Guiding Properties of the Polymer Optical Fibers

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***Abstract* – In this paper the transmission possibilities of polymer optical fiber compared with its glass fiber counterpart are considered. It was confirmed that the PHFIP2 POF has the lowest chromatic dispersion compared to the PMMA POF and multimode glass optical fibers. It is also investigated the wavelength dependence of the refractive index of described fibers. As a result, the PHFIP2-FA is the best candidate for designing broadband local area networks.**

***Keywords* – Polymer optical fibers, material dispersion, refractive index, graded-index fiber.**

I. INTRODUCTION

The recent research interest has been focused on the development of polymer optical fibers that answer on growing requirements on up-to-date telecom applications.

Polymer optical fibers (POF) were first introduced several years ago for use in automobiles and sensors for on machine automation. Well known glass fibers are widely used in high-speed long-distance communication networks because of its high bandwidth and low attenuation. However, regarding the broadband local area networks, since the glass fibers require precise handling and connection, serious increase of the cost of the whole systems is expected. The POF is a promising candidate for providing high speed telecommunication services within the customer's premises. It is worth noting that termination and installation of POF are easier and faster compared to the single and multimode glass counterparts, especially in splicing. The typical large core of POF enables large tolerance on axial misalignment, which results in cheaper connectors.

POF are usually made of polymethylmethacrylate (PMMA) and perfluorinated (PF) polymer material. PMMA- POF with step index profile (SI) has been commercially available for many years. This fiber has high attenuation (approximately 100 dB/km) at the visible region and limited bandwidth [1], [2]. Slightly improvement in the bandwidth characteristics of POF has been obtained by grading the refractive index. A large core, high-bandwidth, and low-loss graded index polymer optical fiber (GI-POF) have been proposed in [3]. Additional reduction of transmission loss has been achieved by development of the PF GI-POF [4], [5]. The PF fibers are with lowest attenuation (40dB/km) due to the elimination of intrinsic absorption loss that exists in PMMA-POF.

It is well-known that transmission capacity of fiber data link is limited by it dispersion properties. Wavelength dependence of the refractive index of the polymer, the finite spectral width of the light source, material composition, index profile, strongly affects the dispersion properties of the fiber and should be taken into accounts.

Optimization of the attenuation and dispersion properties has opened the way for broadband transmission over POF based network. This article is comprehensive review on transmission possibilities of polymer fibers compared with its glass fiber counterpart.

The paper is organized as follows. Firstly, the Sellmeier coefficients determination for investigated POF will be described. Secondly, the transmission properties of designed POF such as dispersion and group delay will be discussed. Finally, optical field distribution in the polymer fibers will be investigated.

A. Dispersion relations for Refractive Index (RI)

The Refractive Index (RI) is a fundamental parameter for any kind of optical material.

If one treats the material as equivalent to a collection of *m* harmonic oscillators resonant to a radiation of various wavelengths A_j, one can derive the equation [6]

$$n^2(\lambda) = 1 + \sum_{i=1}^{m} \frac{A_i \lambda^2}{(\lambda^2 - \lambda_i^2)}, \qquad (1)$$

where λ is the wavelength of the incident radiation, and A_i is a constant that depends on the number of oscillators per unit volume and is called the *oscillator strength* of the oscillators resonant at wavelength λ_i. Eq. (1) is generally called the Sellmeier formula, since Sellmeier proposed it in 1871.

The usual form of the equation for glasses is

$$n^2(\lambda) - 1 = \frac{A_1\lambda^2}{\lambda^2 - \lambda_1^2} + \frac{A_2\lambda^2}{\lambda^2 - \lambda_2^2} + \frac{A_3\lambda^2}{\lambda^2 - \lambda_3^2}, \qquad (2)$$

where *n* is the RI, λ is the wavelength, and $A_{1,2,3}$ and $\lambda_{1,2,3}$ are experimentally determined Sellmeier coefficients. For common optical glasses, the refractive index calculated with the three-term Sellmeier equation deviates from the actual refractive index by less than 5×10^{-6} over the wavelengths range of 365 nm to 2.3 µm.

These coefficients are determined experimentally for common optical materials.

Actually there exists a great diversity of polymeric materials. The most frequently used material for polymer fibers is the thermoplastics PMMA (Polymethylmethacrylate), better know as Plexiglas and perfluorinated polymers

To change the refractive index of optical fiber, pure polymer is often doped with dopants. For example, adding

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germanium can result in an increase in the refractive index, while adding fluorine reduces it. The refractive index of doped material can be determined by Sellmeier equations. Corresponding coefficients for fibers proposed in [7] are given in Table 1. PHFIP 2-FA is one of the fluorinated polymers whose monomer unit contains only three carbon-hydrogen bonds. As dopants to control the refractive-index profile, benzyl benzoate BEN for PMMA and dibutyl phthalate DBP forPHFIP 2-FA were used.

For comparison, the Sellmeier's coefficients of silica-based fiber are also considered.

II. DESIGN AND INVESTIGATIONS OF POF

A. Design of Polymer Optical Fibers

There are two important limitations for applications of polymer optical fiber systems – high attenuation and limited bandwidth. Choosing appropriate fiber parameters is an important issue for a given optical system. Reduction of transmission loss depends on material used for the fiber core. Cross-sectional dimensions, material composition, and refractive index profile all influence the losses, dispersion and the nonlinearities of the fiber and must be chosen carefully to achieve a satisfactory tradeoff for a given application. To fit user requirements all these parameters of existing polymer fiber samples are experimentally measured.

Design of new optical fiber usually starts with defining refractive index profile. This step includes fixing the geometry and the material composition of the fiber.

The material dispersion and dispersion of the profile are calculated from the known Sellmeier coefficients of the used material, which are taken from table1.

The typical characteristics of investigated POF consistent with IEC standard are given in table 2.

TABLE 1
SELLMEIER'S COEFFICIENTS

material	**A_1**	**A_2**	**A_3**	**λ_1^***	**λ_2^***	**λ_3^***
PMMA	0.4963	0.6965	0.3223	0.0718	0.1174	9.237
PMMA-BEN	0.4855	0.7555	0.4245	0.1043	0.1147	4.934
PHFIP2-FA	0.4200	0.0461	0.3484	0.0587	0.0878	0.0927
PHFIP2-FA-DBP	0.2680	0.3513	0.2498	0.0791	0.0838	0.1062
Silica	0.6968	0.4082	0.8994	0.0685	0.1161	9.9140

TABLE 2
THE CHARACTERISTICS OF INVESTIGATED POF CONSISTENT WITH IEC STANDARD

	IEC standard	**Material used**	**Core/ Cladding diameter [µm]**	**RI Core/ Cladding**	**NA**	**Operating wavelength [µm]**
GOF-SI	607932-20 Cat.A2	Silica	62.5/125	1.48/1.45	0.18	0.85
GOF-GI	607932-10 Cat.A1	Silica	62.5/125	1.48/1.46	0.27	0.85
PMMA-SI	60793240 Cat.A4a	PMMA	975/1000	1.49/1.42	0.5	0.65
PMMA-GI	607932-40 Cat.A4e	PMMA	500/750	1.49/1.45	0.25	0.65
PMMA-BEN-SI	607932-40 Cat.A4a	PMMA-BEN	975/1000	1.51/1.34	0.5	0.65
PMMA-BEN-GI	607932-40 Cat.A4e	PMMA-BEN	500/750	1.51/1.47	0.25	0.65
PHFIP2-FA-GI	607932-40 Cat.A4g	PHFIP2-FA	120/490	1.35/1.32	0.19	0.65
PHFIP2-FA-DBP-GI	607932-40 Cat.A4g	PHFIP2-FA-DBP	120/490	1.37/1.34	0.19	0.65

*GOF - Glass Optical Fiber

B. Transmission Properties of Polymer Optical Fibers

It is well known that dispersion in POF can be divided into two main types – chromatic (material and waveguide) dispersion and modal dispersion. The modal dispersion has dominant influence on bandwidth of SI POF. Grading the index profile significantly enhanced transmission capacity of polymer fibers.

The material dispersion is defined as the wavelength dependence of refractive index of the polymer. Fig.1 displays the refractive index dependence of PMMA, PMMA-BEN-doped, PHFIP 2-FA, PHFIP-2-DBP-doped and glass optical fiber (GOF) in respect to wavelength. It is evident from results that the PMMA-BEN polymer has the highest deviation of refractive index versus wavelength, while PHFIP 2- FA – lowest.

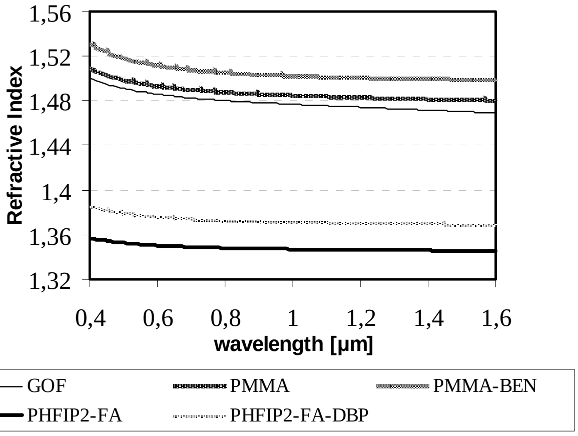

Fig.1. Wavelength dependence of Refractive index of PMMA, PHFIP2_FA polymer and silica

The described fibers are optimized to operate at 0,65μm and 0,85μm wavelength because the low attenuation in these windows. Low attenuation at visible and near infrared region is advantageous even with the dispersion limitation because the material dispersion decreases with increasing wavelength.

In a fiber, the materials of core and cladding are different. If there are L layers in the fiber cross-section, each layer has different refractive index.

The total material dispersion of a fiber is calculated by:

$$D(\lambda) = -\frac{\lambda z}{c}\sum_{i=1}^{L}\Gamma_i \frac{d^2 n_i}{d\lambda^2} \qquad (3)$$

where the confinement factor of each layer is Γ_i. The confinement factor is the portion of total power guided in the i-th layer.

The typical characteristics of PMMA and PHFIP2-FA fibers with SI and GI are summarized in table 3. For comparison, the transmission parameters of glass fibers at 0,65μm and 0,85μm wavelengths are also considered.

Chromatic dispersion, considering material and waveguide dispersions, as described in detail in this section. The waveguide dispersion of investigated fibers is almost zero at 0,65μm and 0,85μm wavelength, so the corresponding material dispersion strongly affects the bit rate performance of POF link.

Fig. 2 shows the experimental results of the chromatic dispersion of the PMMA GI POF, PHFIP-2-FA GI POF and graded index GOF. The PHFIP-2-FA GI polymer fiber has lowest material dispersion in wide wavelength range from visible to near infrared region.

The material dispersion of Perfluorinated (PF) polymer-based GI POF at 0,85μm wavelength is 58.995 ps/km.nm which is much lower than 133.532 ps/km.nm of the PMMA at the same wavelength. Therefore, it is expected that PF polymer-based GI POF will have the highest bandwidth from the visible to the near infrared region. Moreover in case of glass fiber, the material dispersion at 0,85μm wavelength is almost the same as that of PMMA POF and two times higher than that of PHFIP-2-FA GI POF.

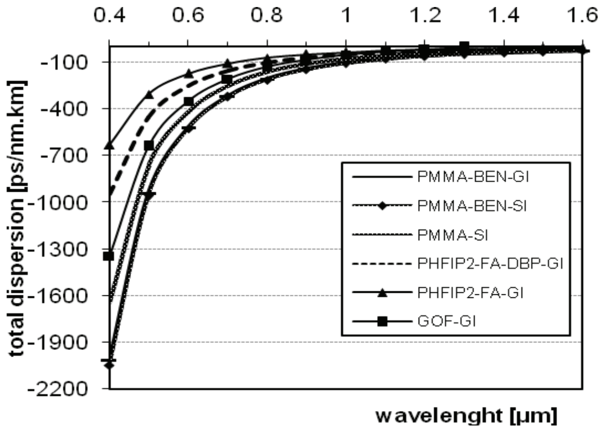

Fig.2. Chromatic dispersion of PMMA-based, PHFIP2_FA-based POF and glass optical fiber.

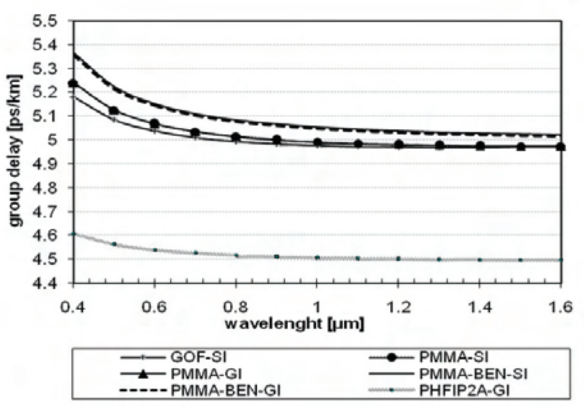

Fig.3. Group delay of PMMA-based, PHFIP2_FA-based POF and glass optical fiber.

It is observed in all optical fibers that the speed of propagation of light differs for different wavelength. Group delay gives the propagation group delay for the selected fiber mode versus the wavelength.

The group delay T_g is defined as:

$$T_g = z\frac{d\beta}{d\omega} = z\frac{d\lambda}{d\omega}\frac{d(nk_0)}{d\lambda} \qquad (4)$$

where n is the refractive index, $\lambda = 2\pi c/\omega$, $k_0 = 2\pi/\lambda$

The group delay of PMMA, PMMA-BEN with SI and GI, PHFIP2A – GI POF and glass optical fiber are indicated in fig.3. As expected, with increasing wavelength the delays become smaller, which means greater speed. Since, fluorinated materials have the lowest values of dispersion loss, therefore PHFIP2A-FA had the lowest values of group delay ($4{,}513\text{x}10^{-6}$,ps/km at 0,850μm wavelength).

It was confirmed from fig.2 and fig. 3 that PHFIP2A – GI POF shows better performance compared to PMMA and GOF with respect to dispersion at discussed wavelengths.

It is well-known that GOF connection operations require specific setups and skilled technicians. POF's have larger core diameters (0,125-2mm) than GOF's (9μm and 62,5 μm). POFs are easier to connect, because of the existing technology allowing customers to do the connection themselves.

The values of the mode field diameters of investigated OF are summarized in table 3. PMMA-SI and PMMA-BEN-SI have the largest diameters of the intersection of OF, within which the main power of optical radiation (mode field) is concentrated. The effective mode field for PMMA-SI is ~670μm and PMMA-BEN-SI is ~680μm, which is result of the larger diameters of the core and cladding of the fibers. On the other hand, increasing the core diameter causes a decrease in the speed of data transmission.

POFs have large numerical aperture related with large effective mode field, which eliminate the necessity to use precise light sources.

TABLE 3
CHARACTERISTICS OF PMMA POF, PHFIP2-FA POF AND GOF

	wavelength [μm]	**RI**	**Dispersion [ps/km.nm]**			**Near field MFD [μm]**	**Far field MFD [μm]**	**Effective MFD [μm]**	**Group delay x10^{-6} [ps/km]**
			Waveguide	**Material**	**Chromatic**				
GOF-SI	0.652	1.458	0.237	–269.289	-268.837	41.763	37.409	43.657	5.021
	0.854	1.479	0.209	–104.574	-104.148	41.290	37.619	43.821	4.986
GOF-GI	0.652	1.484	–0.019	–268.798	–268.982	10.225	10.211	10.202	5.021
	0.854	1.479	0.026	–104.280	–104.384	11.796	11.789	11.786	4.986
PMMA-SI	0.652	1.492	0.166	–322.026	–321.948	647.307	573.833	677.055	5.049
	0.854	1.487	0.142	–133.698	–133.844	643.069	573.985	672.064	5.006
PMMA-GI	0.652	1.4892	0.028	–321.707	–321.610	35.896	33.268	37.497	5.048
	0.854	1.487	0.303	–133.532	–133.329	36.880	34.559	38.490	5.006
PMMA-EN-SI	0.652	1.512	0.255	–408.630	–408.392	651.129	573.503	681.640	5.129
	0.854	1.501	$-5.312\text{x}10^{-6}$	–176.152	–176.121	648.606	573.738	678.589	5.074
PMMA-BEN-GI	0.652	1.510	0.190	–401.172	–401.047	34.278	31.101	35.829	5.120
	0.854	1.505	0.238	–172.419	–172.123	34.684	31.647	36.251	5.067
PHFIP2-FA-GI	0.652	1.350	–0.149	–133.972	–134.265	13.335	13.253	13.346	4.531
	0.854	1.348	–0.132	–58.639	–58.995	15.481	15.425	15.405	4.513
PHFIP2-FA-DBP-GI	0.652	1.375	–0.145	–195.858	–196.209	13.310	13.228	13.323	4.628
	0.854	1.372	–0.071	–84.846	–85.183	15.437	15.380	15.362	4.602

III. CONCLUSION

In this paper the guiding properties of polymer optical fibers compared with its glass fibers counterpart are considered. It was investigated the wavelength dependence of the refractive index of PMMA POF, PMMA-BEN POF, PHFIP2-FA POF, PHFIP2-FA DBP POF and GOF. It was confirmed that the PHFIP2 POF has the lowest chromatic dispersion compared to the PMMA POF and multimode glass optical fibers. As a result, the PHFIP2-FA is the best candidate for providing high speed telecommunication services within the customer's premises.

REFERENCES

[1] T. Kaino, M. Fujiki, and K. Jinguji, "Preparation of plastic optical fibers," Rev. Electron. Commun. Lab., vol. 32, pp. 478–488, 1984.

[2] T. Monroy, H.P.A. vd Boom, A. Koonen, G. Khoe, Y. Watanabe, Y. Koike, T. Ishigure, "Data transmission over polymer optical fibers", Optical Fiber Technology 9, Academic press, pp. 159-171, 2003, available at www.sciencedirect.com .

[3] Y. Koike, T. Ishigure, and E. Nihei, "High-bandwidth graded-index polymer optical fiber," J. Lightwave Technol., vol. 13, pp. 1475–1489, July 1995.

[4] N. Yoshihara,"Low-loss, high-bandwidth fluorinated POF for visible to 1.3-mm wavelength," in Proc. Optic. Fiber Conf. (OFC'98), San Jose,

[5] T. Ishigure, Y. Koike, and J. W. Fleming, "Optimum index profile of the perfluorineted polymer-based GI polymer optical fiber and its dispersion properties", J. Lightwave Technol., vol. 18, pp. 178–184, Feb. 2000.

[6] E. Palik, "Handbook of thermo-optic coefficients of opticl materials with applications", Japan, Academic Press, 1998.

[7] T. Ishigure, E. Nihei and Y. Koike, "Optimum refractive-index profile of the graded-index polymer optical fiber, toward gigabit data links", Applied Optics, vol.35, No 12, 20 April 1996.