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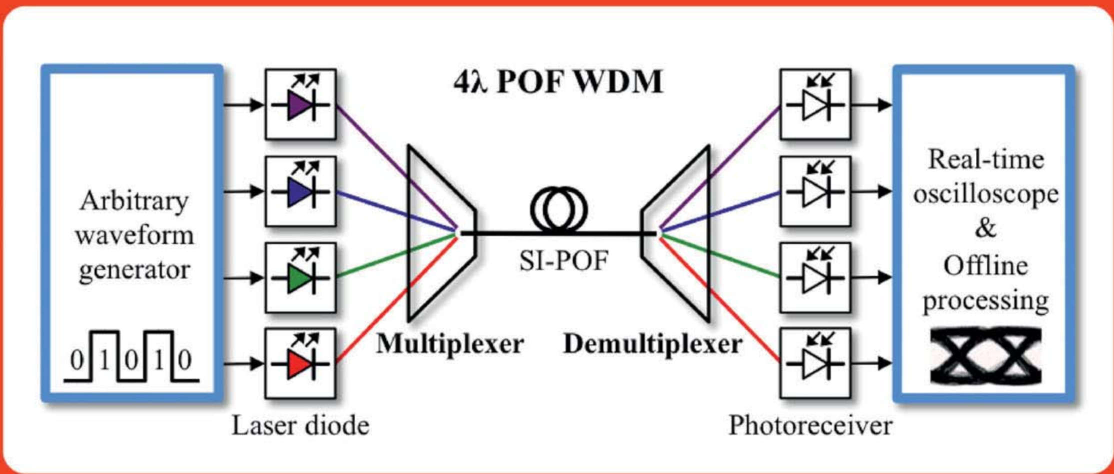
Wavelength Division Multiplexing for Short-Range Communication Over 1 mm Step-Index Polymer Optical Fiber



Mladen Jončić

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Wavelength Division Multiplexing for Short-Range Communication Over 1 mm Step-Index Polymer Optical Fiber

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To my wife Jordana

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Abstract

In short-range communication 1 mm PMMA SI-POF established itself as a reasonable alternative to the traditional data communication media such as glass fibers, copper cables and wireless systems. Due to multiple advantages such as a large core diameter, tolerance to fiber facet damages and low installation costs, the SI-POF is typically used for network systems in homes, vehicles and industrial automation.

The commercial systems with SI-POF use a single channel for data transmission. However, the data carrying capacity of SI-POF is impaired by strong inter-modal dispersion and high optical attenuation. Over the last few years various concepts to overcome the bandwidth limitation of SI-POF have been successfully demonstrated, including optimization of the optoelectronic components and implementation of the digital signal processing techniques. Complying with any of the hitherto developments, utilization of several optical carriers for parallel transmission of data channels over a single fiber, known as WDM, represents another alternative to increase the capacity of SI-POF link.

This thesis investigates the application of WDM in short-range optical communication over SI-POF. The focus of research is on:

- Demultiplexing techniques for SI-POF;
- High-speed WDM transmission over SI-POF;
- Channel allocation for POF WDM systems.

For WDM an optical demultiplexer is a key component. The thesis concentrates on the demultiplexing techniques employing thin-film interference filters and a concave diffraction grating.

An interference filter-based SI-POF demultiplexer was realized using a precisely adjustable opto-mechanical setup, which allowed maximization of the optical throughput in the individual channels. Intermediate setups with two and three channels were first established. In addition, a serial and a two-stage configuration of a target setup with four channels were realized. It was shown that the latter configuration outperformed the former one in terms of IL and IL uniformity. Furthermore, the demultiplexer with two-stage configuration provided low IL (< 5.7 dB) and high channel isolation (> 30 dB). It outperformed other interference filter-based SI-POF demultiplexers reported so far, and was well suited for implementation in high-speed POF WDM transmission experiments.

Within the BMBF project VIP HOPE a demultiplexer with a ruled concave diffraction grating was produced. It is the first demultiplexer with a concave grating ever reported for SI-POF. Since the demultiplexer became available in the late project phase, its demultiplexing properties could not be examined during the project duration. In the thesis a subsequent theoretical and experimental analysis of the demultiplexer was carried out. Two methods for characterization of transmission properties of the demultiplexer were proposed and investigated. A diffraction angle-dependent spectral response over a broad wavelength range and a diffraction angle-dependent transmittance at five lasing wavelengths were measured by scanning the curved focal surface of the demultiplexer with an output SI-POF. The results confirmed the wavelength separating function of the demultiplexer. However, a poor grating quality due to unstable parameters of the ruling process led to high IL (> 20 dB) and low channel isolation (< 15 dB). That prevented the use of the demultiplexer for POF WDM transmission experiments.

To demonstrate experimentally the feasibility and potential of a high-speed POF WDM concept, a four-channel data transmission setup was realized. A four-legged multiplexing POF bundle was developed to combine the signals from four visible laser diodes onto SI-POF link. For the separation of wavelength channels the interference filter-based demultiplexer with two-stage configuration was used. It was shown that POF WDM with lower channel rates and simple transmission technique (NRZ+FFE) could provide aggregate bit rates comparable to those achieved with the single-wavelength systems that used more advanced transmission techniques (DMT or NRZ/PAM+DFE) but required more signal processing. In addition, the record 14.77 Gb/s and 8.26 Gb/s data rates employing the offline-processed DMT modulation were demonstrated over 50 m and 100 m SI-POF, respectively, at the BER=10^{-3}. Compared to the fastest single-wavelength systems, two times higher transmission capacities were achieved.

Finally, the channel allocation for today's and future POF WDM systems was investigated. It was shown that the extension of ITU-T G.694.2 *Coarse* WDM grid into the visible spectrum, with 15 channels and 20 nm channel spacing, is best suited to support WDM applications over SI-POF.

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1 Introduction

Having its origin in the 1960's as well as the silica glass fiber, the polymer optical fiber (POF) stayed long in the shadow of the huge development and success of glass fiber communications. However, the advances in POF technology and the growing need for high-speed short-range communication networks make POF nowadays gain more and more in importance. The key advantage of POF is a large core diameter. It makes POF tolerant to the fiber facet damages and relaxes the alignment tolerances, thus also reducing the installation costs. Furthermore, POF is pliable, durable, and inexpensive, offers small weight and short bend radius, allows easy installation, simple termination and quick troubleshooting, and also provides the immunity to electromagnetic interference. Due to its diverse advantages, in short-range applications POF established itself as a reasonable alternative to the traditional data communication media such as glass fibers, copper cables and wireless systems (see Table 1.1).

Table 1.1: Comparison of different transmission media. Characteristics between very bad (--) and particularly good (++) [Fischer11].

Transmission medium	Data rate	Distance	Safety	Cost	Handling	Installation	Total
Twisted pair cable	+	0	0	++	-	0	**2+**
Coaxial cable	0	0	0	+	0	0	**1+**
Glass fiber	++	++	++	--	--	-	**1+**
Polymer fiber	0	-	++	+	+	+	**4+**
Wireless	--	-	--	++	++	++	**1+**
Powerline	-	-	--	+	+	++	**0**

Today, POF is produced with different core materials, core diameters and index profiles. A comprehensive overview on various POFs is given in [Ziemann08]. Two major POF types are made of polymethyl methacrylate (PMMA) and perfluorinated (PF) materials. The parameters of the common PMMA and PF POFs are specified in the IEC Standard 60793-2-40, which defines eight different POF classes [IEC09].

The PMMA POF is produced with both step-index (SI) and graded-index (GI) profile, whereas the PF POF offers only GI profile. The GI profile of the core ensures high modal bandwidth exceeding 1.5 GHz × 100 m for the PMMA POF and 300 MHz × 1 km for the PF POF. However, the implementation of the PMMA GI-POF is confined to 500-680 nm wavelength range due to the high optical attenuation at other wavelengths (> 400 dB/km). The

PF GI-POF is best suited for use in the infrared region, e.g. in the first (850 nm) and the second (1300 nm) optical window, where of-the-shelf components developed for multimode glass fibers are available. In contrast, the PMMA SI-POF suffers from intermodal dispersion limiting the bandwidth-length product to around 50 MHz × 100 m (see subchapter 2.1), but also provides several attenuation windows in the visible spectrum (400-700 nm). Due to its advantages over the other POF types such as technological maturity, ease and cost of production and high numerical aperture (NA), the standard 1 mm PMMA SI-POF (POF class A4a.2 according to IEC 60793-2-40) is the best known and by far the most widely employed type of POF. This is also the fiber the thesis concentrates on. Throughout the work the terms SI-POF and POF will be equally used to address this fiber type.

Three major application sectors of SI-POF data communication technology are industrial automation, automotive industry and in-house/office networks. Over more than 25 years SI-POF has been employed in industrial automation applications. The bus systems such as Profibus (1.5 Mb/s, 60 m) and INTERBUS (2 Mb/s, 70 m), and industrial Fast Ethernet (100 Mb/s, 50 m) are the typical application scenarios.

In vehicles SI-POF displaces copper in the network structure of a passenger cabin for multimedia data services. The infotainment communication system known as Media Oriented System Transport (MOST) connects different multimedia components in the SI-POF-based ring topology [Grzemba08], as illustrated in Fig. 1.1. First introduced in the BMW 7 Series 2001, the MOST technology is nowadays used by almost all major car manufacturers in the world. In 2011 there were more than 50 different car types on the market employing SI-POF (BMW, Mercedes-Benz, Ford, Hyundai, etc.) [Bunge12]. The current (third) version of the MOST system (MOST150) supports the data transfer at 150 Mb/s over link lengths of about

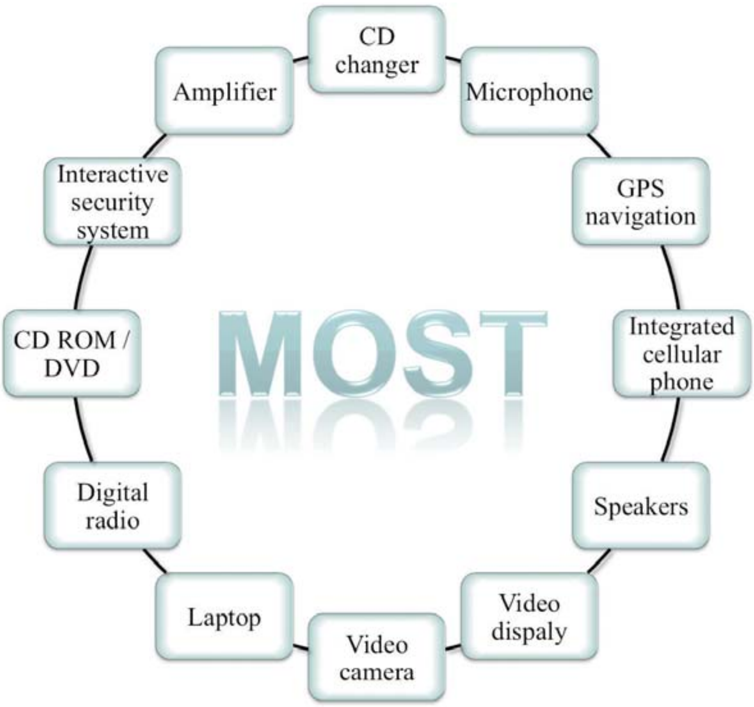

Fig. 1.1: SI-POF-based ring topology of a MOST system in a car.