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Synthesis of Dispersion-Compensating Triangular Lattice Index-Guiding Photonic Crystal Fibers Using the Directed Tabu Search Method

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Abstract**—**In this paper, triangular lattice index-guiding photonic crystal fibers (PCFs) are synthesized to compensate the chromatic dispersion of a single mode fiber (SMF-28) for an 80 km optical link operating at 1.55 µm, by using the directed tabu search algorithm. Hole-to-hole distance, circular air-hole diameter, solid-core diameter, ring number and PCF length parameters are optimized for this purpose. Three Synthesized PCFs with different physical parameters are compared in terms of their objective functions values, residual dispersions and compensation ratios.

Keywords**—**Triangular lattice index-guiding photonic crystal fiber, dispersion compensation, directed tabu search, synthesis.

I. Introduction

CHROMATIC dispersion of optical fibers is one of the most important parameters for optical communication systems because of its strong influence on high data rate transmission systems. To remedy this problem, specific optical fibers with various dispersion profiles have been proposed for dispersion compensation applications; such as chirped fiber Bragg gratings (FBGs), dispersion compensating fibers (DCFs), photonic crystal fibers (PCFs), etc.

Photonic crystal fibers (PCFs) [1], [2] consisting of a central defect region surrounded by multiple air holes that run along the fiber length are attracting much attention in recent years because of unique properties which are not realized in conventional optical fibers. PCFs are divided into two different kinds of fibers. The first one, index-guiding PCF, guides light by total internal reflection between a solid core and a cladding region with multiple air-holes [3], [4]. On the other hand, the second one uses a perfectly periodic structure exhibiting a photonic band-gap (PBG) effect at the operating wavelength to guide light in a low index core-region [5], [6].

The aim of this work is to synthesize index-guiding PCFs with triangular lattices formed by circular air-holes, by the use of the directed tabu search (DTS) method. A comparison between the synthesized PCFs performances will be made to find the best synthesized dispersion-compensating PCF. Our goal is to minimize the chromatic dispersion of an 80 km optical link by placing the synthesized dispersion-compensating PCFs after a single mode fiber (SMF-28) operating at 1.55 µm. For wavelength division multiplexing (WDM) applications, PCFs should provide large negative dispersion values and a negative dispersion slope over a large wavelength range. Our optimization problem consists in the minimization of the residual dispersion over a wavelength range of 100 nm (1.5µm-1.6 µm).

In this work, the directed tabu search (DTS) is applied for the first time in synthesis and optimization of PCFs physical parameters for dispersion compensation applications. More details about this hybrid method will be presented in Section II of this article. We note that a genetic algorithm, combined with a fully vectorial finite-element solver, has been already presented to design PCFs for broadband dispersion compensation in a generic stretcher–compressor system of an ytterbium fiber laser in [7].

II. Synthesis of Triangular Lattice Index-Guiding PCFs Using the Directed Tabu Search

This section deals with synthesis of physical parameters of index-guiding PCFs characterized with triangular lattices and circular air holes. This kind of PCFs is reconstructed with a negative chromatic dispersion that should reduce the positive chromatic dispersion that occurs from a single mode fiber. Let us take an example of a standard SMF-28™ that provides a positive dispersion of 1390.2 ps/nm.km at the 1.55 µm wavelength for an 80 km optical link. This fiber has a positive dispersion slope S_0 of 0.092 ps/ nm^2.km and a zero-dispersion value at λ_0= 1.3115 µm. The SMF-28™ dispersion approximately equals to [8]

$$D_{SMF}(\lambda) \approx \frac{S_0}{4}\left[\lambda - \frac{\lambda_0^4}{\lambda}\right] \tag{1}$$

Our optimization problem consists then in the minimization of the residual dispersion over a wavelength range that extends from λ=1.5 µm to λ=1.6 µm. The objective function (residual dispersion) can be written as

$$ObjectiveFunction = D_{SMF}(\lambda)\times L_{SMF} + D_{PCF}(\lambda)\times L_{PCF} \tag{2}$$

where L_{SMF} equals to 80 km.

To reconstruct a PCF with a negative dispersion value and a negative dispersion slope, the directed tabu search (DTS) is applied to synthesize four physical parameters of this device: hole-to-hole distance, Λ (or pitch), air-hole diameter, d (or air-

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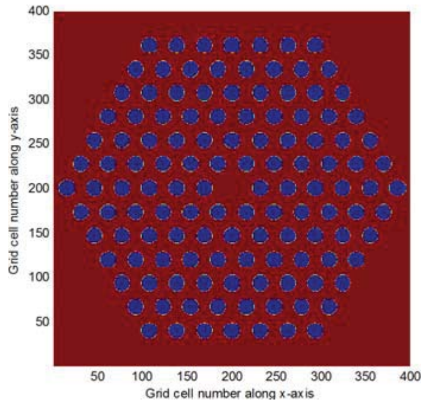
filling fraction, d/Λ), solid-core diameter, d_{co} and ring number, N_r. We note that the synthesized negative dispersion is obtained for a 1 km PCF length. The SMF-28 positive dispersion value is perfectly compensated at the 1.55 µm wavelength by adjusting the PCF length L_{PCF}, according to the synthesized negative dispersion value and a zero residual dispersion at the operating wavelength.

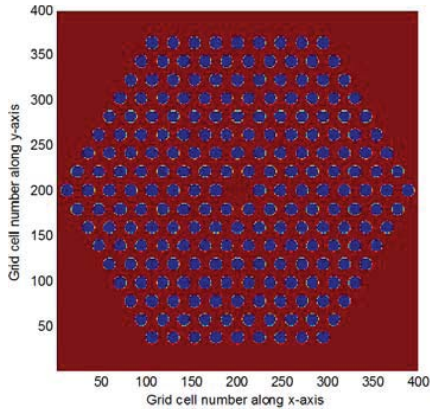
The directed tabu search (DTS) method has been chosen for synthesis according to their good performances previously demonstrated in [9], [10]. This method has been for the first time described in [11]. It has been applied to estimate thermo-optic coefficient and thermal expansion coefficient of a chirped fiber Bragg grating [9], the hybrid tabu search algorithm has been also used to optimize strain profiles of a sampled Bragg grating [10]. The performances of this method have been compared with those of other hybrid metaheuristics in [9], [10]. DTS has given the best objective function with a minimum evaluation function number. This comparison has proved that DTS is advantageous in higher dimensional systems.

DTS is a memory-based hybrid algorithm, it uses the Adaptive Pattern Search (APS) based on the Approximate Descent Direction (ADD) and the Nelder-Mead (NM) search in its exploration search as neighborhood-local search strategies to generate trial points. The Nelder-Mead algorithm is used in the DTS intensification part as a local search strategy to refine the best solutions visited so far. A Tabu List (TL) is introduced to save and rank solutions due to their recency and their objective function values. Therefore, some positions in the TL are kept for the best visited solutions, which helps an intensification scheme to refine the search from these best solutions at the final stage. Around each solution saved in the TL, two types of regions are specified in the search space. The first one is a Tabu Region (TR) in which no new trial point is allowed to be generated. The other is a Semi-Tabu Region (Semi-TR) that comprises a surrounding region around TR. The main role of the Semi-TRs is to generate neighboring trial points in a special way so that returning back to a visited TR is avoided when the trial solution lies inside a Semi-TR.

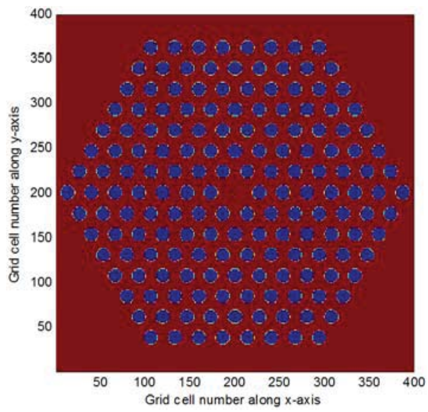
Fig. 1 illustrates the cross-section of three synthesized triangular lattice solid-core PCFs showing the core and cladding permittivity, ε, distribution. We have chosen only three PCFs, the best optimized, after several simulation trials using the DTS. These PCFs will be compared between them according to their synthesized physical parameters, objective function values, residual dispersions, compensation ratios and PCF-to-SMF length percentages. We note that the air-holes are periodically distributed along the x and y axes and homogeneously distributed along the z-axis. We consider only a Transverse Magnetic (TM) propagation mode, therefore, the electric field E_z is propagating according to the z-axis direction, while the magnetic fields H_x and H_y are propagating along the x-axis and y-axis directions, respectively. We remark from Fig. 1 that the pitch, the air-hole diameter, the solid-core diameter and, consequently, the air-holes number are different for each synthesized PCF. In our work, the Finite Difference Time Domain (FDTD) method is used for analysis of the PCFs. This method is an approach that directly solves Maxwell's equations by a proper discretization of both time and space domains. Since PCFs are considered as two-dimensional photonic crystals, the PCF cross-section is divided into several grid cells along x and y axes. The grid cell number is taken to 400 along each axis (see Fig. 1), while the total number of time steps equals to 4000.



(a) Λ= 0.51 µm; d/Λ= 0.56; d_{co}= 0.73 µm; N_r= 6



(b) Λ= 0.39 µm; d/Λ= 0.56; d_{co}= 0.56µm; N_r= 8



(c) Λ= 0.44 µm; d/Λ= 0.56; d_{co}= 0.63 µm; N_r= 7

Fig. 1 Core and cladding permittivity distribution of three synthesized triangular lattice solid-core PCFs

It has been already demonstrated that triangular PCFs are endlessly single mode, where only the fundamental mode is guided for any wavelength, if their air-filling fraction, d/Λ, is lower than 0.406 [12], [13]. However, since all synthesized air-filling fractions are higher than this value, it is evident that these PCFs present higher-order modes.

Table I recapitulates the numerical simulation results that concern the three synthesized dispersion-compensating PCFs already presented in Fig. 1. We note that the apparition order in Fig. 1 is respected in Table I.

It has been demonstrated in [8] that when the pitch value Λ is lower than 1µm, the chromatic dispersion value of triangular PCFs is always negative over any wavelength range. Since the synthesized hole-to-hole distances values are all lower than 1 µm, the three PCFs present negative dispersion values over the wavelength range 1.5 µm-1.6 µm. We remind that the aim of this study is to minimize the residual dispersion value over this wavelength range. Since the optical signal attenuation is the lowest at the 1.55 µm wavelength we will be interested to present the optimized PCFs numerical simulation results at this operating wavelength. For that, we take a SMF of 80 km operating at 1.55 µm (third window).

We remark from Table I that DTS has given the lowest objective function value for PCF1, if we place PCF1 after the SMF we still have a residual dispersion of -5.27 ps/nm at 1.55 µm. PCF3 has given the best residual dispersion (-1.43 ps/nm) at the operating wavelength. We note that the PCF dispersion is synthesized for a 1 km PCF length. The residual dispersion will be perfectly minimized at 1.55 µm when the exact PCF length is determined from the residual dispersion relationship as

$$L_{PCF} = D_{SMF}(1.55) \times L_{SMF} / D_{PCF}(1.55) \tag{3}$$

where L_{SMF}=80 km and D_{SMF} (1.55) =1390.2 ps/nm.

By using (4), we find that the corresponding PCF1, PCF2 and PCF3 lengths are 0.9962 km, 1.0024 km and 0.9989 km, respectively, which gives a PCF-to-SMF length percentage of 1.245%, 1.253% and 1.248%, respectively.

In WDM applications, the positive dispersion and the positive dispersion slope of a SMF should be at the same time compensated by a PCF negative dispersion and a PCF negative dispersion slope. To verify this aspect, the compensation ratio (CR) will be calculated. CR(λ) is the fraction of the SMF dispersion which the PCF compensates at a wavelength λ, that is [8],

$$CR(\lambda) = \frac{D_{SMF}(\lambda)}{D_{SMF}} \times \frac{D_{PCF}}{D_{PCF}(\lambda)} \tag{4}$$

Fig. 2 illustrates the CR plot of the three synthesized PCFs. We remark from this figure that the best compensation ratio is obtained for all reconstructed PCFs at the operating wavelength (CR (1.55) =1). Since PCF1 presents the highest residual dispersion average and maximum error, we remark from Fig. 2 that PCF1 presents the highest CR values when it is compared with PCF2 and PCF3. We note that PCF2 presents the minimum residual dispersion average error over the operating wavelength range.

Fig. 3 illustrates the dispersion curves of the three synthesized triangular lattice solid-core PCFs. We note that the chromatic dispersion (CD) is calculated from the real part of the complex effective index, n_{eff}, as [14];

$$CD(\lambda) = -\frac{\lambda}{c} \times \frac{d^2 \operatorname{Re}(n_{eff})}{d\lambda^2} \tag{5}$$

where c is the velocity of light in vacuum.

TABLE I
NUMERICAL SIMULATION RESULTS OF THREE SYNTHESIZED DISPERSION-COMPENSATING PCFS

	Λ= 0.51 µm; d/Λ= 0.5688; d_{co}= 0.73 µm; N_r= 6 PCF1	Λ= 0.39 µm; d/Λ= 0.5641; d_{co}= 0.56µm; N_r= 8 PCF2	Λ= 0.44 µm; d/Λ= 0.5662; d_{co}= 0.63 µm; N_r= 7 PCF3
Objective function value	4.07×10^2	5.90×10^2	6.11×10^2
Residual dispersion (nm)	-5.27	3.37	-1.43
PCF-to-SMF length (%)	1.245	1.253	1.248
Residual dispersion average and maximum error	-1.83/8.83	-1.01/7.25	-3.47/7.18

We remark from Fig. 3 that PCF1, PCF2 and PCF3 present negative dispersion values and negative dispersion slopes over the wavelength range 1.5 µm-1.6 µm. We can conclude that the three synthesized PCFs are suitable for dispersion compensation in WDM transmission systems.

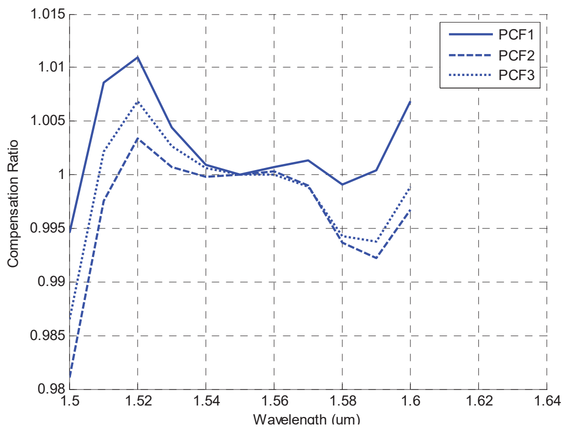


Fig. 2 Compensation ratio of the three synthesized triangular PCFs

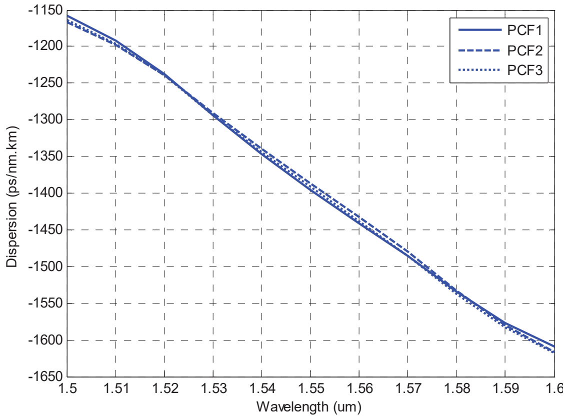


Fig. 3 Dispersion of the three synthesized triangular PCFs

III. Conclusion

In this paper, three synthesized dispersion-compensating triangular lattice index-guiding PCFs have been compared according to their objective function values, residual dispersions and compensation ratios. The directed tabu search (DTS) has been used to synthesize the pitch, the circular air-hole diameter, the solid-core diameter and the ring number. We note that all synthesized PCFs are not endlessly single mode; they present other higher-order modes according to their cutoff conditions. We note that a PCF-to-SMF length percentage of only 1.25 % has been obtained to compensate the chromatic dispersion of an 80 km optical transmission link. In a single mode transmission system centered on 1.55 µm, PCF3 is considered as the best dispersion compensating fiber with a residual dispersion of -1.43 ps/nm.km, despite it was reconstructed with the highest objective function value, while PCF2 is the best dispersion compensating fiber in a WDM transmission system because it presents the minimum residual dispersion average error over the whole operating wavelength range 1.5 µm-1.6 µm. We mention that the three synthesized PCFs present the best compensation ratio (CR=1) at the 1.55 µm wavelength.

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