Power Transmission by Optical Fibers for Component Inherent Communication

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Abstract

The use of optical fibers for power transmission has been investigated intensely. An optically powered device combined with optical data transfer offers several advantages compared to systems using electrical connections. Optical transmission systems consist of a light source, a transmission medium and a light receiver. The overall system performance depends on the efficiency of opto-electronic converter devices, temperature and illumination dependent losses, attenuation of the transmission medium and coupling between transmitter and fiber. This paper will summarize the state of the art for optically powered systems and will discuss reasons for negative influences on efficiency. Furthermore, an outlook on power transmission by the use of a new technology for creating polymer optical fibers (POF) via micro dispensing will be given. This technology is capable to decrease coupling losses by direct contacting of opto-electronic devices.

Keywords: polymer optical fiber, power transmission, micro dispensing, component inherent communication

1. INTRODUCTION

The concept of optical powering has been initially mentioned by DeLoach. In the late 1970s he presented a paper describing the activation of a remote sound alerter by optical means only [1]. Since this work has been published, different systems have been developed to take advantage of optical power. All researchers are guided by the advantages of optical power transmission which are based on the immunity to all forms of electromagnetic interference, short circuits and sparks [2]. Optical fiber is less bulky than copper cabling and is capable to operate over long distances [3]. It is also resistant to corrosion and moisture [4]. The field of applications is widely spread. The technology is applied to systems for remote sensing, for powering networks and is even used in medical applications [5, 6]. Generally there are two different architectures used for optical power transmission, wavelength division multiplex (WDM) and space division multiplex (SDM) or a combination of both [7]. The second section of this paper will outline WDM and SDM. Afterwards the use of these technologies for optical power transmission will be explained in detail citing diverse examples. In the third section different parameters such as photovoltaic converter efficiencies, temperature and illumination related losses, fiber attenuation and coupling losses will be specified. Based on the state of the art a new method for optical power transmission by dispensed POF has been developed. A prospect of this new method and its application within component inherent communication will be given. Finally a summary will complete this paper.

2. DESCRIPTION OF MULTIPLEX-TECHNOLOGIES

Multiplex-technologies are known to increase the channel capacity. For example, WDM has been first established due to the need for higher transfer rates within glass fibers. Even for duplex communication systems WDM is state of the art. Different wavelengths are used to modulate separate channels in one fiber. In principle different carrier frequencies are emitted by the source. Combination, separation or filtering is carried out by optical means only. In experimental setups using glass fiber the separation of 100 different channels has been demonstrated. By using POF Mizusawa proposed a system running by four different wavelengths. The sources are directly positioned in front of the fiber with a distance of 125 µm, adjusted quadratically. The receivers are adjusted in the same way. The emitted light is separated by the use of dielectric filters [8]. For duplex communication Takezawa developed a system, whose 830 nm source sends a 6 MHz signal, and simultaneously a different source of 660 nm emits a 10 kHz control signal [9]. An increase of performance was achieved by significantly larger diameters for photodiodes compared to typical LEDs. Both components were positioned on top of each other [10].

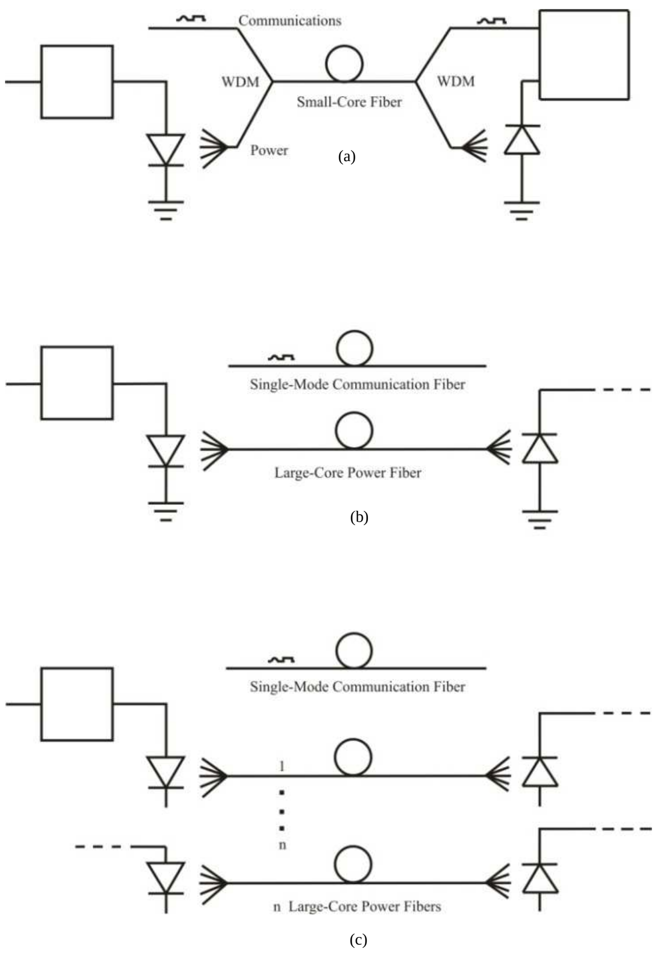

Fig. 1. Powering Architectures. a) Power and data multiplexed on a small-core communications fiber by WDM. b) Separate (single) power fiber. c) Multiple power fibers.

If the fiber characteristics are restricted to a limited number of wavelengths, which can be modulated as different data channels, SDM is an alternative. SDM means the separation by the use of two or more fibers. This, of course, will raise the costs. Based on the idea of increasing channel capacity, these technologies were transferred to the main architectures for optical power transmission. In figure 1 the differentiation made by Banwell is shown schematically [7].

3. APPLICATIONS OF POWER BY LIGHT SYSTEMS

Overview of Power by Light Systems

Besides the research mentioned above, different scientists have worked on the development of optically powered systems. Many papers deal with optical power delivery for network applications. In the early 1990s a review of alternatives for powering equipment at the customer end of an optical Customer Access Network has been done by Kuhn [11]. At this stage he mentioned optical power delivery as an elegant solution, but this specific application was not feasible by then because the delivered optical power did not meet the requirements. Within experimental investigations he reached an overall output power of 0.5 W. Miyakawa presented a fiber optic power and signal transmission system for a local area network [12]. A system module for passive optical networks, which deliver the power using the same fiber bundle that is transmitting the data, is described by Werthen [13]. For powering a remote node within network applications, Lee [14] used WDM. Optically powered splitters [15], fiber optic manifolds [16], monitoring systems and signal measurement for feedback control [17, 18] are further applications. Furthermore, Peña [19] designed a 205 mW system to power remote units. In experimental setups, for example to determine the characteristics of radiated electric fields of anechoic chambers [20] and in medical applications to power eye implants [21, 22], power transmission via optical fibers is of main interest. Examples for remote optical powering of sensors are shown in [23, 24].

Space Division Multiplex Used for Optical Power Transmission

Separate or multiple fibers are used for SDM technology. Below different application examples are described in detail to give an overview of the capability of this technology. Dahlmann [25] has developed a remote power supply unit for an electrically isolated sensor system. This system, using one optical fiber for energy supply and the second fiber to transfer the signals, is capable to supply a voltage of 5 V at the remote part. Optical power of about 15 mW is launched into a 200/230 µm gradient index fiber. Inside the measuring head a power converter transfers the optical power back to electrical energy. Therefore, GaAs-diodes connected in series are used. They have a circular shape and deliver an electrical energy of 6 mW. Once the power storage device, represented by a capacitor, reaches a value of 5 V, the sensor head sends a short impulse to indicate readiness of operation. Recharge time for the power storage device is about 500 ms.

Yasui [4] and co-workers developed a stable 2 W system with an integrated feedback control function and a safety function, which shuts down the laser if an optical fiber is cut. This system provides a continuous energy flow and is capable to work in high-voltage environments without malfunction. A laser diode operating at a wavelength of 808 nm delivers a maximum power of 3 W. The light is launched into a 200 m step index silica fiber (200 µm core diameter) and converted by a photovoltaic cell. Six segments (circular sectors) connected in series are protected by a heat sink in order to avoid temperature increase even if the cell is illuminated at high optical power. The performance of this system is limited by fiber loss and efficiencies of system components such as a photovoltaic cell and a laser diode. The fiber loss due to attenuation is denoted with 10 %. Optical power transmitted into the photovoltaic cell is 1.4 W with an efficiency of 31%. One unit is capable to deliver 430 mW, by connecting five units in parallel the system will deliver continuous output power of 2 W.

Valentine [26] presented a system working between a central office in a telecom network and a high voltage transformer substation. It is a 3 fiber system, 2 of the fibers transmit energy at a wavelength of 830 nm and the third fiber transfers signals over a maximum distance of approximately 450 m. Every energy channel has an output voltage of 12 V. To tie these two photovoltaic power converters in series a voltage of 24 V is generated.

Wavelength Division Multiplex Used for Optical Power Transmission

Liu and co-workers set up a system to provide power and signals at different wavelengths. They are multiplexed to a single 50 µm core step index fiber and demultiplexed at the remote side of the unit. The idea behind this system configuration is an optimization for data detection and power conversion. Therefore different transmitters and receivers are used. A 40 mW AlGaAs laser (820 nm) for power supply and an InGaAsP laser (1300 nm) for data transmission are affixed on the transmitter side. Three large area GaAs photovoltaic cells convert the power. The 820 nm wavelength signal is split into three beams with a power ratio of 2:2:1 to supply a photo detector (used for signal detection at 1300 nm) and a preamplifier. For collimating the laser beams gradient index rod lenses are used and for multiplexing a dichroic filter [27].

An optically powered video camera link by WDM is described by [28]. System characteristics are as follows: 1 W of optical power at a wavelength of 810 nm is coupled into a single gradient-index multimode fiber. The video stream is transmitted at 1310 nm. Combination and separation of both wavelengths are carried out by thin-film-filter-based wavelength-division couplers. To convert the optical into electrical power a single GaAs photovoltaic cell is optimized for illumination of 810 nm. This cell was designed by Fraunhofer ISE (Institute for Solar Energy Systems) and is tolerant to partial illumination. This system delivers 100 mW to the remote part and has a continuous data stream of 100 Mbit/s.

4. INFLUENCES ON SYSTEM PERFORMANCE

General Aspects on System Design

An optical powered system consists of a light source, a transmission medium and a light receiver. For this reason the overall system performance is influenced by different parameters, such as temperature increase of semiconductor materials or fiber attenuation. Limitations of overall system performance mostly depend on the efficiencies of the transmission medium and the photovoltaic converters. In this section general design requirements of photovoltaic cells are given. After that the efficiencies of common semiconductor materials used for power by light applications are summarized. Afterwards the losses caused by temperature effects and by mismatched illumination are discussed. Finally the attenuation affected losses of the transmission medium will be displayed.

Peña [29] defines typical design requirements of optical power receivers as follows:

- The spectral range of the light source must match the one of the photovoltaic converter.
- To supply any remote equipment, the output voltage must be matched to the application.
- Sufficient output power must be supplied to the remote unit.
- Degree of efficiency has to be as high as possible.
- To obtain efficient coupling of optical power to the receiver, shape and size of light spot and device have to be matched.
- Operation of the receiver has to be in photo sensor mode.
- Operating life time has to match the system lifetime.
- Endurance to the specific environmental and application conditions.

Efficiencies of Common Photovoltaic Converter Materials

The most important single indicator of the performance of photovoltaic devices is the power conversion efficiency [30]. Therefore, it is necessary to determine the optimum of optical input power and the device conversion efficiency [31]. Research on the field of a high current density laser power converter for different application such as the operation in photovoltaic concentrator modules [32] or special investigations on GaAs photodiodes for light wave network applications [33] are supported by the deeper understanding and characterization of semiconductor materials for optical to electrical power conversion. Most common are Silicon (Si), Gallium Arsenide (GaAs), Indium Gallium Arsenide (InGaAs) and Gallium Antimonide (GaSb). Main differences between these materials can be found in open circuit voltage for a single cell converter. In table 1 the open circuit voltage U_{OC} and the energy gap E_g for different semiconductor materials at 300 K are shown.

TABLE I

Open circuit voltage and energy gap for common photovoltaic materials

Semiconductor materials	U_{OC} [V]	E_g at 300 K [eV]
Si	0.7	1.12
GaAs	1.0	1.42
InGaAs	0.5	0.74
GaSb	0.5	0.73

Because of the low output value of a single Si cell a voltage booster or an array of several converter cells in series is necessary. Besides the high open circuit voltage, GaAs has a great stability over a wide range of temperatures. InGaAs and GaSb are on the same output voltage level. Within different experiments efficiencies of 34% (InGaAs) and 40% (GaSb) were shown [34]. For GaAs cells efficiencies of over 52% have been reported [35].

Losses Induced by Temperature

Because photovoltaic cells operate over a wide range of temperatures and irradiances, the temperature and irradiance-related behavior must be known [36]. Material dependence on temperature shows different behavior for common semiconductor photovoltaic cells. GaAs cells are well known to be less sensitive to increased temperatures [37]. The short circuit current tends to increase slightly. Nevertheless, to accurately model electrical performance over a wide range, four temperature coefficients (for I_{mp}, V_{mp}, I_{SC} and V_{OC}) are necessary and sufficient. Details regarding the system engineering of photovoltaic cells and the correct use of temperature coefficient are given by King [38]. The current and voltage at the maximum power point are represented by I_{mp} and V_{mp}. The theoretical power is given by the short circuit current I_{SC} and open circuit voltage V_{OC}. Combining these values the fill factor (FF) is defined as the ratio (given as a percentage) of the actual maximum obtainable power to the theoretical power.

$$FF = \frac{V_{mp} * I_{mp}}{I_{SC} * V_{OC}}$$

Negative temperature dependency of the FF is caused by high intensity illumination of photovoltaic cells [39]. A theoretical study of the performance and optimization of monolithically series-connected GaAs photovoltaic converters under homogeneous monochromatic illumination was made by Peña [40]. The work describes the effects of power densities of the maximum achievable efficiency related to the influences of device area and series resistance. Increased temperatures are not the only restricting factors for photovoltaic cells. In the next paragraph illumination affected losses will be discussed.

Losses Induced by Illumination

Optical input power fluctuation and mismatch illumination have an impact on electrical output power. Miyakawa [41] and co-workers have intensely analyzed the photovoltaic cell characteristics by illumination with high intensity laser light. An optical input fluctuation of ± 14% of 1.0 W/cm² leads to a voltage output fluctuation of 1.0 % for single crystalline silicon (sc-Si) and 0.47% for GaAs photovoltaic cells. As a result optical power transmission, even if the light intensity will change slightly, leads to stable voltage output. For this experimental analysis the quantum efficiency was 0.93 for sc-Si and 0.65 for GaAs at a wavelength of 808 nm. The measured open circuit voltage stably stays at a level of 0.59 V for sc-Si and 1.05 V for GaAs. To evaluate the mismatch of illumination on the efficiency, Peña [42] carried out a study of monolithically series-connected GaAs photovoltaic converters under laser illumination. This work shows that mismatch illumination influences the device performance in following aspects:

- Photocurrent is limited by the sector which receives the lowest light power.
- Partially illuminated sectors causes an increase in some contributions to series resistance.
- Laser light which is taken out of the active area is lost power, called spillage losses.

The limited photocurrent and partially illuminated sectors lead to different current-voltage characteristics for each sector and to mismatch losses. In order to minimize light spillage the laser beam diameter could be arranged smaller than the diameter of the device, resulting in increased nonuniformity in illumination of each sector when there is misalignment. This will cause an increase in mismatch losses as well. If the beam diameter will be increased to values larger than the device, light spillage will increase, but nonuniform illumination losses will be decreased dramatically or even eliminated. A maximum efficiency will be achieved if low optical power intensity illuminates large area cells. For high power applications a small active area is required, even if it leads to decreased efficiency.

Losses Caused by the Transmission Medium

Taking the losses mentioned above into account it is possible to characterize one part of the overall power by light system efficiency. With respect to the transmission medium (the optical fiber) attenuation occurs by coupling optoelectronic transmitters and receivers to the fiber. These coupling losses and fiber attenuation are also restricting parameters to the overall system performance. A definition of fiber attenuation measurements are given by Peitscher and Paar [43, 44]. It is essential to characterize the fibers in the same way and make them comparable to each other. The attenuation behavior for silica and POF leads to similar physical effects. Differences have to be made between single mode and multi mode fibers. For POF only passive transmission systems exist, that means that amplifiers being currently developed are not able to play an important part in the near future. For that, all elements belonging to the transmission system are affected by losses.

Another fact is that optical fibers, especially POF because of its low glass transition temperature, are limited to a maximum of optical power that can be launched into the fiber. Dovolnov [45] shows in theoretical and experimental investigations temperature dependency of POF for optical power transmission. With increased light power the core temperature will increase significantly.

Coupling losses of the transmitter to fiber interface are caused by unideal fiber end surfaces and by refraction index difference between air and fiber. This will lead to reflections and losses of light that is launched into the fiber. The critical source parameter describes the dependence of emitted light by the angle relative to the optical axis. Receiver coupling to the fiber is mentioned as relatively easy because of the well known far field characteristics of diodes. Performance losses within photovoltaic cells have been summarized before. Therefore the fiber attenuation will be described more detailed.

Mainly the attenuation losses within an optical fiber can be summarized by following aspects:

- Rayleigh diffusion
- Absorption
- Losses through geometrical interferences at cladding-core interface
- Losses due to attenuation within the optical cladding

Rayleigh diffusion (scattering of electromagnetic wave on orbicular particles, at which the particles diameter is small compared to the wavelength) and absorption are volume limited processes. This means all modes are affected by these processes. Absorption is mainly caused by impureness of hydroxyl ions [46]. Geometrical interferences at cladding and core interface and attenuation within the optical cladding are dependent on the angle under which the light propagates in the fiber. Mode conversion and mode coupling describe the influences of bended fibers and inhomogenities of fibers. The Goos-Hänchen-Shift explains the effect of planar waves along a surface and the infiltration of the optical cladding in the range of the wavelength by the electric field. That means every reflection at the core-cladding-interface will lead to higher attenuation because of the narrow cladding behavior [47].

5. METHOD FOR POWER TRANSMISSION BY DISPENSED OPTICAL FIBERS

Dispensed Optical Fibers

Within a research project, part of an Independent Junior Research Group in a Collaborative Research Centre Program (SFB), SFB 653 - Gentelligent Components in their Lifecycle - Utilisation of Inheritable Component Inherent Information in Production Engineering, a new production process for directly applied POF has been developed at the Institute of Transport and Automation Technology (ITA). Using micro dispensing it is possible to apply POF in surface integrated structures or on top of 3D-shaped metallic devices [48].

In the first production step, after creating the trench structure, the first cladding will be dispensed. Due to low material viscosity and surface tension the adhesive is allocated regularly in the trench. In a second step, the core material is filled in the cured lower cladding. By covering the core with the second part of the cladding the structure is closed. After each step the applied polymers have to be cured with UV-radiation. In figure 2 the production steps are shown schematically.

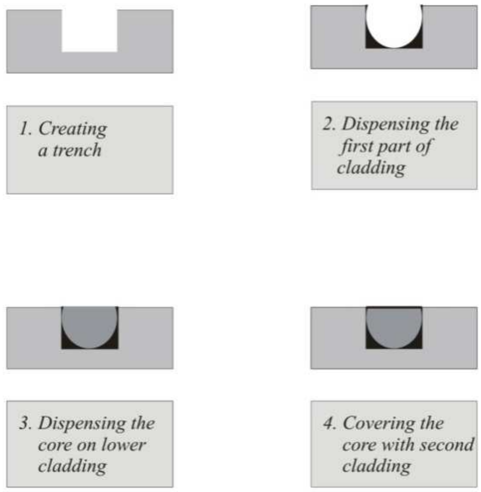

Fig. 2. Production steps for surface integrated dispensed POF

One advantage of this production process is the high flexibility and selectivity. Furthermore a direct coupling of laser- and photodiodes is possible within this process [49]. Therefore the coupling losses are assumed to be less than in conventional fiber applications. Figure 3 shows an optically contacted laser diode by using micro dispensing.

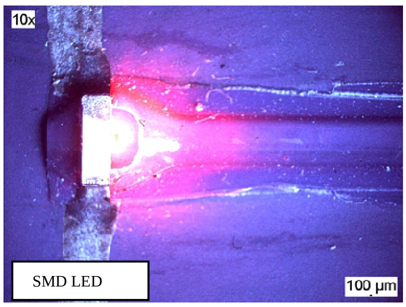

Fig. 3. Directly connected SMD-LED using micro dispensing

Power Transmission by Dispensed Optical Fibers

Taking influences mentioned above into account, which will decrease the overall efficiency of power by light systems, dispensed optical fibers show advantages for optical power transmission. The complexity of system design in order to determine an efficient power by light system was shown before. By using micro dispensing coupling losses can be reduced. The possibility of direct contacting is new and advantageous. In order to supply energy to a remote unit on a device, dispensed fibers will be a solution. Because of the high selectivity and flexibility it is an innovative way to ensure component inherent information and energy transmission.

The new method for power supply bases on Mode Group Diversity Multiplex (MGDM). MGDM means the separation of different angels under which the light propagates in the fiber. Within MGDM it is possible to create different mode groups and to detect these different angels independently [50]. By MGDM varied excitation conditions are used to generate separate channels within the fiber. This is a length depending process, which means that the detection of different mode groups is possible only for short distances. Schöllmann [51] demonstrated the successful implementation of MGDM to increase the channel capacity within an experimental setup, using a GI-POF of 10 m length. Dispensed fibers are suitable to apply POF directly on devices; hence this process can be fully integrated into a highly automated production area. Furthermore, these fibers are used for short distance applications. Therefore, they are suitable for MGDM technology. In further investigations the MGDM technology will be analyzed regarding the interactions of propagated light emitted by directly coupled laser diodes and photovoltaic converter cells.

6. SUMMARY

Power by Light (PBL) Systems are attractive to use in harsh environments and special applications due to their convenient characteristics, immunity to all forms of electromagnetic interference, short circuits and sparks. Over the last years a lot of research works in the field of optical powering and development of PBL systems has taken place. During that time the understanding of fiber technologies for optical data and energy transmission and the behavior of semiconductor materials regarding data detection and optical power conversion has increased a lot. The main aspect of correct PBL system designing is to match the requirements.

For SDM systems with photovoltaic cells connected in series an output voltage of 24 V was reached. Even high data rates of 100 Mbit/s with simultaneous power transmission are achieved by WDM. All these systems need a complex design. For SDM multiple fibers for energy and data transmission are necessary. The use of WDM technology requires the combination and separation of different wavelengths. This results in coupling losses and complex system design as well.

An important fact for the future is the flexibility of processes to apply PBL systems with a high selectivity. Applications for optical fibers on printed circuit boards or directly on devices in the automotive industry to power remote sensor systems are possible. Many applications do not need very high data rates or lot of energy but a low cost production process. Leading to a high degree of flexibility and selectivity a new approach for processing of optical fibers has been developed. With micro dispensing it is possible to create optical fibers on 3D shaped devices. Furthermore, direct contacting of electro-optical elements is possible. The capability of MGDM for optical power and data transmission within short distances was shown.

7. ACKNOWLEDGEMENT

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