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THEORETICAL PERFORMANCE OF THE PF-GIPOF TRANSFER FUNCTION UNDER DIFFERENT W-SHAPED REFRACTIVE INDEX PROFILE DESIGNS

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Abstract: The frequency response of PF-GIPOF with W-shaped refractive index profile is theoretically investigated. The proposed index profile incorporates a trench in the cladding region to tune the modal dispersion of outer groups. We focus on the effect of this design on the PF-GIPOF baseband bandwidth. The relationship between new index profiles and a high-bandwidth fiber condition is highlighted in order to increase the maximum achievable aggregated transmission capacity over PF-GIPOFs.

Key words: Refractive index profile, PF-GIPOF, frequency response, fiber bandwidth.

1. Introduction

Growing research interests are focused on the high-speed telecommunications and data communications networks with increasing demand for accessing even from the home, due to the huge successes during the last decade of new multimedia services (high-definition (HD), three-dimensional visual information (3D) or remote "face-to-face communication") which forecast requirements for data transmission speed more than 40Gbps by 2020, which can be achievable only with optical network [1]. This strong increase of bandwidth demand presents an increasing challenge for service operators to delivery their high-quality service to the end user's device. At this moment, commercially available progressive service plans range between the 50-100Mbps while premium services typically range around 100-150Mbps. And it should be reminded that the bandwidth in the local loop is forecasted to grow with an average of 20%-50% annually.

Recent interests are focused on gigabit-order data transmission, being desirable, at the same time, to introduce optical fiber networks even to the customer's premises for covering more than 10Gbps in the near future, introducing the concept of FTTx (Fiber To The Home/Node/Building/Curb) deployments. There is a worldwide consensus that the optical fiber solution provides enough bandwidth to attend user's demand at the required transmission distances in the short-reach domain (typically up to 200meters). Regarding this data transmission capability, Polymer Optical Fiber (POF) technology has emerged as a useful medium for short-reach distances scenarios such as Local Area Networks (LANs), in-home and office networks, automotive and avionic multimedia buses or data center connections among others. And, especially, Perfluorinated Graded Index POFs (PF-GIPOFs) offer several advantages over conventional silica multimode optical fiber over short distances [2]. Particularly, PF-GIPOF can provide a bandwidth per length product ~400MHz x km at both 850nm and 1300nm, respectively, and can support bit rates of 40Gbps up to 200m for any launch condition [3]. This fact is due to the PF-GIPOF low material dispersion characteristics (even lower compared to silica multimode optical fibers) [4].

Although PF-GIPOFs reveal a cost effective solution for these short-reach optical deployments, their bandwidth characteristics still limit the reaching distances and the capacity to attend future end users' transmission requirements. Overcoming the bandwidth limitation of such fibers requires the development of techniques oriented to extend the capabilities of POF networks to attend the consumer's demand for multimedia services. Different efficient and advanced modulation formats and/or adaptive electrical equalization schemes over a single fiber channel can be applied. Alternatively, in order to acquire wide bandwidth and low dispersion characteristics, optical fibers can be fabricated with various refractive index profiles, such as step form and graded form. In particular, W-shaped refractive index profile in the GIPOF was proposed by Ishigure et al. [5,6], with the advantage of reducing modal dispersion compared with graded index counterpart.

However, the potential PF-GIPOF capacity (in any of its refractive index design) for communication needs a greater exploitation to meet user requirements for higher-data rates and to support the emerging multimedia applications. To enable the design and utilization of PF-GIPOF, the analysis of its frequency response becomes of prime importance. In this work we give some insights into the impact of the PF-GIPOF frequency response under different W-shaped refractive index profile designs.

2. Fiber profile description and frequency response theoretical analysis

Within this section both the refractive index profile design and the theoretical model to evaluate the frequency response of the PF-GIPOF are briefly described.

2.1. *PF-GIPOF frequency response theoretical model*

The proposed theoretical model relies on the propagation of the electric field signals rather than optical power signals. It provides an adequate description of the electrical field behavior when considering the propagation of analogue signals or when a detailed knowledge of the baseband and radiofrequency (RF) transfer function is required since in these situations the effect of the signal phase is important. For a deeper comprehension of the frequency response theoretical model works reported in [4,7] are recommended.

From the mathematical framework it is possible to obtain the overall transfer function as a closed-form analytic expression to compute the baseband and RF transfer function of a PF-GIPOF link (with fiber length z). Eq. (10) in Ref. [8] provides a description of the main factors affecting the frequency response of a multimode optical fiber link, in which Ω represents the frequency of the RF modulating signal. The RF frequency response of a multimode fiber link can be divided as the product of three terms of factors. From the left to the right, the first term is a low-pass frequency response which depends on the third order chromatic dispersion parameter β_o^3 and σ_c which is the source coherence time directly related to the source linewidth. The second term is related to the carrier suppression effect due to the phase offset between the upper and lower modulation sidebands. Finally, the third term represents a microwave photonic transversal filtering effect, in which each sample corresponds to a different mode group *m* carried by the fiber and in which coefficients C_{mm}, X_{mm} and G_{mm} stand for the light injection efficiency, the mode spatial profile impinging the detector area and the mode coupling coefficient, respectively. Parameters α_m and τ_m represent the differential mode attenuation (DMA) effect, which causes the attenuation coefficient to vary from mode to mode, and the delay time of the guided modes per unit length, respectively. All these factors affecting multimode optical fibers have been considered in the theoretical model.

2.2. *Refractive index profile design*

The refractive index profile under consideration which is composed by a graded core and a cladding trench is shown in Fig. 1.

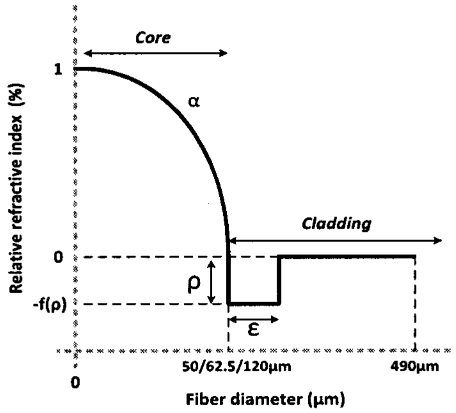

Fig. 1. Schematic of the refractive index profile under consideration.

The refractive index profile of a graded index optical fiber with core radius 'a', maximum refractive index $n_1(\lambda)$ and a graded index exponent α may be written as:

$$n(r,\lambda) = n_1(\lambda)\left[1 - 2\Delta(\lambda)\left(\frac{r}{a}\right)^{\alpha}\right]^{1/2} \quad \text{for } 0 \le r \le a \qquad (1)$$

where *r* corresponds to the cylindrical radial coordinate (offset distance from the core center), $\Delta(\lambda)$ is the relative refractive index difference and $n_2(\lambda)$ refers to the cladding refractive index. For high bandwidth applications the value of α is approximately 2, which corresponds to a parabolic index profile. It is straightforward to insert the above refractive index profile given by Eq. (1), which can include any trench design, into the PF-GIPOF frequency response theoretical model above described.

3. PF-GIPOF frequency response performance for W-shape designs

In the following different theoretical simulations will be shown analyzing the impact of the cladding trench design on the PF-GIPOF frequency response. This trench creates a barrier that improves the confinement of the fundamental mode thus improving the bend-insensitivity characteristics of the optical fiber (this analysis is outside the scope of this work) as well as increasing the available bandwidth characteristics of the PF-GIPOF. In this work the impact on the baseband spectrum of the trench depth/width is analyzed. High-order resonances that are also present in the PF-GIPOF frequency response [4] have been excluded from this analysis for the sake of simplicity although they are expected to suffer from different trench designs.

To enable computer evaluations, it has been assumed that the refractive indices of the core and cladding materials follow a three-term Sellmeier function of wavelength. Differential mode attenuation effects have been simulated by an empirically function which depends on the p-th order modified Bessel function of the first kind and a weighting constant η [7]. Those parameters have been set to $p=11$ and $\eta=12.2$. The mode coupling coefficient has been defined by a Gaussian autocorrelation function [7] with a rms deviation of $\sigma=0.0005$m and a correlation length of $\varsigma=1.6\cdot 10^4\cdot a$, being 'a' the core radius. A wavelength of 1300nm has been considered to be the best case for PF-GIPOF operation performing an attenuation coefficient of 55dB/km. A link length of 200m has been considered in the simulations covering most of the fiber deployment scenarios in the short-reach distance domain. A DFB laser source with 10MHz of spectral width has been considered as the optical source. For the sake of simplicity, a graded index exponent $\alpha=2$ has been applied to all cases.

Fig. 2 shows the standard (i.e. no trench design) 62.5μm core diameter PF-GIPOF frequency response under different launching conditions: a) overfilled launch condition OFL (i.e. the light injection coefficient is set to $C_{mm}=1/M$, where M is the total number of mode groups), and b) centered restricted mode launching (RML). Within Fig. 2 the RML launch frequency response curve applying an offset of +17μm from the core center is provided for comparison purposes. As expected, one method to increase the available fiber bandwidth is to inject few modes into the fiber. This fact has been widely reported in literature. However, this technique can be combined with the manufacture of different W-shaped refractive index profiles.

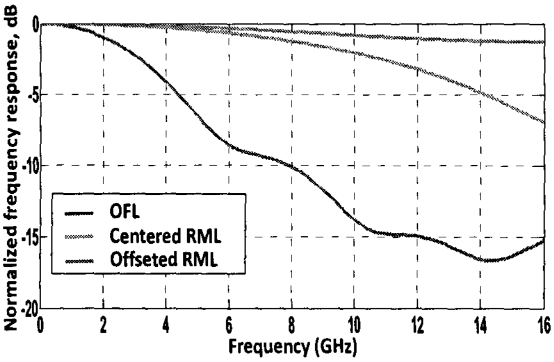

Fig. 2. PF-GIPOF frequency response under different launching conditions with no trench design.

Fig. 3a depicts the frequency response at OFL condition at different trench depths (ρ parameter) defined as illustrated in Fig. 1. Trench width was set to $\varepsilon=5\mu$m. Trench depth (ρ) is given in terms of absolute refractive index value where the inner cladding interface refractive index results by subtracting the given value of ρ from the nominal cladding refractive index at 1300nm (we assume $n_{cladding}=1.3189$@1300nm). From this latter figure it is clearly seen the enhancement on the baseband bandwidth as the trench depth increases. This is due to the fact that the differential mode delay (DMD) slope can be reduced by increasing the trench depth. However, this trend is expected to have an optimum value that maximizes the baseband bandwidth provided by the PF-GIPOF frequency response. From the curves illustrated in Fig. 3a a PF-GIPOF baseband bandwidth of 6.1GHz can be achieved with a trench depth of $-8\cdot 10^{-3}$ with respect to the 3.4GHz of bandwidth obtained from the nominal case. On the other hand, Fig. 3b illustrates the impact of the PF-GIPOF frequency response under centered RML launching condition with regards to different trench depth designs. Same discussion as Fig. 3a applies although the baseband bandwidth enhancement is not so noticeable. In this latter case, baseband bandwidth is increased from 11.7GHz ($\rho=0$) to 13GHz ($\rho=8\cdot 10^{-3}$). Similarly, it is expected to achieve an optimum value that maximizes the baseband bandwidth.

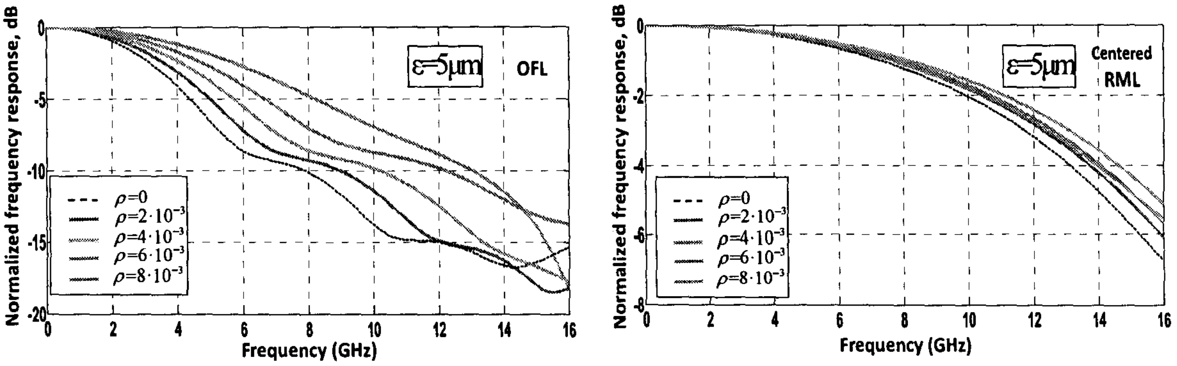

Fig. 3.(a) Impact of the PF-GIPOF frequency response on the trench depth for OFL condition; (b) Impact of the PF-GIPOF frequency response on the trench depth for centered RML condition.

Finally, the trench width can also be seen as a parameter under consideration in order to enable very low dispersion profiles on the PF-GIPOF over the wavelength of interest. From our simulations it has been concluded that a trench width value within the range 4µm-7µm enabled the achievement of a high-bandwidth condition. This range results from a tradeoff as a trench too wide would make the fiber fabrication more expensive. However, a deeper study would be required to precisely assess the optimum value to achieve the highest achievable bandwidth.

4. Conclusions

We have given some insights into the impact of the baseband bandwidth of PF-GIPOF fibers by adding a trench with a negative relative refractive index in the cladding. This trench improves the guidance of the outer modes reducing the DMD effect and so the dispersion profile of the optical fiber. Remarkable improvements can be achieved with regards to the PF-GIPOF baseband bandwidth and, consequently, over the aggregated transmission capacity over this fiber type. However the size and location of the trench must be carefully controlled to ensure the aforementioned benefits. We verified through modeling that an optimum trench design can be achieved although further research is needed to fix the exact manufacturing requirements of the trench depth and trench width depending on the core gradient exponent and fiber radius.

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