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Photonic-Crystal Fibre Modeling using Fuzzy Classification Approach

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***Abstract*— In this paper, a fuzzy classification algorithm is proposed for photonic-crystal fibres (PCF) modeling. This approach is based on fuzzy classification decisions. A training dataset composed of the most recent commercialized PCF fibers is used. Each category of fibers is defined by a set of reference patterns. The fuzzy modeling allows eliminating many problems like ones related to the strict thresholding and helps to overcome some difficulties encountered when data are expressed in different units. Typical PCFs with specific optical properties are designed using this approach. As an example, we present index-guiding fibres with manipulated chromatic dispersion using appropriate parameters. The fuzzy classification algorithm was implemented successfully and interesting optical properties of the designed PCFs were presented.**

***Index Terms*— optical fiber design, photonic crystal fiber, chromatic dispersion, fuzzy classification, multicriteria.**

I. Introduction

In this work, we use a fuzzy algorithm to classify photonic-crystal fibres and to design and prose new structures. This approach contributes to determine the PCF structure starting from the optical characteristic required for a given application. It helps us to overcome some difficulties encountered because geometrical and optical proprieties are expressed in different units. Genetic algorithm based approaches have been proposed and used in the literature to optimize and/or to design the PCF fibers [1-4]. A combination of differential evolution and estimation of distribution algorithm have been used to design photonic crystal fiber structures with desired properties [5].

A PCF fibre is a new optical fiber based on the properties of Photonic-Crystals (PC). The last is an artificial structure with a periodically modulated dielectric constant. This modulation can be in one, two or three spatial guidance and affects electromagnetic proprieties of the modes [6] [7] [8] [9]. This is among others, the case for light confinement or its emission, and the elaboration of basic structures adapted to intra chip, integrated systems on chip optical communications, or optical fibre telecommunications [10]. These structures are now starting place of many optical experiments such spontaneous emission inhibition [11] [12], high reflectivity omni directional mirrors, as well as low losses waves guides, or more light refractive proprieties like self-collimation or negative refraction [13][14][15]. In these fibres, the cladding is distinguished from the core only by the presence of air hole what gives him an index of refraction average lower than that of the core. For example, it is possible to produce PCF with very high birefringence [16], to obtain fibres with very flat near zero chromatic dispersion curve on a large wavelength range [17] [18], or to get a single-mode fibre with unusual dispersion regime in the visible wavelength domain [19] [20]. The optical properties are related to the fibre design, specifically, the pitch (Λ) of the periodic array, the holes diameter (d) and the number (N) of rings around the core. One of these fibres the M-TIR fibres, in this type of fibre the wide choice in the geometrical parameters and the large refractive index difference between air and silica enable much greater flexibility in the design of the dispersion of the guide. Consequently, the chromatic dispersion of M-TIR fibres can be controlled by a suitable choice of the parameters d and Ë [21]. Many applications such as telecommunications, supercontinuum generation or parametric amplification require an accurate control of the chromatic dispersion [22][23]. It is well known that chromatic dispersion can be controlled by adjusting the parameters d and Λ [19].

The optimization of PCF design is often complicated owing to the fact that the optical parameters do not habitually vary in a simple manner with the geometrical parameters of the PCF fibre. This complexity increases exponentially with the numbers of variables of the problems (Λ, N, d…) and with the number of properties that have to be considered (chromatic dispersion, confinement losses etc…). In this paper, the geometrical parameters are used in the design The optimization is principally performed by experiment and test approach. The designer and the computer have to interact regularly with the results of the calculation to design a new type of fibre but this is a time consuming approach.

II. Fuzzy classification decision

Multicriteria methods have been first introduced by Roy in 1985 [22] and they are now applied in many fields as environment, finances, production, localization, (Vincke, 1987; Roy and Bouyssou, 1993; Pomerol and Al, 1993; Mayster and Al, 1994).These methods are divided into two groups. The first one includes the automatic classification methods called clustering methods, based on the notion of

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unsupervised learning, and consists in assembling individuals in restricted classes so that all objects of the same class are less dispersed [4]. The second one comprises the assignment methods, which are based on the notion of supervised learning and employ a set of examples belonging to well-known classes. In this paper, we apply a fuzzy classification method one of the second type of multicriteria method. This method formulated the problem in terms of assigning objects to one or several classes by examining the intrinsic value of each object and by referring to pre-existing rules. The problem can be considered as a supervised learning problem. So, our method is an assignment method based on the preference relational system described by Roy [26] and Vincke [27]. This method employs a comparison between the alternatives through the scores of different criteria. So, it avoids resorting to distance and allows us to use qualitative and /or quantitative criteria. Moreover, it helps us to overcome some difficulties encountered when data are expressed in different units. In this section, we present the fuzzy classification method and we focalise on the PROAFTN algorithm developed in previous work [28]. This algorithm is able to resolve the assignment problems in the nominal sorting problematic. In order to assign the fuzzy belonging degree of action to each category, this algorithm determines the fuzzy indifference relations by generalizing concordance and discordance indices used in the ELECTRE III method [25].

Each object, which we need to classify, is described by a set of m attributes $\{g_1, g_2, \ldots, g_m\}$, we consider also a set of k classes : $\{C_1, \ldots, C_k\}$ [29] with A is the Set of objects or actions to assign to different categories. b_i^h is the I th prototype of the hth category and B is the set of all prototypes. A synthesis outranking processes is used and partial indifference relations are determined. The prototype scores are given by intervals, so for each criterion is associated to a prototype b_i^h the interval $[S_j^1(b_i^h), S_j^2(b_i^h)]$, with $S_j^2(b_i^h) \geq S_j^1(b_i^h)$. Formally, three comparative situations, between the action a and prototype b_i^h according to criterion g_i, are obtained using the two discrimination thresholds and given by the following.

$$\begin{aligned} & S_j^1(b_i^h) \le g_j(a) \le S_j^2(b_i^h) \\ & \left[g_j(a) \le S_j^1(b_i^h) - d_j^-(b_i^h)\right] \text{ or } \left[g_j(a) \ge S_j^2(b_i^h) - d_j^+(b_i^h)\right] \\ & \left[S_j^1(b_i^h) - d_j^-(b_i^h) \prec g_j(a) \prec S_j^1(b_i^h)\right] \\ & \text{or } \left[S_j^2(b_i^h) \prec g_j(a) \prec S_j^2(b_i^h) + d_j^+(b_i^h))\right] \end{aligned} \tag{1}$$

where $d_j^-(b_i^h)$ and $d_j^+(b_i^h)$ are the discrimination thresholds. For the first case, a is clearly indifferent to b_i^h In the second one, a is not indifferent to . In the third case there is a weak indifference between a and . Based on argumentation of discrimination thresholds, the partial indifference index represents the degree of validity of the three previous situations and verifies the following properties:

$$C_j(a, b_i^h) = 1 \Leftrightarrow S_j^1(b_i^h) \le g_j(a) \le S_j^2(b_i^h);$$

$$\begin{aligned} & 0 < C_j(a,b_i^h) < 1 \Leftrightarrow S_j^1(b_i^h) - d_j^-(b_i^h) \le g_j(a) \\ & \le S_j^1(b_i^h) or S_j^2(b_i^h) < g_j(a) < S_j^2(b_i^h) + d_j^+(b_i^h); \end{aligned}$$

$$\begin{aligned} & C_j(a,b_i^h) = 0 \Leftrightarrow g_j(a) \le S_j^1(b_i^h) - d_j^-(b_i^h) \\ & or g_j(a) \ge S_j^2(b_i^h) - d_j^+(b_i^h); \end{aligned}$$

The index $C_j(a,b_i^h)$ is represented between the value $S_j^1(b_i^h)$- $d_j^-(b_i^h)$ and the $S_j^1(b_i^h)$ on one hand, and $S_j^2(b_i^h)$ and $S_j^2(b_i^h)+d_j^+(b_i^h)$ on the other hand, through the linear interpolation function [29]. The value of $C_j(a,b_i^h)$ is determined using equation (2) where $C_j^-(a,b_i^h)$ and $C_j^+(a,b_i^h)$ are specified in equation (3).

$$C_j(a,b_i^h) = \min \{ C_j^+ (a,b_i^h), C_j^- (a,b_i^h) \} \tag{2}$$

$$\begin{cases} C_j^-(a,b_i^h) = \dfrac{d_j^-(b_i^h) - \min\{S_j^1(b_i^h) - g_j(a), d_j^-(b_i^h)\}}{d_j^-(b_i^h) - \min\{S_j^1(b_i^h) - g_j(a), 0\}} \\ C_j^+(a,b_i^h) = \dfrac{d_j^+(b_i^h) - \min\{g_j(a) - S_j^2(b_i^h), d_j^+(b_i^h)\}}{d_j^+(b_i^h) - \min\{g_j(a) - S_j^2(b_i^h), 0\}} \end{cases} \tag{3}$$

Since the partial concordance index, the comprehensive concordance index is defined in the following way, $C_I(a,b_i^n) = \sum_{j=0}^{n} (w_j^h * C_j(a,b_i^n))$ where w_j^h, $j=1,\ldots,n$ and $h=1,\ldots,k$,are positives weights adding to one and reflecting the intrinsic relative importance attached by a decision maker to a criterion g_j. The method determines also the partial discordance index $D_j(a,b_i^n)$. This index is represented between the value $S_j^1(b_i^h) - v_j^-(b_i^h)$ and the $S_j^1(b_i^h) - d_j^-(b_i^h)$ on one hand and $S_j^2(b_i^h) - d_j^+(b_i^h)$ and $S_j^2(b_i^h) - v_j^+(b_i^h)$ on the other hand, by the linear interpolation function. $v_j^-(b_i^h)$ and $v_j^+(b_i^h)$ are the veto thresholds. The discordance is deduced as follows.

$$D_j(a,b_i^h) = \min \{ D_j^+(a,b_i^h), D_j^-(a,b_i^h) \} \tag{4}$$

Where $D_j^-(a,b_i^h)$ and $D_j^+(a,b_i^h)$ are expressed in eq. (5).

$$\begin{cases} D_j^-(a,b_i^h) = \dfrac{g_j(a) - \max\{g_j(a), S_j^1(b_i^h) - d_j^-(b_i^h)\}}{d_j^-(b_i^h) - \max\{S_j^1(b_i^h) - g_j(a), v_j^-(b_i^h)\}} \\ D_j^+(a,b_i^h) = \dfrac{g_j(a) - \min\{g_j(a), S_j^2(b_i^h) + d_j^+(b_i^h)\}}{-d_j^+(b_i^h) - \max\{-S_j^2(b_i^h) + g_j(a), v_j^+(b_i^h)\}} \end{cases} \tag{5}$$

From these partial discordance indexes, the comprehensive discordance index is defined in the following way:

$$D_I(a,b_i^h) = 1 - \prod_{j=1}^{n} (1 - D_I(a,b_i^h))^{w_j^h} \tag{6}$$

With theses indexes, we can assign an action to pre-defined categories by the analysis of the fuzzy relations.

III. Photonic-crystal fibre modelling

In this section, we explain our reasoning to design the PCF. In order to design a fibre, we start by building database (training and test).We have elaborated a training dataset with more then 100 different photonic crystal fibres. Then, we have reconstructed a simulated fibre with a known geometri

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cal characteristics (core diameter, distance between two holes, cladding dimension…) and unknown optical characteristics. After that, we applied the fuzzy classification method in order to obtain the optical characteristics. In fact, the classification procedure POAFTN is based on the fuzzy indifference relation between a fibre to model and the training fibre data. By means of the assignment decision, we can have an idea about the optical characteristics. To model a photonic crystal fibre, we start from the structure of the fibre (the geometrical proprieties), we can calculate the optical properties as the chromatic dispersion .With the optimization of these proprieties, we are able to control the structure of the PCF fibre to be designed. As stated above, the photonic crystal fibre model can be finalized with the simulation. To model a PCF fibre, we proceed by the following steps. We consider a simulated fibre with defined geometrical characteristic and undefined optical characteristic using the training dataset and the classification procedure; we can classify this fibre to a category of photonic crystal fibres (for example the large mode PCF fibre…). We can evaluate the fuzzy indifference relation between a fibre to design and the prototypes and through assignment decision; so we can have an idea about the fibre model. In order to model PCFs, we have developed software tool based on a the fuzzy classification algorithm. This tool makes it possible to classify a fibre to any categories of photonic crystals fibres (large mode fibres, maintaining polarization fibres...). Aiming at analyzing optical characteristics of these fibres, we defined and measured the fuzzy indifference relations between a fibre to model and the prototype. In an index-guiding PCF, the average index of the cladding is smaller than the core index because of the presence of air holes. In fact, the existence of air holes decrease the cladding index and the fibre can guide the light by total internal reflection. Particularly, the propagated light has an effective index n_{eff} that satisfies the following condition (8).

$$n_{co} > n_{eff} = \frac{\beta}{k_0} > n_{FSM} \tag{7}$$

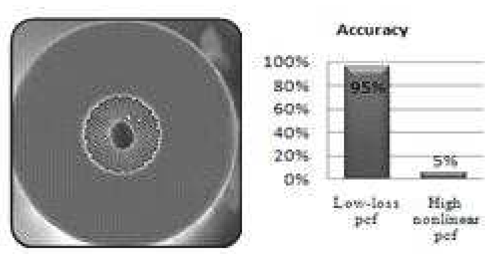
where β is the propagation constant, n_{co} is the core index, and n_{FSM} is the cladding effective index of the FSM (Fundamental Space-filling Mode). The core index n_{co} is reduced to the index of silica. Contrary to index guiding PCFs and conventional ûbers, the core of the photonic bandgap fibres has a lower refractive index than the effective index of the surrounding microstructured cladding. Similarly, to electronic bandgaps of semiconductors, the cladding exhibits some forbidden wavelength bands. Light incident on the cladding structure with wavelengths within the bandgap of the structure will be reûected since they are not allowed to propagate in the cladding. Therefore all wavelengths within the bandgap will be trapped in the low index core [28]. The chromatic dispersion can be easily controlled by varying the hole diameter and the pitch. The chromatic dispersion control in PCFs is a very important for practical applications to optical communication systems, nonlinear optics and dispersion compensation. In fact, until now diverse PCFs with extraordinary dispersion properties have been experimentally examined and numerically studied. The dispersion characteristics of PCFs are investigated by taking into account the refractive index of pure silica by means of the sellemier formula. The chromatic dispersion D is given as:

$$D = -\frac{\lambda}{c}\frac{d^2 n_{eff}}{d\lambda^2} \tag{8}$$

where n_{eff} is the effective index of the fundamental mode. The dispersion curve is near to the material dispersion of pure silica when the pitch is large and the relative air hole size is very small. In fact, the influence of waveguide dispersion becomes more important since the hole diameter d is increased. We can remark that it is possible to shift the zero dispersion wavelength to visible to near-infrared (IR) regions by appropriately changing the geometrical parameters such as pitch and hole diameter d. Consequently, a PCF with a large hole diameter and very small pitch has large normal dispersion in the 1.55µm wavelength range. Theoretically, the fibre with an inûnite cladding structure is considered as a fibre with leakage-free. Conûnement derives from the ûnite width of the cladding structure. The large negative waveguide dispersion around 1550 nm can be achieved by letting the ûeld penetrate into the cladding region, which in turn gives rise to increased conûnement loss. So, low conûnement loss can be achieved for small core Photonic Crystal Fibres by designing the ûber with at least 6 rings of air holes. In addition, increasing the number of air hole rings reduced conûnement loss. In fact, we can also diminish the conûnement loss rate by doping the core to reach a stronger mode confinement.

IV. Results

We have tested the validity of this method. The fuzzy classification is able to classify PCFs using our dataset and allows a new fibre structure modeling with specific optical proprieties. As an example, we propose an index-guiding fibre as shown in figure 1. This fibre displays a hexagonal array of air-holes in the cladding with solid-core area. This PCF has been analyzed. For this PCF structure, the hole diameter is d=10.12µm and the distance between two holes (pitch) is Λ=23.2µm. In fact, the core diameter of this fibre is large R=35µm. So, the PCF structure is optimized for single mode operation in the telecom wavelength range. This fibre is characterized with a large effective mode field area ~ 530µm^2 and low loss rate.



(a) Thorlabs HC19-532 - Hollow Core PCF

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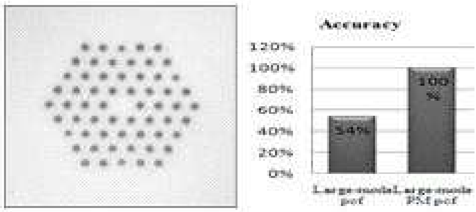
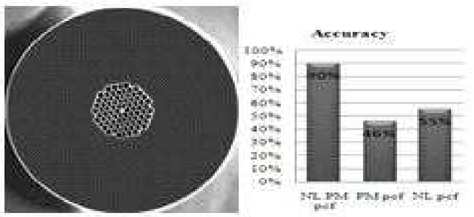


(b) Crystal-Fibre Large Mode Area PCF LMA-PM-5

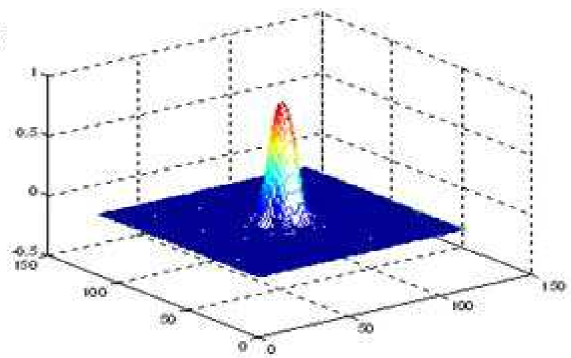


(c) Thorlabs NL-PM-750 - Highly Nonlinear PM PCF

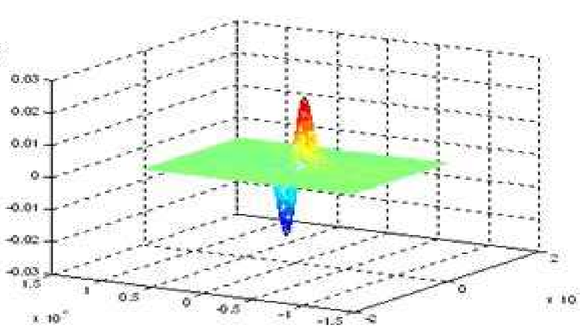
Figure 1. Accuracy results for showed PCFs

The advantage of the photonic crystal fibre HC-19-532 (fig. 1.a) is a low loss rate transmission. This fibre is classified to the class of low loss PCF fibre with 95% of accuracy. So, we have confirmed that this fibre is a member of the category of low loss fibre. Figure 1 (b) shows another example of the tested PCF fibres. This large core polarization maintaining photonic crystal fibre is optimized for single-mode operation in the UV to 800 nm wavelength range and it is an endlessly single mode fibre. The fuzzy classification shows that this fibre is large mode polarization maintaining fibre. For this kind of PCF, we obtained a high membership scores to the large mode PM PCF, in the same time it is a member of the large mode PCF fibre. So, for the same fibre, we can have two characteristics or more of the classified fibre and this fibre can be assigned to two classes. The obtained results for the NL-PM-750 confirm that this fibre is a high nonlinear polarization maintaining fibre with a 90% rate of accuracy (fig. 1.c).

(a)



(b)



(c)

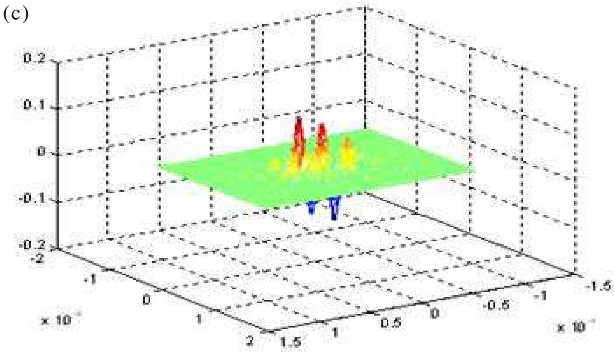


Figure 2. Magnetic ûeld distributions at 1550 nm: (a) Mode 1; (b) Mode 3; and (c) Mode 10

For the wavelength 1550nm, the total chromatic dispersion (we consider waveguide dispersion and also material dispersion) is around 25ps/km/nm. The chromatic dispersion is influenced by the PCF geometrical properties. In fact, the dispersion curve is near to the material dispersion of pure silica, when the hole diameter to pitch ratio is very small and the pitch is large. While the hole diameter is increased, the influence of waveguide dispersion becomes stronger. Consequently, we can shift the zero dispersion wavelength to visible to near-infrared (IR) regions by accurately changing the geometrical parameters for example the pitch and hole diameter. Moreover, it is possible to design a PCF with a large normal dispersion in the 1.55µm wavelength range, simply by having a very small pitch and the a large hole diameter. Figure 2 shows the 3D magnetic field component of the modes 1,3 and 10 at the wavelength of 1550nm. The modes of the PCF are labeled by the step-index analogs. So, the mode pairs 1, 2 represented by (HE_{11}) the mode pairs 4, 5 (HE_{21}) and the pairs 8, 9 (EH_{11}) are considered as degenerated modes. It is deduced that the modes 3, 6, 7, and 10 are non-degenerate pairs. These modes correspond respectively to TE01, TM_{01}, HE_{311}, and HE312.

Conclusions

In this study, we have presented a fuzzy classification algorithm for photonic-crystal fibres (PCF) modeling and optimization. In this approach, the decision is made using a training dataset of existing and commercialized PCFs. Specific optical properties were analyzed and a special interest was given to the chromatic dispersion, one of the most important optical proprieties for many high bit-rate communication applications. As an application, we have presented index-guiding fibres with manipulated chromatic dispersion using the appropriate modification of the geometrical parameters. The application of a fuzzy classification was successful and optical properties of simulated PCFs were presented.

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