances. Reference [6] manufactures their fiber optics in different diameters as shown in Table 6.

Table 6. Fibre optic sizes

Fibre optic type	Diameter (mm)	
	Core	Cladding + Core
End-emitting	3.1	6.5
	4.8	7.4
	6.4	9.0
	9.5	12.8
	12.7	17.7
	18.0	26.3
Side-emitting	4.7	6.7
	6.0	7.0
	8.8	10.2
	12.2	13.7

I. Strength

Fiber optics, despite being made of glass or plastic, are not fragile. Fibers are proof-tested to a minimum stress level equal to 100kpsi [7]. The theoretical strength of fiber optics is 2,000kpsi, and typical strength is about 600kpsi [7].

J. The effect of water

In most outside applications, water will have little effect on the performance of fiber optics. Nevertheless, if fiber optics are under tension and in presence of moisture, a flaw may grow, causing fibers to break [4].

K. Maintenance and Installation

Reference [11] demonstrated empirically that actual field ageing of a fiber optic cable does not degrade the fiber's ability to be handled. That was verified even after five years of field ageing concluding that there is no difficulty in handling fiber optics for maintenance and also for installation. Fibers need to be kept clean. Therefore, dirt, moisture and oil from an operator's hands need to be avoided when handling them [9] 1psi=703.235kg/m^2=0.0703235kg/cm^2; 1kpsi=703,235kg/m^2=70.3235kg/cm^2.

III. APPROACH OF OPTICAL POWER CONVERSION

Optical power converters produced by Photonic Power Systems were acquired for the purpose of testing the ultimate limitations of optical power transfer using off-the-shelf components. These power converters are advertised as having a high efficiency of about 50%. They are optimized for this efficiency only over a narrow wavelength range from 790-850 nm. They use a specially designed photovoltaic cell to convert the input optical power to electrical power. The power converters are designed to produce a specific voltage and have impedance that decreases with increasing optical power. Thus, to maximize the efficiency, the load impedance must be selected to match the level of incident light. For these approaches, with a 1000 ohm load, this converter is most efficient at about 80mW, with a 53% conversion efficiency. Below this light level, voltage and current are each reduced linearly with optical power. Above 100mW, the current and voltage do not increase.

The efficiency for several load impedances at different optical power levels is shown in Figure 8 with the maximum power converted in Table 3. A 100 ohm load is probably approaching the practical limit for these converters. With 700mW of optical power incident on the converter, the metal package of the converter exhibits significant heating. Proper heat sinking could alleviate this, however, the manufacturer does not spec the output, so there is probably a risk of damage at optical powers much higher than 1 watt.

In theory, an unlimited number of converters could be connected together via fused couplers to further increase the power so as to keep the incident optical power on a single converter below 1 watt. However, other factors intervene to provide an upper limit to the number of converters possible and the amount of power that can be converted.

Different load impedances do not result in any differences in maximum efficiency, but the maximum power that can be converted from optical to electrical increases substantially using a lower resistance load. This indicates the importance of careful circuit design when using these powers.

IV. DISCUSSIONS

Optical fibers with a higher damage threshold would permit transmission of higher optical powers. The photonic power converters tested here are limited in their ability to convert large amounts of optical power to electrical power, mainly due to their susceptibility to thermal damage. The development of larger area converters would allow more power to be incident on a single converter for the same power density, reducing heating.

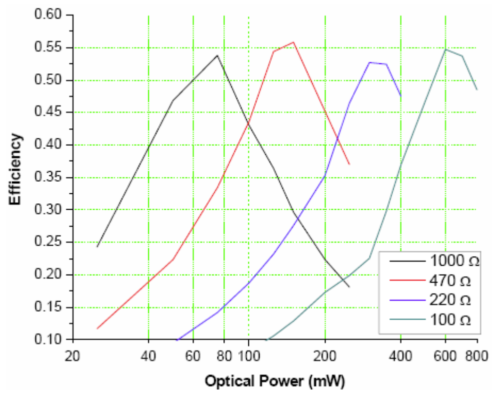

Figure 8. Efficiency of a power converter under various loads as a function of input optical power

A number of techniques are being developed to increasing the ability of optical fibers to safely handle high powers. Most failures appear to occur at connection interfaces, which in a real working environment are even more susceptible to damage through the introduction of contaminants or physical damage from disconnects and reconnects. Methods of reducing the risk of connector failure through the use of a special type of connector that isolates the fiber from the connector ferrule have recently been commercially developed. One approach uses a sleeve of quartz or high-temperature ceramic around the fiber along with a high temperature epoxy to achieve sustained 200 ◦C temperatures. Another approach uses a milled out ferrule where the fiber extends forward through air to the face of the connector. In this way, the epoxy is spaced room the region of maximum optical power, reducing the likelihood that it will burn.

Both of these approaches can still suffer from contamination and physical end point damage. A different approach is to create a new connector type that expands and collimates the beam through the use of small lenses. The fiber end points are mounted such that they are suspended in air away from any other surfaces shown in Figure 9.

The portion of the connectors containing the end face can be assembled in a clean environment and sealed, preventing contamination in the field. The only exposed part is the lens face where the optical power density is comparatively low. Contaminants or scratches in this location would not result in localized heating or damage to the fiber.

With this connector, the damage threshold should approach that of un-connectorized fiber. The limitations of silica as a fiber material are evident in the process of fiber fuse. Other materials, such as sapphire, have been investigated for higher power applications. Sapphire has a melting point of 2000 ◦C but is much more rigid and difficult to manufacture than silica fibers.

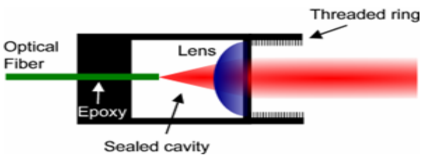

Figure 9. High power fiber optic connector uses a lens to permit a separation between fiber end faces and a lower power density, along with a suspended fiber in a sealed cavity to prevent epoxy melt and end face contamination or scratching.

V. CONCLUSIONS

It is known that buildings account for high amounts of energy consumption all over the world and that artificial lighting systems are responsible for high percentages of this consumption. Since the 1980s, lighting equipment has seen great improvements in its energy efficiency and this has subsequently helped to improve the energy efficiency of buildings. However, many of the buildings in the world, even new ones, are still energy inefficient and lack well-designed integration of daylight with artificial lighting systems. This work has assessed the role of windows on daylight supply by quantifying energy savings likely to be achieved by integrating daylight with artificial light. The potential for even higher energy savings by using fiber optics to provide daylight to the rear side of rooms was also investigated.

The first part of the work focused on the assessment of daylight provision on the working surfaces of rooms of different dimensions, room ratios and window areas through the calculation of Daylight Factors. It was observed that if there was integration of daylight with the artificial lighting system significant energy savings could be achieved. It was also found that there was still a high potential for energy savings on lighting in either large rooms or rooms with a narrow width. This was an indication that if new technologies, such as fiber optics, could be used to transport daylight to the rear side of rooms, there could be a further increase made to the energy savings on lighting.

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