Genetic algorithm: a solution to design photonic crystal fibers

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Abstract: The optimization of the design of photonic crystal fiber by genetic algorithm is demonstrated for the first time. It is shown how the combination of this inverse problem approach with a full vectorial finite element method enables to reach user-defined propagation property. The definition of a fiber geometry enabling near-zero flat dispersion over a wide wavelength range is performed as an illustration of the possibilities offered by this approach.

1. Introduction

Photonic Crystal Fibers (PCF) have generated a lot of interest because of their unusual and very attractive optical properties. They are usually made of silica with a regular array of air-holes running along the length of the fiber acting as a cladding. A defect (in our case a missing hole) acts as a core. For instance, it is possible to produce PCF with very high birefringence [1], to get a single-mode fiber with anomalous dispersion regime in the visible wavelength domain [2, 3], or to obtain fibers with very flat near zero chromatic dispersion curve on a large wavelength range [4, 5, 6]. All of these properties are related to the fiber design, namely, the pitch (Λ) of the periodic array, the holes radius (r) and the number (N) of rings around the core. The optimization of PCF design is often difficult due to the fact that the optical properties do not usually vary in a simple way with the fiber geometry parameters. This difficulty increases exponentially with the numbers of variables of the problems (Λ, N, different r and different materials that can be allowed in the same structure etc…) and with the number of properties that have to be considered (chromatic dispersion, slope of this dispersion, confinement losses etc…). The design optimization is mostly performed by trial and test approach. This is a time consuming approach, both for the computer and the designer who has to interact regularly with the output of the calculation to design a new test fiber. It is proposed here to apply the Genetic Algorithm (GA) method to solve the inverse problem, i.e. to determine the PCF structure starting from the optical characteristic required for a given application. As the chromatic dispersion is a key parameter for many applications, this study was focused on the determination of the PCF structure that can lead to the minimum dispersion over a large wavelength range.

2. Genetic algorithm and photonic crystal fibers (PCF)

Genetic Algorithms (GAs) have been first introduced by Holland in 1975 [8] and they are now applied to several fields in physics for which the resolution of inverse problem is needed [7-10]. This GA is stochastic global search method that uses a direct analogy with the laws of nature: GA operates on a population of potential solutions applying the principle of survival of the fittest to produce better approximations to a solution. At the first generation, a population of "individuals" is randomly created, each individual being a possible solution to the problem. In the particular case of this study, each individual correspond to a particular design of PCF. Each individual is made of 2 "chromosomes" $\{\Lambda,r\}$ which constitute the variables of the problem, Λ being the pitch and r the hole radius. The individuals are then ranked as a function of their "fitness" which is a measure of how well the solution agrees with the requirements, the requirements being for example a given dispersion curve. The fitness is converted into a probability of reproduction and then, the individuals that better fit the requirements (the ones with the highest probability) are conserved and combined together for the creation of the next generation. Mutation processes are also implemented at each generation. As in nature, mutation consists of modifying randomly a chromosome. The individual who has mutated is conserved in the case of a better adaptation to the environment (better dispersion curve).

3. Description of the modeling

The characteristic of the individual chosen here is the chromatic dispersion curve in the spectral range from 1 μm to 1.7 μm. This dispersion curve is labeled $D(\lambda)$ and is calculated using the set of chromosomes $\{\Lambda,r\}$. Note that the number of rings has been fixed for each case. For the simulation, the air-holes of the PCF structure were assumed to be circular and regularly spaced on a hexagonal array. Background is pure silica. The fitness of each individual is directly related to an error function J which has to be minimized to find the best solution. The error function used is given in Eq. (1):

$$J = \sqrt{\sum \left(D_{target}(\lambda) - D(\lambda)\right)^2} \quad (1)$$

Where $D_{target}(\lambda)$ is the chromatic dispersion at the wavelength λ that has to be reached. $J = 0$ corresponds in this case to an exact solution. Calculation of the chromatic dispersion is achieved using a Finite Element Method (FEM). At the first generation, the structure of each individual is generated with a randomly chosen pitch and radius. A mesh is then generated using standard triangle elements and a full vectorial analysis of the electromagnetic field is achieved in the generated PCF. The determination of the effective index of modes is obtained by solving the eigenvalue Helmholtz equation. The resolution of this equation as a function of the wavelength allows the determination of the chromatic dispersion using Eq. (2). The spectral dependence of the refractive index of the material was assumed to follow the Sellmeier formula for fused silica.

$$D(\lambda) = -\frac{\lambda}{c}\frac{dn_{eff}^2}{d\lambda^2} \quad (2)$$

4. Results

In order to test the validity of this method, a first PCF structure was generated and its dispersion curve calculated. The following parameters have been used: 2.10 µm for the pitch and 0.95 µm for the holes radius. These parameters correspond to a real fiber but with an idealized structure (regular hexagonal array of perfectly circular air holes). The targeted dispersion curve corresponds to that of this idealized fiber. The ring number was fixed to 3 in order to limit the calculation time. The GA has then been applied to the computed dispersion curve (with a population of 40 individuals) and the resulting structure has been compared to the initial one.

The black line on Fig. 1 represents the target chromatic dispersion curve calculated with the above parameters. Grey curves correspond to the chromatic dispersion as a function of wavelength for the best offspring at the first generation (empty circles) and at the thirteenth generation (empty squares). A good accordance with the target dispersion curve was achieved at the thirteenth generation (with an error function J = 1.91 ps/(nm.km) instead of 135 ps/(nm.km) at the first generation). The resulting PCF structure calculated by the GA proves to be in good agreement with the initial PCF structure since the pitch was found to be equal to 2.12 µm (instead of 2.1 µm) and the holes radius to 0.96 µm (instead of 0.95 µm), leading to a relative error in the order of 1 % as compared to the initial PCF structure. Therefore the GA allows the design of PCF structure with a precision below 1 %. Considering the fabrication problems, there is in practice no meaning to decrease further this relative error by increasing the number of generations. It can also be seen from Fig. 1 that, as it was expected, the convergence increases with the number of generations (and also with the number of individuals considered at the first generation, results not shown).

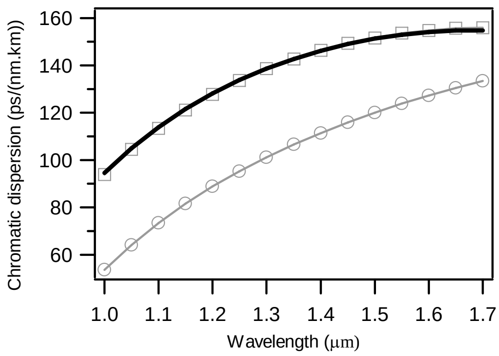

Fig. 1: Chromatic dispersion curves calculated by GA routine for a three rings PCF. Grey curves correspond to the chromatic dispersion for the best offspring at the first generation (empty circles) and at the thirteenth generation (empty squares).

The usefulness of GA was then demonstrated by applying the method to the determination of a PCF structure exhibiting a near-zero flat dispersion from 1 µm to 1.7 µm. As the dispersion properties are strongly related to the number of rings N, it was decided to fix N to 9. This value represents a compromise between the flatness of the dispersion curve over a wide range of wavelength and the time necessary to perform the calculation. Indeed, ultra-flattened dispersion curves around zero have been achieved between 1.24 µm and 1.44 µm using a 7 rings structure and between 1 µm and 1.6 µm by means of a 11 rings structure (which corresponds to 455 air-holes) [4].

According to the results obtained with the 3 rings structure, a population of 40 individuals has been used to perform the simulations. The target dispersion is now the horizontal line of Fig. 2(a) (zero dispersion from 1 µm to 1.7 µm). The black curve (full squares) represents the chromatic dispersion of the best individual after 30 generations. The corresponding hole radius, pitch and error function are respectively r = 0.33 µm, Λ = 2.35 µm and J = 21 ps/(nm.km). Note that as the target dispersion is not a realistic one the J value will never be equal to zero. As a comparison, the grey curve (empty circles) represents the dispersion of a nine rings structure with the parameters of reference [4] (parameters for an eleven rings structure), which gives an error function J equal to 33 ps/(nm.km) in regards to J = 21 ps/(nm.km) with the structure obtained with the GA method. As a matter of fact, it is highly probable that if it had been possible to simulate the eleven rings PCF, a result close to Reeves et al one would have been found. This computation has not been possible yet because of memory limitation.

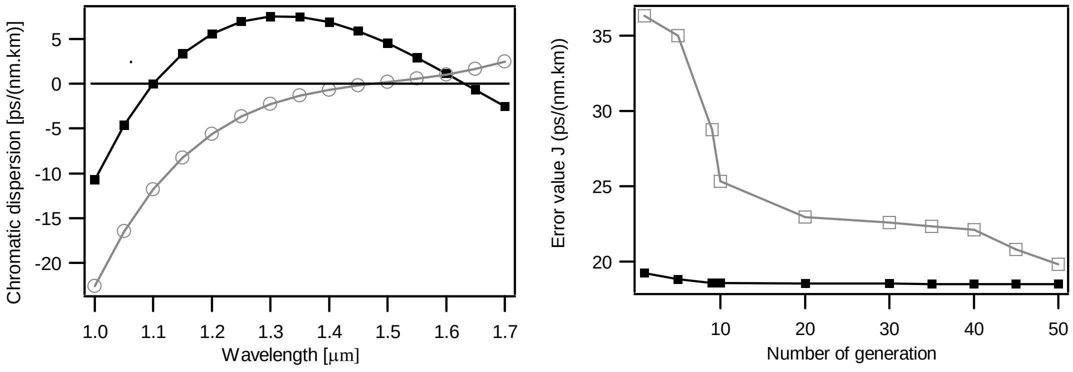

Fig. 2(a): Black curve (filled squares): Chromatic dispersion as a function of wavelength calculated by GA routine for the 9 rings structure. The pitch Λ and the radius r are respectively equal to 2.35 µm and 0.33 µm. Grey curve (empty circles): chromatic dispersion obtained for a 9 ring structure with the following parameters: Λ = 2.59 µm and r = 0.29 µm, corresponding to reference [4]. Fig. 2(b): Evolution of the error function J as a function of the number of generation for a 5 individuals GA calculation (grey curve, empty squares) and for the 40 individuals one (black curve with filled squares)

It is also to note that the convergence of the GA increase with the number of generations but also with the number of individuals considered at the first generation. Fig. 2(b) shows the evolution of the error function J for a 5 individuals GA calculation (grey curve, empty squares) and for the 40 individuals one (black curve with filled squares). As one can see, a faster convergence is obtained for the case of the forty individuals calculation.

5. Conclusion

GA proves to be a powerful tool for optimization of PCF structures in order to obtain target optical properties. Two demonstrations have been realized to obtain PCF structures with a predefined chromatic dispersion: one with a realistic three rings PCF and one with a non-realistic zero dispersion from 1 µm to 1.7 µm. After these first demonstrations, this GA method should prove all its interest by including more than two chromosomes, for instance it is planned to allow different hole radii for each ring, the breaking of the fiber symmetry (for birefringence purpose), the use of different materials… This method also allows us to include more complicated error function that will take into account not only the dispersion curve but also its slope, the fiber confinement loss and other numerous parameters. Other results will be presented at the conference.

1. A. O. Blanch, J. C. Knight, W. J. Wadsworth, J. Arriaga, B. J. Mangan, T. A. Birks, and P. St. J. Russell, “Highly birefringent photonic crystal fibers,” Opt. Lett. **25** (18), 1325 (2000)
2. D. Mogilevtsev, T. A. Birks, and P. St. J. Russell, “Group-velocity dispersion in photonic crystal fibers,” Opt. Lett **23** (21), 1662 (1998)
3. J. K. Ranka, R. S. Windeler, and A. J. Stentz, “Visible continuum generation in air-silica microstructure optical fibers with anomalous dispersion at 800 nm,” Opt. Lett **25** (1), 25 (2000)
4. W.H.Reeves, J.C.Knight, and P.St.J.Russell, “Demonstration of ultra-flattened dispersion in photonic crystal fibers,” Opt. Express **10** (14)**,** 609 (2002) http://www.opticsexpress.org/abstract.cfm?URI=OPEX-10-14-609
5. A. Ferrando, E. Silvestre, J.J. Miret, and P. Andrés, “Nearly zero ultraflattened dispersion in photonic crystal fibers,” Opt. Lett. **25** (11), 790 (2000)
6. A. Ferrando, E. Silvestre, and P. Andrés, J.J. Miret, M.V. Andrés, “Designing the properties of dispersion-flattened photonic crystal fibers,” Opt. Express **9** (13)**,** 687 (2001) http://www.opticsexpress.org/abstract.cfm?URI=OPEX-10-14-609
7. D. Correia, V. F. Rodriguez-Esquerre, and H. E. Hernandez-Figueroa, “Genetic-algorithm and finite-element approach to the synthesis of dispersion-flattened fiber,” Microw. Opt. Techn. Lett., **31** (4), 245 (2001)]
8. J. H. Holland, “Adaptation in Natural and Artificial Systems”, Cambridge, MA : The M.I.T. Press, (1975)
9. F. Zeng, J. Yao,and S.J. Mihailov, “Fiber Bragg-grating-based all optical microwave filter synthesis using genetic algorithm,” Opt. Eng. **42** (8), 2250 (2003)
10. H. Wei, Z. Tong, and S. Jian, “Use of a genetic algorithm to optimize multistage erbium-doped fiber-amplifier systems with complex structures,” Opt. Express **12** (4)**,** 531 (2004) http://www.opticsexpress.org/abstract.cfm?URI=OPEX-12-4-531